Fast, Low Noise Photodetectors for Nuclear Physics

Principal Investigator

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Program Goals

To develop high gain, low noise, compact CMOS based silicon photomultipliers as optical detectors for scintillation studies in nuclear and particle physics experiments. These sensors can be formatted as large area discrete devices, multi-element arrays, and can be fabricated to possess position sensitivity. These solid-state photomultipliers (SSPMs) will compete with PMTs as photodetectors in scintillations spectroscopy and calorimeter applications.

Motivation to Replace PMTs

PMTs possess high gain (10^6) and low noise (ENF ~ 1) but…

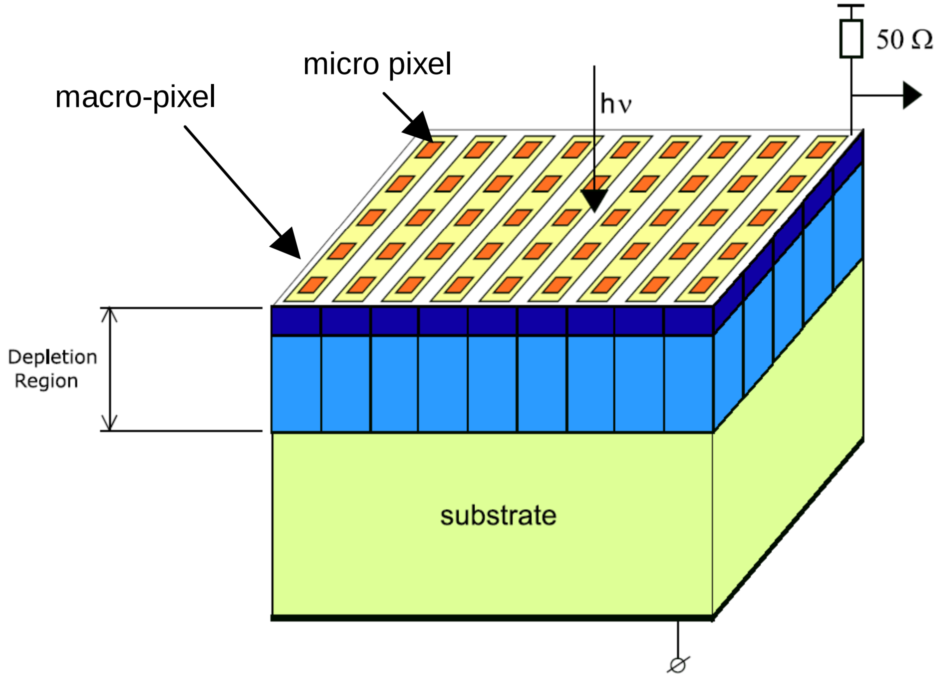
- **PMTs are bulky and fragile**
- **PMTs are sensitive to magnetic fields**
- **PMTs require high bias (~1000 V)**
- **PMTs have low quantum efficiency**
- **Spectral response of PMTs is narrow**
- **Red response of low noise PMTs is poor**

Solid-State Photomultipliers

General SSPM main features

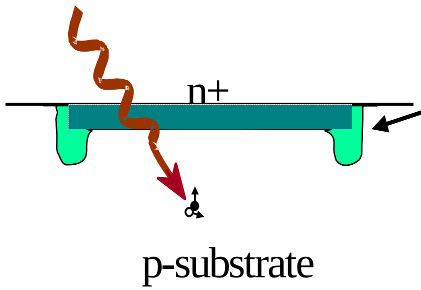
- Very high gain (>10^5), very simple electronic readout
- Low bias operation (~30 V)
- Fast response (sub-ns rise time)
- Very low excess and electronic noise (<1 electron level)
- Dark noise a problem at very low light levels
- Insensitive to magnetic fields
- Position sensitive structures possible
- RMD fabricates these devices by CMOS process, hence cost should be very low upon mass production.
- On-chip integration of readout electronics possible

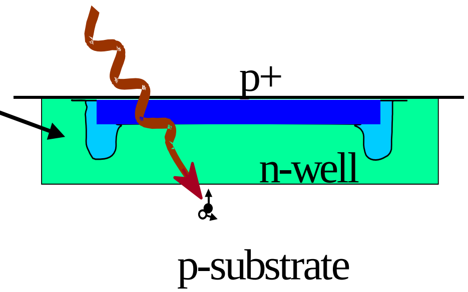
MRS Silicon Photomultiplier



- Independent Geiger Mode Micro-APDs (~ 30 μm)
- Binary output, constant amplitude
- Passively quenched
- Common substrate, signals are summed
- Single analogue output

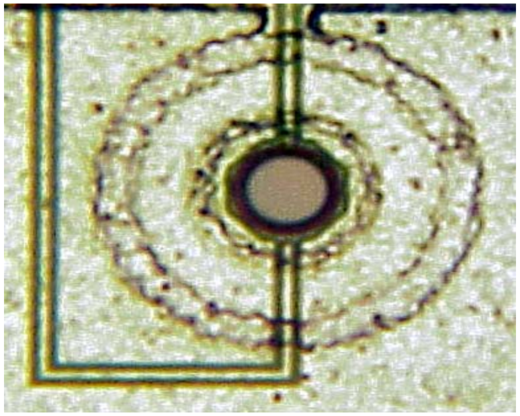
CMOS SSPM Micro-Pixels

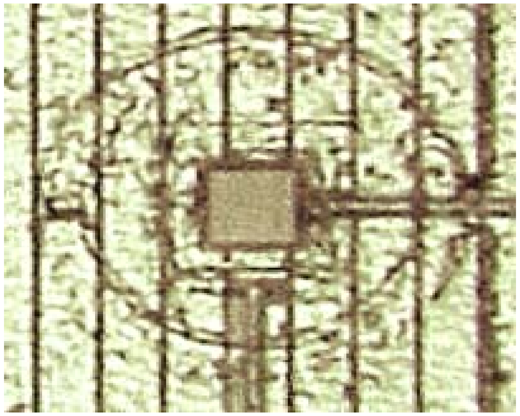




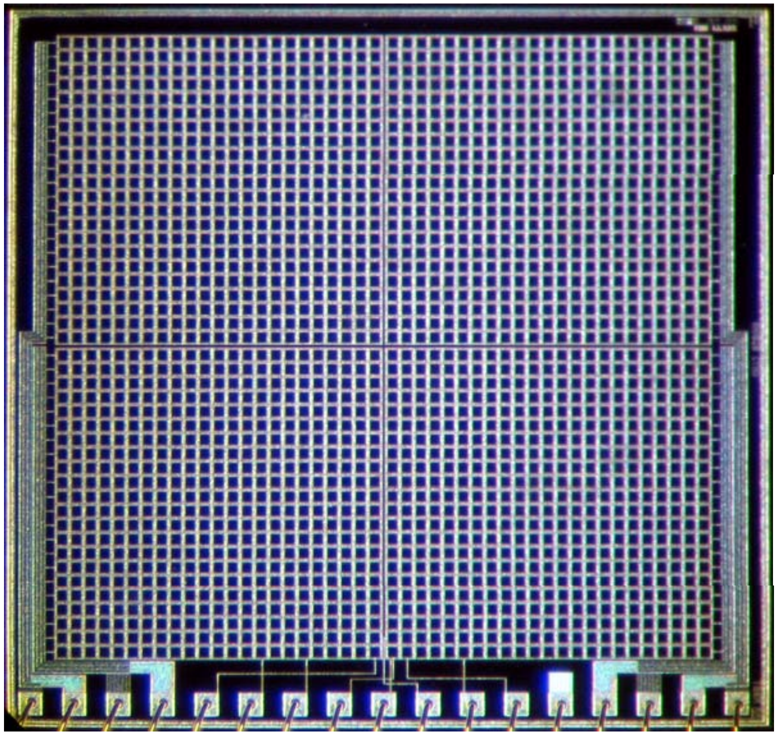
Design 1 (n-on-p) deep

Design 2 (p-on-n) shallow, but isolated from substrate

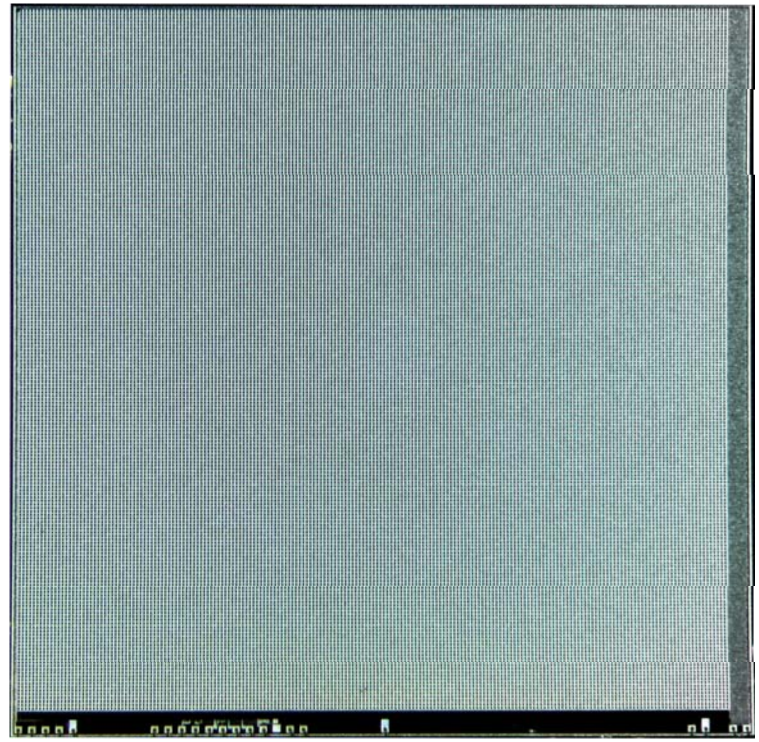




CMOS SSPMs



3 x 3 mm^2 area
50 micron pixels
61% fill factor



10 x 10 mm^2 area
30 micron pixels
49% fill factor

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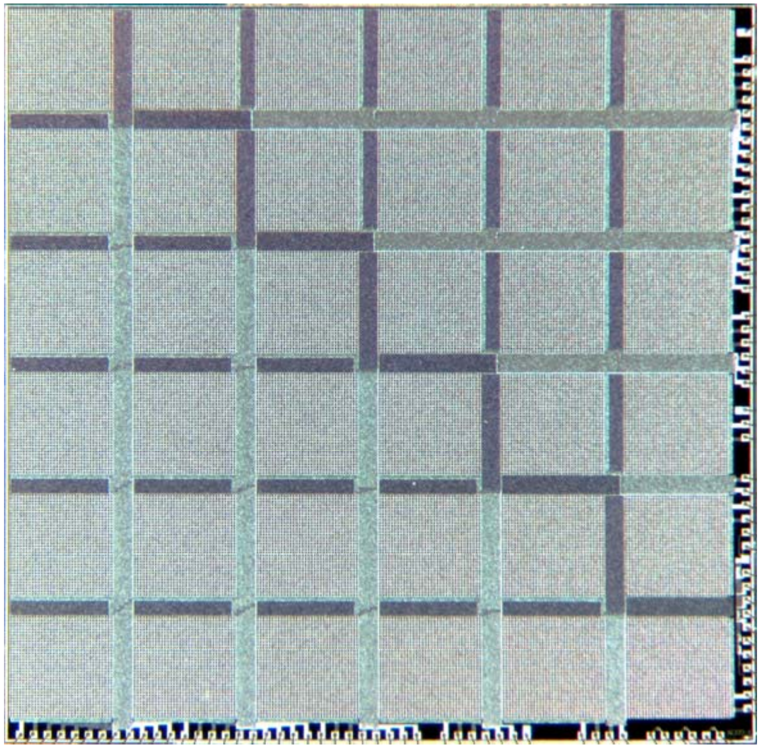
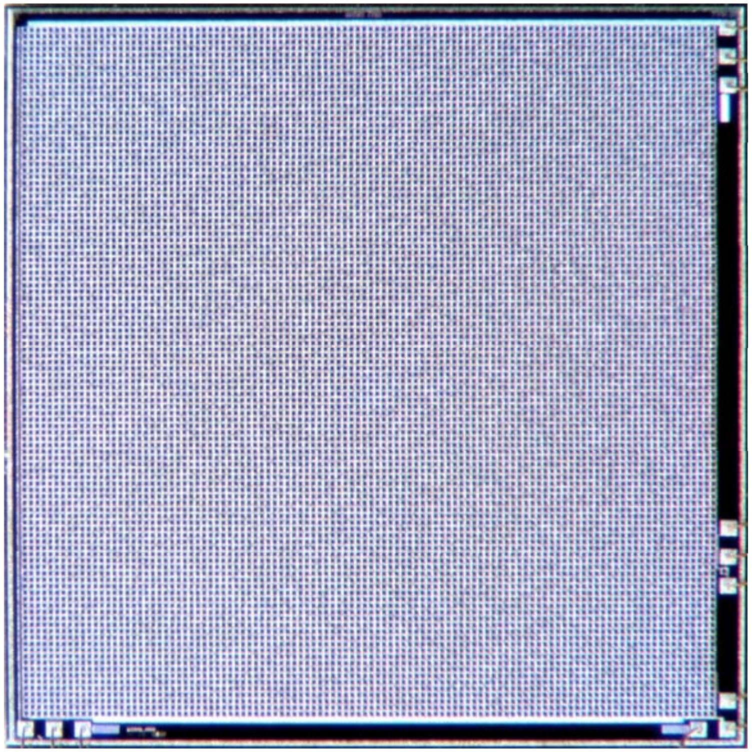
CMOS SSPMs

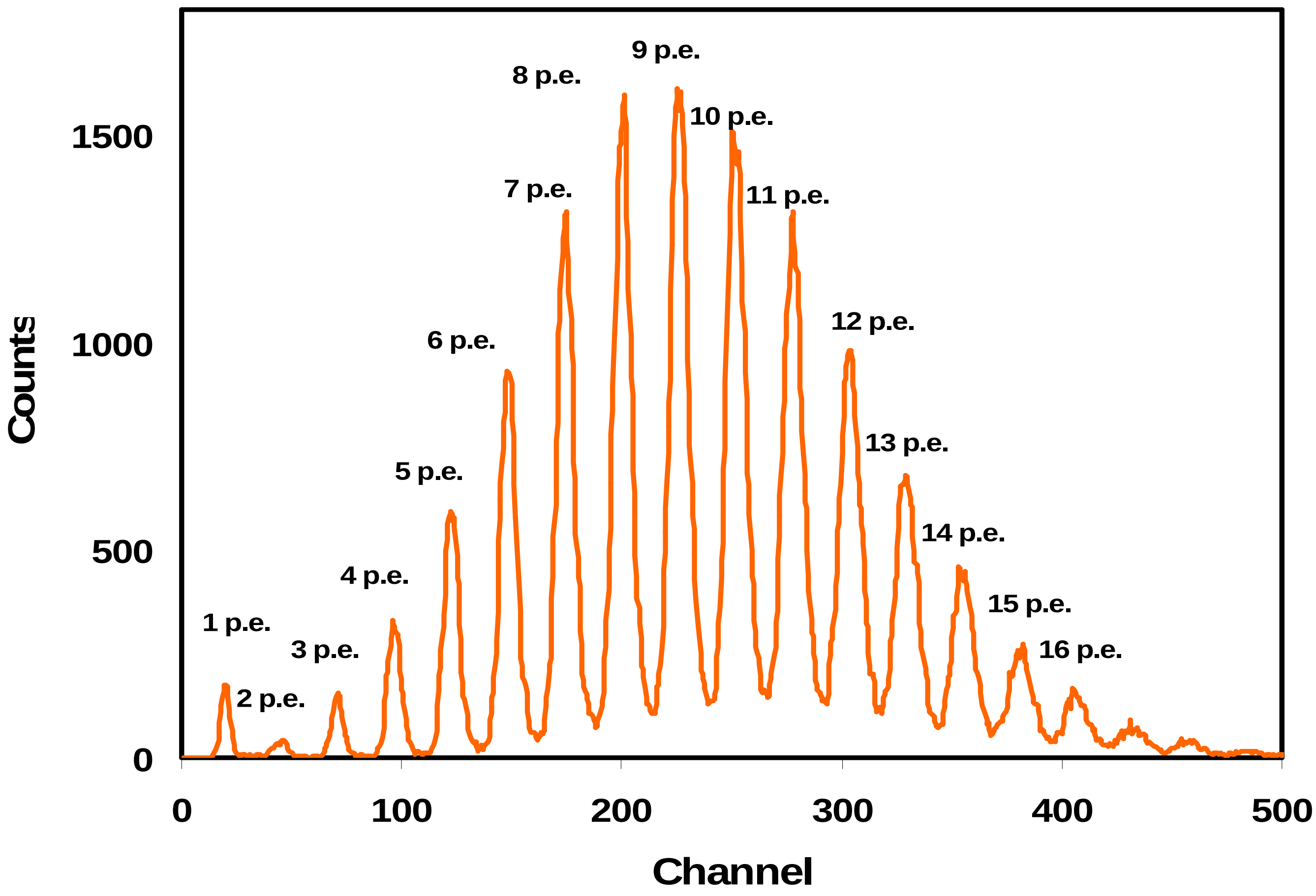


6 x 6 SSPM Array

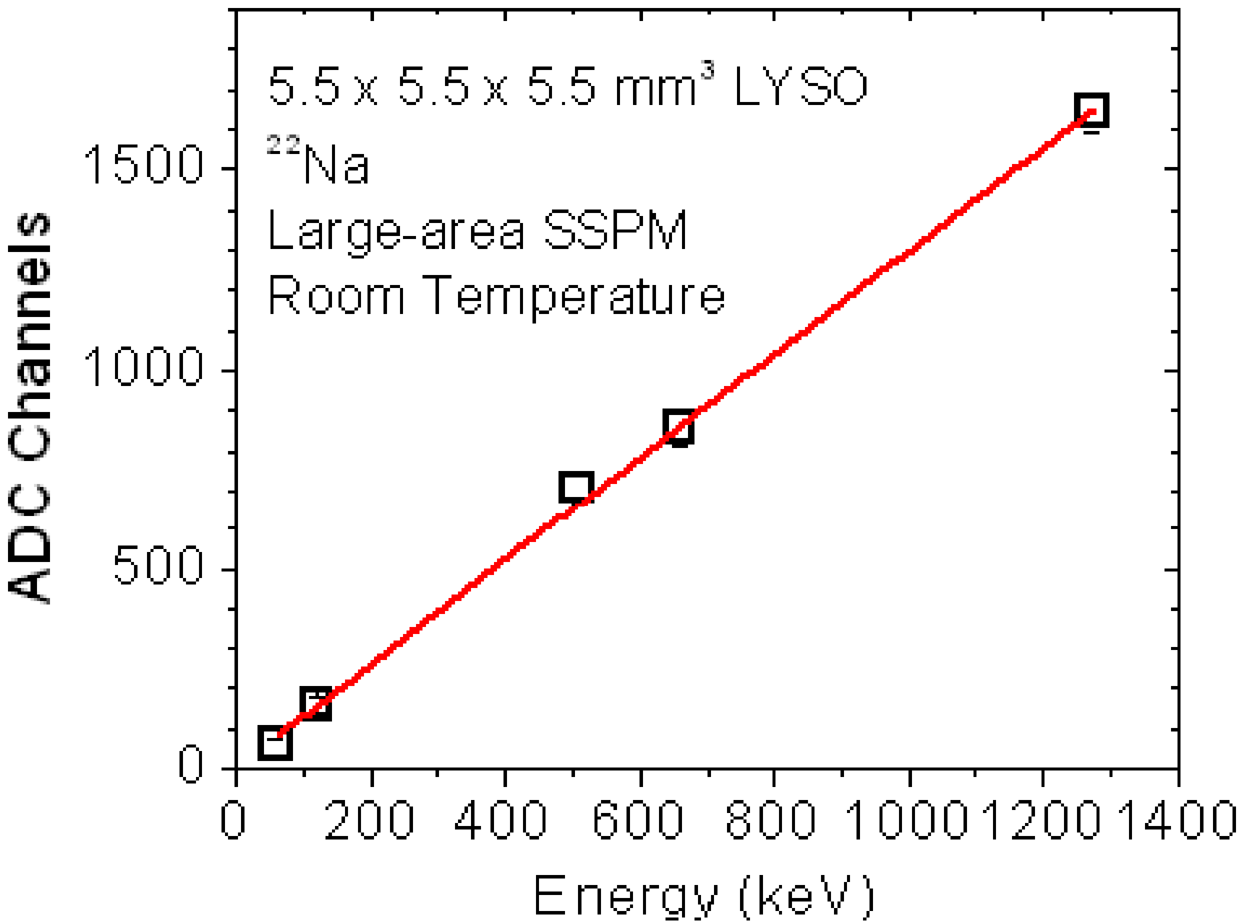


5 x 5 mm^2 PS-SSPM

SSPM Single Photon Sensitivity



1 cm^2 SSPM Linearity



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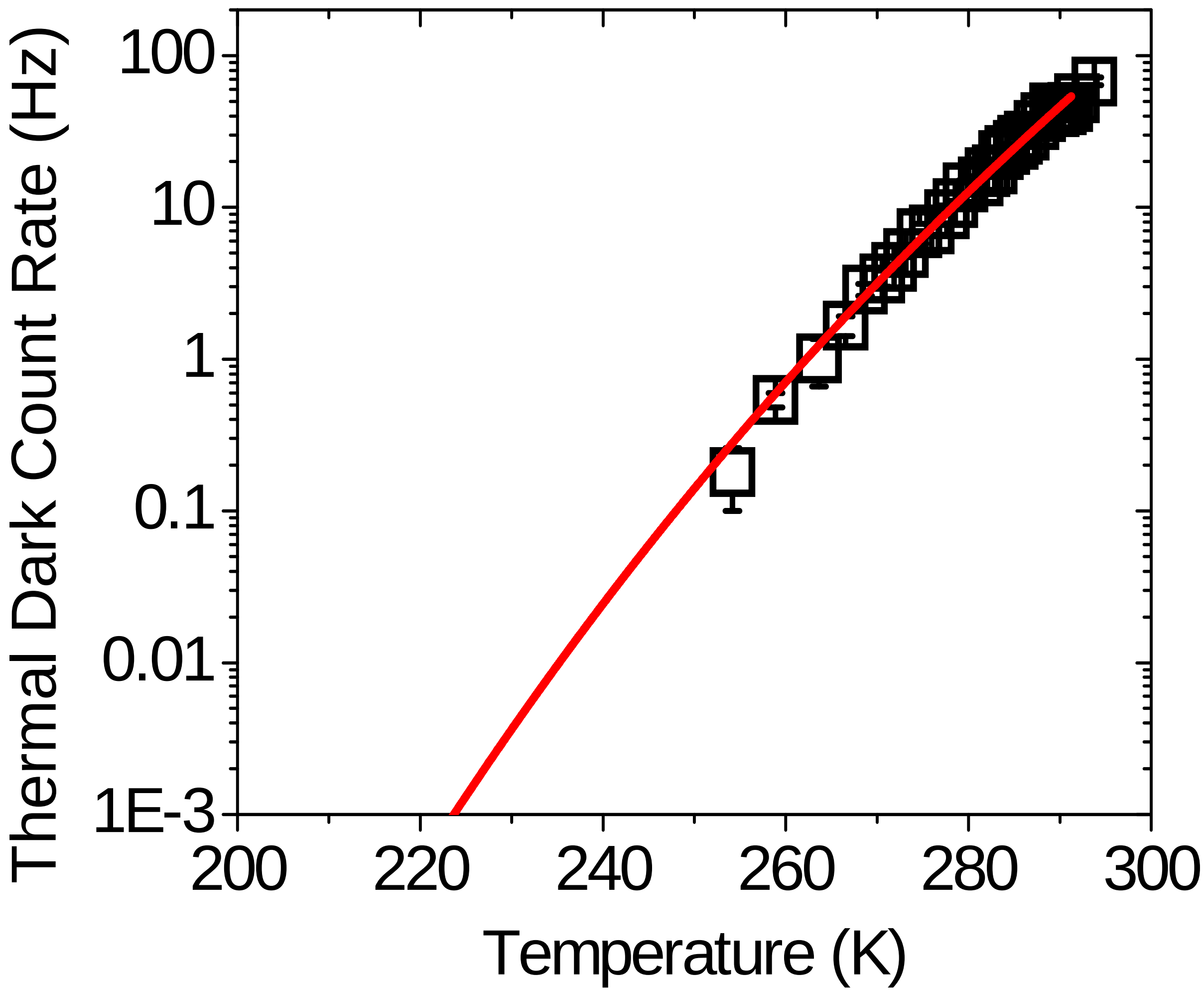
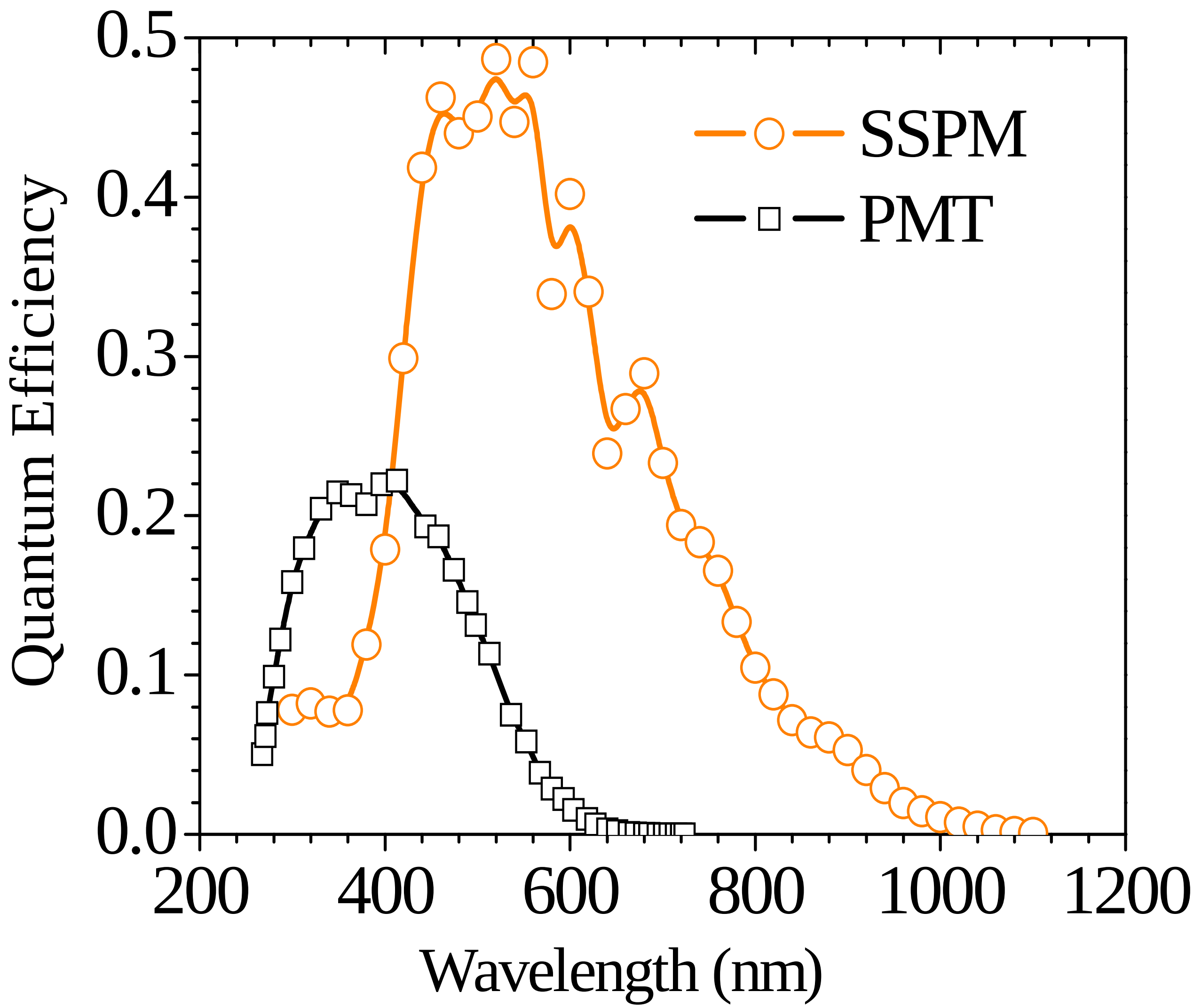
SSPM Dark Count Rate



SSPM Quantum Efficiency



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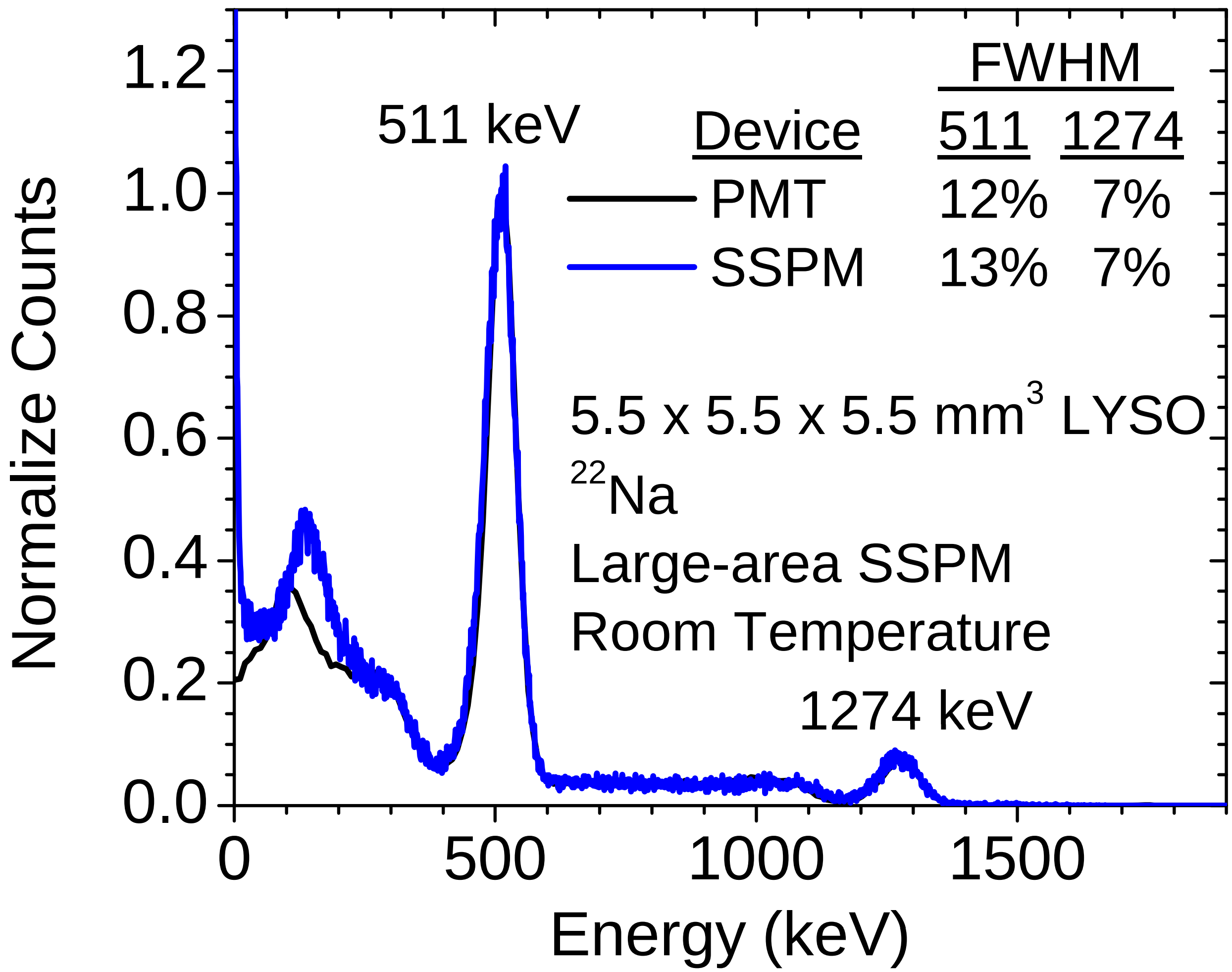
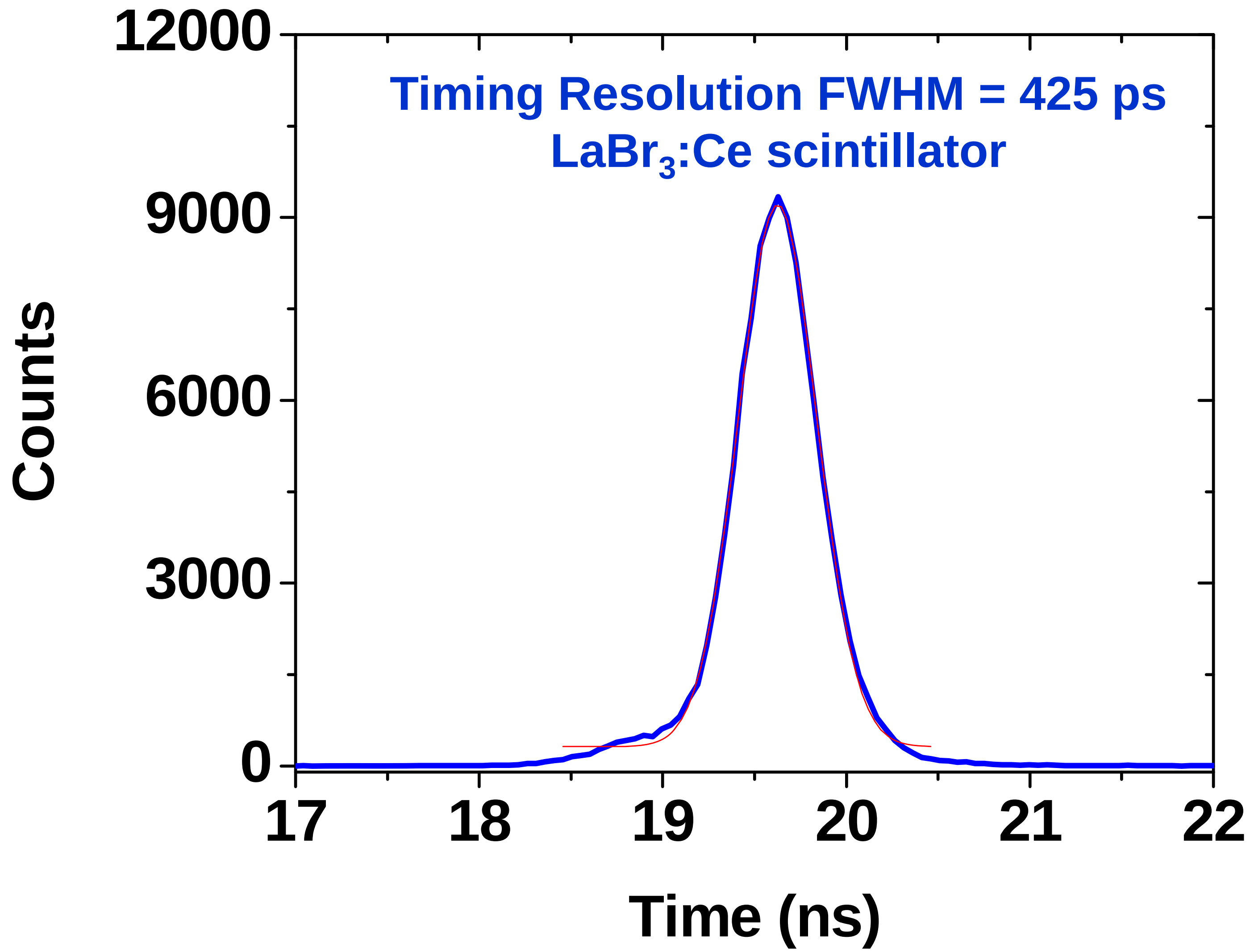
SSPM Energy Resolution



SSPM Timing Resolution



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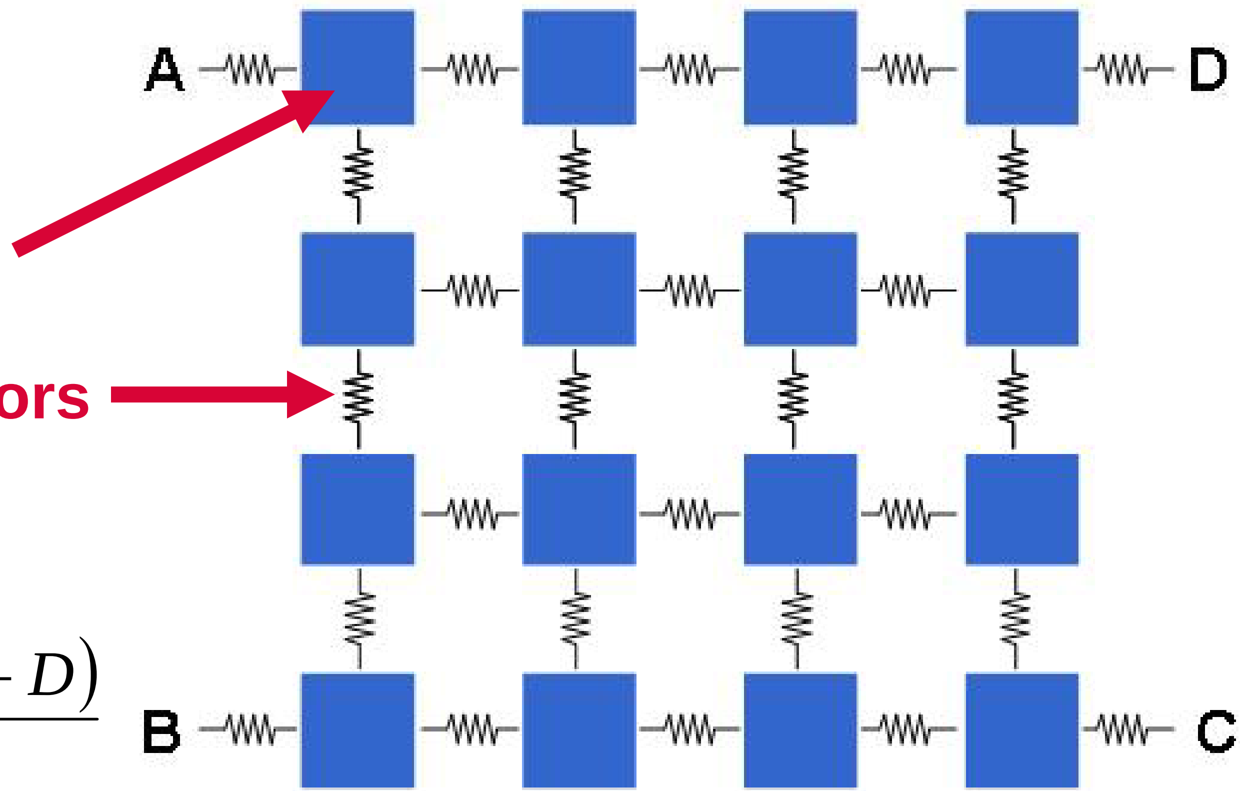
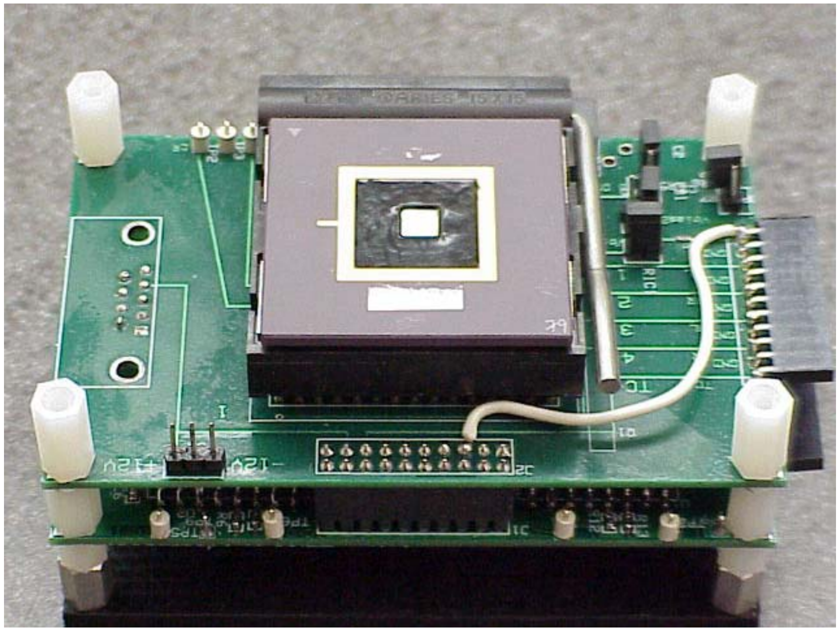
Position Sensitive SSPM Concept



$$X = \frac{(A+B)-(C+D)}{\Sigma}$$

$$Y = \frac{(A+D)-(B+C)}{\Sigma}$$

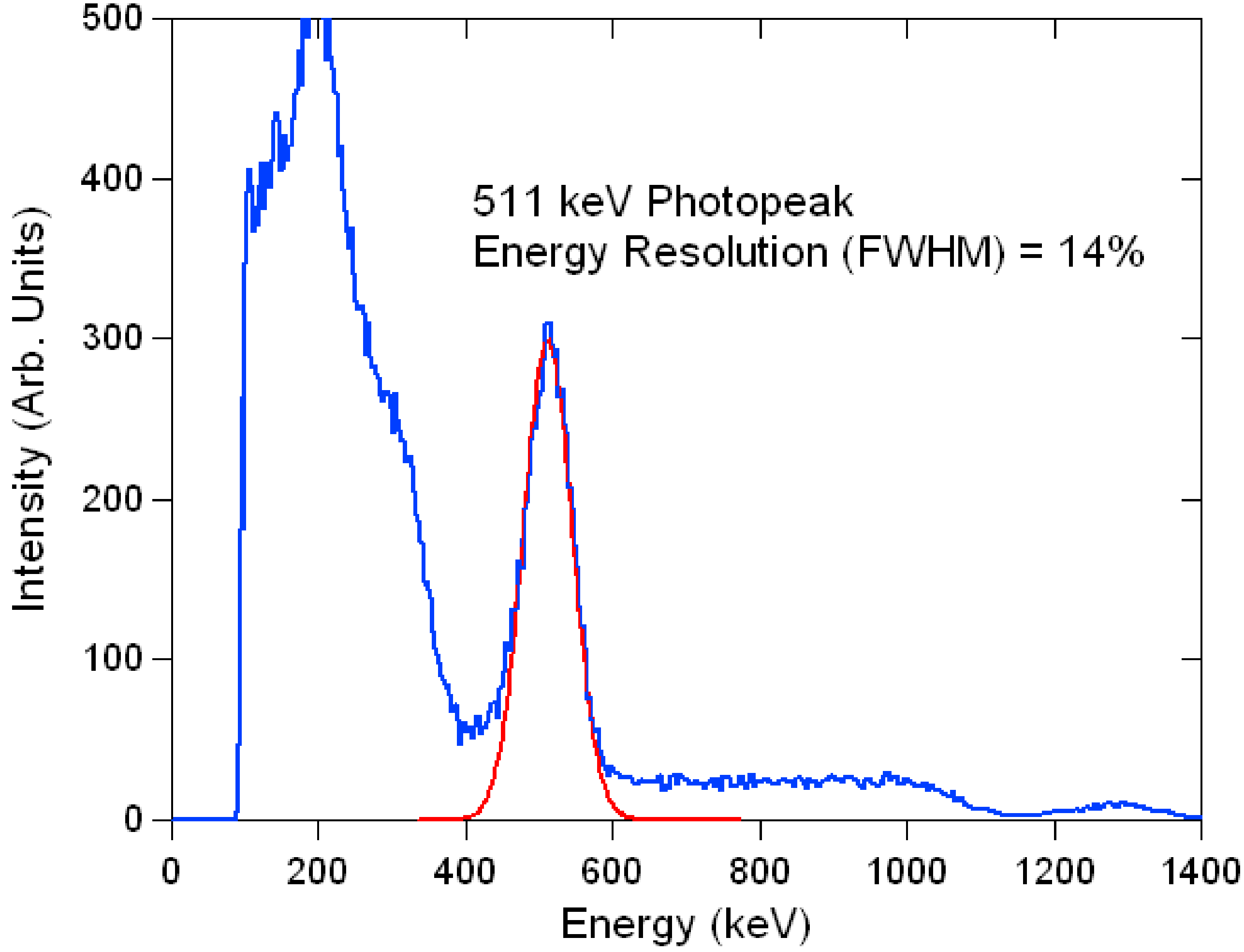
PS-SSPM & Readout PCB



PS-SSPM Parameters	
Number of micro-pixels	11,664 (108 x 108)
Micro-pixel area	30 x 30 μm^2
Micro-pixel pitch	44.3 x 44.3 μm^2
Geometrical Fill Factor	46%
Quench Resistors	143.8 kΩ
Network Resistors	246.5 Ω
Detection efficiency @ 400 nm	~ 10%
Dark Current ($\mu A/mm^2$)	10
Dark Count Rate (kHz/pixel)	~ 117
Operating Bias	~ 32 V
Operating gain	~ 10^6
Excess Noise Factor	~ 1
Capacitance (fF/pixel)	150

- **PS-SSPM chip was packaged on a ceramic 145 pin grid array**
- **Zero insertion force (ZIF) socket for easy removal**
- **Custom PCB, preamplifiers located under PS-SSPM**

PS-SSPM Energy Resolution



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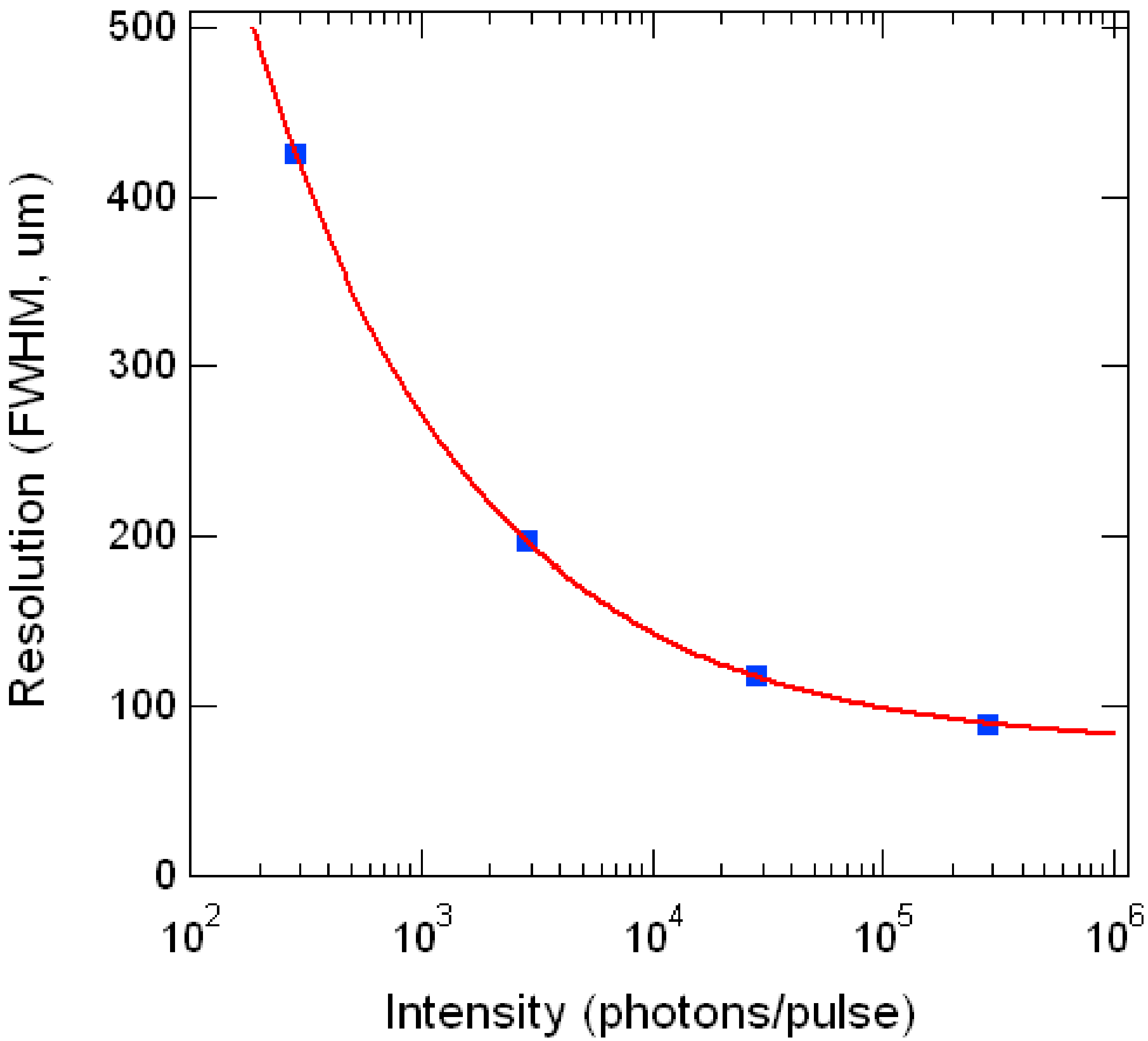
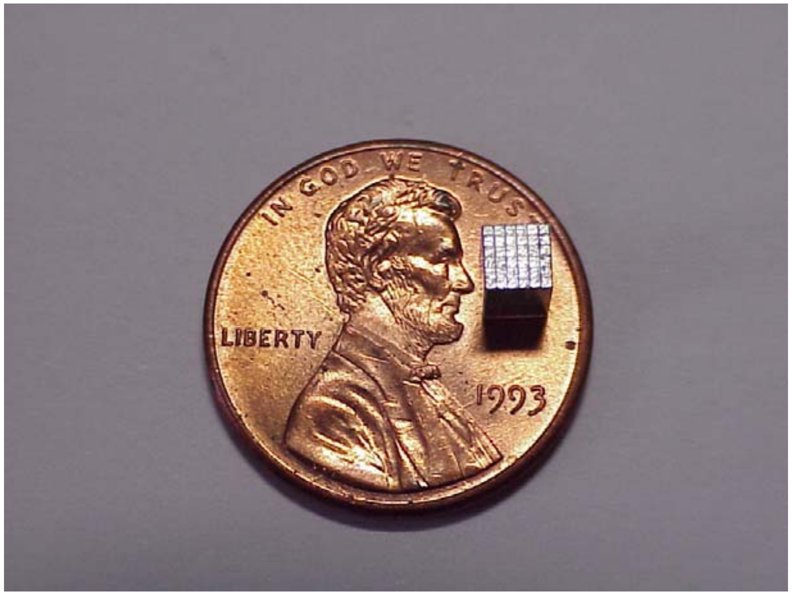
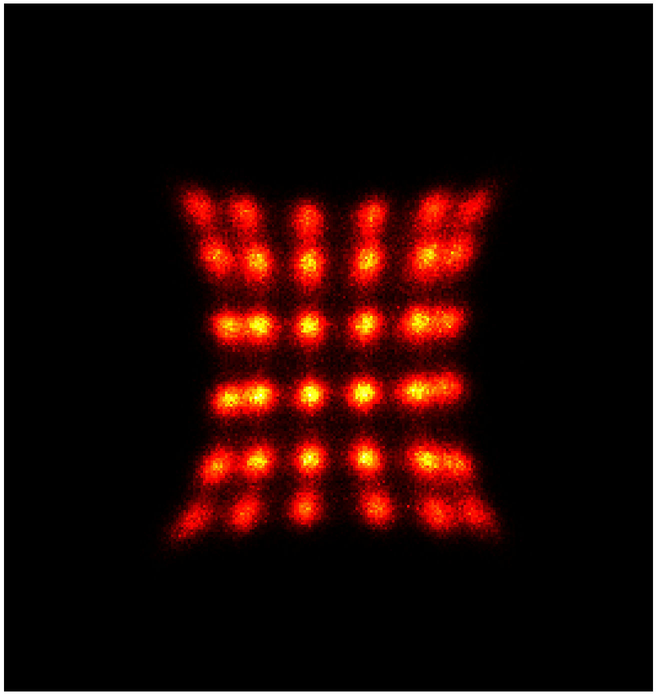
PS-SSPM Spatial Resolution



PS-SSPM Scintillator Images



6 x 6 LYSO array having
500 μm pixels

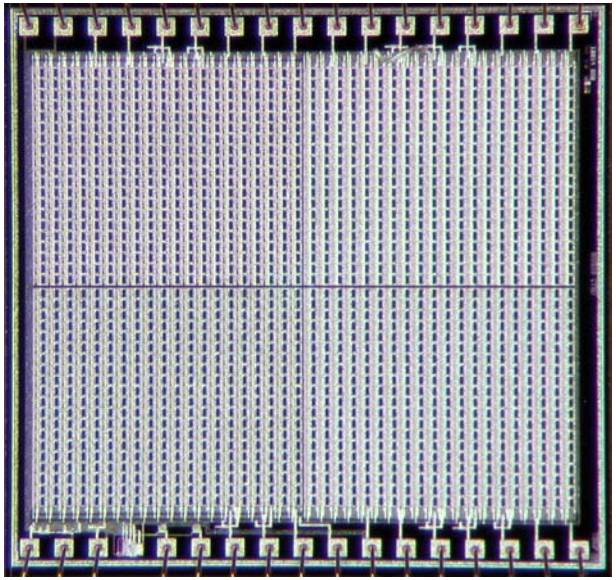


Uniform flood with ^{22}Na
(511 keV)

RMD has filed for IP on the PS-SSPM concept

Temperature-insensitive SSPM

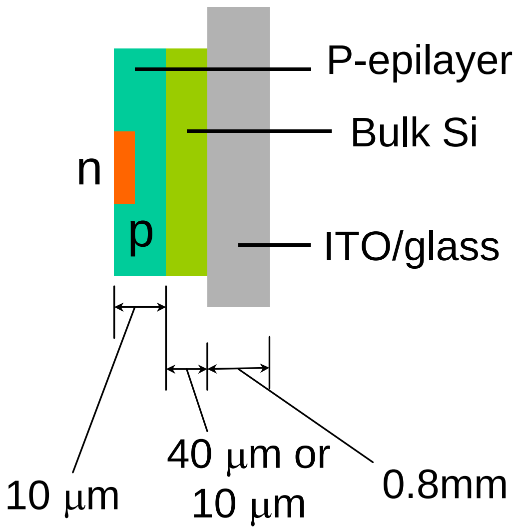
$$Q_{OUT} = DE(V_X) \times N \times C(T) \times V_X(T)$$

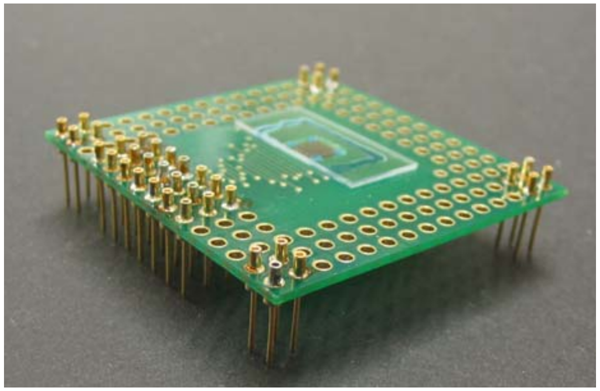


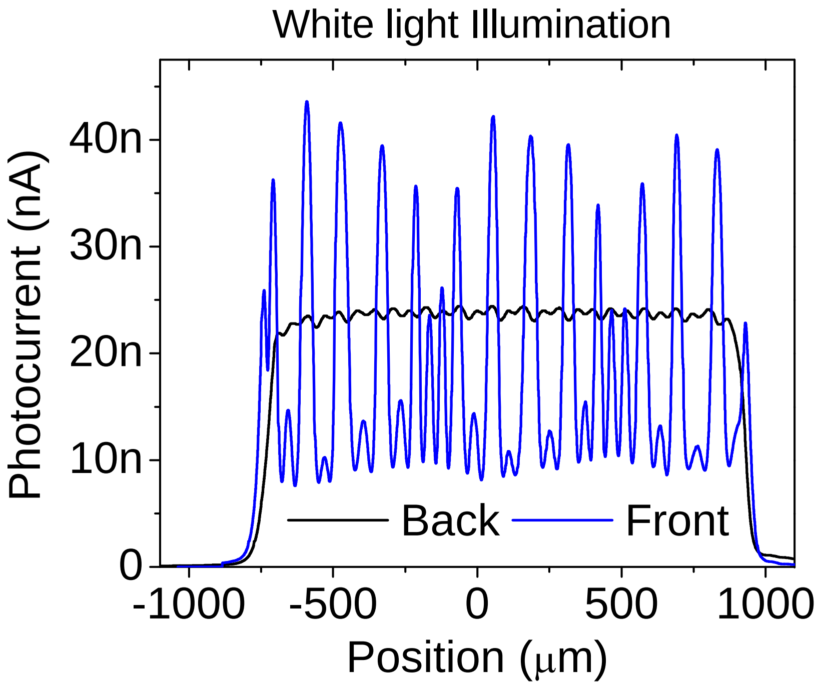
Excess bias affects detection efficiency and gain

- **Breakdown voltage is temperature dependent.**
- **To maintain a constant excess bias, the applied bias must change with temperature.**
- **Feed isolated pixel signal from dark events into a peak-hold circuit to monitor changes in the excess bias.**

Back-Illuminated SSPMs







Thinned to 50µm and 20µm (thinner chips are in process).

Packaged for front and back illumination.

DCR same

FF ~100%, detection efficiency is currently high only in red

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Comparison of Photodetectors

Device	Gain	Excess Noise	QE (> 350 nm)	Voltage	Rise time	Magnetic sensitivity
SSPM	~ 10^6	~ 1.3	~ 30%-50%*	~ 30 V	~ 0.1 ns	No
Si APD	~ 10^3	> 2	~ 60%	> 1 KV	1-2 ns	No
Si PIN	1	~ 1	~ 70%	~ 30 V	> 10 ns	No
PMT	~ 10^6	~ 1.2	~ 30%	> 1 KV	~ 0.1 ns	Yes

*This value is the 'photon detection efficiency' and 50% represents the projected value based on our designs.

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Future Work

- Package and characterize thinner (~ 10 μm) back illuminated SSPMs.
- Characterize imaging and non-image 1 cm^2 SSPM
- Develop on-chip electronics for pixel conditioning, pulse processing, and data management.
- Characterizing 6 x 6 SSPM array
- Deploy SSPM detectors for integration into nuclear and particle physics experiments running at BNL (calorimetry) and UMass-Lowell (beam monitoring in particle accelerators, α-γ angular correlations and charged particle detection).