Instrument Research & Development

Solid-State Photomultiplier with Integrated Front End Electronics

Optical Detector with Integrated ADC for Digital Readout

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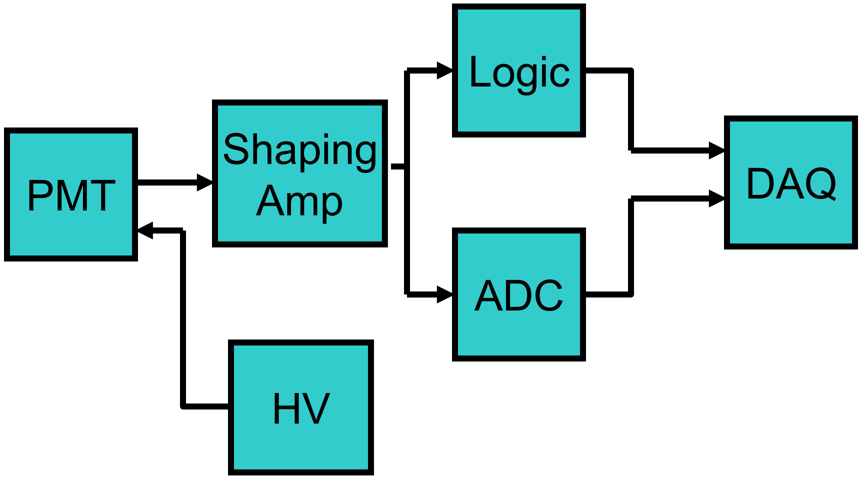
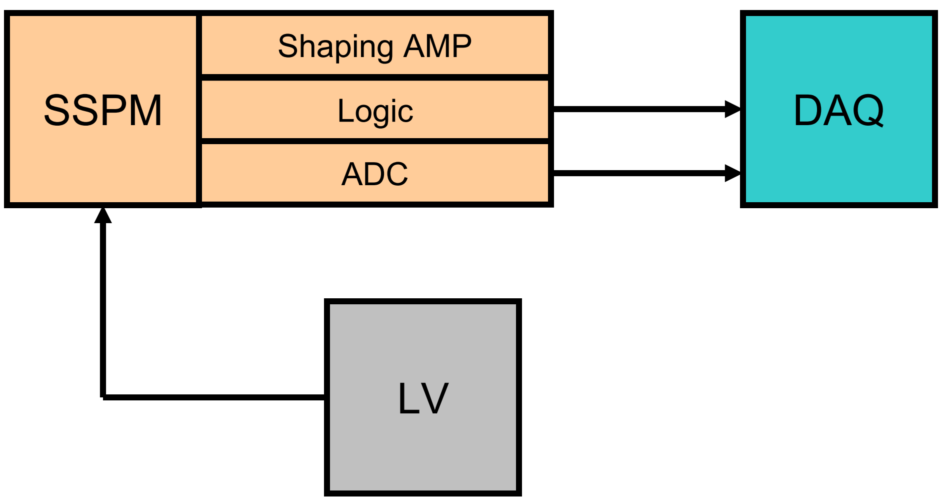
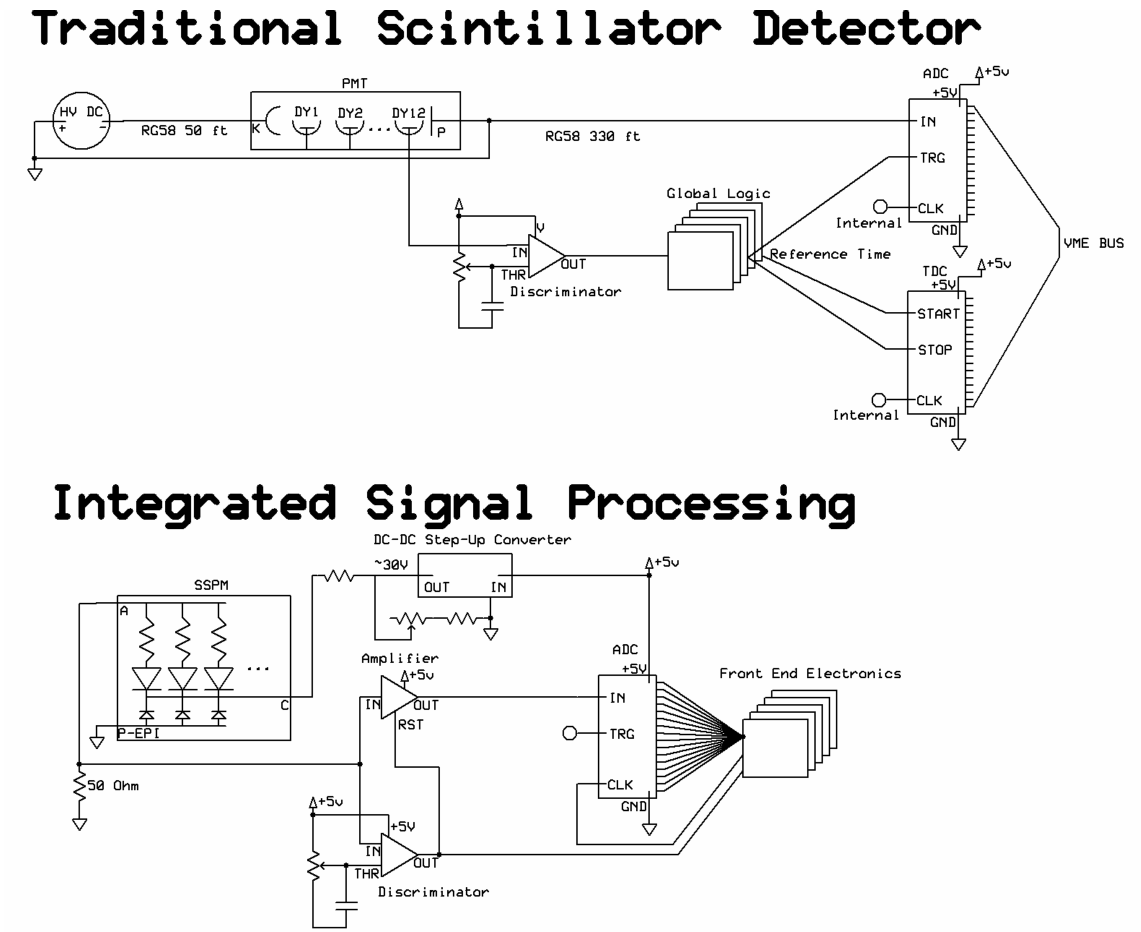
Cost for Doing Physics





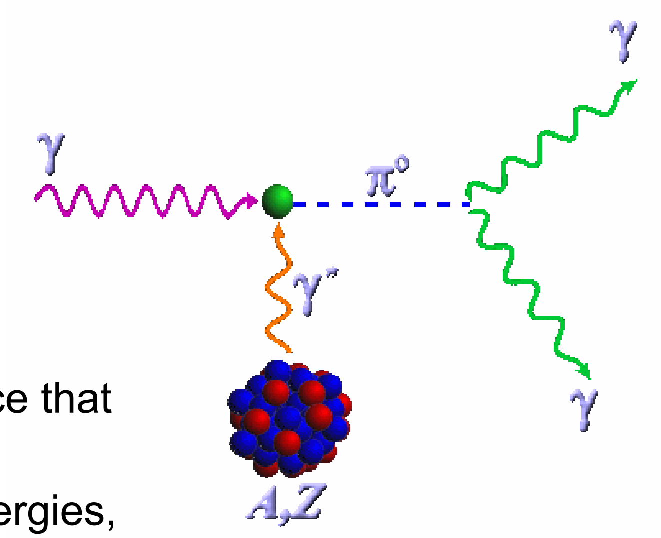
- Scintillator Readout
- Traditional
  - PMT
  - HV
  - Shaping Amp
  - Logic
  - ADC
- Integrated
  - SSPM
  - LV
  - Insensitive to fringe B fields and He gas.
- Cost Reduction
  - minimizing the number of modular components.
  - Reduce cabling
  - Reduce need for Fastbus or VME modules

Cost Analysis

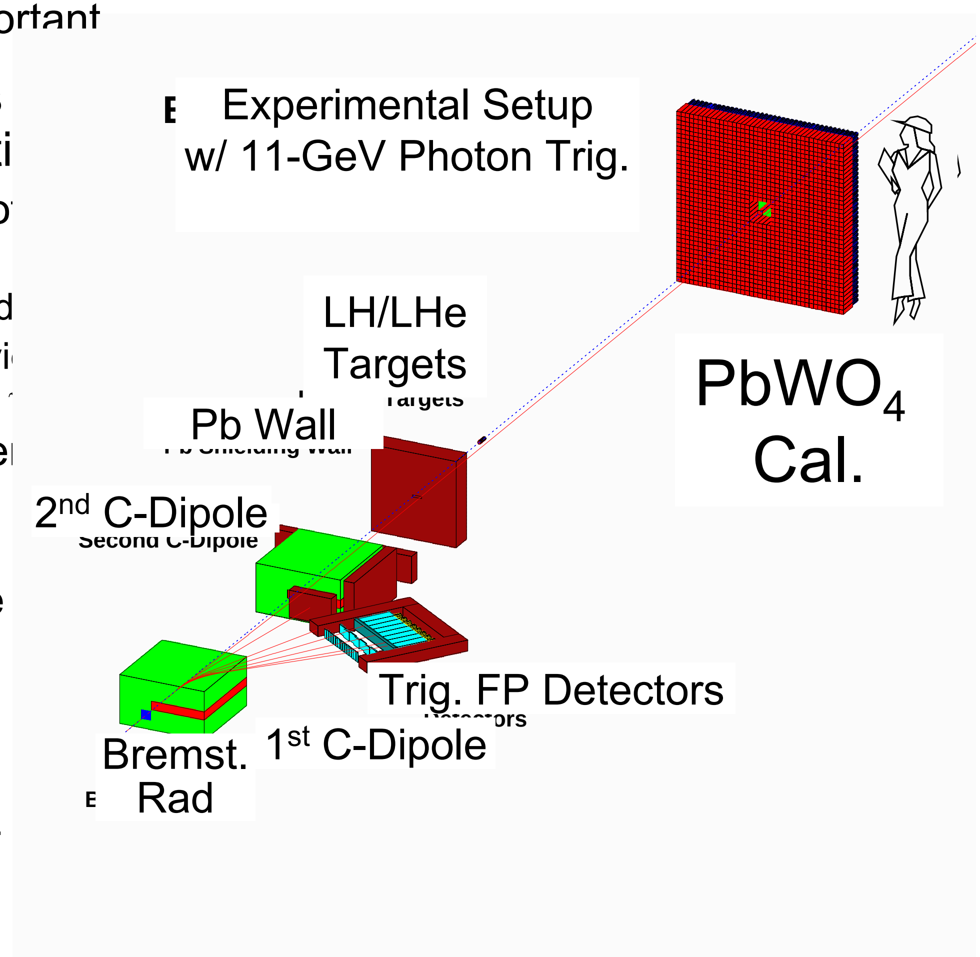


- PMT Readout
  - Cables.
  - VME, CAMAC, HV Crates
  - Signal processing modules.
  - HV modules.
- SSPM with Integrated Electronics
  - On-chip processing
  - External 250 MSPS 12-bit ADC
  - External DC-DC Converter
  - +5V Supply
  - Front End FGPA
- Estimated a cost reduction of a factor of two.

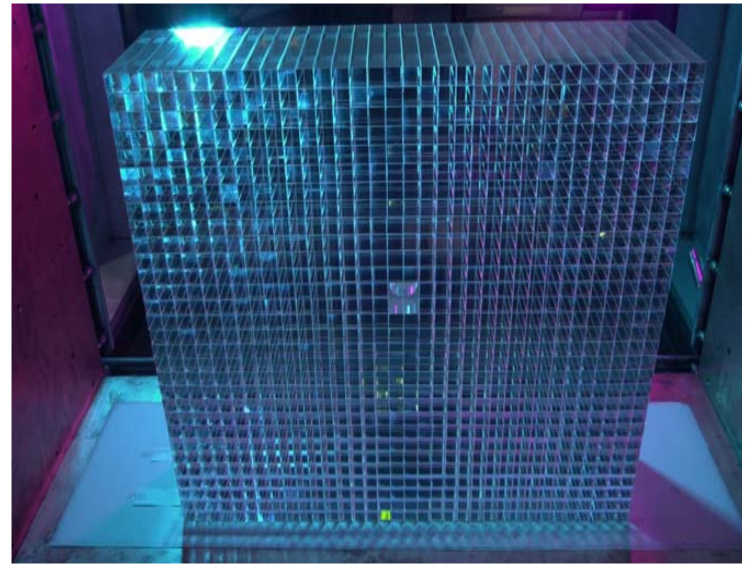
Physics Overview



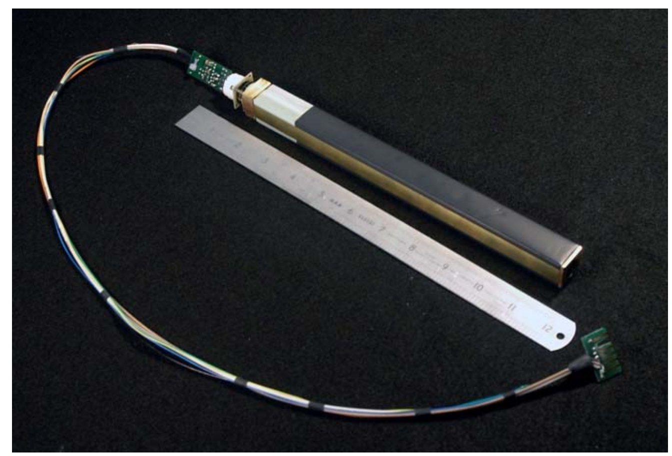
- Provide direct measurements at low energies of parameters of Quantum Chromodynamics (QCD)
  - Low energy < GeV (proton mass ≈ 1 GeV)
  - The measurement of the π^0 life time provides evidence that the QCD theories are valid at these low energies.
  - It provide additional support for QCD at these low energies, the η and η' lifetimes are equally important
- An upgrade at Jefferson Laboratories allows for studies of the η and η' life ti
  - η and η' are produced by the Primako Effect
    - 10-GeV photons incident on Liquid Hyd
    - Photon and virtual photon interaction yi neutral pseudo-scalars, such as η and
  - They decay into two photons with ene > 1 GeV.
  - The PRIMEX experiment will house a $PbWO_4$ calorimeter for measuring the energy of the decay photons to within



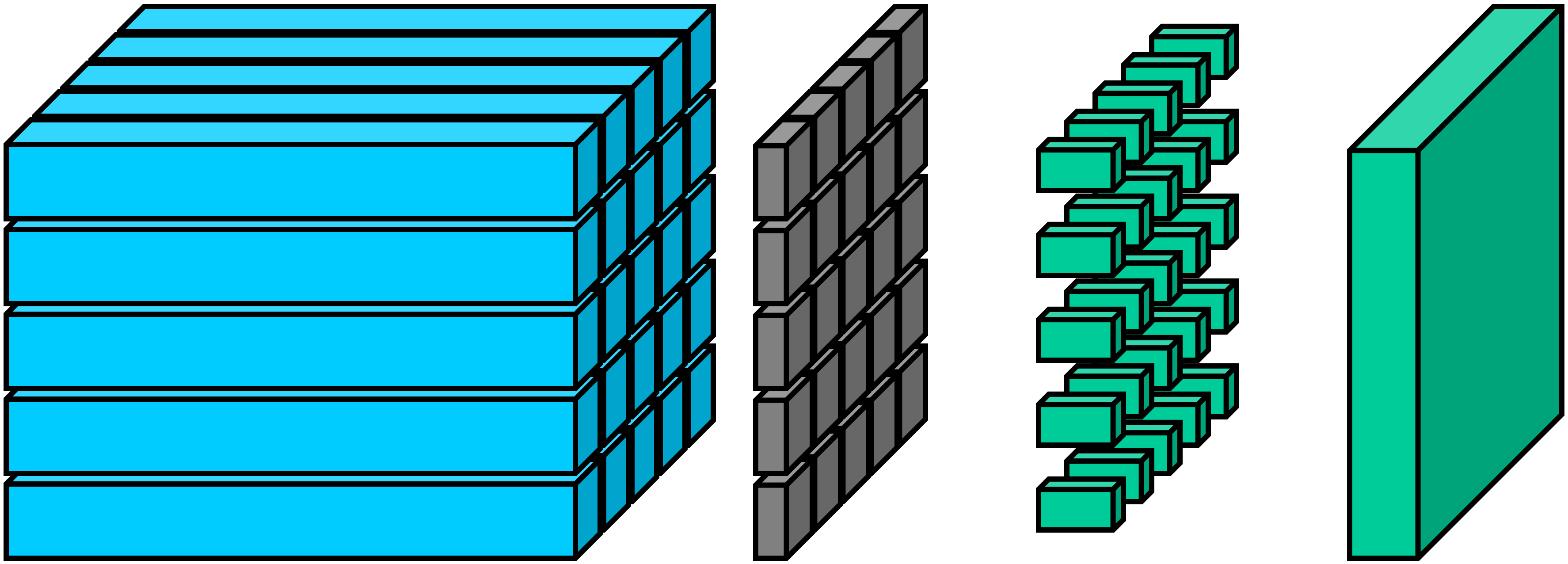
The PRIMEX $PbWO_4$ Calorimeter



- Planned Calorimeter
  - 60 x 60 element array of $PbWO_4$
  - <1% energy resolution for 4.5 GeV
  - ~ 1 mm position resolution
  - 2.125 x 2.125 x 21.5 cm^3
  - $PbWO_4$ Parameters
    - Fast Decay: ~10 ns
    - Density: 8.3 g/cm^3
    - Light Yield at 0 ºC: 50-300 γ/MeV.
- Detecting two high energy gamma rays
  - Scattering along scintillator
  - Scattering radially
  - Bundle 5x5 clusters of scintillator



Building the Calorimeter



PbWO Crystals
5x5 Array

SSPM
Integrated Signal
Processing

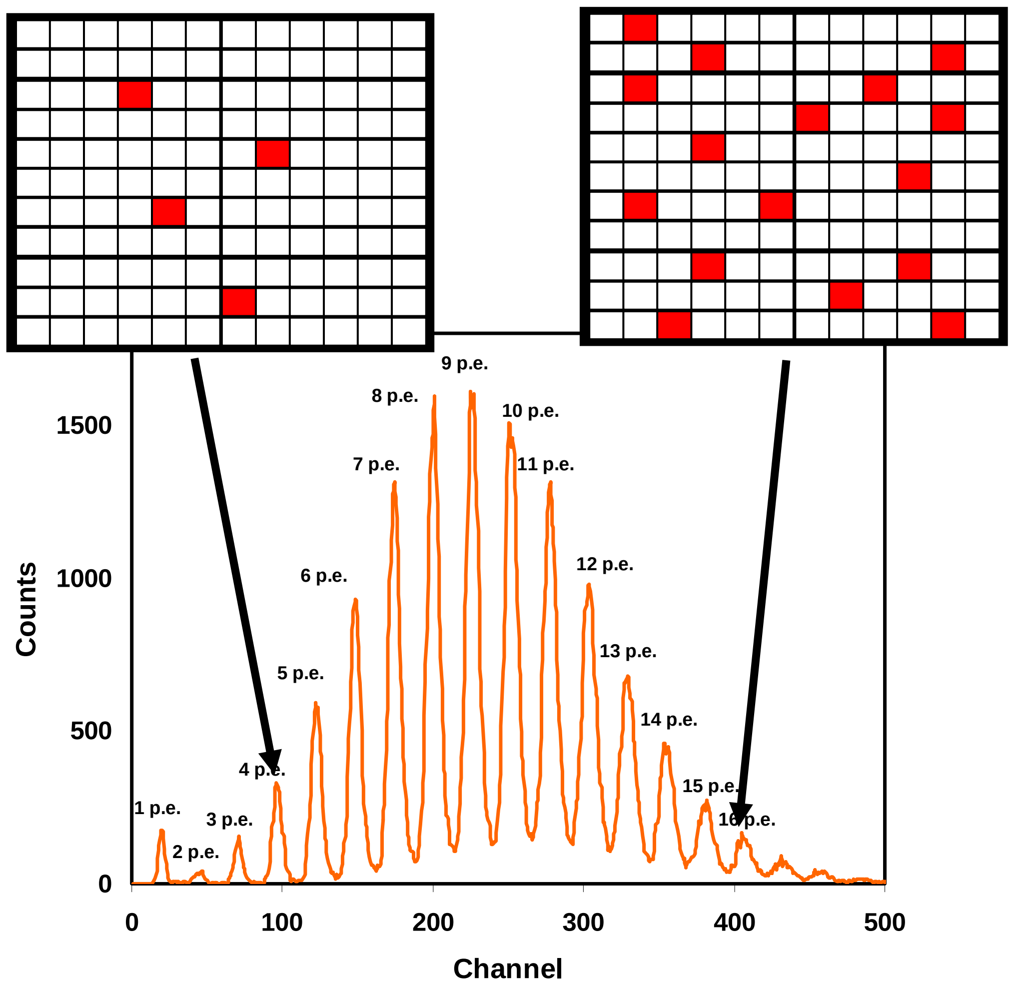
Interface
ADC
≥250MSPS

FPGA
DSP
Position
Time
Pulse Height

- Segment components for construction.
- Integrate electronics at front-end.

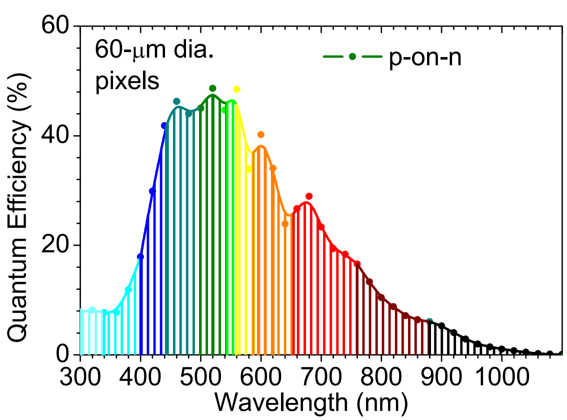
CMOS SSPM Primer

- Low-cost, compact, high gain photodetector:
  - Active dosimeters/ area monitors
    - Gamma-ray
    - Charged-particle
    - Neutrons
  - Spectrometry
  - Positioning and Imaging
  - PET, SPECT, Optical tomography
- Fabricate photodetector using commercially available CMOS process.
- Low cost
- Reproducible
- Integrated signal processing
- Array of photodiodes with large signal gain associated with single optical photons.
- Proportional response to incident light intensity.

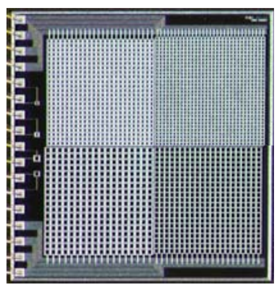


CMOS SSPMs

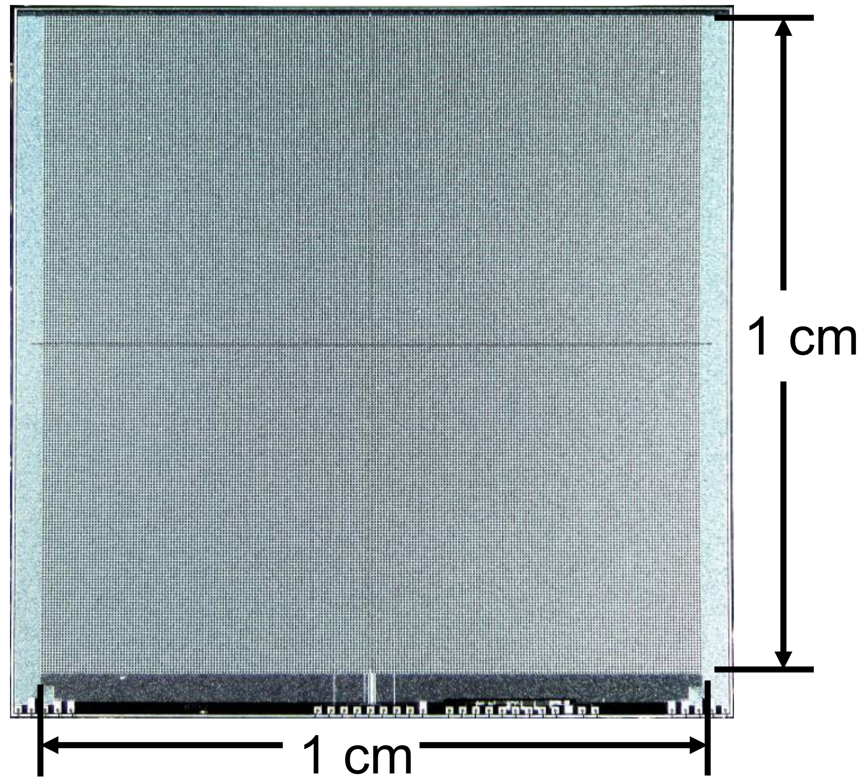
- Large scale detector designs- simple connection, single instrument, lower cost.
- Development for high performance instruments, such as large calorimeter arrays.
- A complete understanding of the SSPM behavior will allow for optimal design.

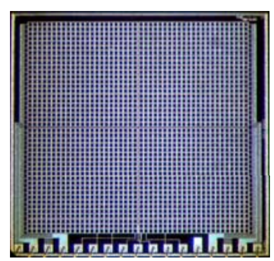


Prototype SSPM designs.



Large-Area SSPM:
~50k, 30-micron pixels
49% Fill Factor



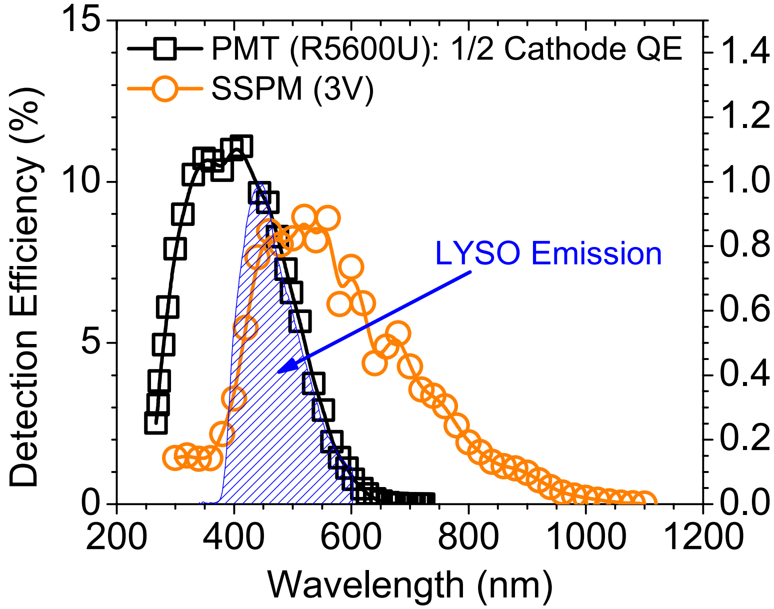


Small-area SSPM:
~2k, 50-micron pixels
61% Fill Factor

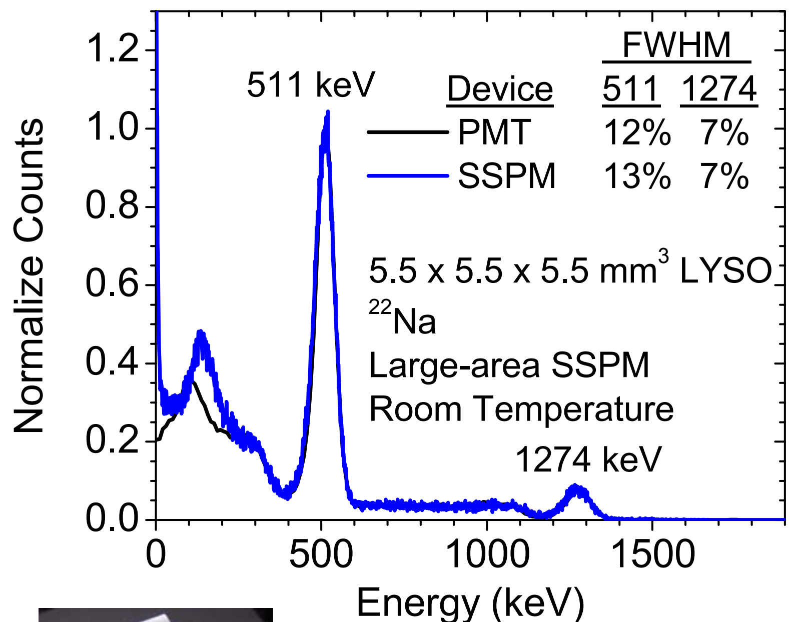
Large Gain: ~10^6 (approx. $V_x \cdot C_{jn}$)
Room Temperature Breakdown: 26.9 V ± 0.2 V
Breakdown Temperature Coefficient: 50 mV/°C
Recharge time: 100ns with 50 Ω termination.

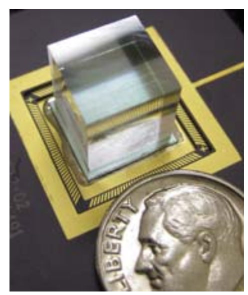
Energy Resolution

To compare with a PMT, LYSO is a good match for both photodetectors.



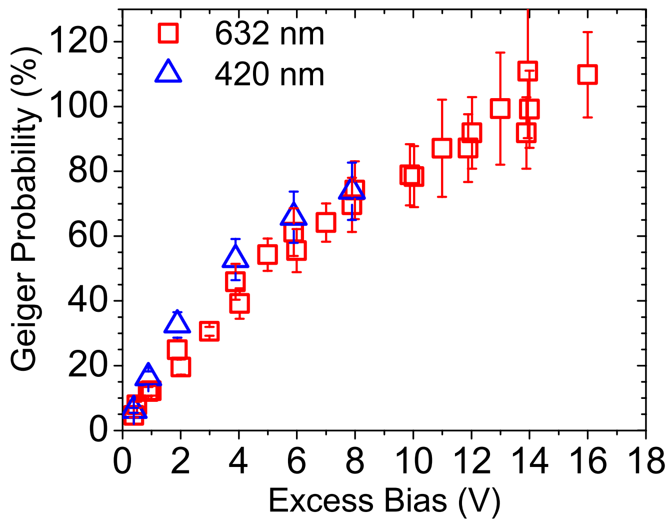
The large-area SSPM is a viable replacement for a PMT.



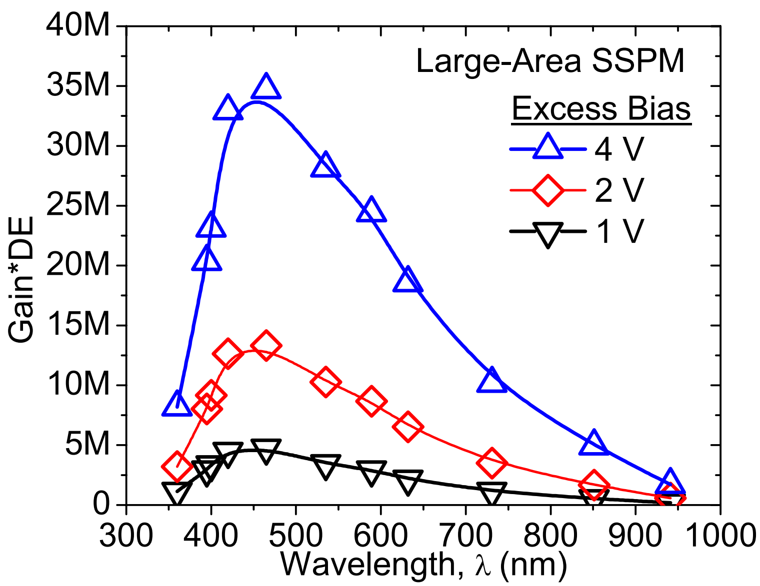


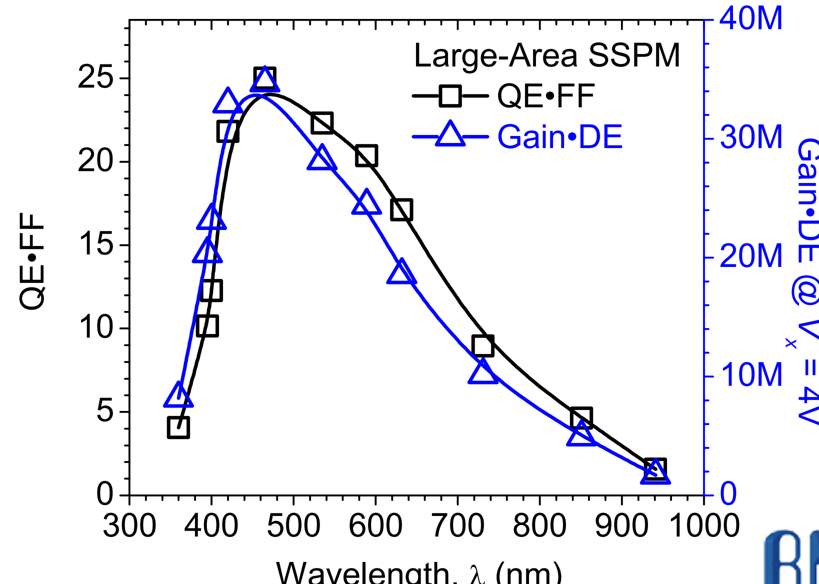
To optimize scintillation detector performance, we need to examine the signal and noise terms

Detection Efficiency

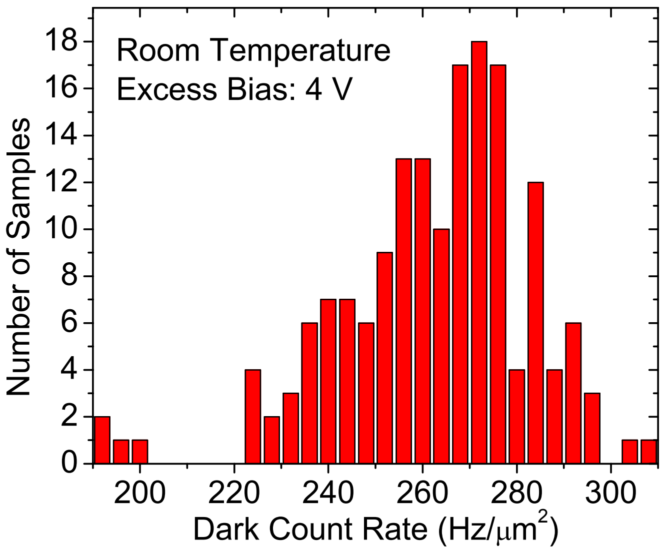


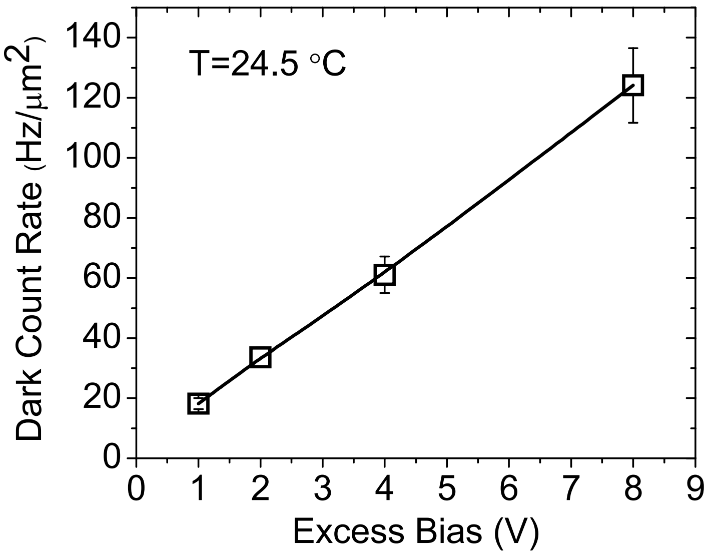
- Detection efficiency is a product of the QE and the Geiger probability.
- Difference in ionization rates between holes and electrons.
- There may be differences in the Geiger avalanche probability, P_g, as a function of wavelength.
- Many scintillation materials emit in the blue.
- Small changes in the DE for blue light can result in a significant improvement in the signal.



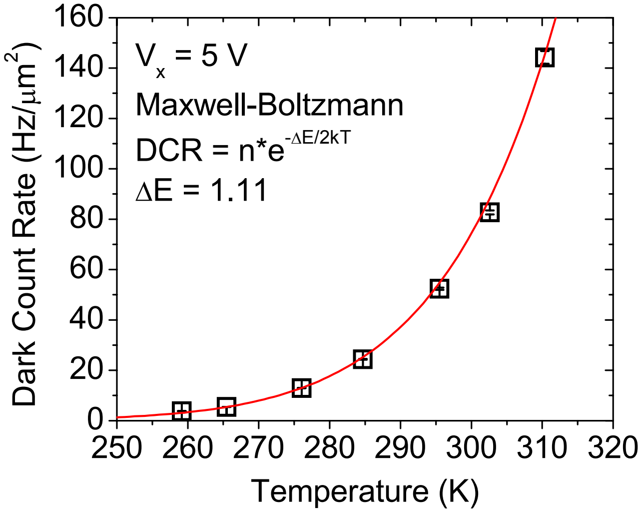


Dark Current





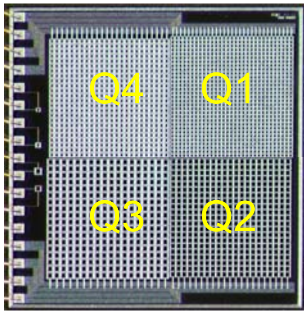
Dark current is temperature dependent.



- The dark *current* was measured on a sample of large-area SSPMs and converted into a dark count rate.
- The product of the dark count rate and the integration time gives the contribution to the noise.
- The dark count rate follows a Maxwell-Boltzmann distribution.
- Low temperature and fast integration times can be used to mitigate dark noise.

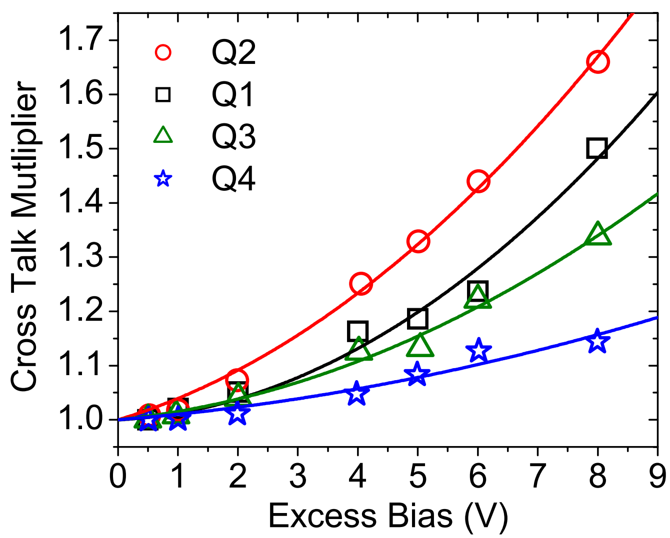
Excess Noise Terms

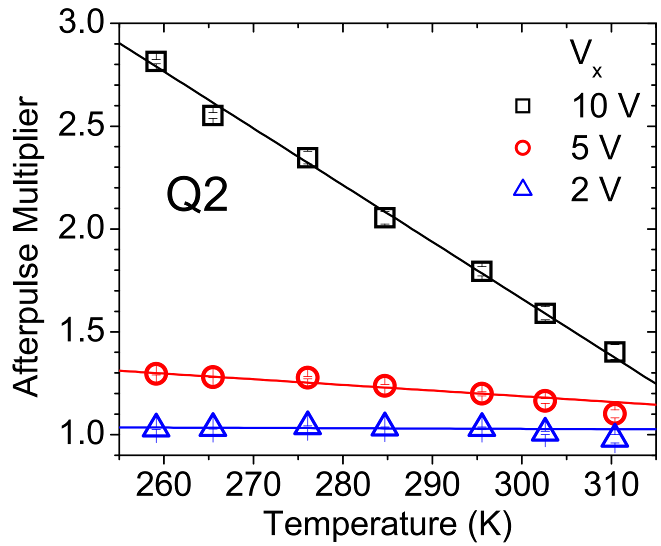
$$q_{SSPM} = M_A \cdot M_x \cdot G(V_x) \cdot n_t + q_0$$



Spacing	Size	Quadrant
Close	Large	Q2
Close	Small	Q1
Far	Large	Q3
Far	Small	Q4

- Crosstalk and afterpulses can be considered as gain terms.
- We can define an excess noise factor associated with these gain terms.
- It is the fluctuations in gain that is the key factor we are interested in quantifying.



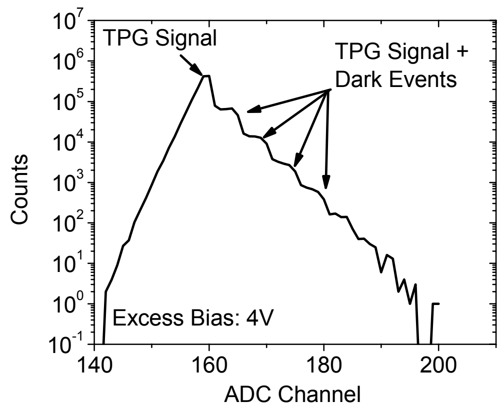


Not a complete picture of AP

Crosstalk Characterization

- Crosstalk is a contributor to excess noise.
- Tail Pulse Generator- Simple but dirty.
- Trace analysis- computationally intensive.

- Bin spectra into groups representing the number of triggered pixels.
- Calculate the expected mean and variance for dark events without excess noise.
- Determine the mean and variance of the measured spectrum.

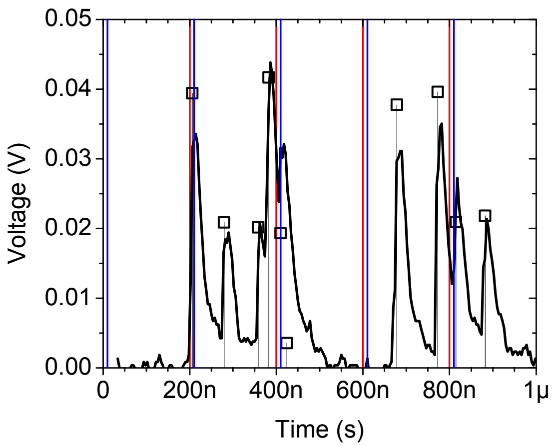


Use a tail pulse generator.
Collect dark events.

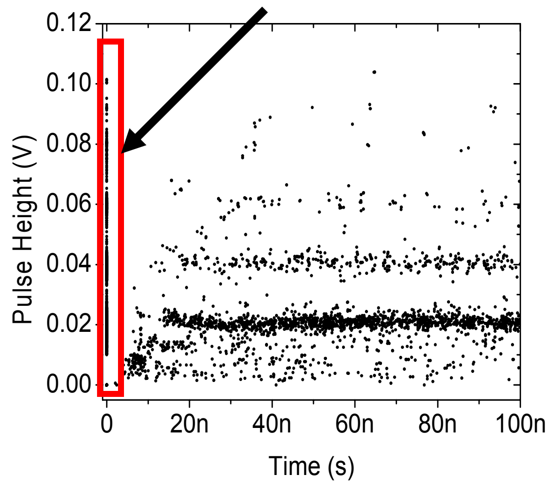
$$P(\mu,0)=\left(1-\frac{\mu}{n_{ttl}}\right)^{n_{ttl}}=\frac{C(0)}{\sum_{n} C(n)}$$

Du et al., NIMA, v. 596, p. 396-401, (2008)

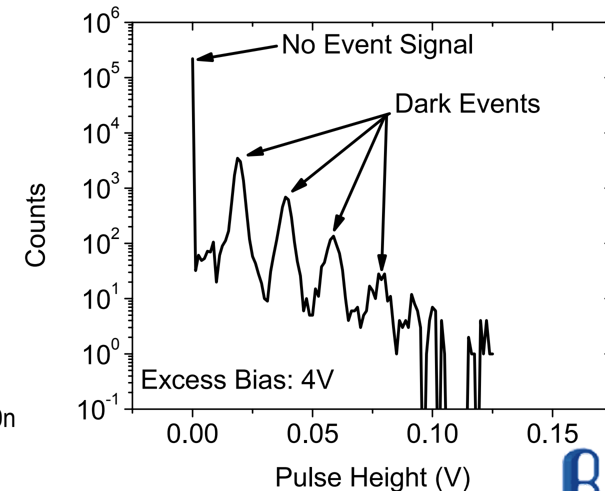
Fit and bin data.



Look at events within a small window.



Generate dark spectrum and bin data.



Excess Noise Factor: Short Integration

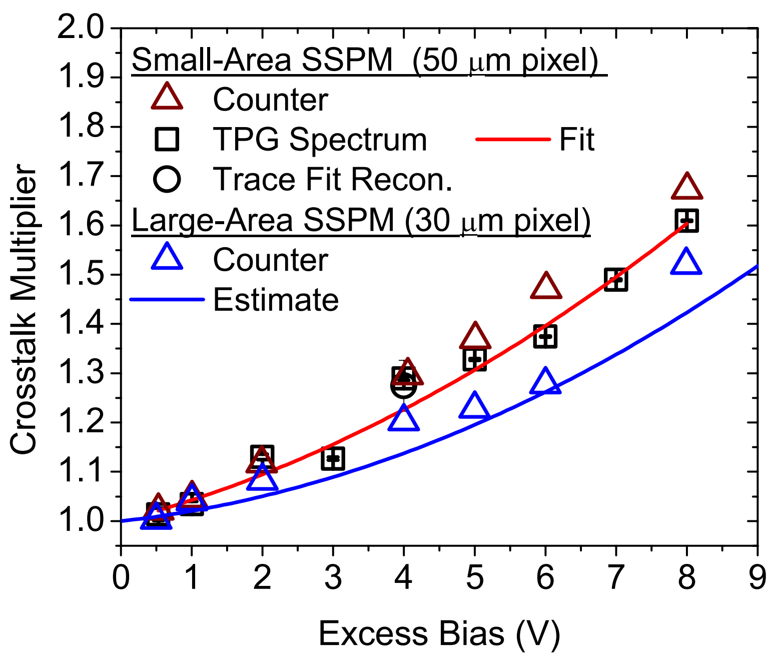
- For short integration times crosstalk is the only excess noise term.
- Third method to measure crosstalk is to measure count rates.
- TPG and ADC sample methods are similar.
- Count rate method is close but is naturally high due to lack of accounting for afterpulses and dark counts.

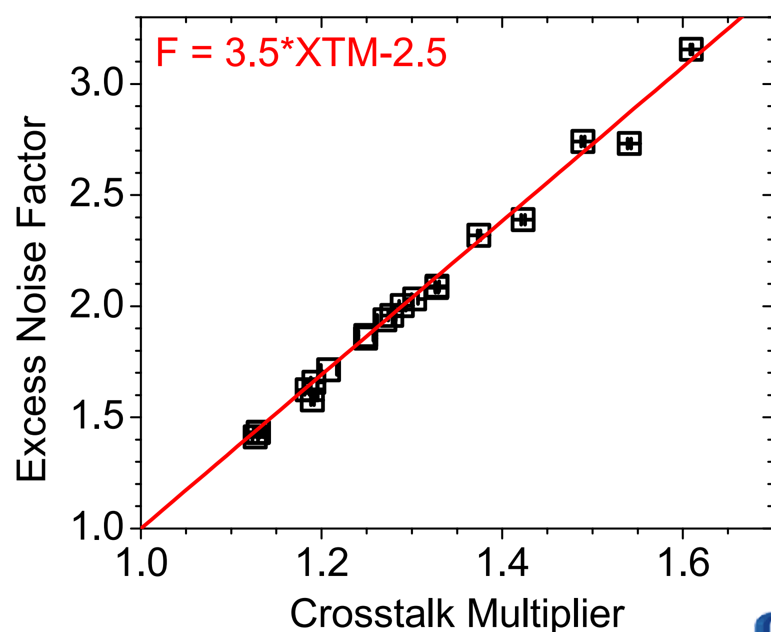
Multiplier

$$M = \frac{\mu_{meas}}{\mu_{dark}}$$

Excess Noise Factor

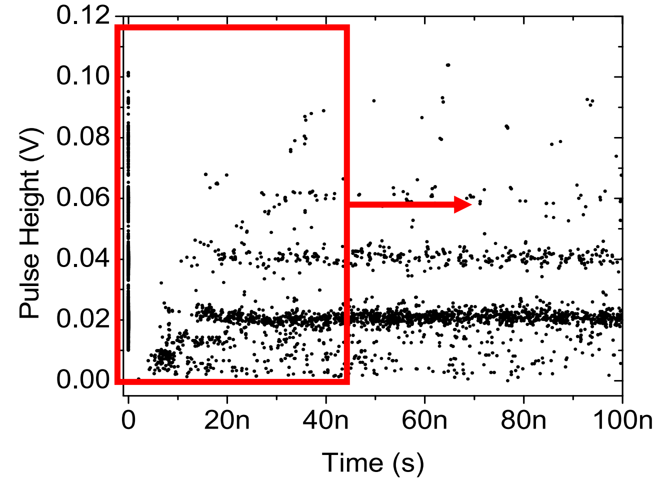
$$F = \frac{\sigma_{meas}^2}{\sigma_{dark}^2}$$

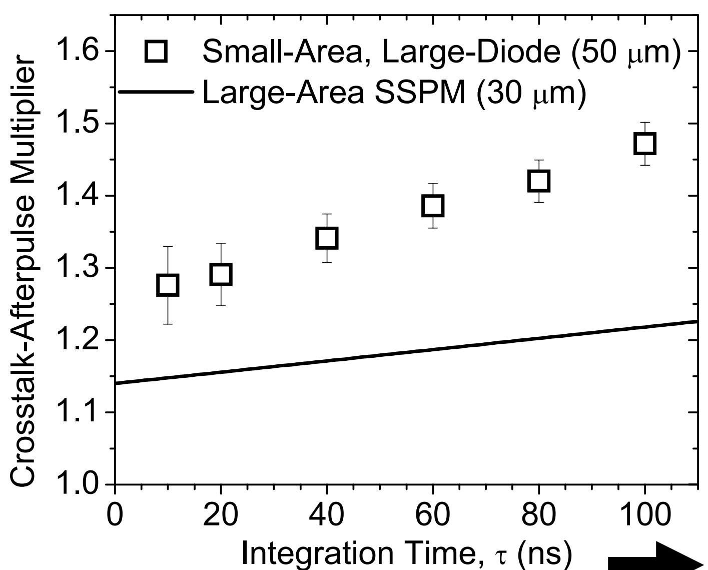




Excess Noise Factor with Integration

- Afterpulsing and crosstalk are correlated.
- Afterpulsing is highly dependent on the integration time.
  - Charge output from pixel is dependent on the excess bias.
  - Early afterpulses will not generate as much charge since the pixel is in a recharging process.
  - After some point in time, the time correlation between a pulse and afterpulses becomes random again.
- Consider the trace analysis to measure a comprehensive gain multiplier and excess noise terms.





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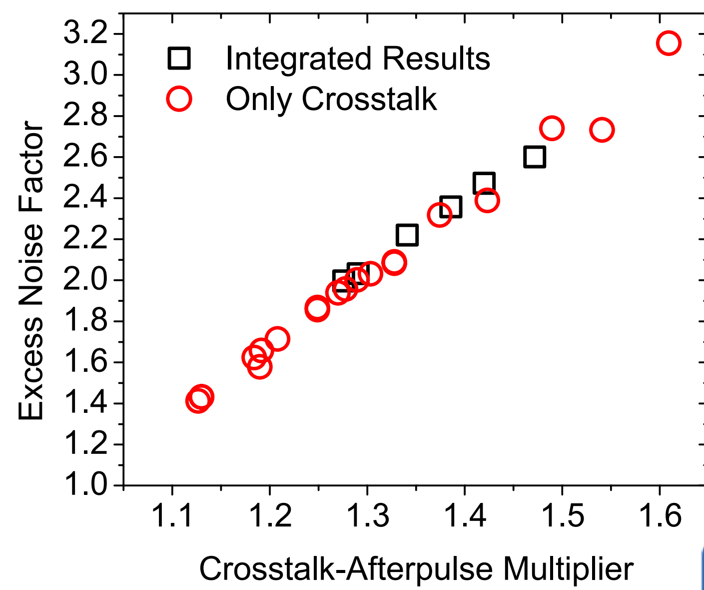
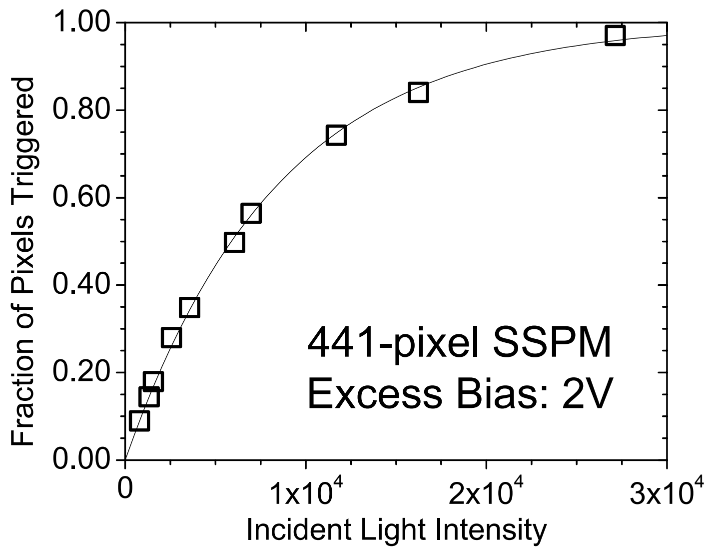


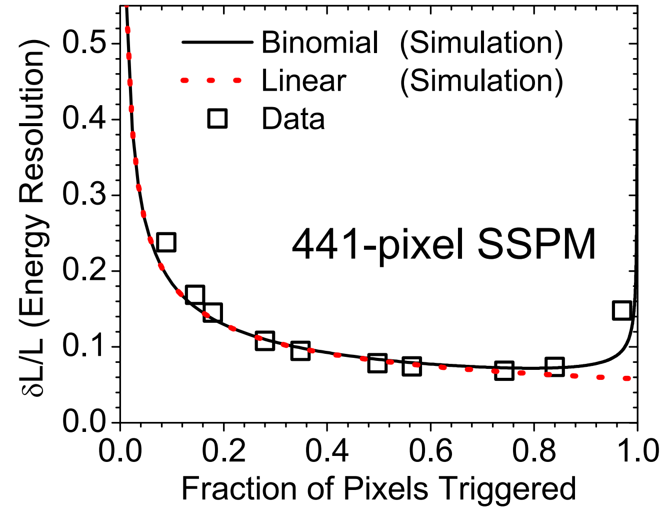
Non-linear Effects

Triggered Pixels

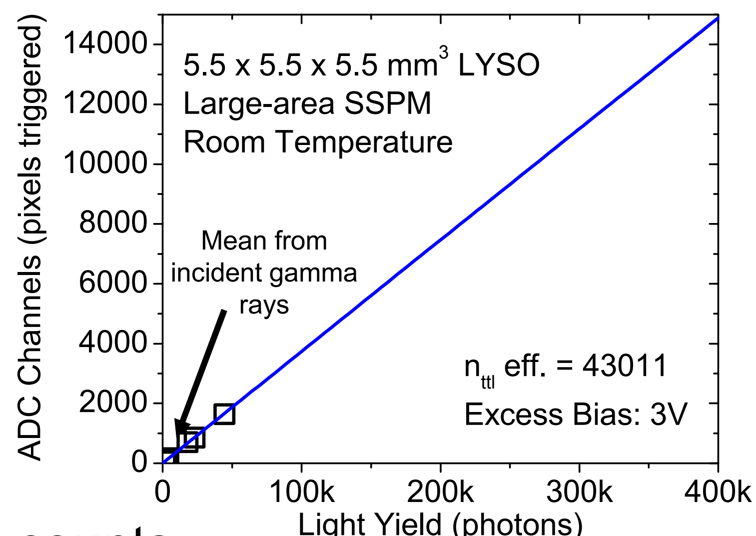
$$\langle n_t \rangle = n_{ttl} \cdot \left(1 - e^{\frac{-P_g(V_x,\lambda) \cdot FF \cdot QE \cdot L}{n_{ttl}}} \right)$$

SSPM Non-linear Behavior





The large-area SSPM benefit from large pixel numbers.



- Spectra need to be “rebinned” to conserve counts
- Noise from binomial statistics near saturation

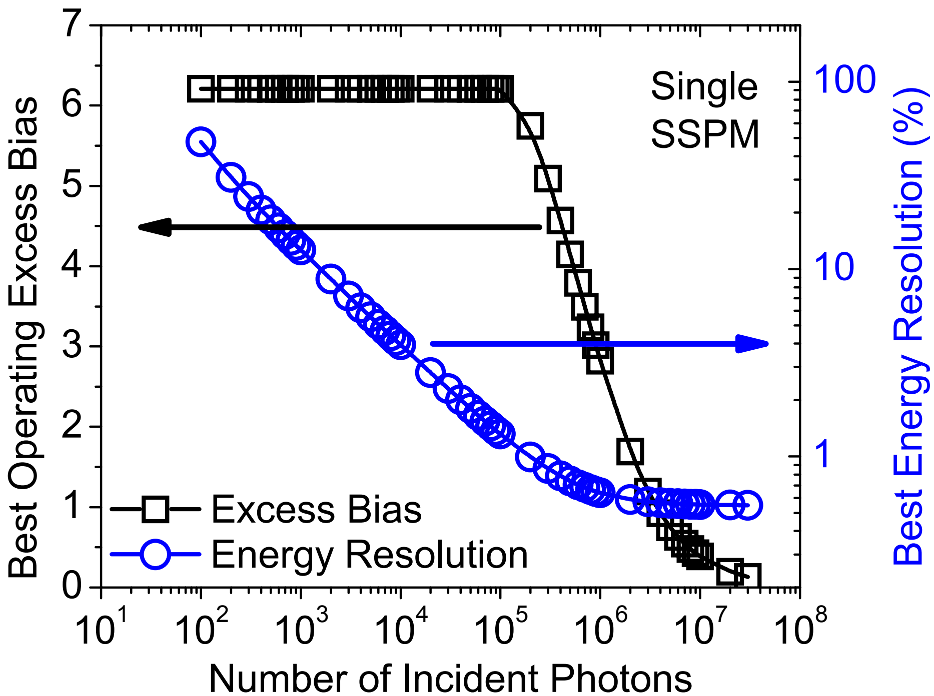
Noise terms and τ–scaling

$$\left(\frac{\sigma_E}{E}\right)^2_{\det} = \frac{F_{SSPM}\left[\langle n_t\rangle\left(1-\frac{\langle n_t\rangle}{n_{ttl}}\right)+\langle n_{dark}\rangle\right]}{\left(-\ln\left(1-\frac{\langle n_t\rangle}{n_{ttl}}\right)\cdot\left(n_{ttl}-\langle n_t\rangle\right)\right)^2}$$

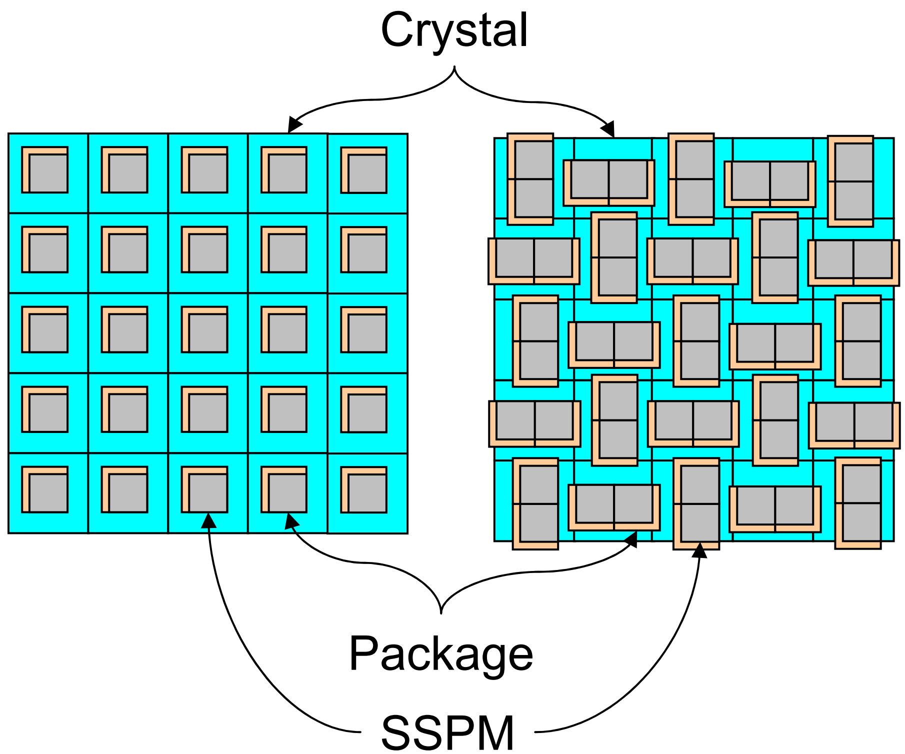
- Resolution from SSPM: Other factors are needed to get a complete energy resolution.
- Bright and fast scintillation best: long integration times increase noise
  - From DCR
  - From F_{AP} (generally small compared to F_{XT})
- Relative magnitude of the terms (1 SSPM):
  - $\langle n_t \rangle \sim$ 1-20k
  - $\langle n_{dark} \rangle \sim$ 10-50
  - $F_{sspm} \sim 2$
  - $n_{ttl} \sim$ 50k

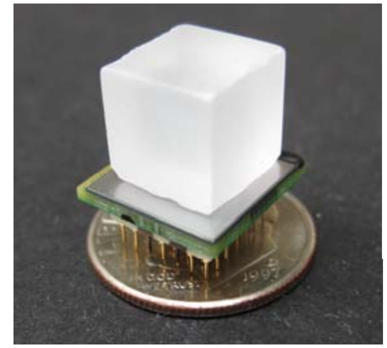
Estimating the Energy Resolution

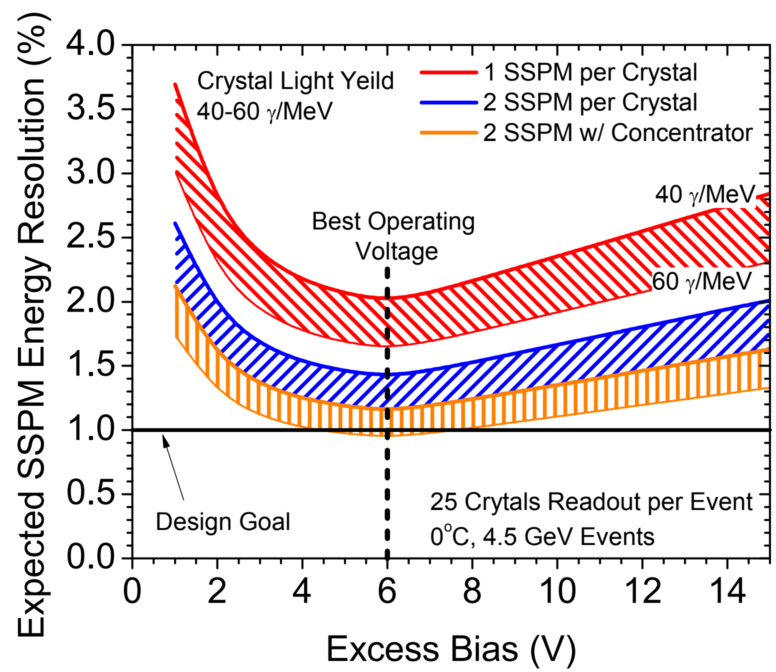
- Compile each signal and noise term discussed for the large-area SSPM.
- Calculated the expected energy resolution for the large-area SSPM.
- Focus is on short integration times only. (No after pulsing.)
- Specific Application: High Energy Gamma Ray Calorimeter
  - Used a 10 ns integration time to estimate dark noise.
  - Operation of the device is at 0 °C.
  - Effective quantum efficiency is 38%.



Design Optimization

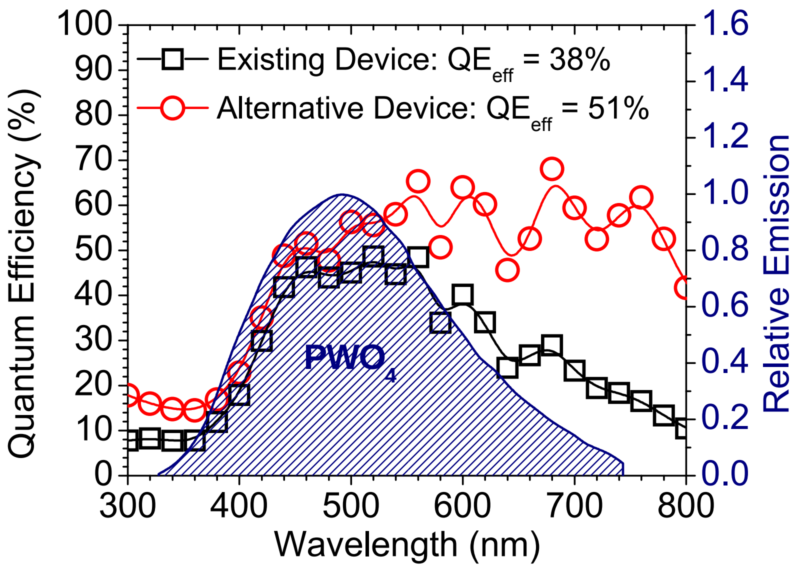




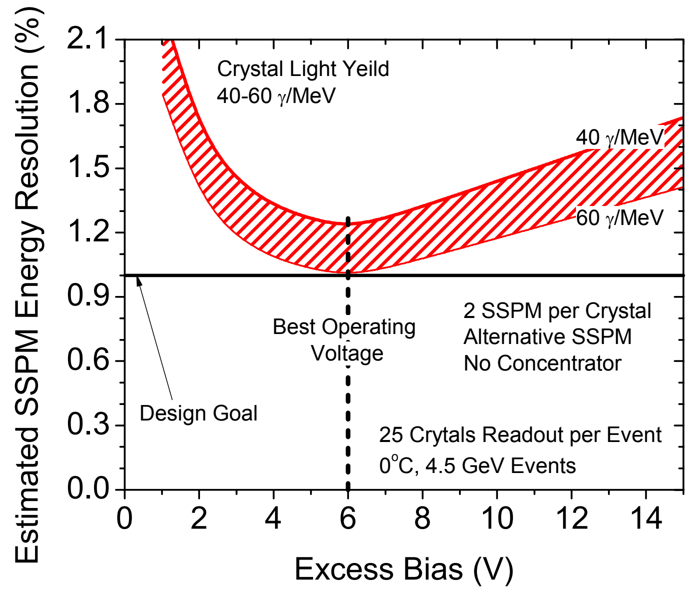


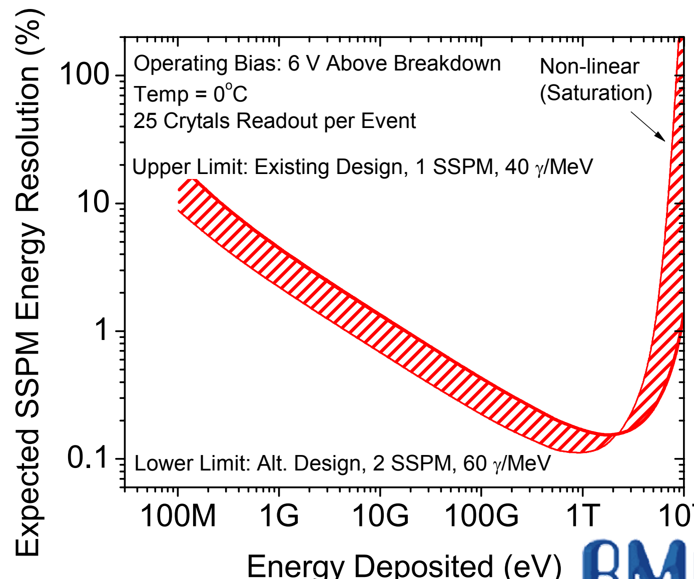
- Single pass- using only the geometrical efficiency
- 1 SSPM per Crystal: ~11% Geo. Eff.
- 2 SSPM per Crystal: ~22% Geo. Eff.
- Light Yield of $PbWO_4$ may be from 40-60 p/MeV - *Annenkov, Korzhik, Lecoq, NIMA 490, 30-50 (2002)*
- Consider optics to improve light collection. (Estimated with 50% increase in light collection.)

Alternative SSPM Design



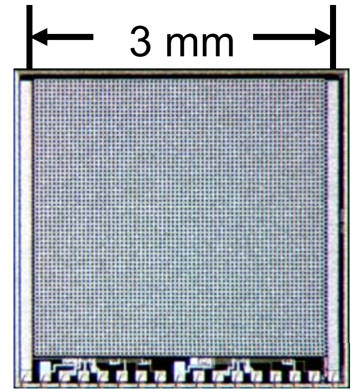
- Alternative SSPM design has different diode structures.
- QE is larger over a larger bandwidth, improving DE.
- Using identical performance characteristics as existing device- energy resolution improves.
- This design has shown to have larger noise characteristics, but a through analysis is needed to determine if there are any improvements in the signal to noise.





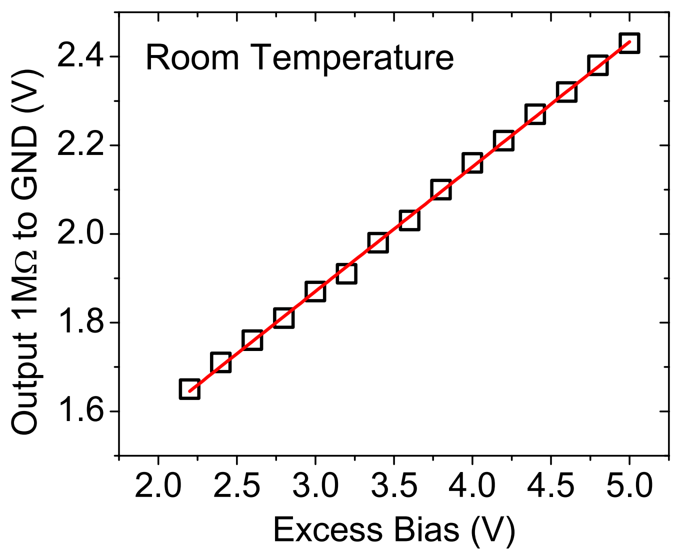
Temperature Stability

- Changes in the breakdown voltage affect the detector response.
- The size of these effects are dependent on the excess bias and the temperature coefficient on the breakdown voltage.
- Use on-chip circuitry to monitor the excess bias.
- Use this signal for a feedback loop to maintain a constant excess bias.

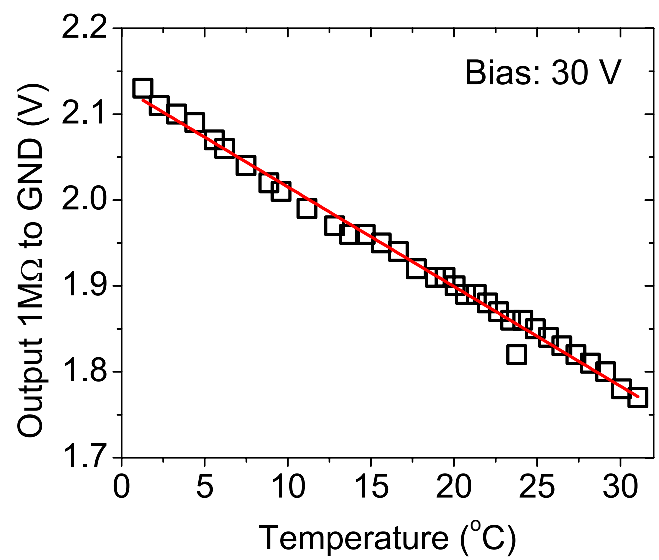


4300-pixel SSPM with integrated circuitry

The response of the device is linear with an applied excess bias.



For a constant bias voltage , the excess bias is inversely proportional to the temperature.

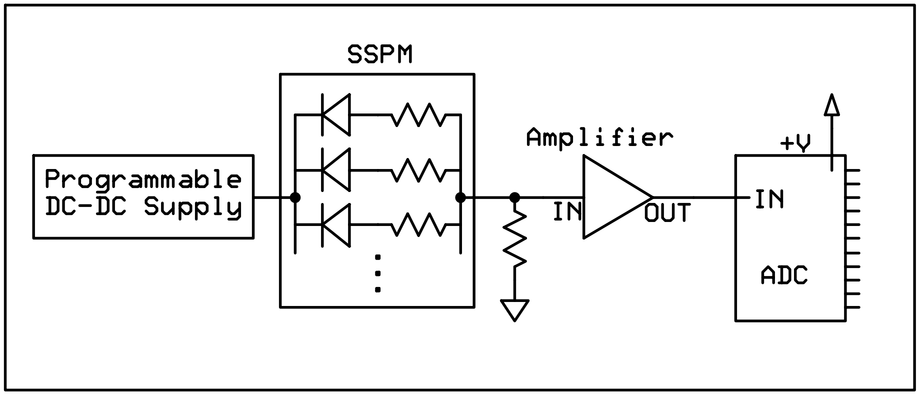


Next Generation of CMOS SSPMs

- Low Cost SSPMs can be achieved using a CMOS process with large features- Low Cost per Area.
- How do we improve the performance?
- Smaller CMOS Process: Smaller pixels are possible
  - Improve dynamic range of a linear response.
  - Reduce hot carrier emission
  - Reduce after pulsing
  - Reduce fill factor but operate at a higher bias to maintain DE.
  - Smaller dark current.
  - Is this viable:
    - How does the hot carrier emission change?
    - What is the final signal to noise at a higher bias?
    - Are there circuits that can be used to reduce noise terms?
  - Integration of higher-level circuits (i.e. ADC) takes up less real-estate and should perform faster.

ADC Front End Assembly

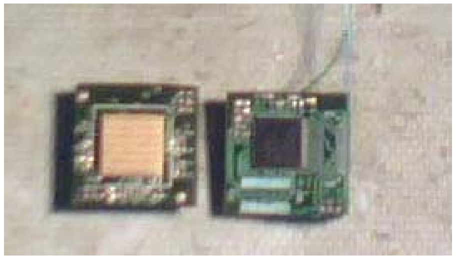
Sensor Head



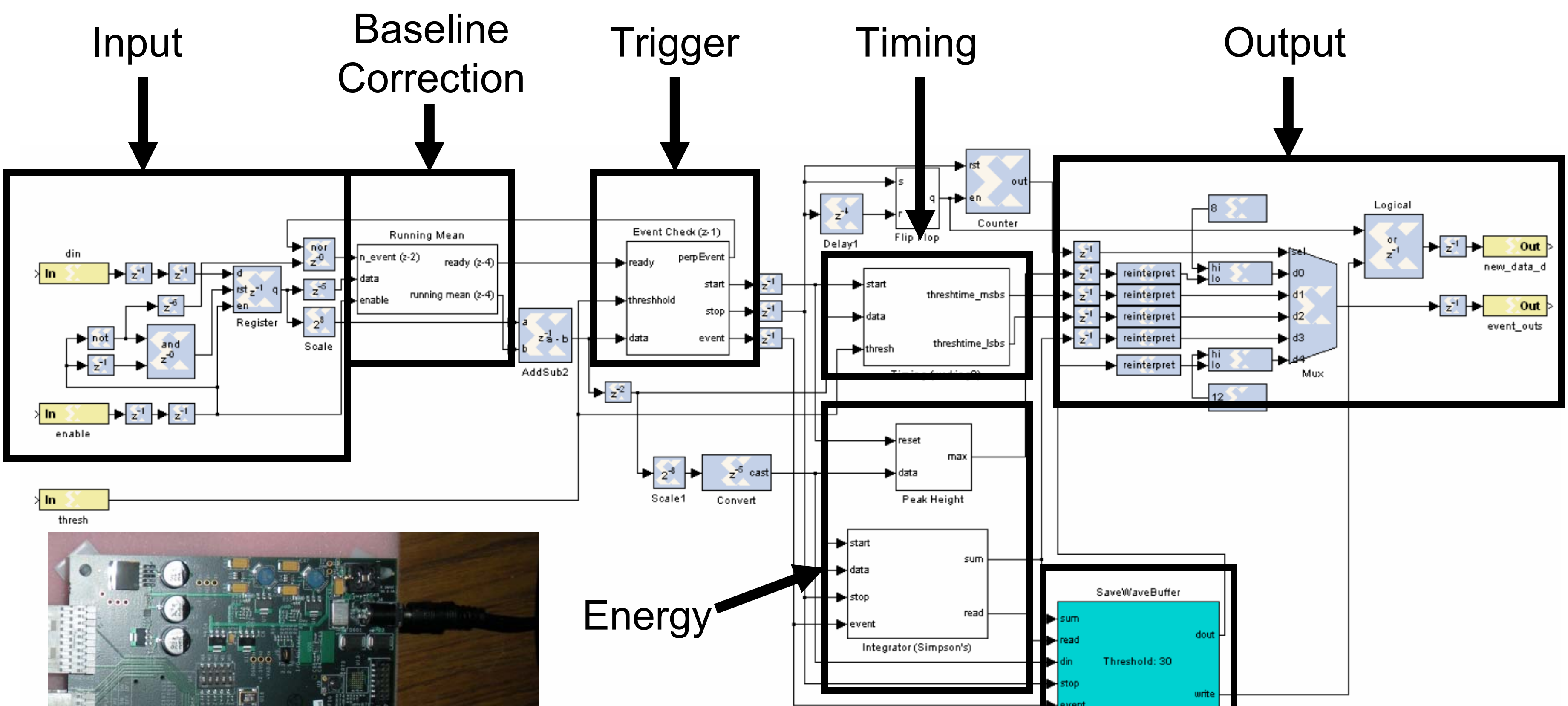
Connection to FPGA Board

Input	**Output**
+5V	ADC Data
Com to DC-DC Supply	Gain Monitor Signals
Clock	
+1V	

- Sensor head will be directly coupled to the $PbWO_4$ Crystal.
- Area is roughly 2 cm x 2 cm.
- Prototype consists of 1 SSPM, Amplifier, ADC, and DC-DC supply.
- There are a number of methods for monitoring gain using circuitry on the silicon die.
- Plan to evaluate this instrument extensively with $PbWO_4$ Crystals and high energy gamma rays.
- The prototype has recently been assembled for testing.



Data Capture for Characterization



Schedule

Task	Percent Complete	To Be Completed
Evaluate Existing CMOS Designs	100%	
Simulate Detector Modules for Optimal Design	70%	Dec 2010
Design and Construct Prototypes for a Large Area SSPM	100%	
Construct an Apparatus for High-Energy Gamma Interactions	50%	Sep 2010
Evaluate Prototypes with $PbWO_4$ Scintillators	0%	Nov 2010
Design and Simulate CMOS SSPMs with Integrated Signal Processing	0%	Feb 2011
Construct CMOS SSPMs for Calorimeter Application	0%	Jun 2011
Design Interconnect Board for Digitization	50%	Jun 2011
Construct a PRIMEX Calorimeter Cluster Module	0%	Jun 2011
Evaluate Cluster Module at an Accelerator Facility	0%	Jul 2011
Provide Phase-II Progress Reports	50%	Aug 2011

End of Program August 2011

Summary

- A Large-Area SSPM has been fabricated for implementation for nuclear physics applications.
- The existing device has been studied extensively, and we are looking at additional options for improving the energy resolution of the calorimeter.
- The SSPM has been mounted on a chip-scale substrate and will be coupled to a small PCB with an fast ADC.
- We most of the components and software in place and will be expecting to evaluate a single PbWO element within the next few months.