Instrument Research
& Development

CMOS Solid-State Photomultipliers for High Energy Resolution Calorimeters

Optical Detector with Integrated ADC for Digital Readout

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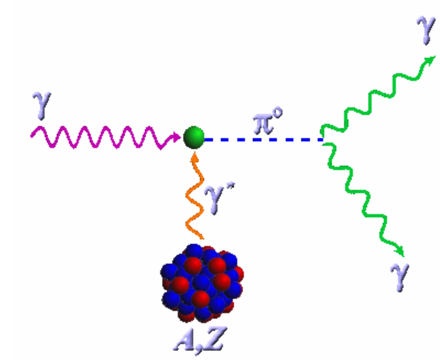
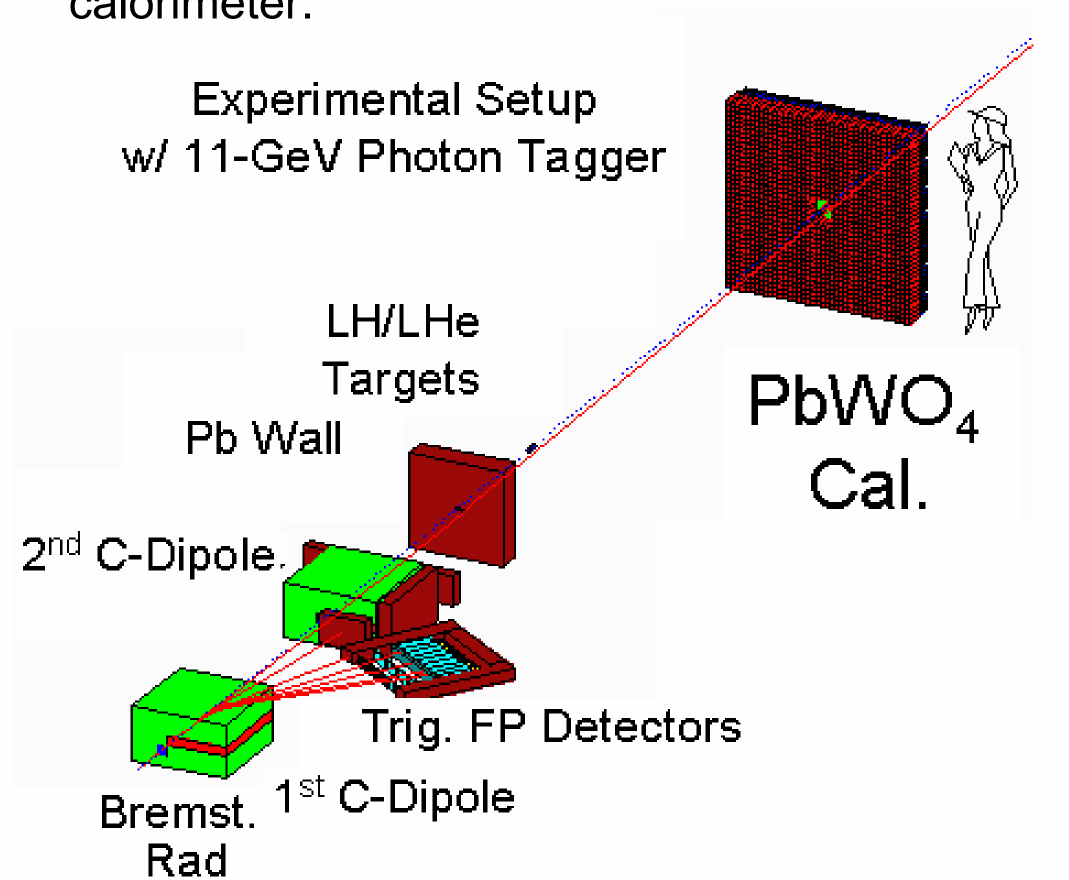
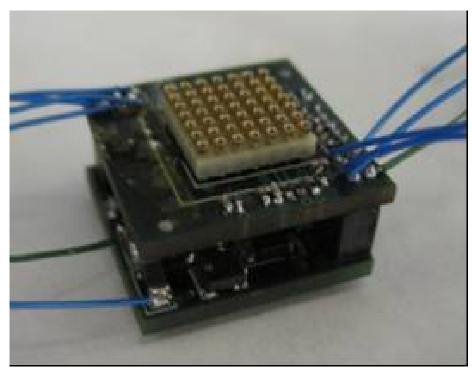
PRIMEX Calorimeter Readout

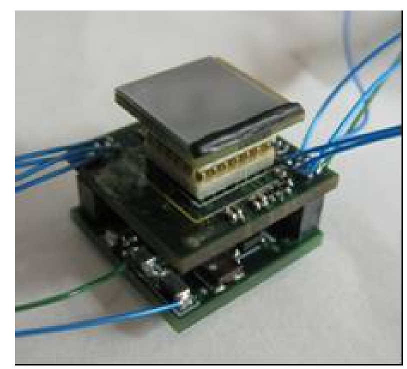
- Utilizing the Jefferson Lab Upgrade.
- Provide direct measurements at low energies of parameters of Quantum Chromodynamics (QCD) using η and η' lifetime measurements.
- Primakoff effect production of neutral mesons, which decay.
- Need to measure position and energy deposition in calorimeter.





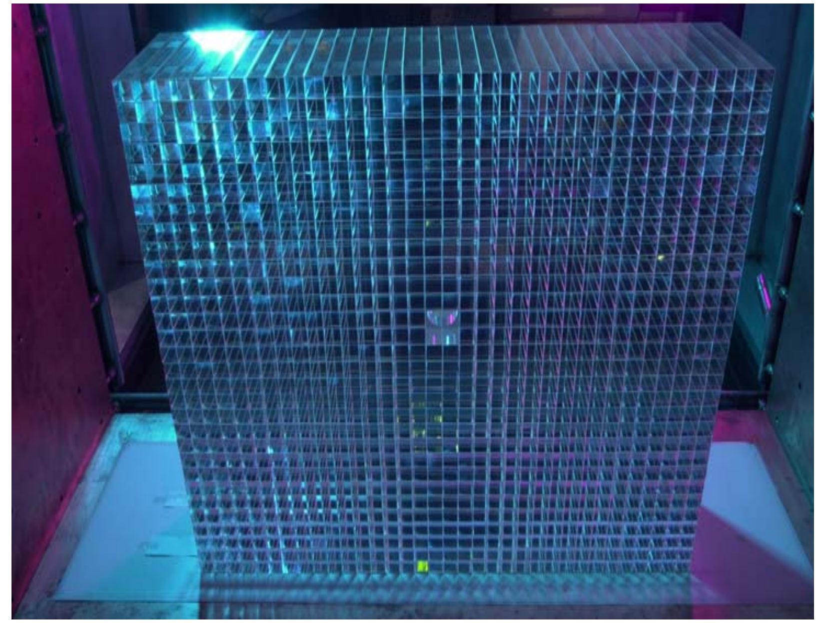
- About 1% energy resolution at 4.5 GeV
- Replace lead glass with smaller $PbWO_4$
- Cost effective readout will make this possible.

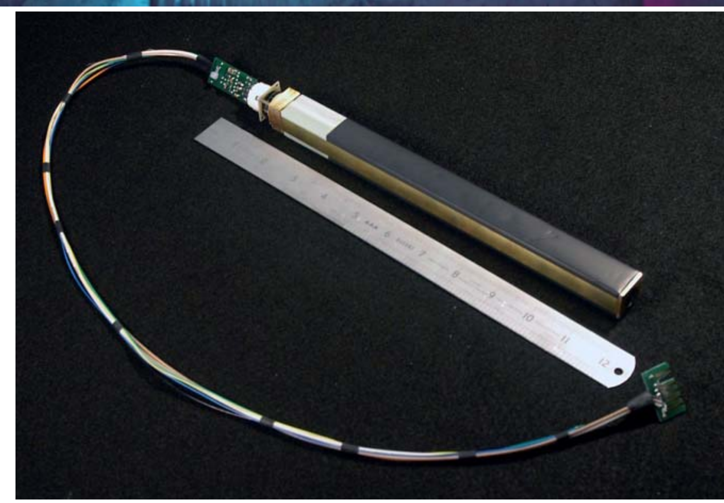




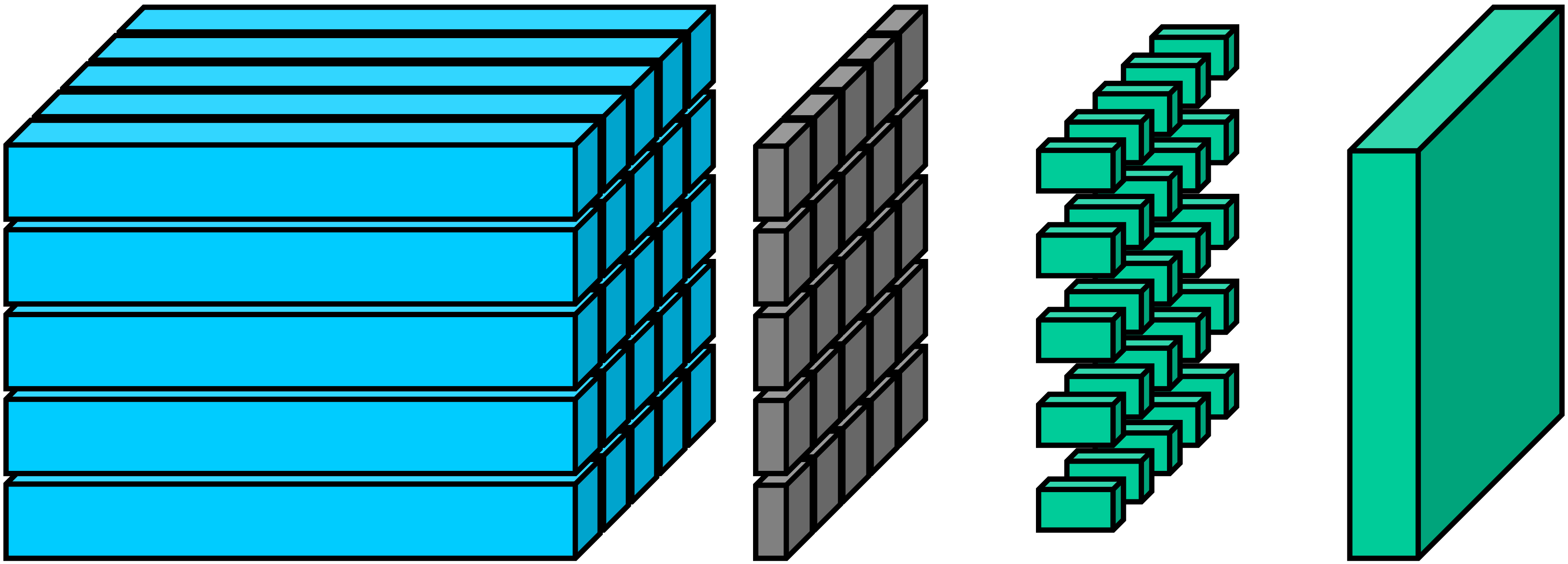
The PRIMEX $PbWO_4$ Calorimeter

- 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
- Detecting two high energy gamma rays
  - Scattering along scintillator
  - Scattering laterally
  - Bundle clusters of scintillators



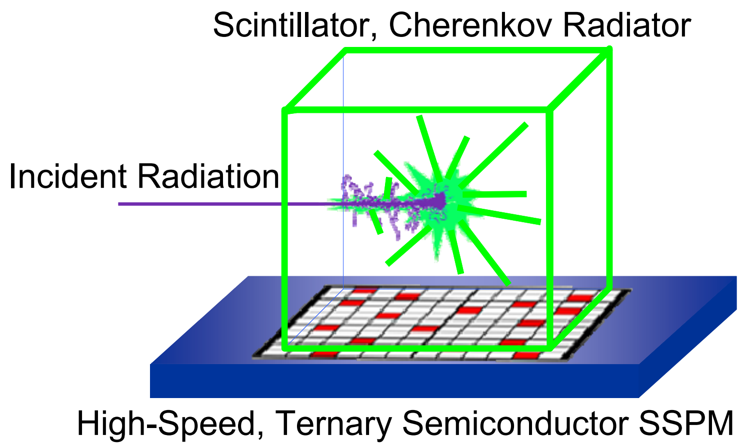


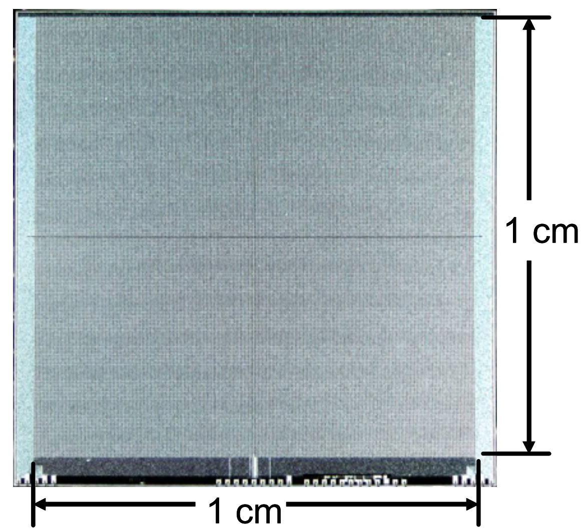
Building the Calorimeter

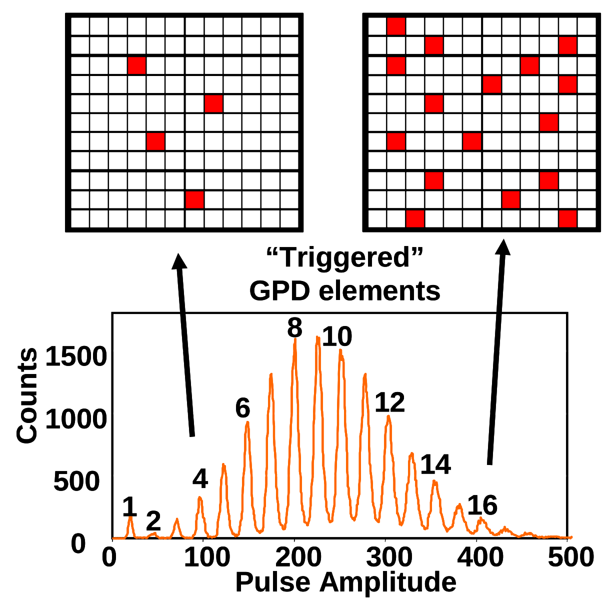


- Segment components for construction.
- Integrate electronics at front-end.

Solid-State Photomultipliers

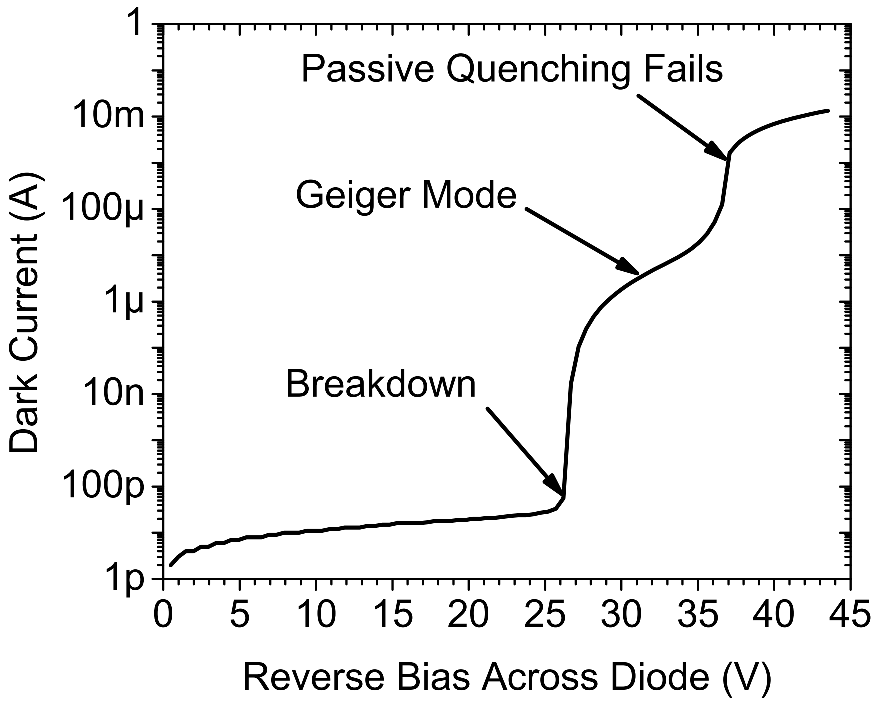


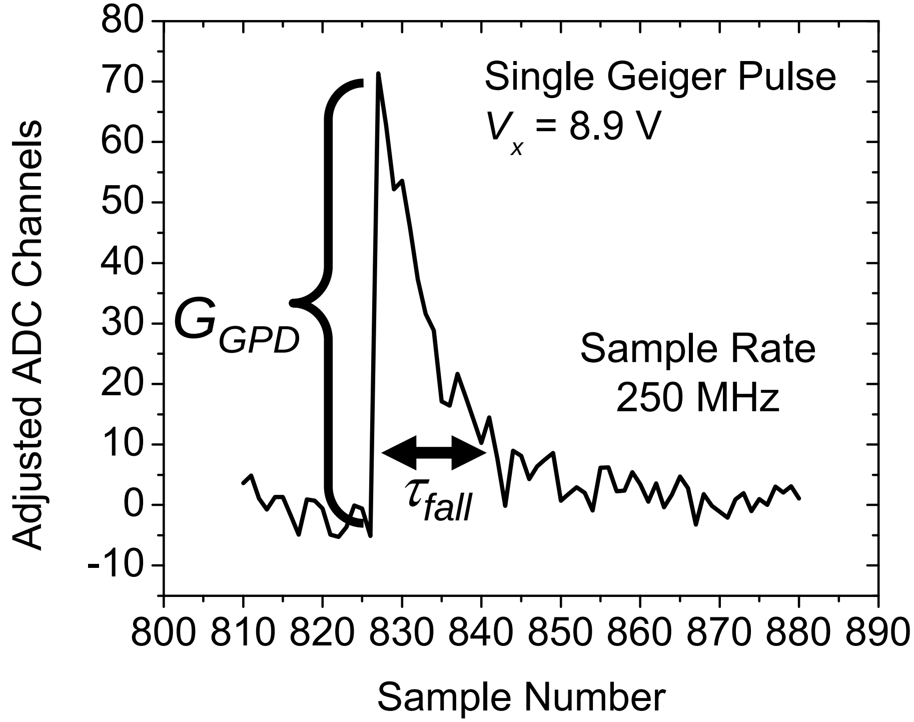




- Solid-state photomultiplier (SSPM) is an array of Geiger photodiodes read out in parallel.
- Each photodiode has a gain of 10^6 for single photon events.
- Number of diodes triggered is proportional to the incident light flash.
- Compact and phototube like response.

Single Geiger Photodiode Response

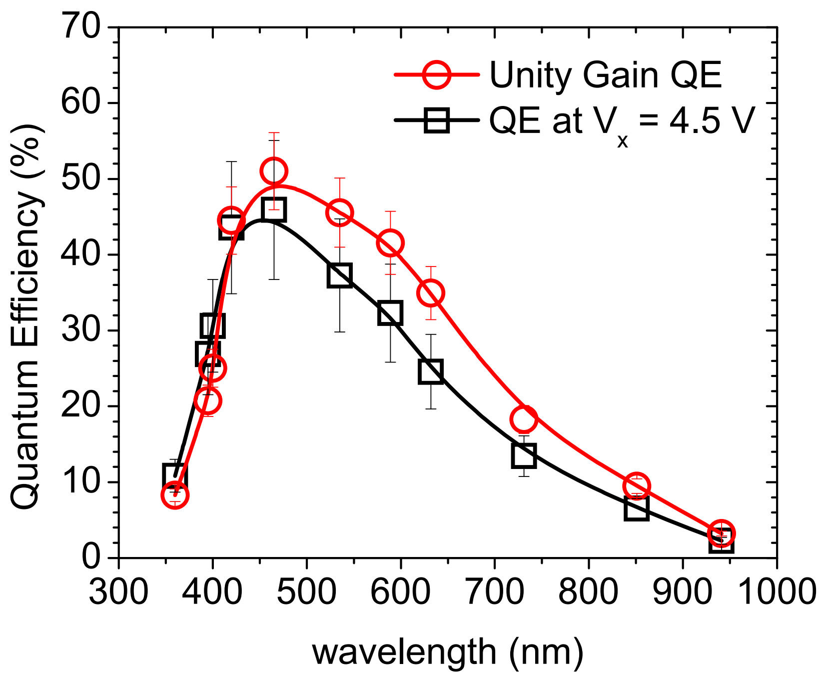


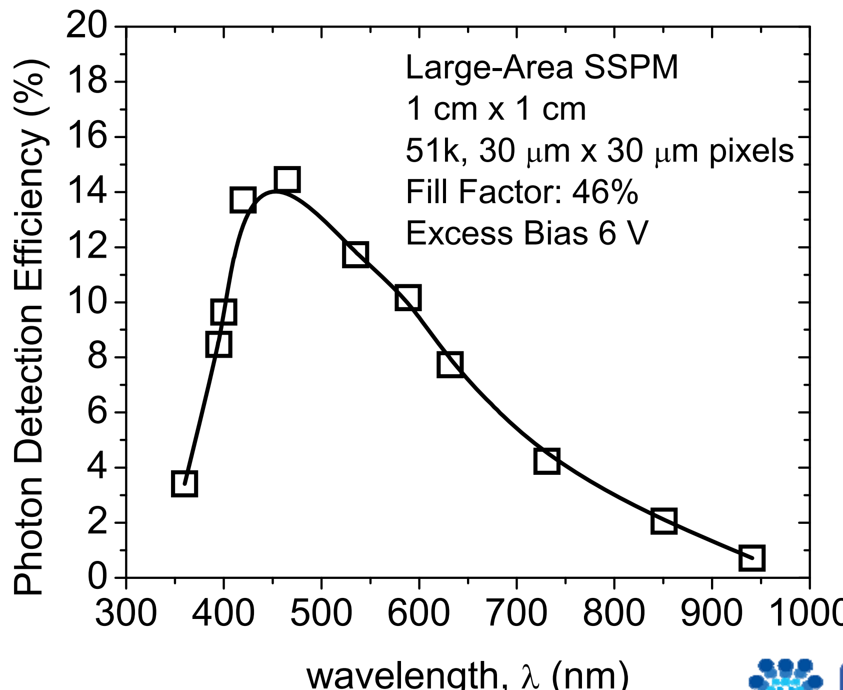


- Breakdown: ~26.7 V
- Range of Operation: 10 V above breakdown.
- C_{jn} = *150 pF*
- Gain @ V_x = 1 V: 9×10^5
- $\tau_{rise} \approx$ 1.7 ns
- $\tau_{fall} \approx$ 30 ns

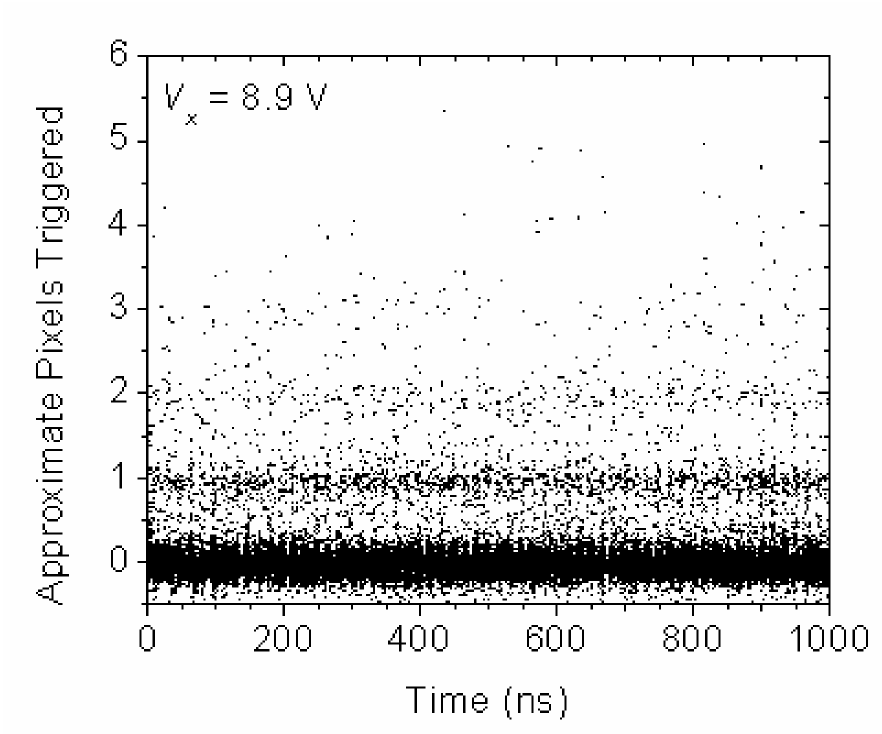
Detection Efficiency

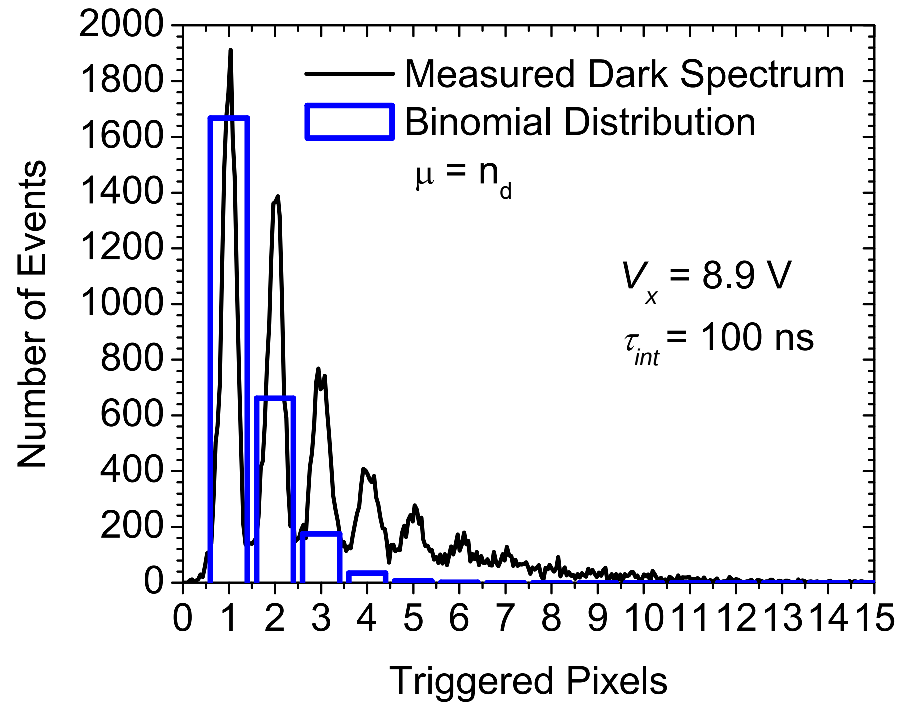
- Detection efficiency is a product of the QE and the Geiger probability.
- Difference in ionization rates between holes and electrons.
- There may be differences in the Geiger avalanche probability, P_g, as a function of wavelength.
- Many scintillation materials emit in the blue.
- Small changes in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





Excess Noise Analysis





- Conducted an extensive analysis on processing the waveforms.
- Robust method for characterizing each noise term.
- Identify differences between expected and measure dark spectra.
- Distinguish dark noise, cross talk, and after pulsing.

Geiger-Mode Multiplier

$$n_t(\tau) = M_X \cdot M_{AP}(\tau) \cdot n_d(\tau) = M \cdot n_d(\tau)$$

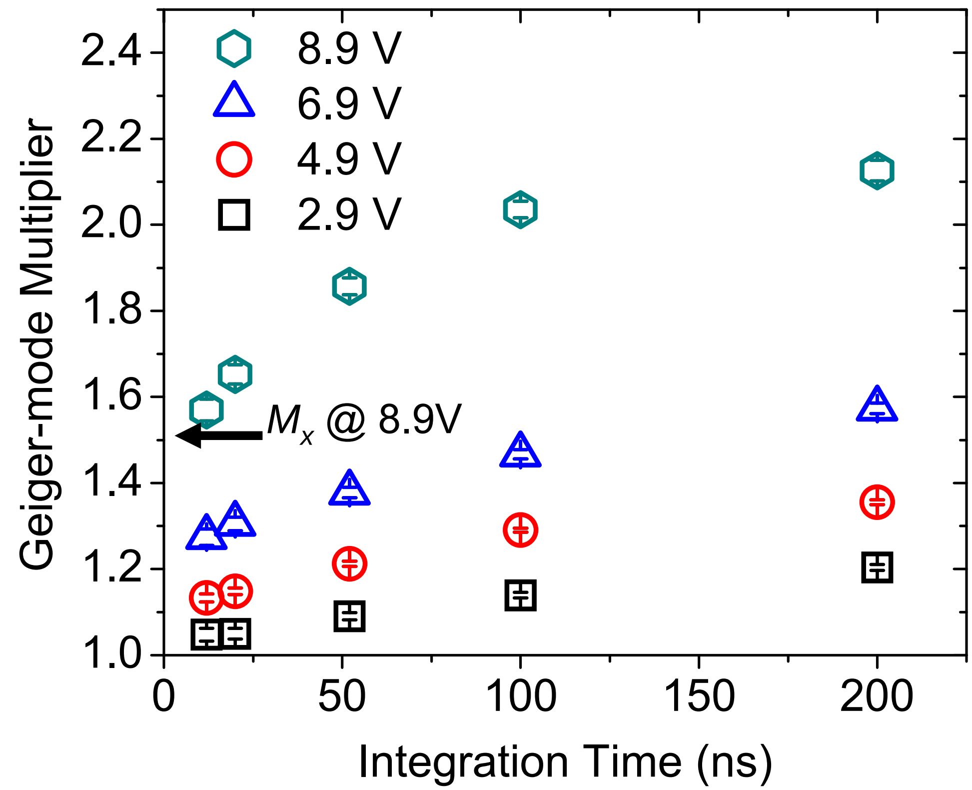
Spectral Mean

Dark Triggers Binomial

$$n_d(\tau) = n_{ttl}\left(1 - \left[\frac{N_0}{N_T}\right]^{\frac{1}{n_{ttl}}}\right)$$

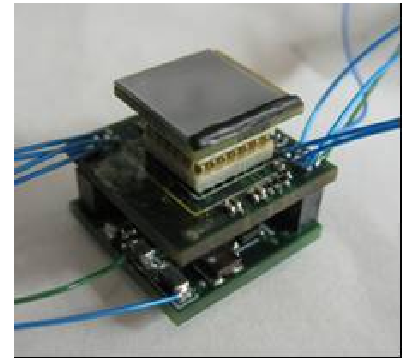
- All terms are averages.
- Estimate total number of possible diode triggers based on integration time and number of diodes in the SSPM.
- Determine spectral mean.
- Calculate expected mean.
- Ratio gives the multiplier.

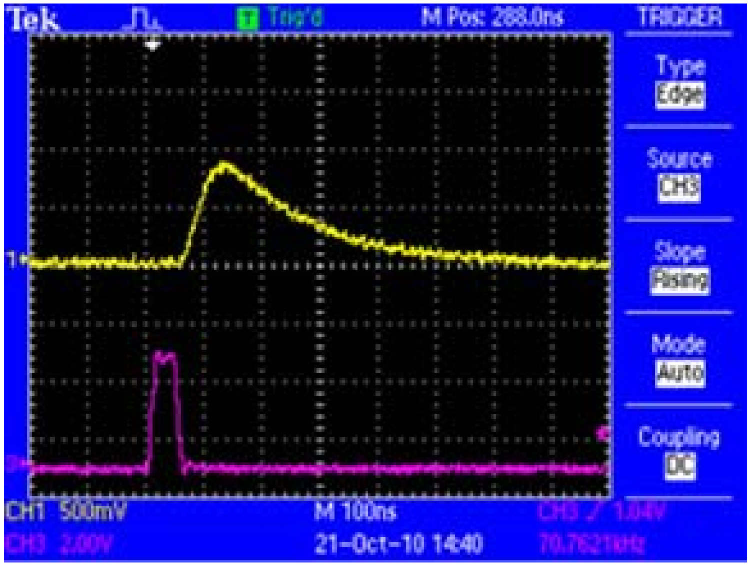
- Determine excess noise factor, but we are still looking at it.



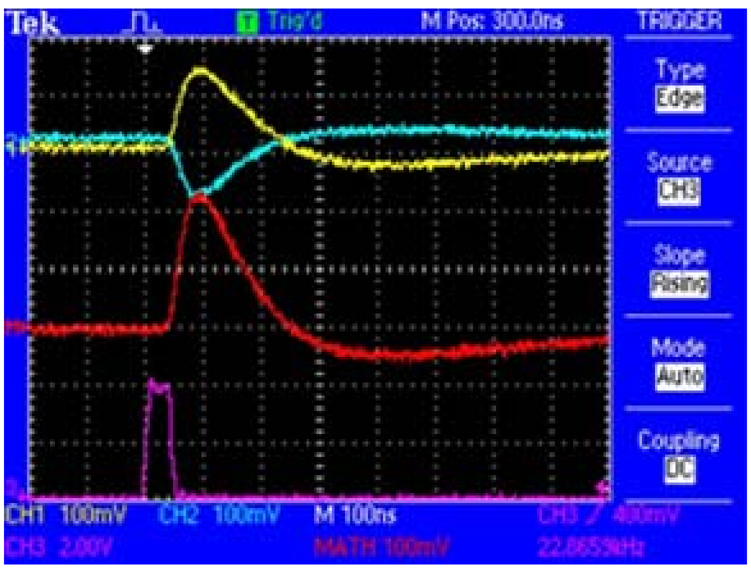
- Short Integration:
  - M_X is given
  - Scales only with bias
- Long Integration:
  - Product of M_X and M_{AP}

SSPM Connection and Amplifier



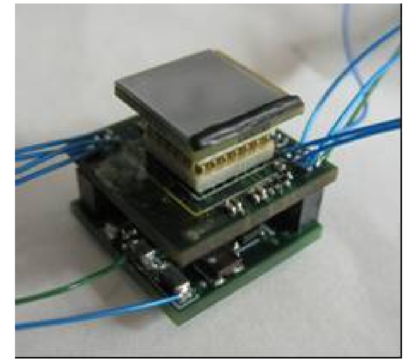


- SSPM Function:
  - Evaluated each component of the modular readout boards.
  - SSPM connections were tested.
  - Simple trans-impedance amp and a light pulse from an LED was used.

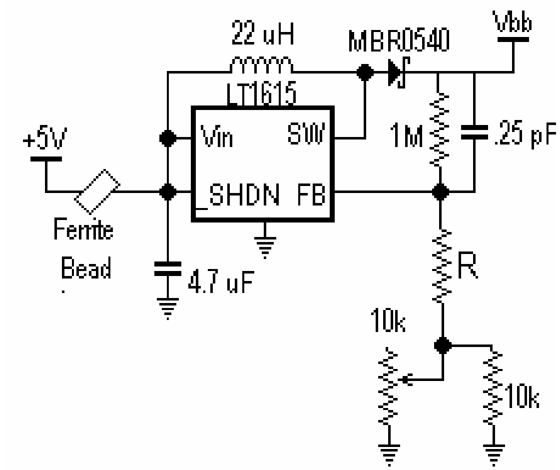


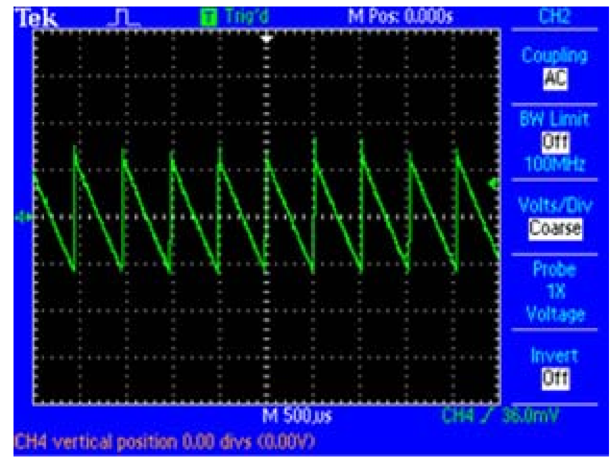
- Amplifier Function:
  - Each photodetector on the device is connected properly. The fast amplifier used is a 2.2 GHz differential amplifier.
  - The signal from the SSPM is readout after the amplifier.

Boost Converter

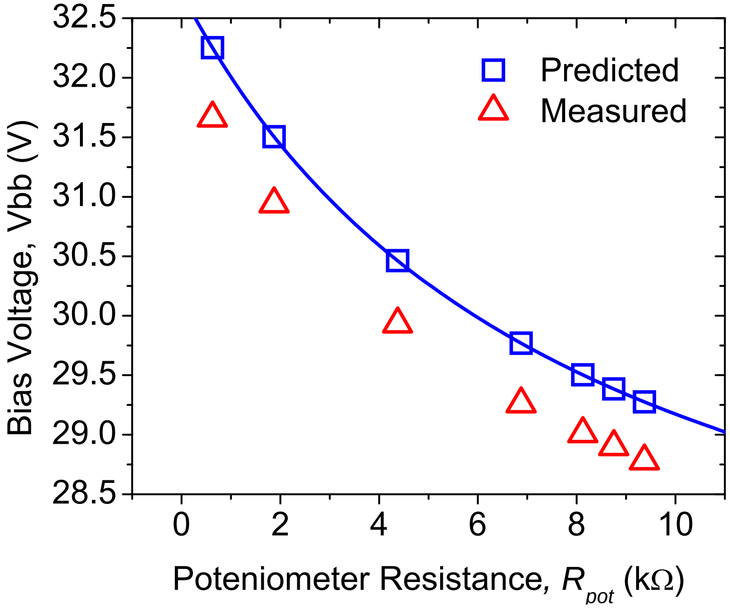


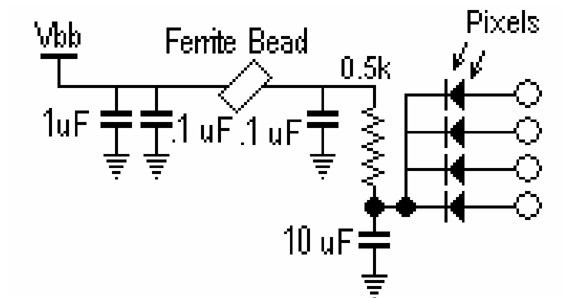
- A DC/DC boost converter is used to power the SSPM.
- The voltage will be controlled through an interface through the FPGA.
- Each circuit will need to be calibrated.
- Filtering is used to remove the switching noise from the converter.

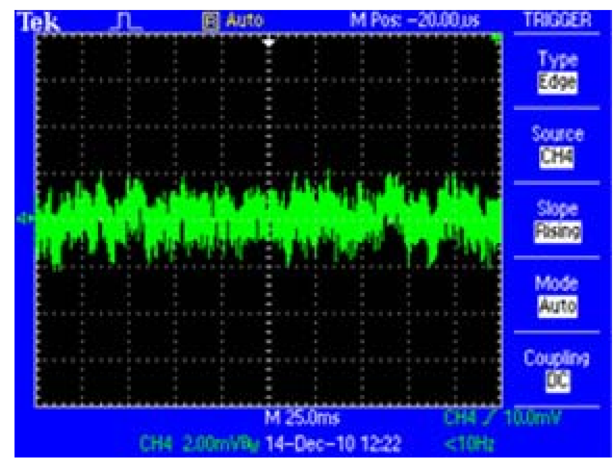




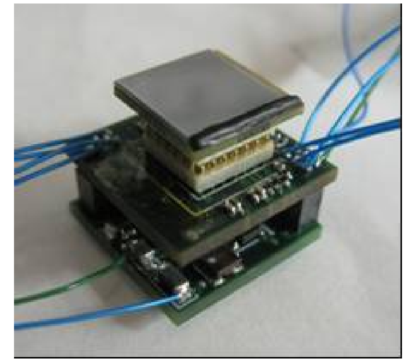
Predicted and actual step-up bias voltages (Vbb)

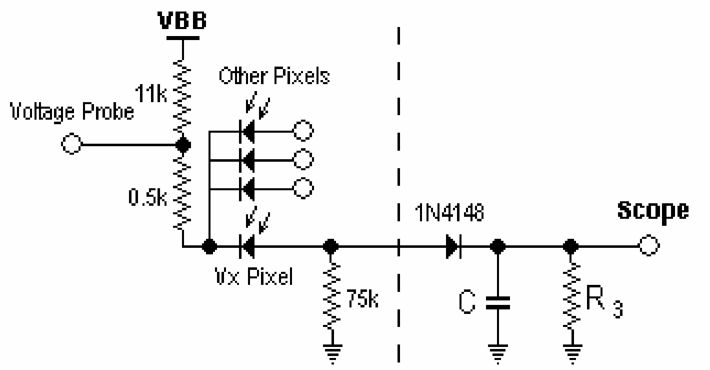




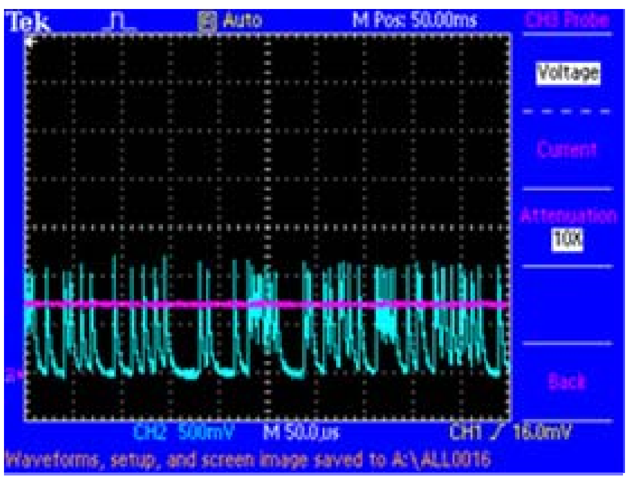


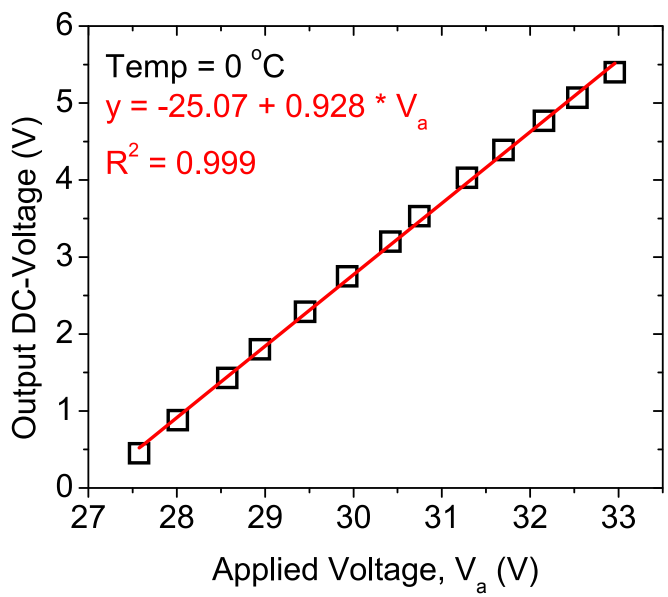
Excess Bias Monitor

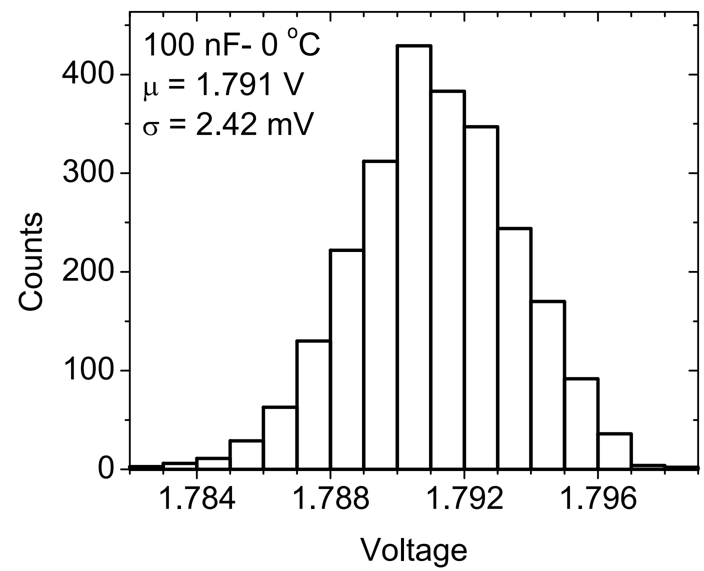




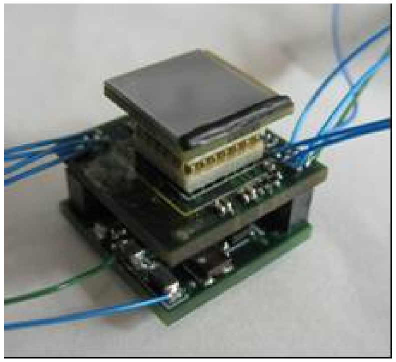
- A large isolated pixel is used to monitor the excess bias.
- The voltage drop across the diode is held by a slow RC circuit.
- The dark current is sufficiently large to keep the voltage stable.
- The response is linear will applied bias over a 5 V swing.
- The offset is accurate to within 2.5 mV.

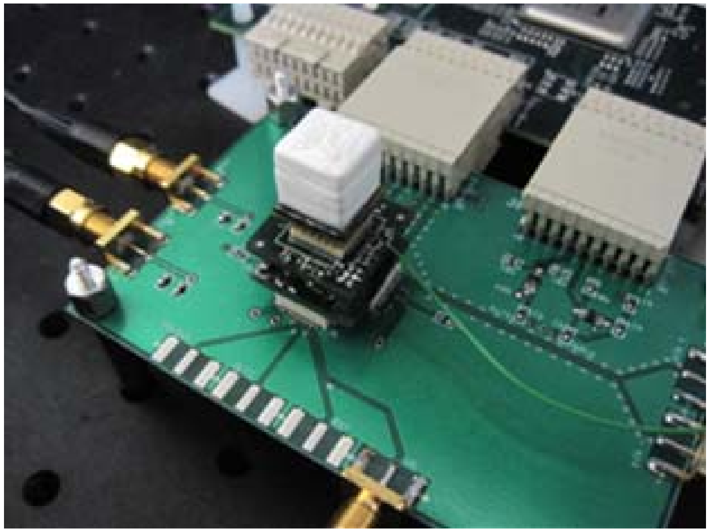


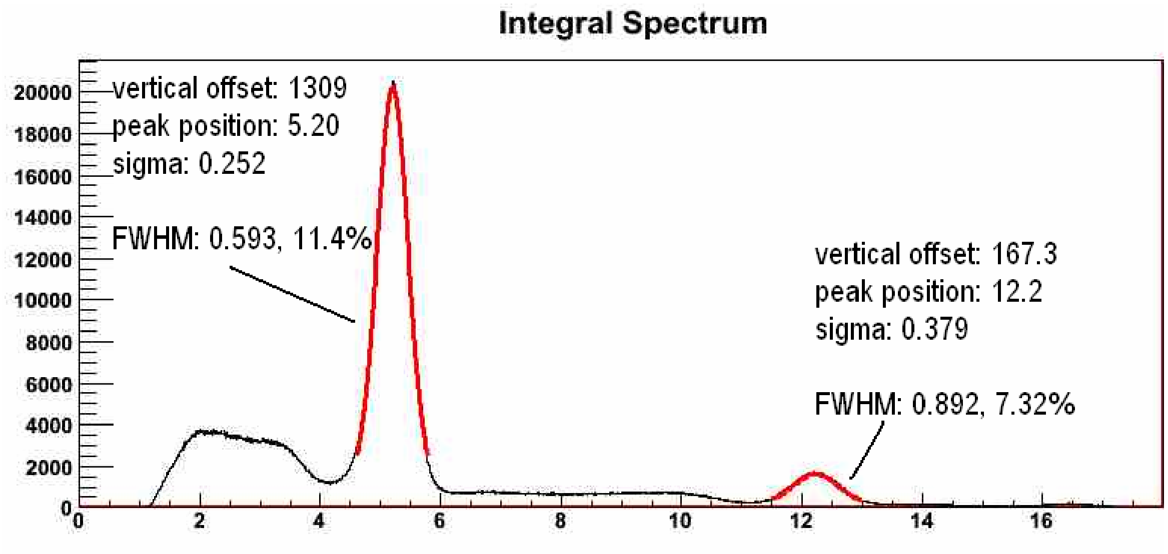




Complete Functionality

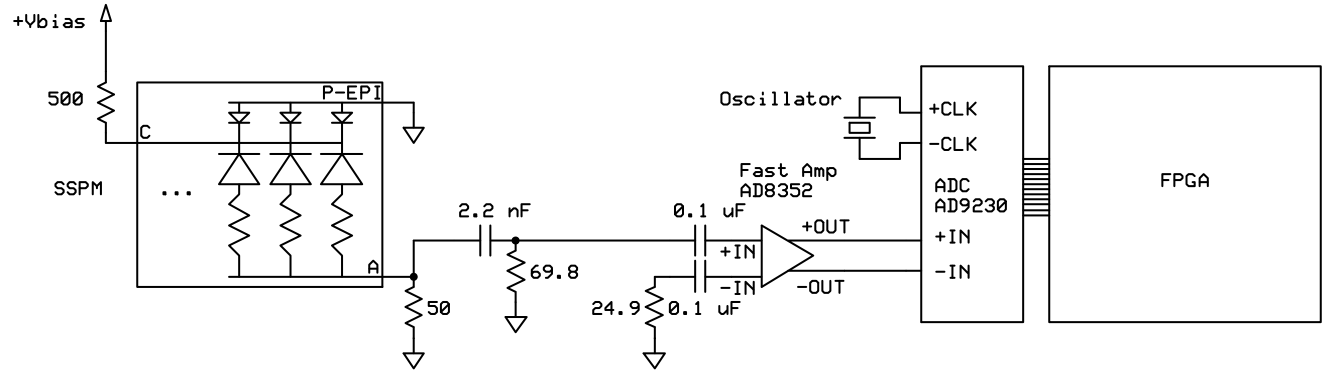




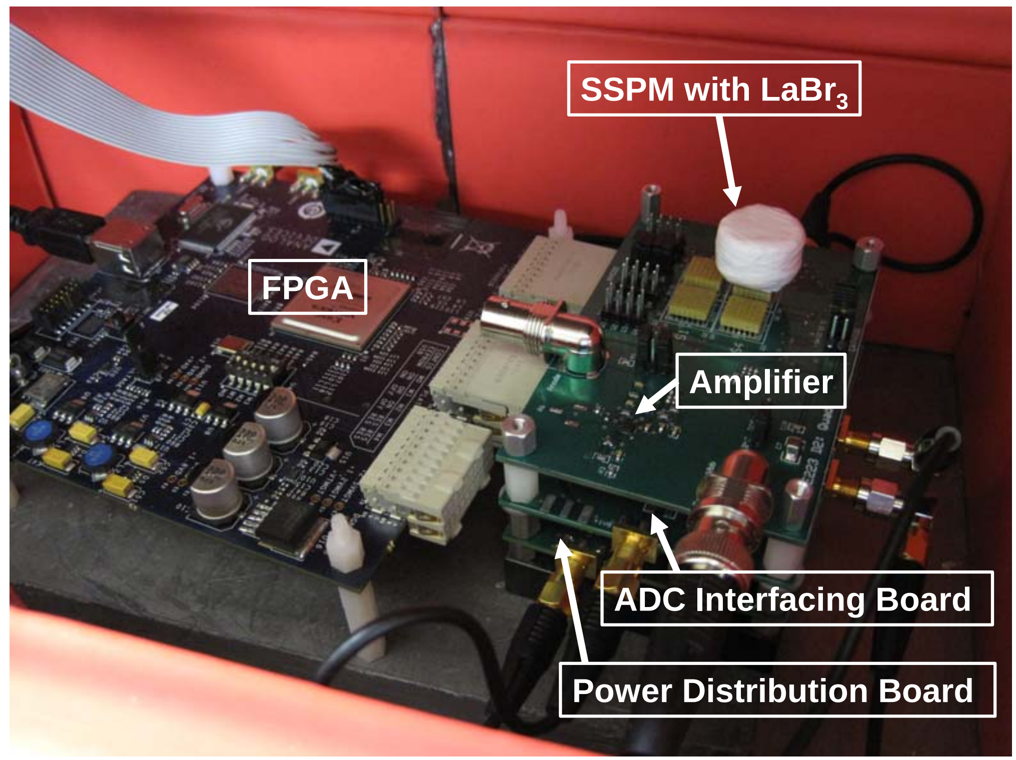


- Coupled to an FPGA evaluation board.
- Placed a LYSO crystal on the SSPM and powered the device through the boost converter.
- The 12-bit word from the ADC was sent into the FPGA and processed.
- The code calculated an integral for each gamma event from a 22Na source.
- The integrals were saved for a file and a histogram was generated, reproducing the expected results.

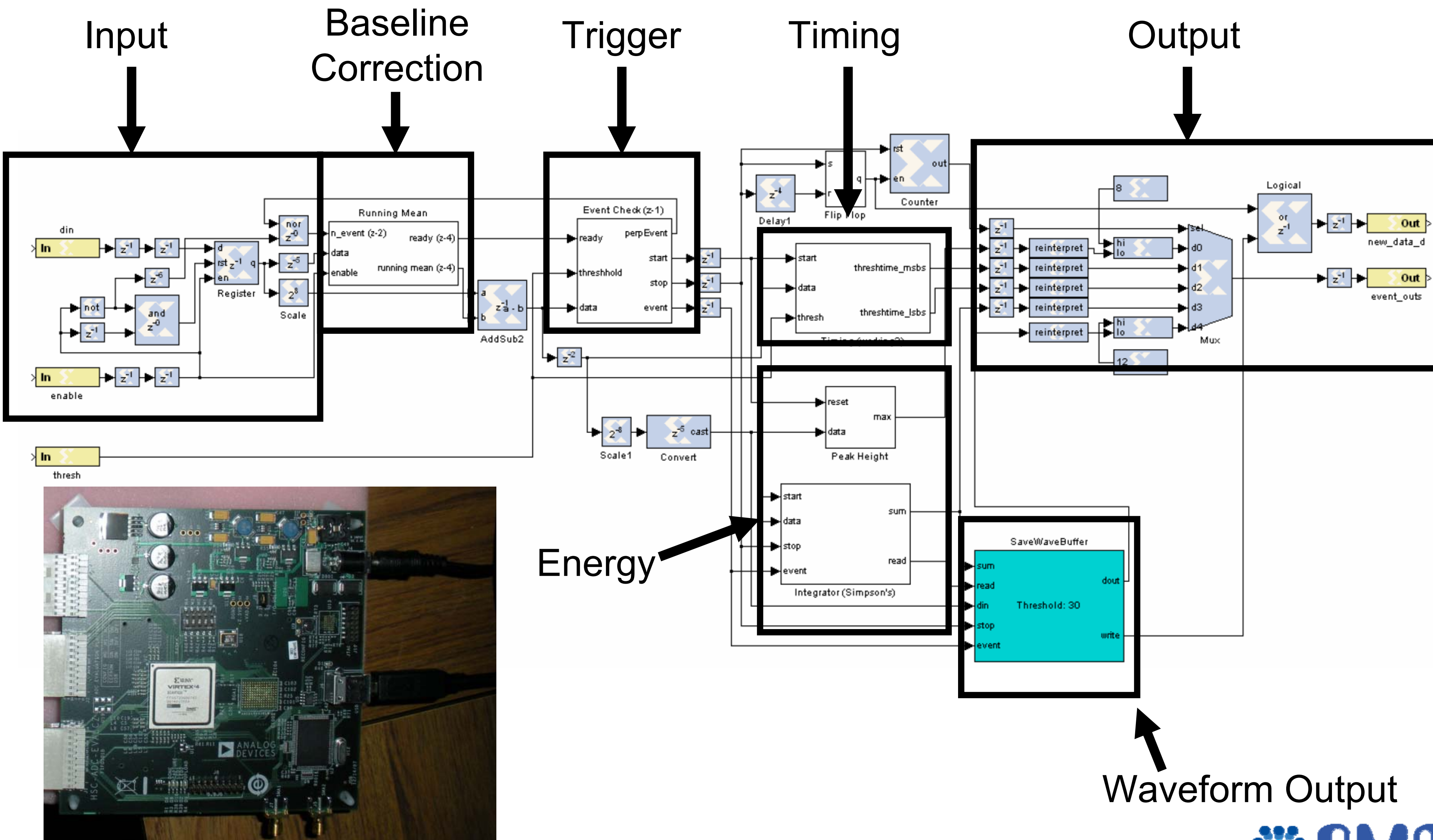
Determining the Expected Performance



- We want to provide a model that will accurately predict the behavior of an SSPM-based detector.
- Excess noise is the unknown factor.
- Readout Scheme:
  - Large gain from the SSPM allows for a very simple readout COTS components.
  - Fast electronic components are necessary for extracting the physics information.
  - Evaluation components were built and tested at 0 °C.

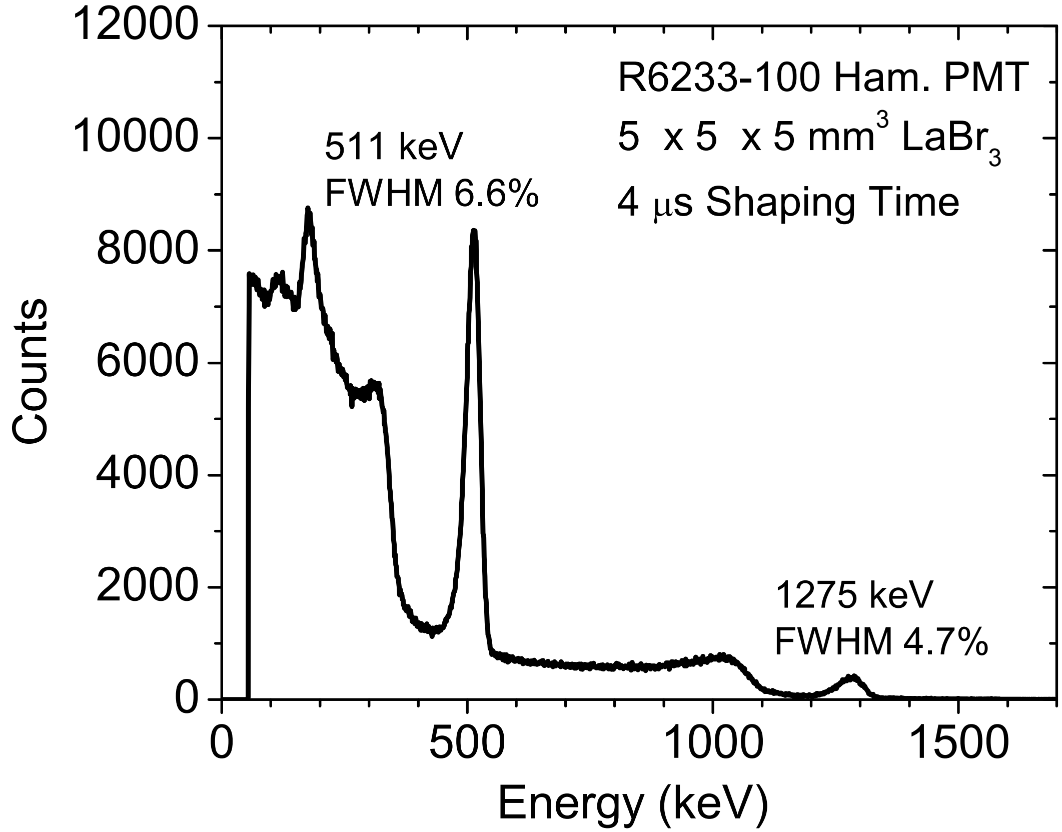


Data Capture for Characterization



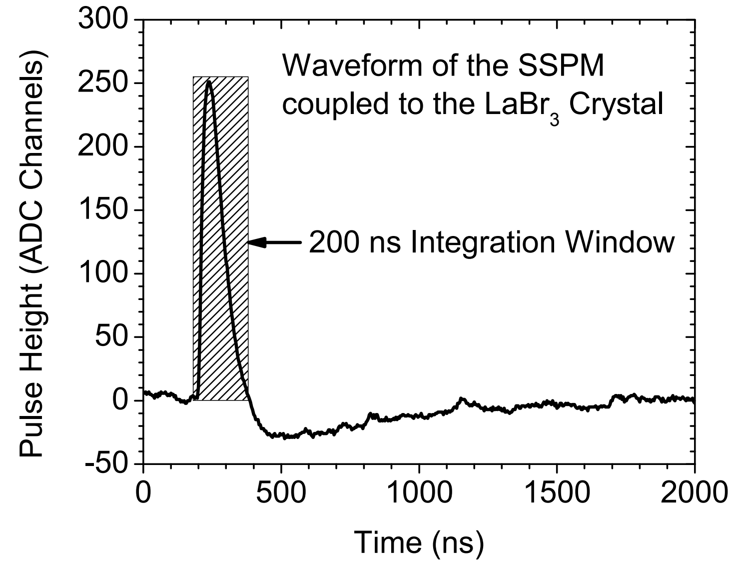
$LaBr_3$ on PMT

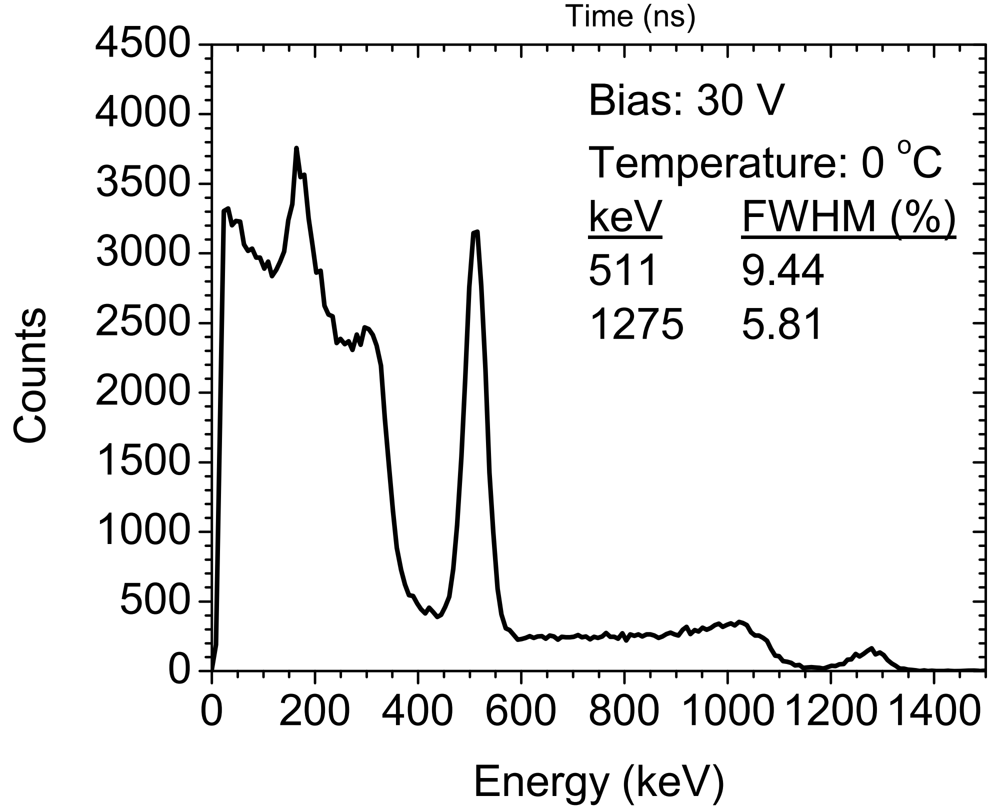
- No readily available high-energy gamma ray source for evaluation with $PbWO_4$.
- Used a high-quality, fast, bright scintillator.
  - Lanthanum Bromide.
  - ~60 photons/keV
  - Decay Time: 16 ns
- Evaluate with PMT
  - Optically coupled with grease.
  - Crystal in aluminum can.
  - Super bialkili cathode
  - QE_{Eff}: ~ 32.8%
- Scintillator Contribution:
  - 511 keV: 6.1% (FWHM)
  - 1275 keV: 4.4% (FWHM)



SSPM Spectra

- Generated spectrum as it will be done in the PRIMEX experiment.
- Collect wave forms and process.
- Use a 200 ns integration window.
- Find maximum.
  - Capture a waveform over 8 μs.
  - Step over waveform with 200 ns window.
  - Find point with largest integration value.
  - Generate histogram of maximum values.
- Measurements:
  - Temperature: 0 °C
  - Bias: 29, 30, 31, 32, 33 V
  - Optically coupled using grease.
  - Exposed with gammas from ^{22}Na.



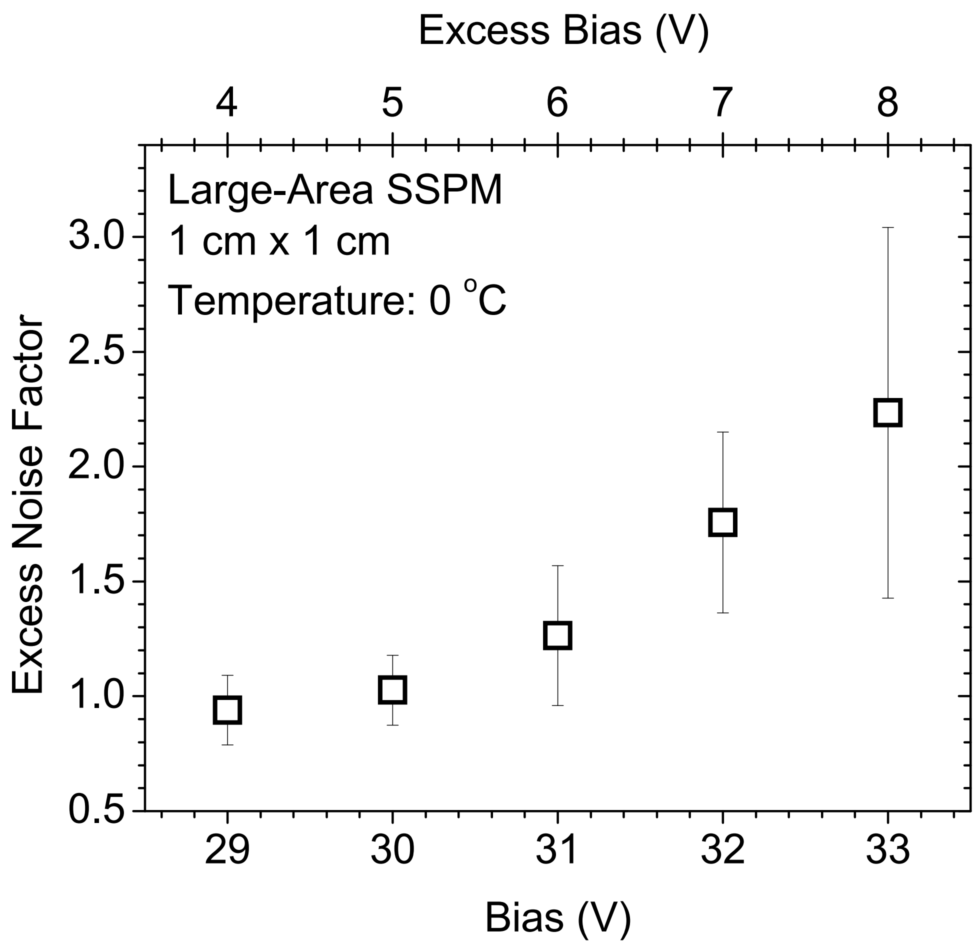


Radiation Monitoring Devices, Inc.

Excess Noise Factor

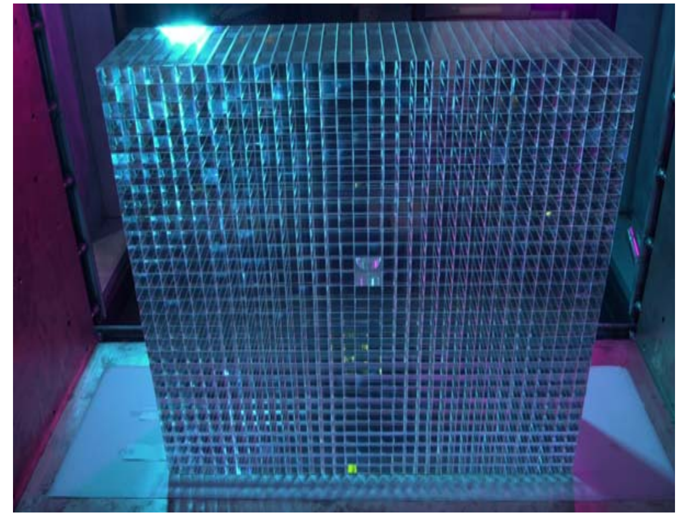
$$\left(\frac{\sigma_{Total}}{E}\right)^2 = F\left(\frac{\sigma_{Det}}{E}\right)^2 + \left(\frac{\sigma_{Scint}}{E}\right)^2$$

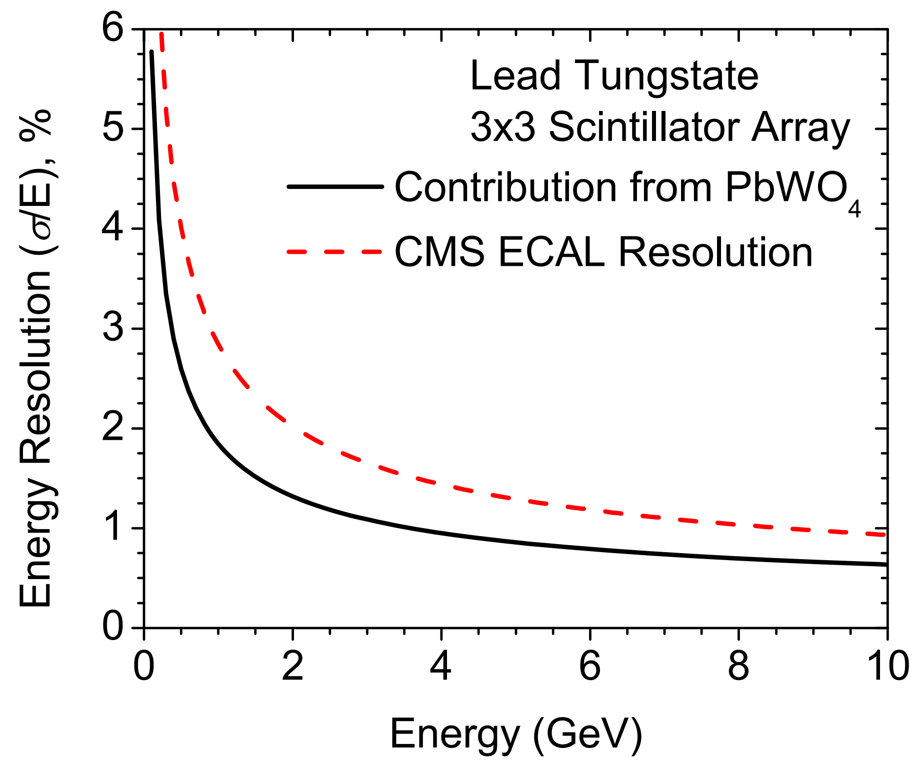
- Know quantities:
  - PDE and DCR from SSPM
  - Scintillator response
- Scaling factor, F, is used to account for excess noise:
  - After pulsing
  - Cross talk
- Systematic Error:
  - Light yield
  - PMT response
  - Varied assumptions and used average.
- At an excess bias of 6 V (P_g ~60%), the excess noise factor is 1.26.
- F of 2 at V_x = 7.5 V, P_g ~70%



Lead Tungstate

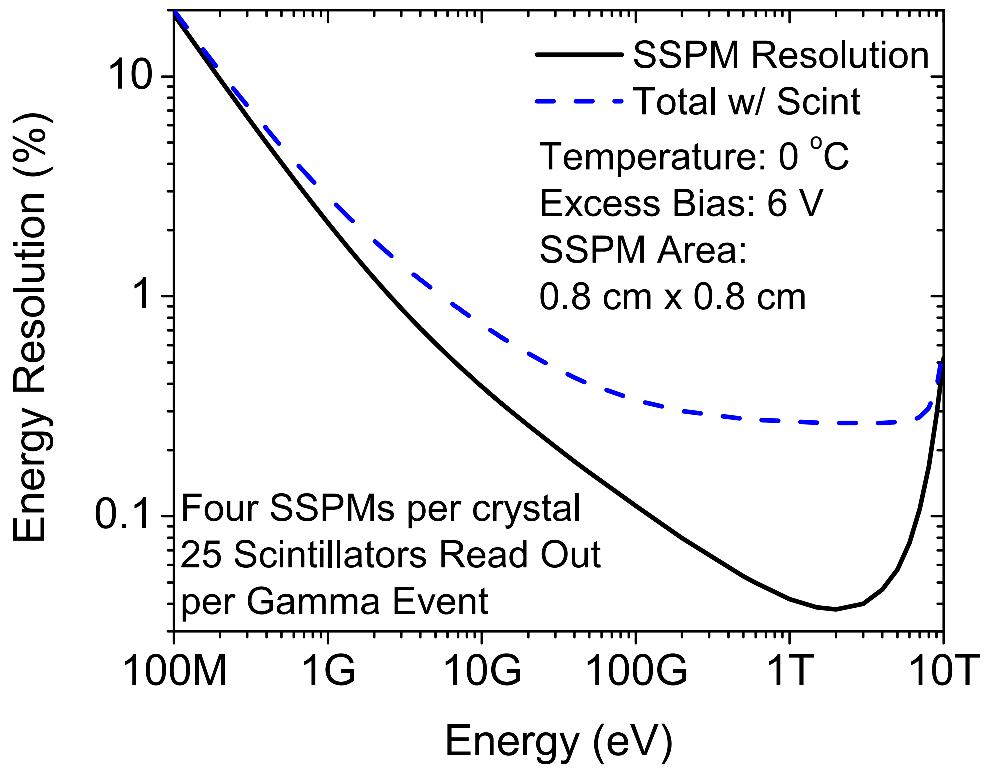
- CMS experiment at CERN
  - Lead Tungstate based calorimeter (ECAL)
  - Use Hamamatsu APDs
  - Extract APD expected performance from measured resolution.
- PRIMEX upgrade
  - Replace lead glass.
  - Higher density of scintillators.
  - To be operated at 0 C.
- Lead Tungstate
  - Decay Time: ~ 16 ns
  - Light yield: 151 photons/MeV at 0 C.
  - Peak emission: 480 nm





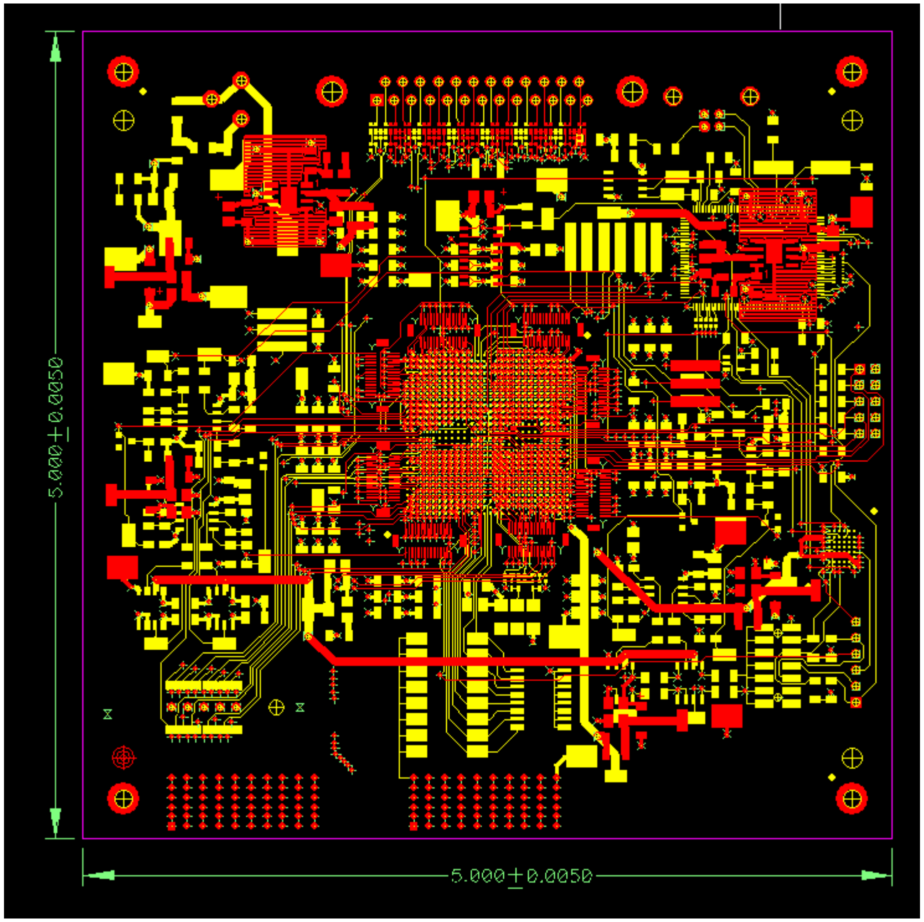
Calorimeter Performance

- Calorimeter geometry:
  - 2.05 cm x 2.05 cm crystals
  - Use 4, 0.8 cm x 0.8 cm SSPM.
  - Accounting for packaging
- Physics:
  - High energy gamma ray
  - Electron cloud: Moliere Radius
  - 5 x 5 scintillator array is used for each gamma ray interaction
- SSPM performance:
  - Include PDE, DCR, F
  - Time response: pixels may trigger more than once
  - Scintillator light yield and decay
- Calorimeter performance:
  - Fold in scintillator response based on CMS measurements
  - Scintillator is the limiting factor
  - Speculation at this point: Needs to be measured in high energy gamma field



FPGA Board

- Two prototype FPGA evaluation board has been fabricated.
  - Mounts four SSPM modules.
  - ADC with MUX for digitizing excess bias monitoring signals.
  - 1 USB port for data transfer.
- The board has not shorts to ground.
- The parts have been purchased and assembly has begun.
- The assembly will be done next month and evaluation will be immediately on each component.



Summary

- The specified SSPMs are being designed into our next submission.
- We are looking at the optical interfaces of the SSPMs to improve the photon collection.
- The SSPM module works; minor design revisions will be implemented to reduce cost and improve performance.
- Digitizing the signal at the detector will significantly reduce cost while preserving sufficient signal to noise for the experiment.
- This work is expanding the capabilities for RMD:
  - Serving the DOE and other government agencies.
  - Developing instruments for broader applications.