A Dynasil Company

Recent Progress of Solid-State Photomultipliers at RMD and Status for PrimEx

- Erik Bjorn Johnson, Staff Scientist

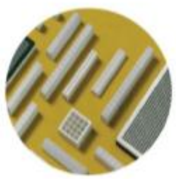
July 31, 2012

Dynasil Family of Companies

RMD INSTRUMENTS

Gamma imaging probes and
Lead paint analyzers
(Watertown, MA)

Hilger Crystals



High-performance synthetic crystals
and arrays for PET/CT/SPECT
and Homeland Security
(Margate, United Kingdom)

Optometrics

Optical gratings and filters
(Ayer, MA)

Dynasil SYNTHETIC FUSED SILICA

Fused silica optics
for lasers
(West Berlin, NJ)

emf EVAPORATED METAL FILMS

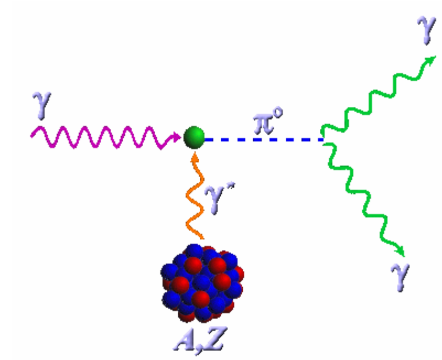
High performance
reflective coatings
(Ithaca, NY)

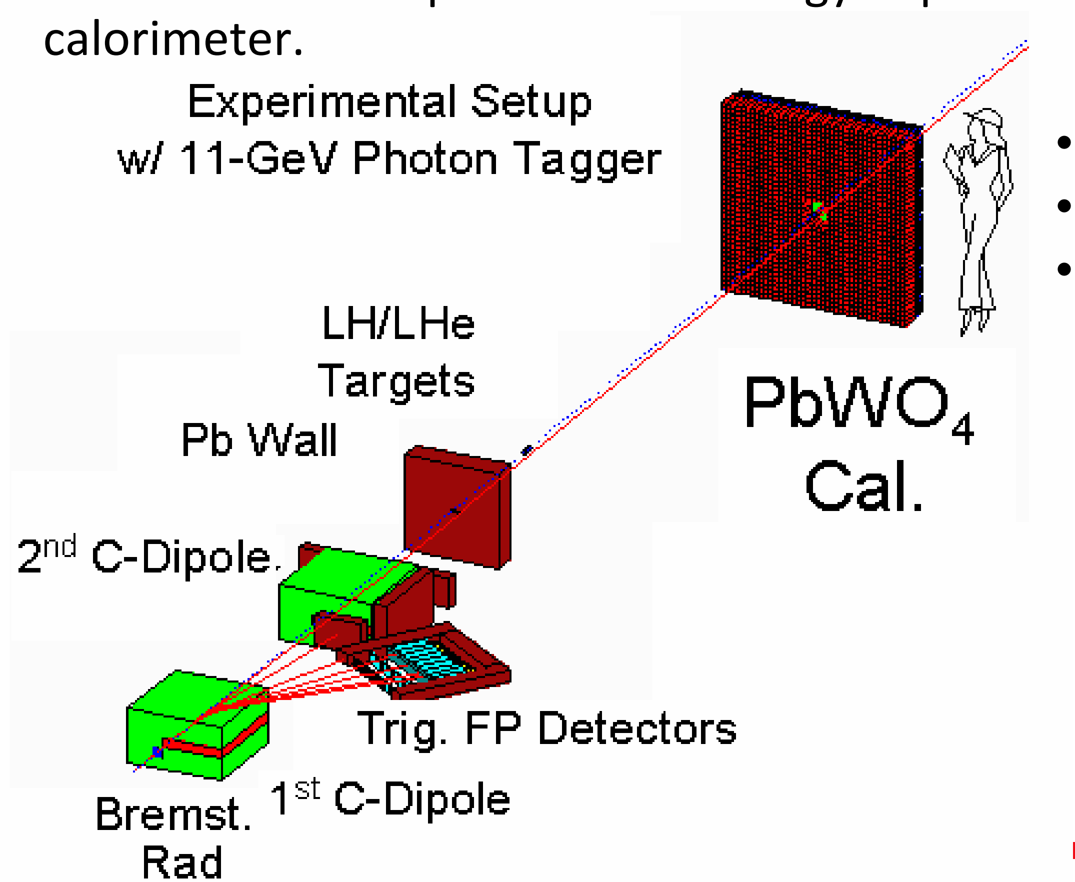
RMD RESEARCH

Contract research &
development
(Watertown, MA)

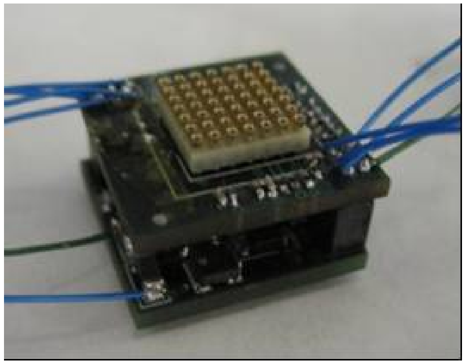
PRIMEX Calorimeter Readout

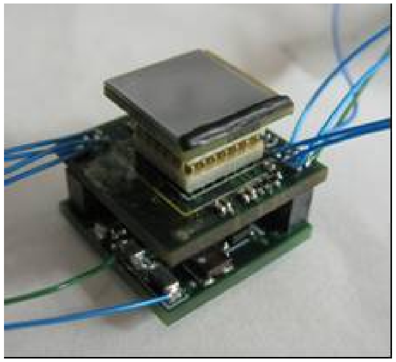
- Utilizing the Jefferson Lab Upgrade.
- Provide direct measurements at low energies of parameters of Quantum Chromodynamics (QCD) using η and η' lifetime measurements.
- Primakoff effect production of neutral mesons, which decay.
- Need to measure position and energy deposition in calorimeter.



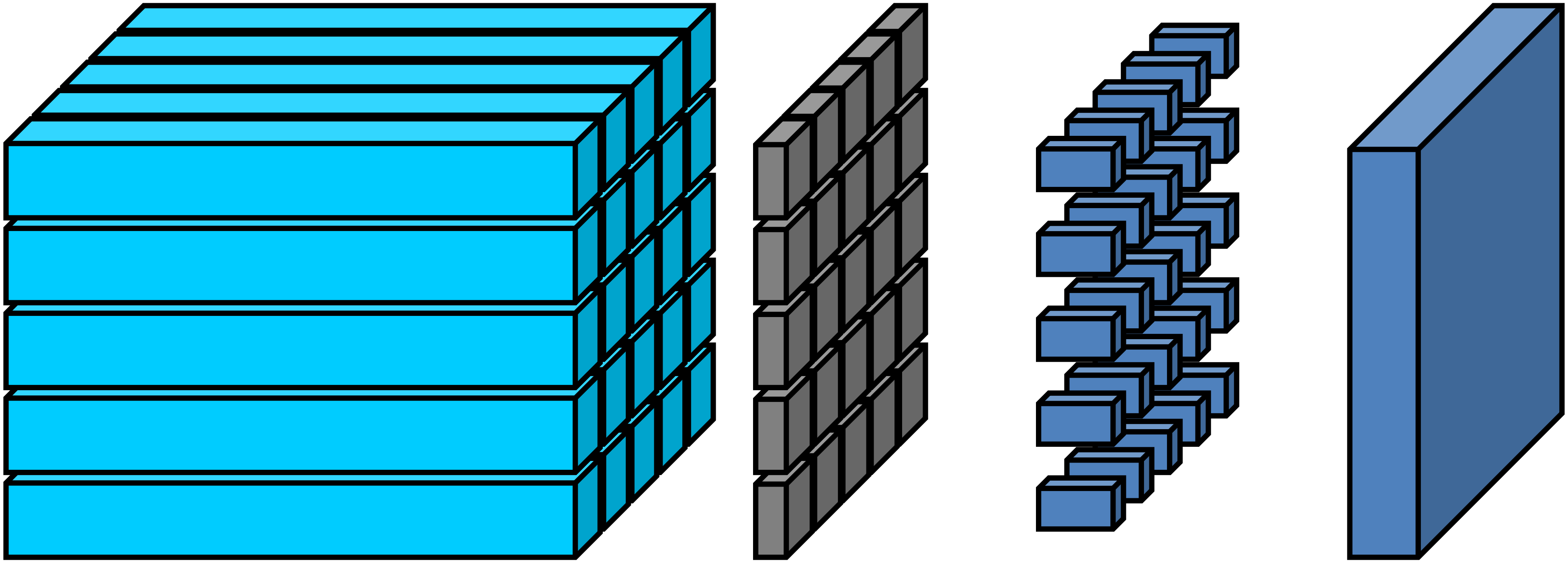


- About 1% energy resolution at 4.5 GeV
- Replace lead glass with smaller $PbWO_4$
- Cost effective readout will make this possible.





Building the Calorimeter



PbWO Crystals
5x5 Array

SSPM
Integrated Signal
Processing

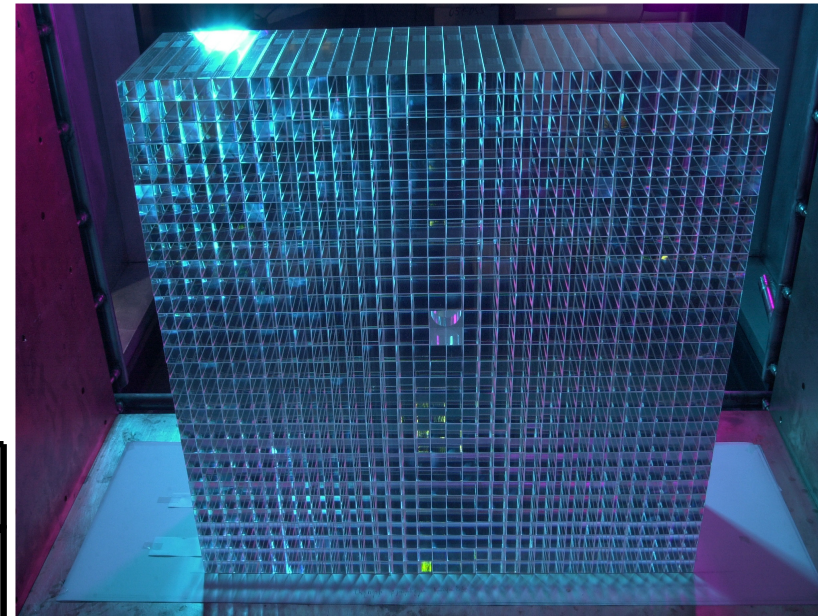
Interface
ADC
≥250MSPS

FPGA
DSP
Position
Time
Pulse Height

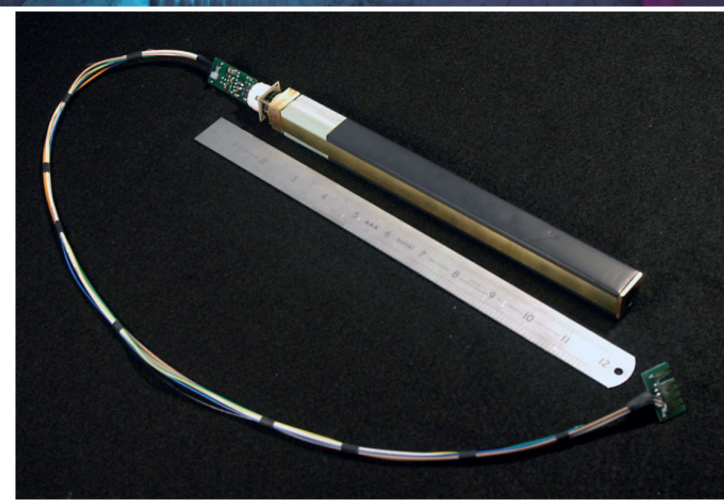
- Segment components for construction.
- Integrate electronics at front-end.

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 (ρ = 8.3 g/cm^3)



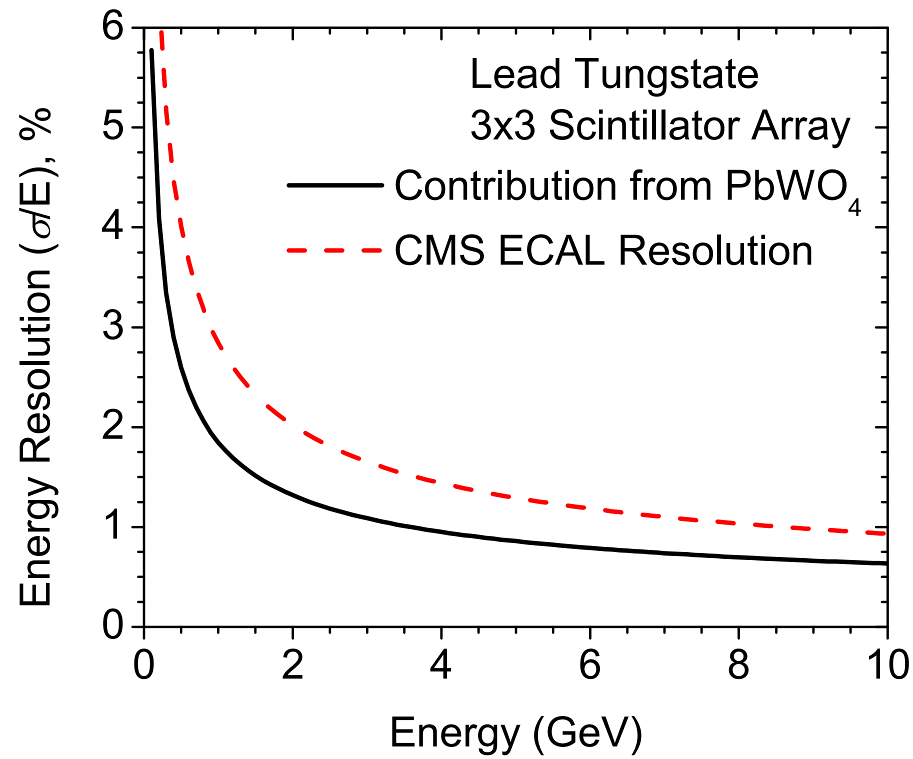
Reference	Decay Time	Light Yield (0 °C)
R Mao NIMA 537, 406-410 (2005)	30 ns	140 photons/MeV
M. Ippolitov Rad Meas. 38, 813-816 (2004)	93 ns	120 photons/MeV
CERN/LHCC 2006-001 CMS TDR 8.1 2 February 2006	16 ns	150 photons/MeV



Used most recent (CERN) measurements for calculations.

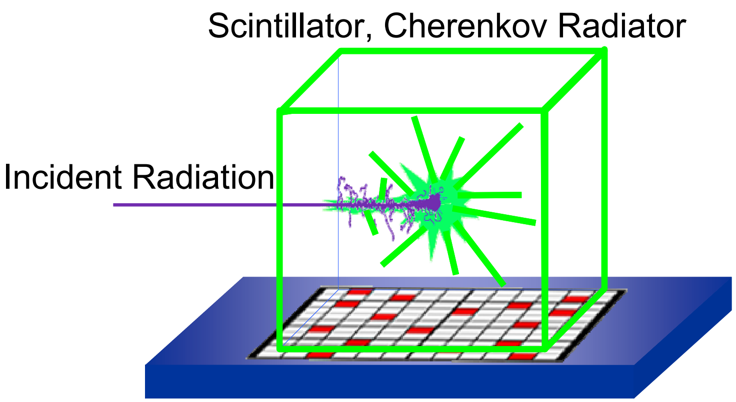
Lead Tungstate

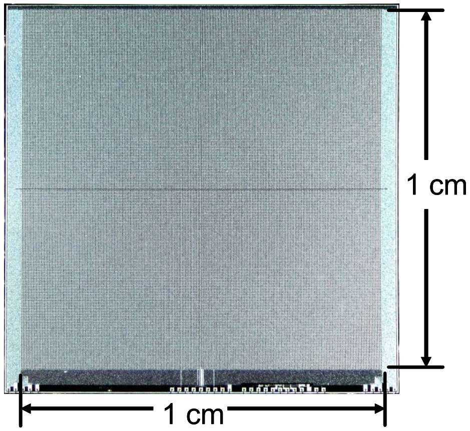
- CMS experiment at CERN
  - Lead Tungstate based calorimeter (ECAL)
  - Use Hamamatsu APDs
  - Extract APD expected performance from measured resolution.
- PRIMEX upgrade
  - Replace lead glass.
  - Higher density of scintillators.
  - To be operated at 0 C.
- Lead Tungstate
  - Decay Time: ~ 16 ns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



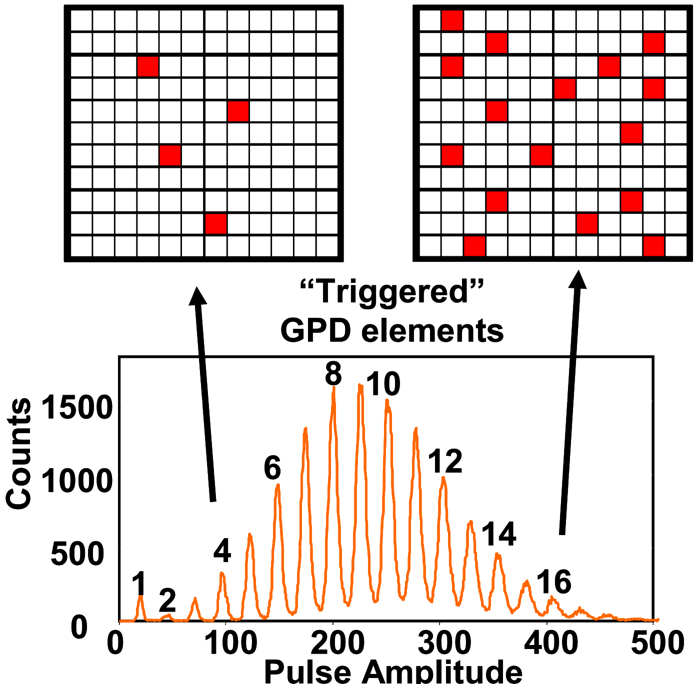
Status of RMD Solid-State Photomultipliers

Solid-State Photomultipliers



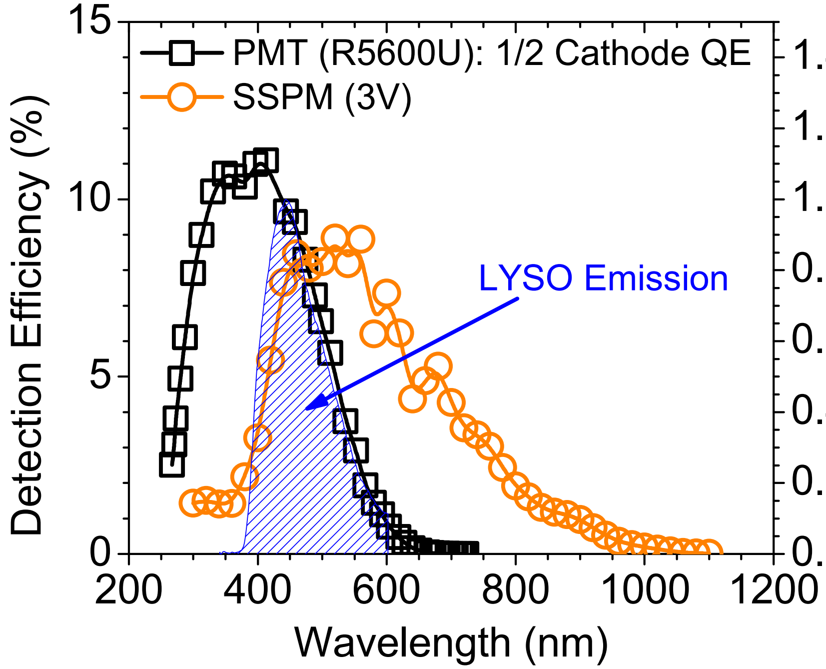


- Solid-state photomultiplier (SSPM) is an array of photodiodes read out in parallel.
  - Active dosimeters/ area monitors
    - Gamma-ray
    - Charged-particle
    - Neutrons
  - Spectrometry
  - Positioning and Imaging
  - PET, SPECT, Optical tomography
- Each photodiode has a gain of 10^6 for single photon events.
- Number of diodes triggered is proportional to the incident light flash.
- Compact and phototube like response.

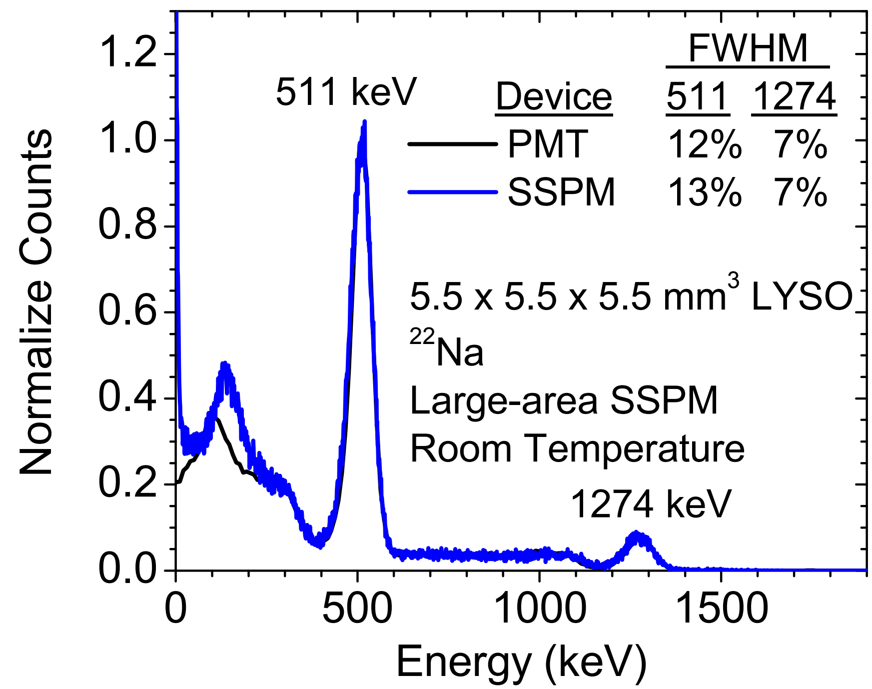


Gamma Ray Spectrum

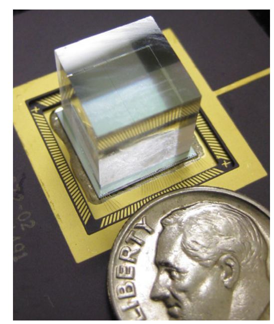
To compare with a PMT, LYSO is a good match for both photodetectors.



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



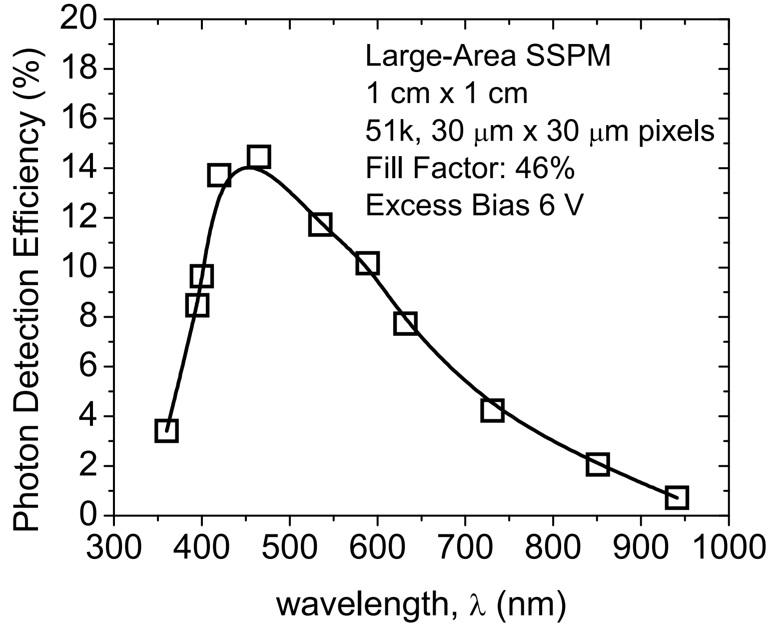
- SSPM estimated contribution to the noise at 511 keV is roughly 4-5%.

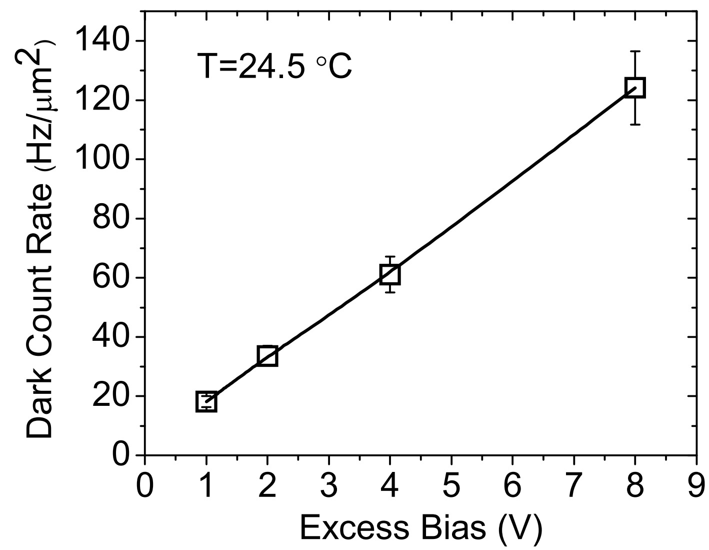


PDE and Dark Count Rate

- The photodetection efficiency product:
  - Quantum efficiency
  - Geiger probability: @ V_x = 6 V, ~60%
  - Fill Factor: 46%
- Dark Current
  - Thermally generated events
  - No after pulsing or cross talk included.
  - Schockley-Read-Hall (Maxwell-Boltzmann) dependence on temperature

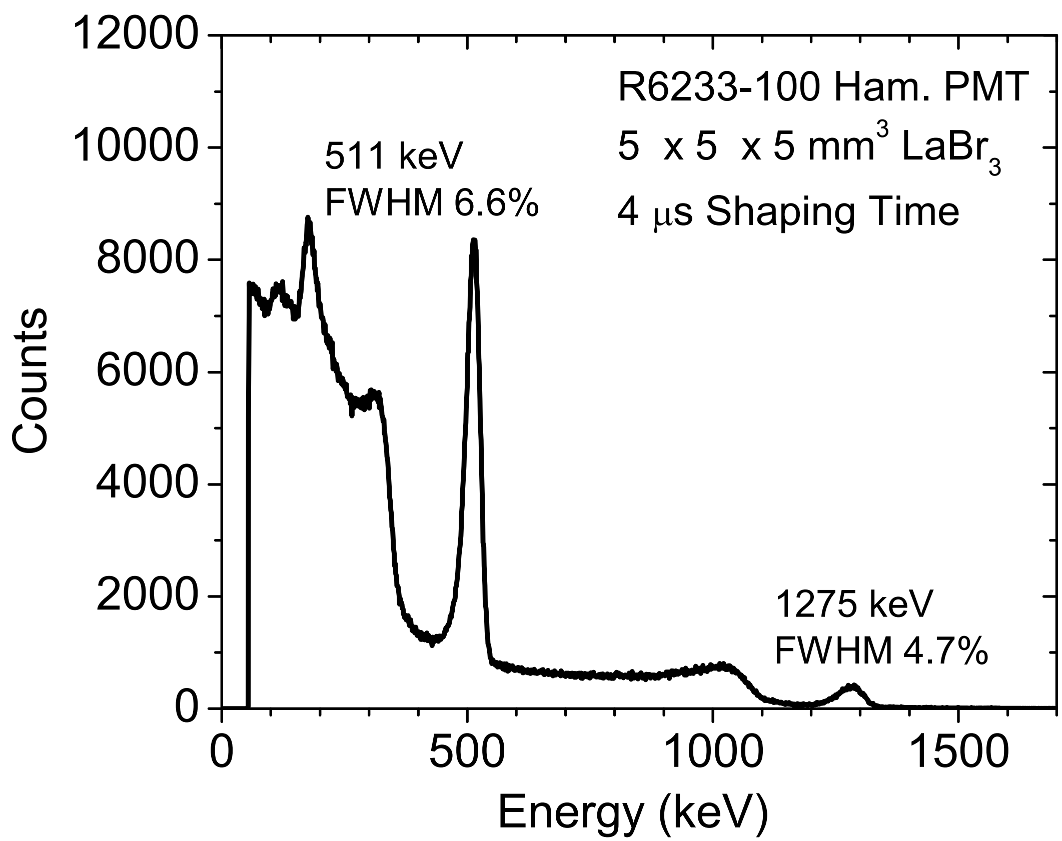
$$DCR = 2.2514\frac{\mathrm{Hz}}{\mathrm{V}} \cdot V_x \cdot e^{\frac{1.11\mathrm{eV}}{2k \cdot 273.15\mathrm{K}}} \cdot e^{\frac{-1.11\mathrm{eV}}{2kT}}$$





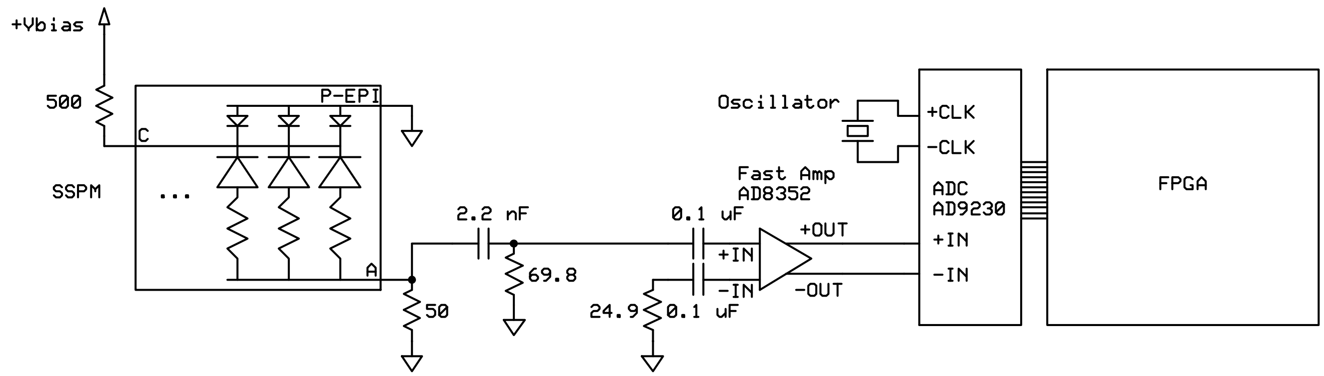
$LaBr_3$ on PMT

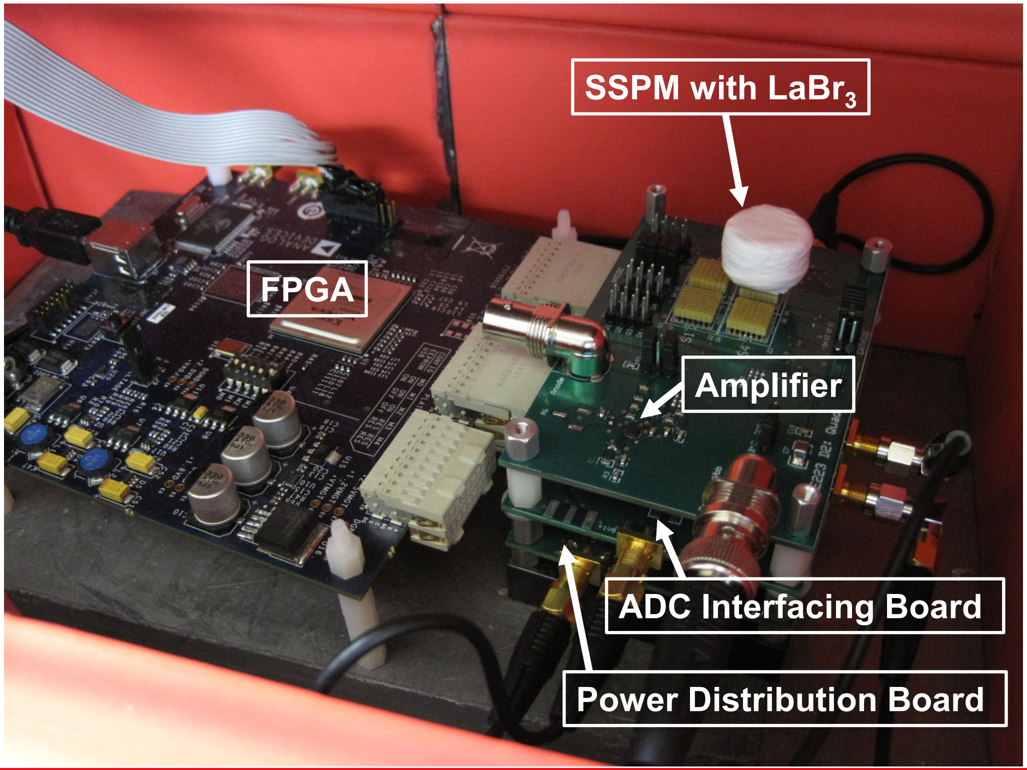
- No readily available high-energy gamma ray source.
- Used a high-quality, fast, bright scintillator.
  - Lanthanum Bromide.
  - ~60 photons/keV
  - Decay Time: 16 ns
- Evaluate with PMT
  - Optically coupled with grease.
  - Crystal in aluminum can.
  - Super bialkili cathode
  - QE_{Eff}: ~ 32.8%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



Readout and Determining Response

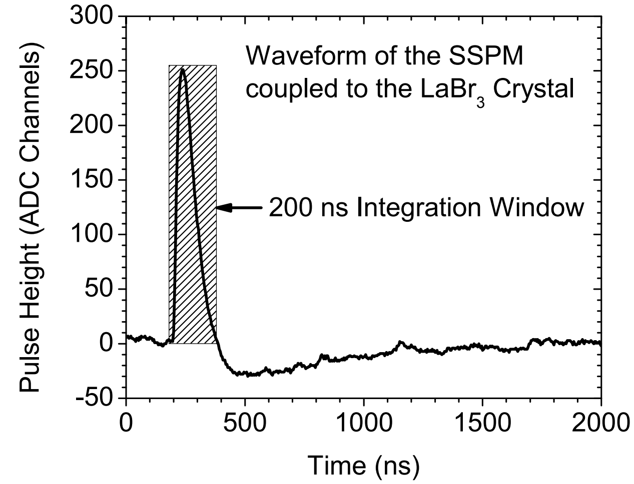
- Large gain from the SSPM allows for a very simple readout COTS components.
- Module was evaluated and works well.
- Fast electronic components are necessary for extracting the physics information.
  - 2.2 GHz Differential Amp
  - 250 MSPS, 12-bit ADC
- Evaluation components were built and tested at 0 °C.
- What to calculate how it will respond in the calorimeter.
  - No high energy gamma source available.
  - Use $LaBr_3$ and a ^{22}Na test source.
  - Used PMT to determine contribution to noise from scintillator.

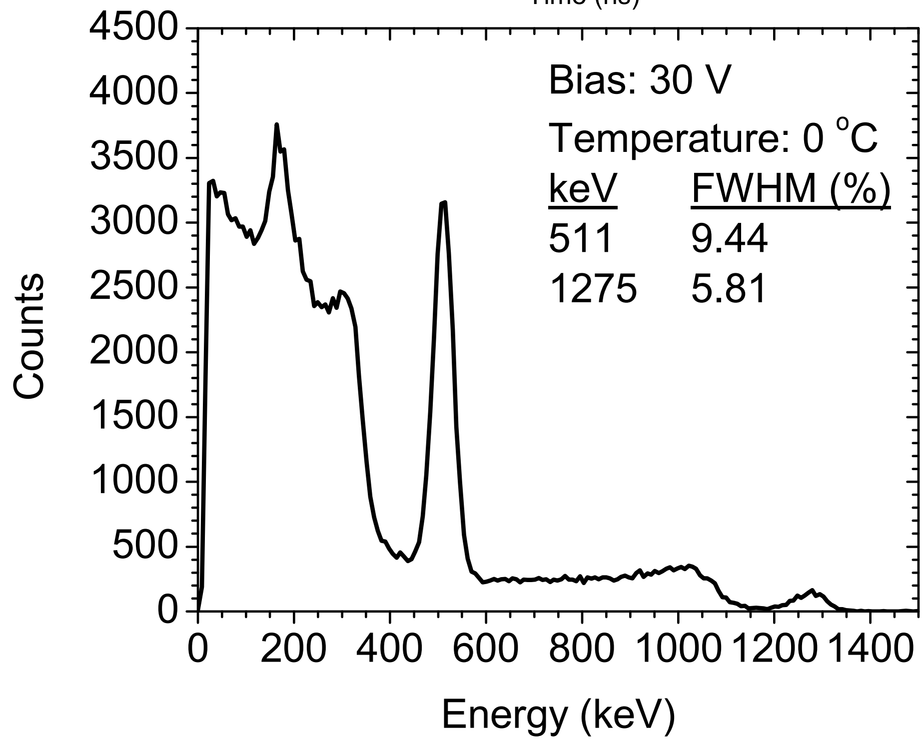




SSPM Spectra

- Generated spectrum as it will be done in the PRIMEX experiment.
- Collect wave forms and process.
- Use a 200 ns integration window.
- QE_{Eff}: 11%
- 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.

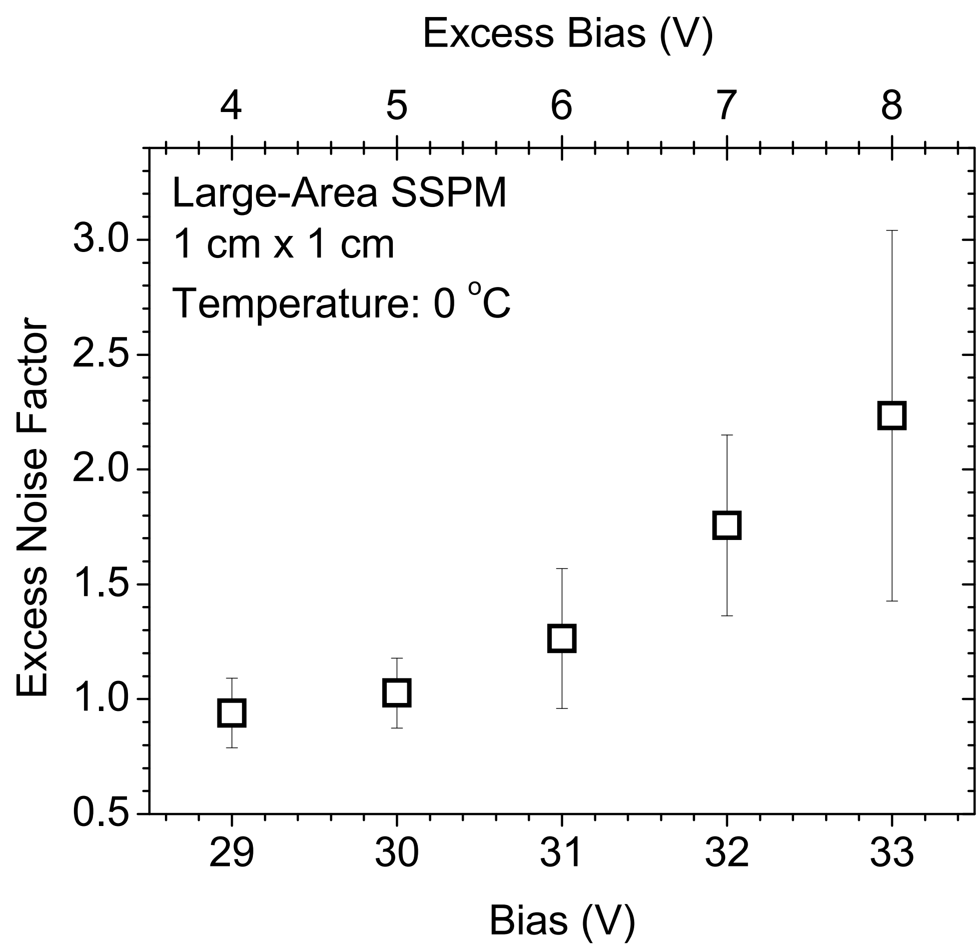




Excess Noise Factor

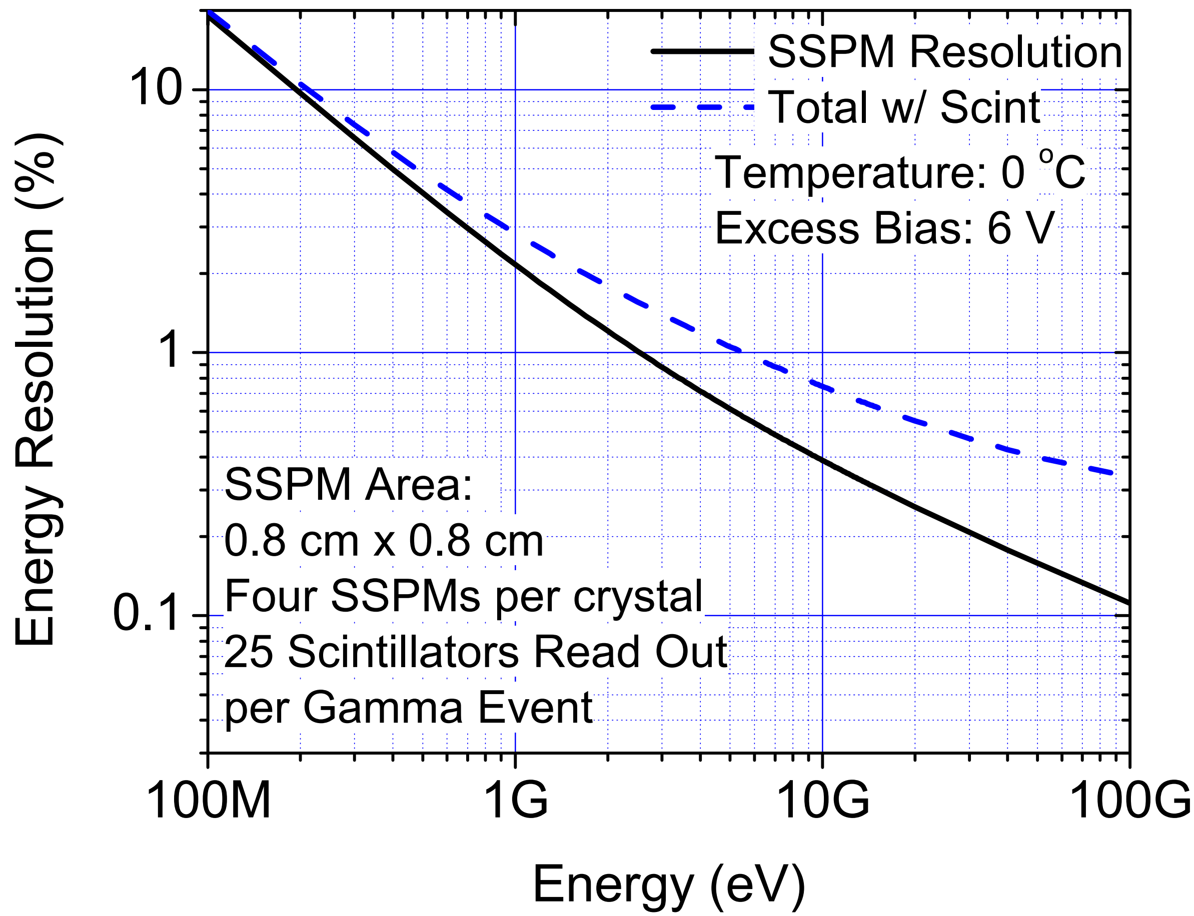
- Know quantities:
  - PDE and DCR from SSPM
  - Scintillator response
- Scaling factor, F, is used to account for excess noise:
  - After pulsing
  - Cross talk
- Systematic Error:
  - Light yield
  - PMT response
  - Varied assumptions and used average.
- At an excess bias of 6 V (P_g ~60%), the excess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

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

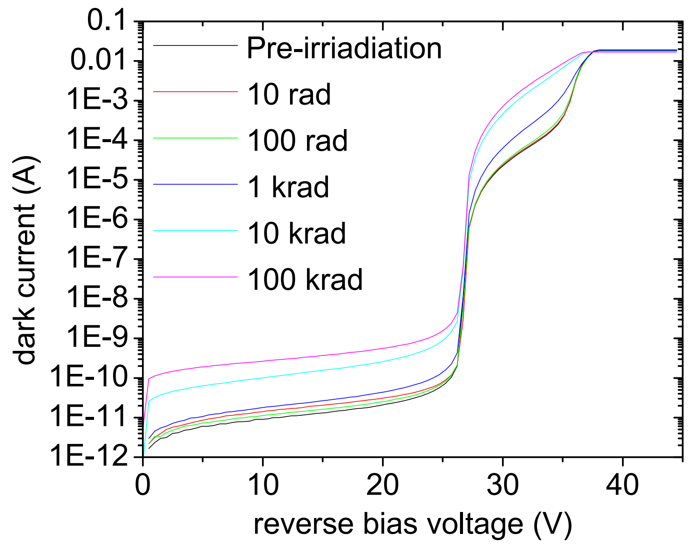


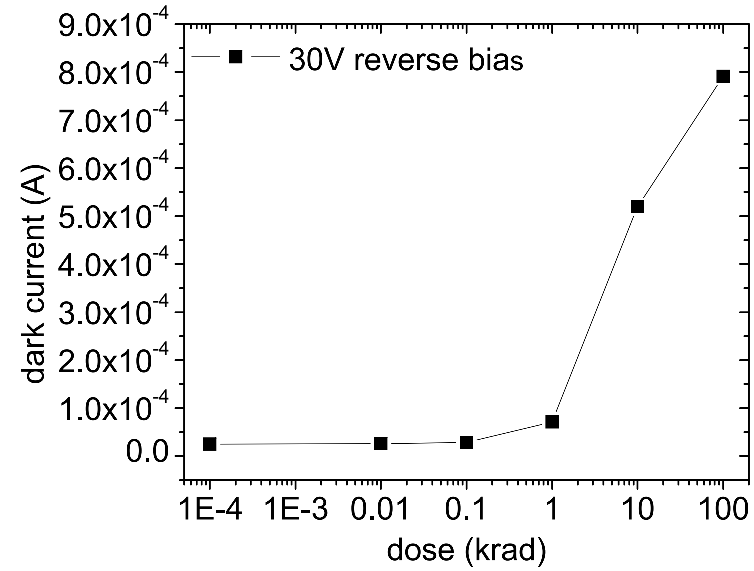
Calorimeter Performance

- 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
  - 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

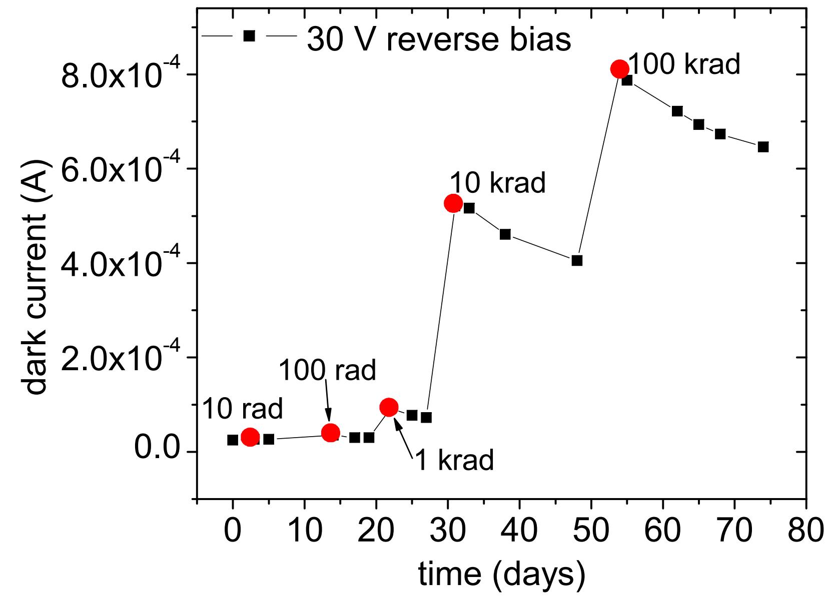


Radiation Hardness (Dark Current)

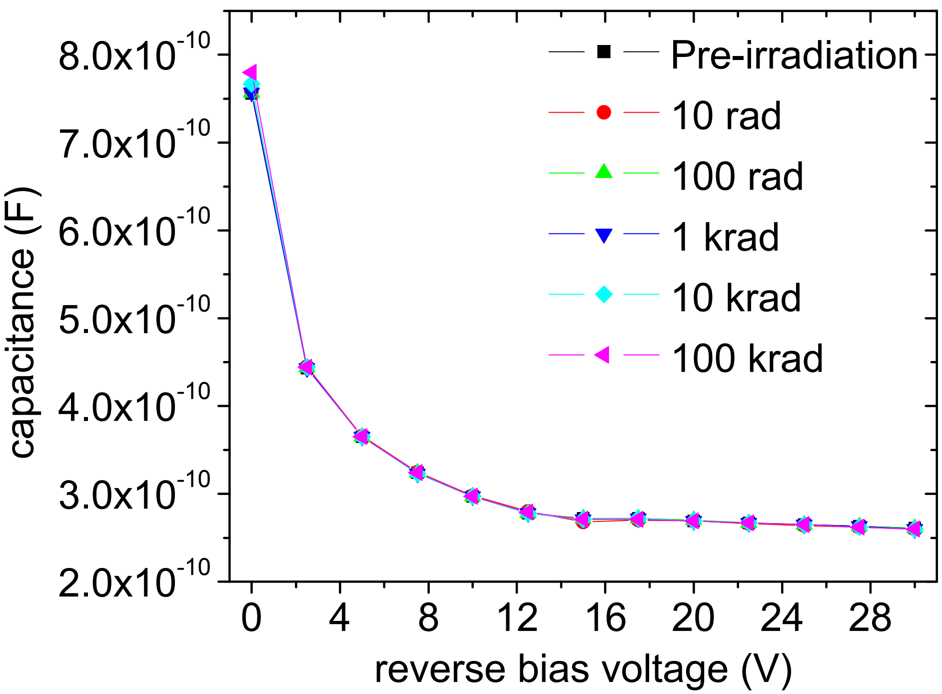


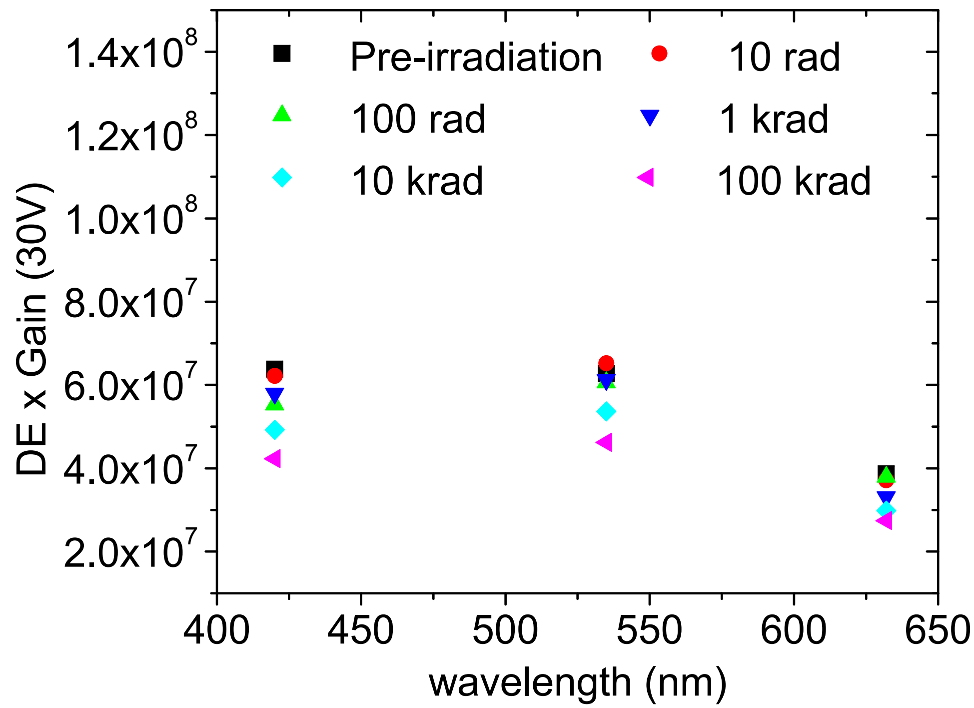


- Exposure to 200 MeV protons.
  - Surface charge is built up.
  - Bulk defects are increased.
  - The build up of defects from photons will be slower for an equivalent flux.
- Like all silicon devices, dark current increases.



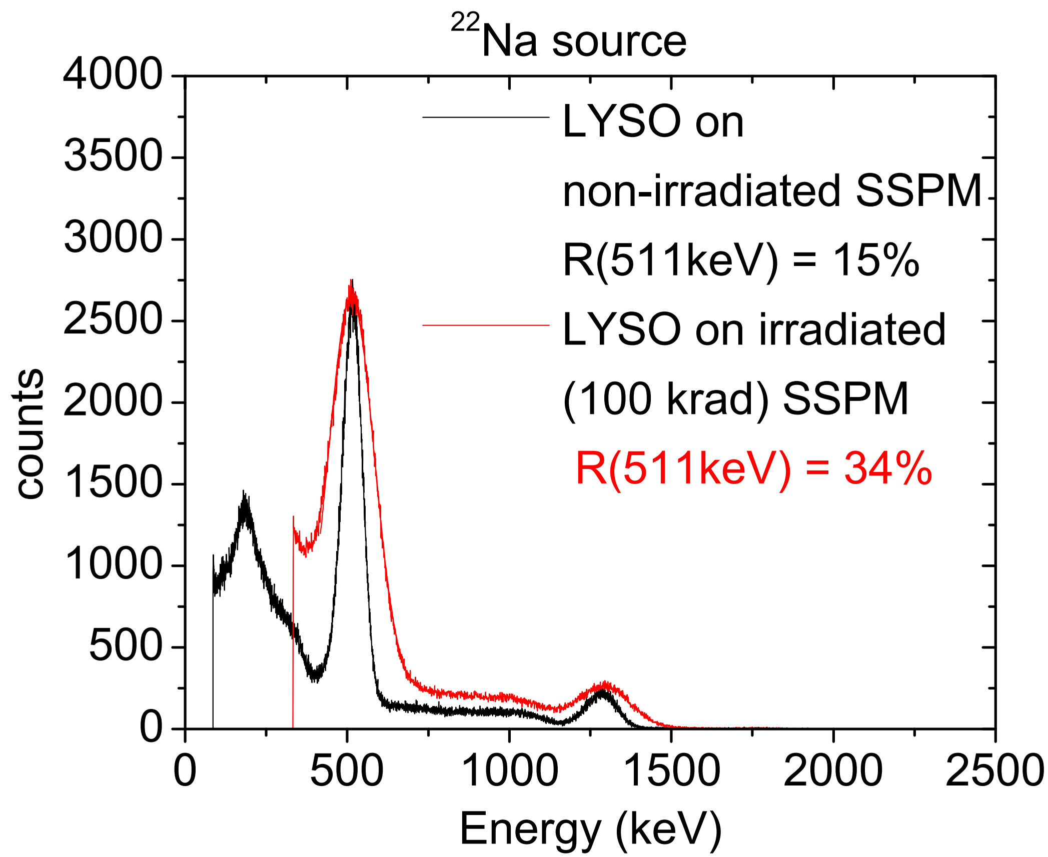
Radiation Hardness (Gain)





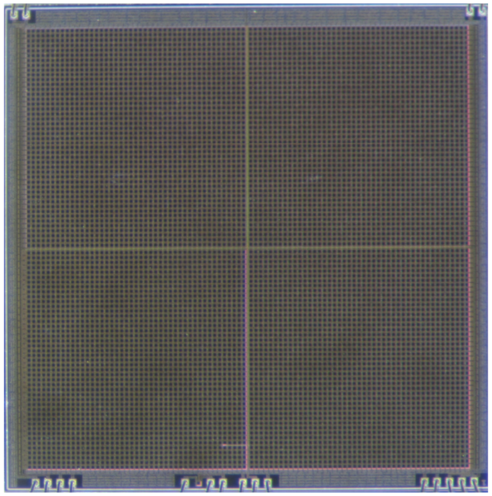
- Capacitance is directly proportional to the gain associated with each diode.
- Complete detector capacitance shows no change as a function of dose.
- A decrease in the DE × Gain is observed with a slight difference as a function of wavelength, due to recombination effects.

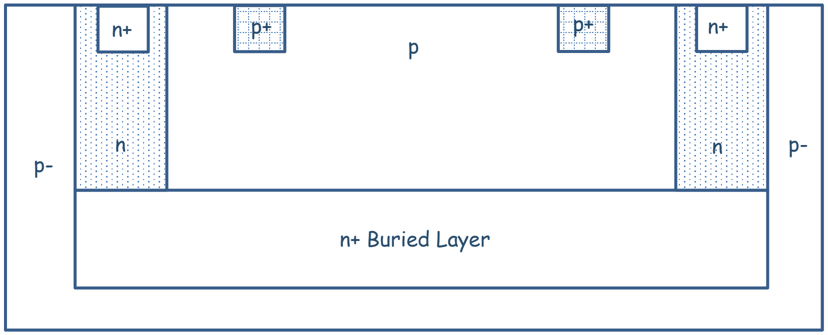
Radiation Hardness (Spectrum)

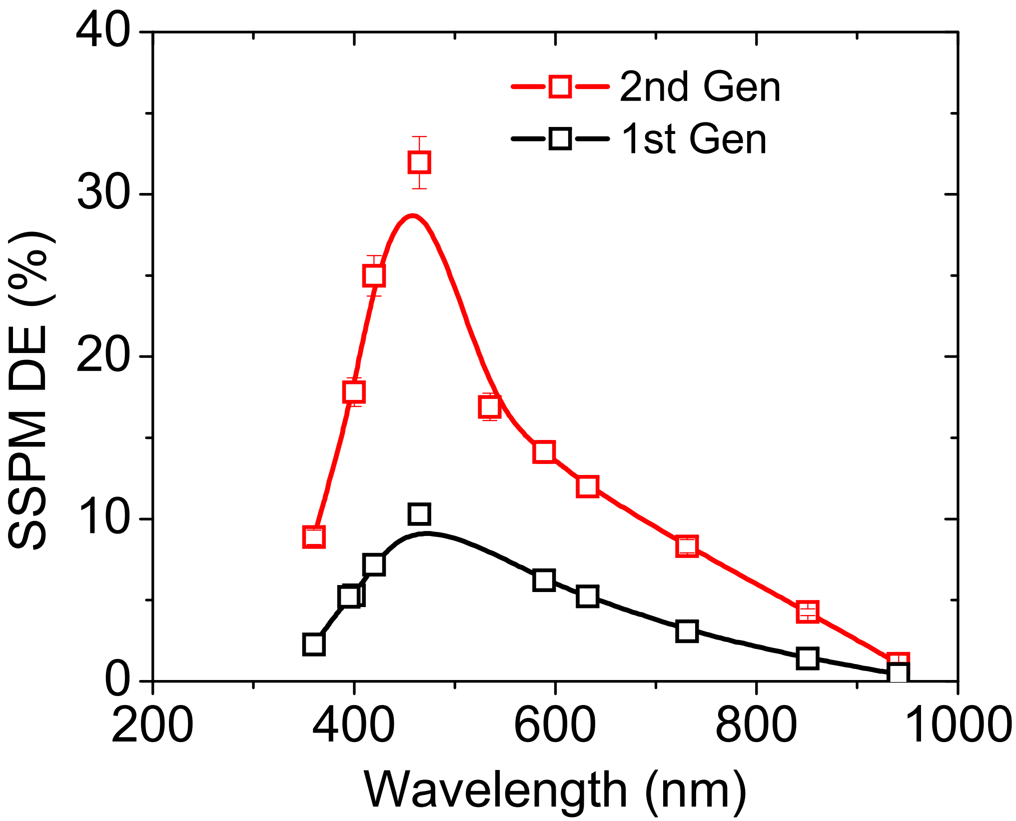


- If JLab is interested in effects due to gamma rays,
  - We are also.
  - We would be more motivated to conduct those measurements.
  - But we would most like conduct measurements on the next generation of devices.
- We do not have a dependence of the energy resolution as a function of dose.

Next Generation of SSPM

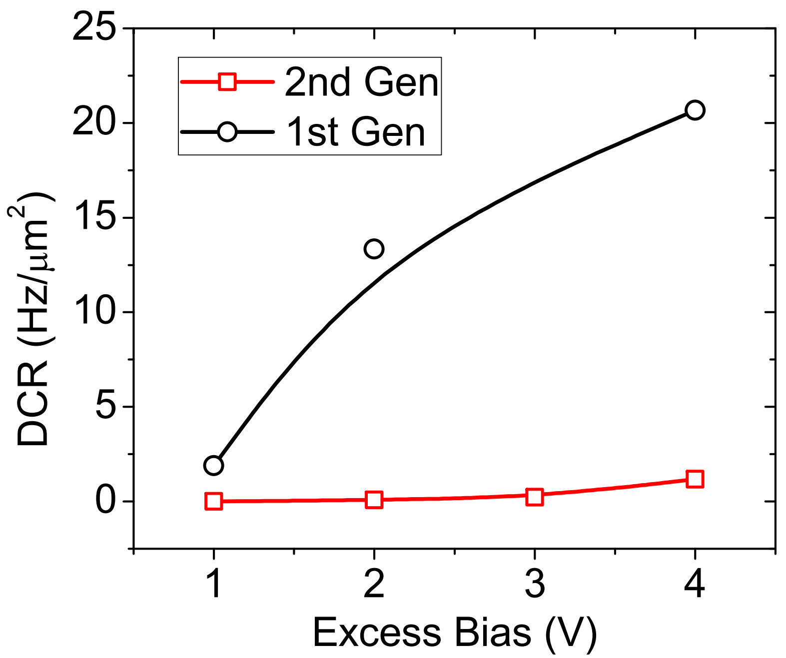


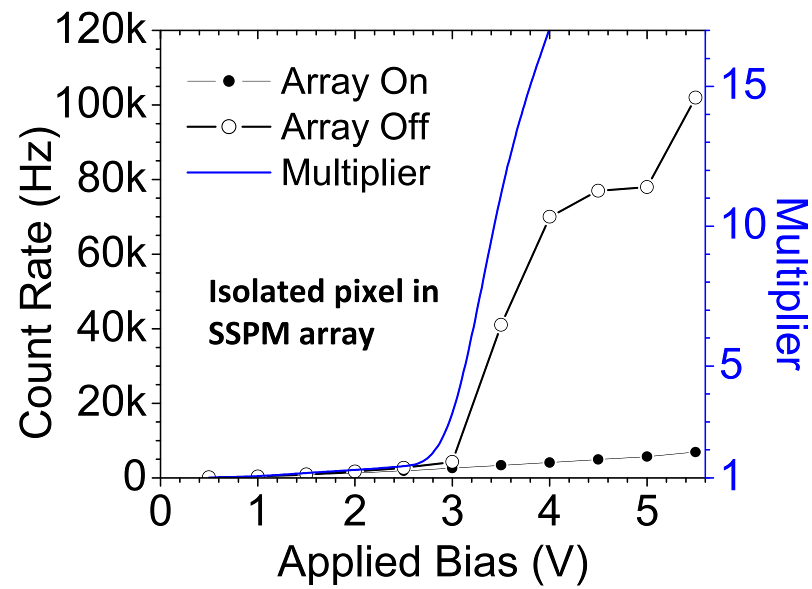


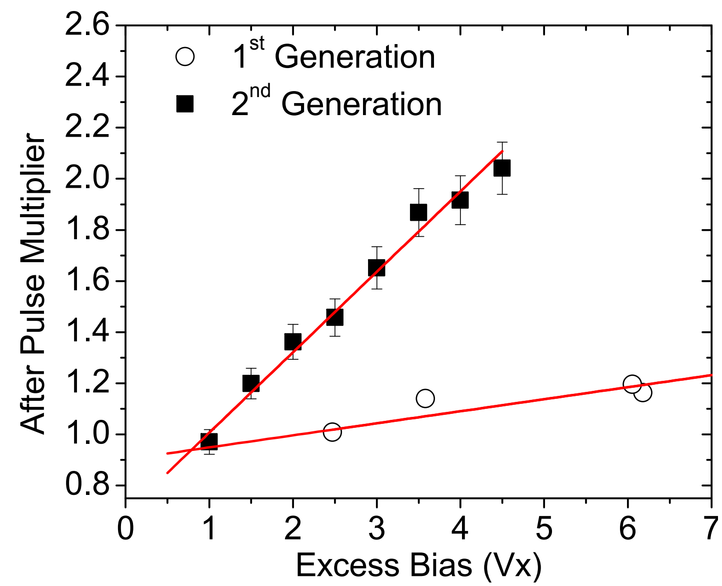


- Small feature size CMOS technology.
- New GPD pixel different from traditional design.
  - Using buried layer to define Geiger junction, charge collection region depletes upward toward the surface.
- 3.9 mm × 3.9 mm SSPM fabricated with 90 × 90 array of 37 μm pixels.

SSPM Noise Terms



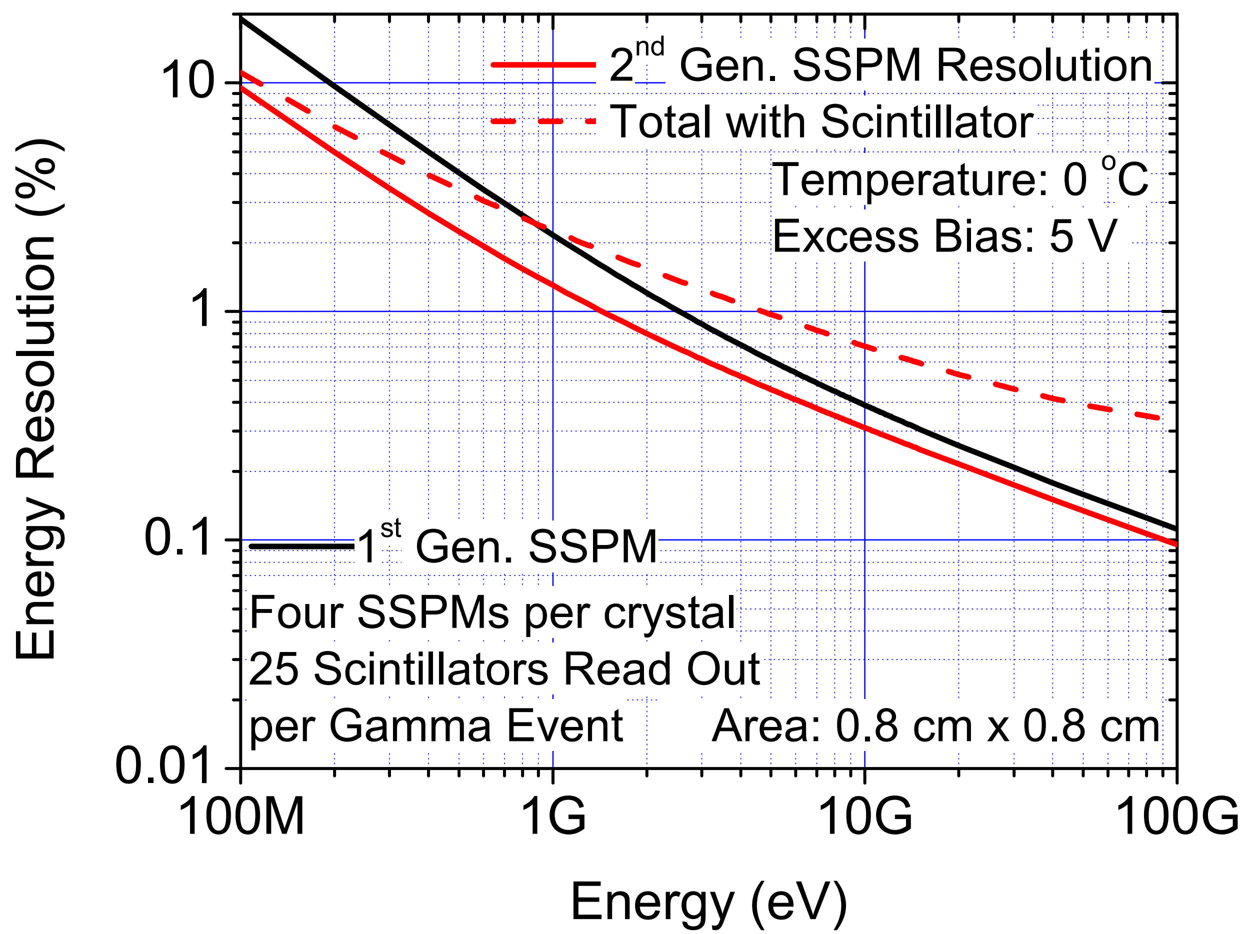




- Dark current is significantly less.
- A measure of the cross talk multiplier is less than 2 for a reasonable range of operation.
- The after pulsing has increased; possibly due to the higher operating bias.

Calorimeter Performance

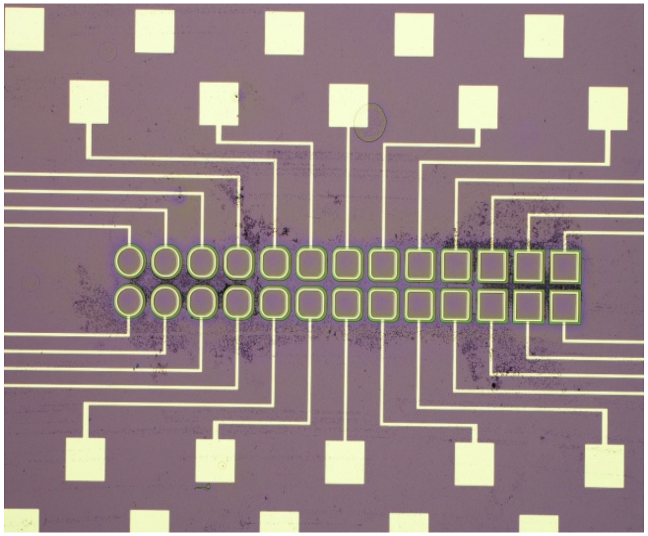
- Replace 1st Generation SSPM with 2nd Generation.
  - Use same active area.
  - Improved fill factor.
  - Lower dark current.
  - Significantly higher detection efficiency.
  - Overestimate the excess noise.
  - Use F = 2 compared to 1.26
- Energy resolution improves dramatically.
- Expands physics scope of the calorimeter for lower energy processes.

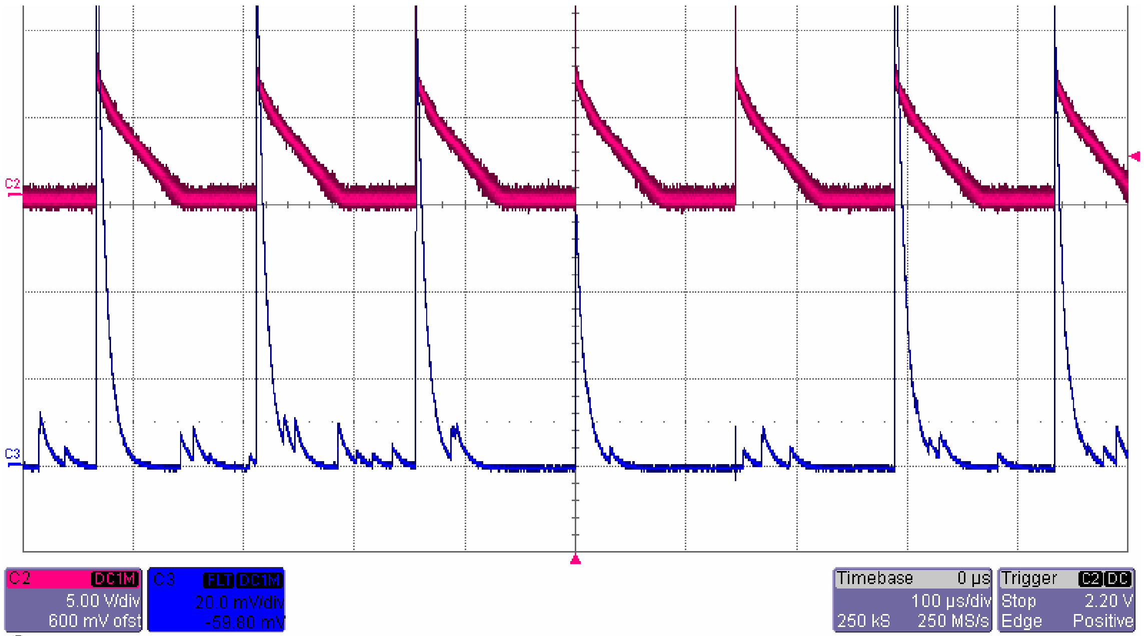


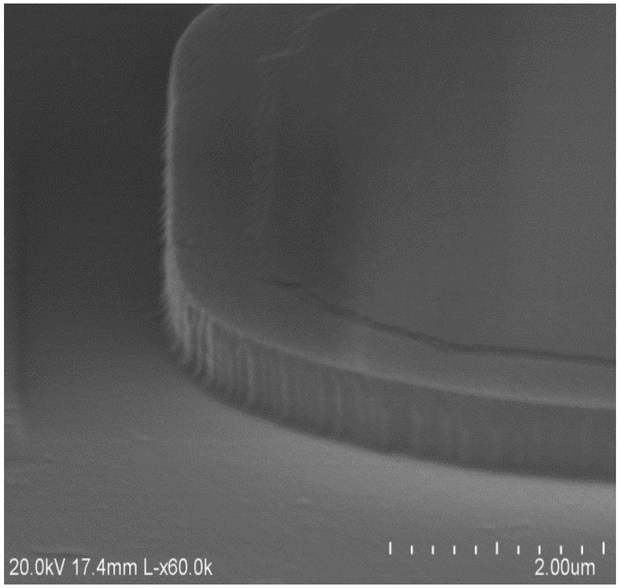
- Large-area prototypes are expected in 6 to 12 months (maybe).

AlGaAs Solid-State Photomultipliers

- DNDO funded program has ended.
- Collaboration with:
  - University of Michigan (Mark Hammig).
  - University of Virginia (Joe Campbell).
- Wide-band-gap semiconductor epitaxy.
- Fabricated diodes and demonstrated a high-gain response to photons.
- The schedule for SSPM prototypes is not determined.

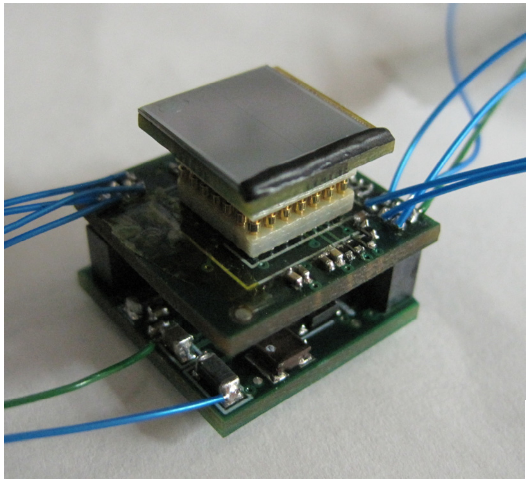






Status of PrimEx Calorimeter Readout

Readout Prototypes

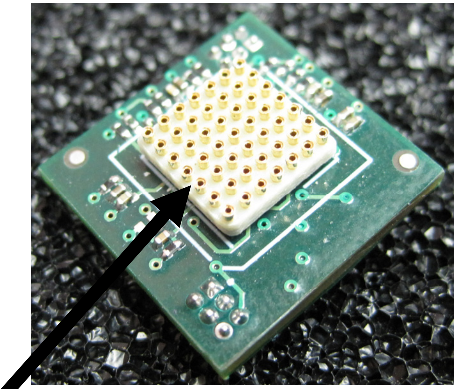


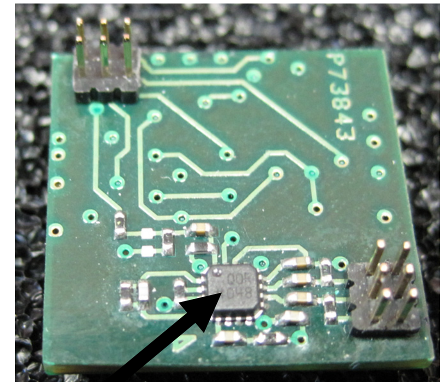
- Three layers.
- Design, layout and fabrication by Don Lydon (UMass).

FRONT

Back

Amp Board

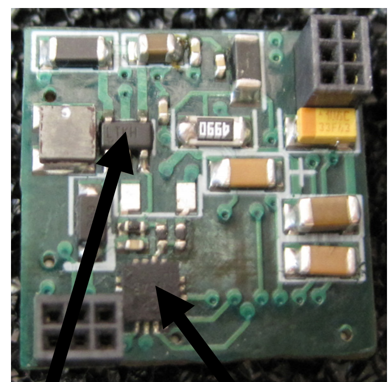


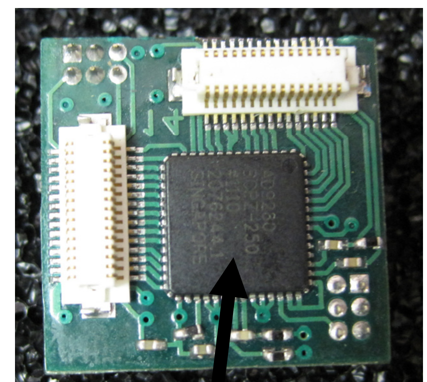


Socket (obsolete)

2.2 GHz Diff. Amp (AD8352)

ADC Board



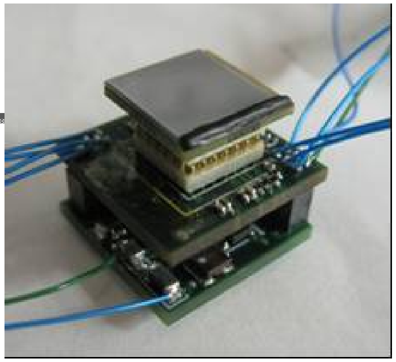


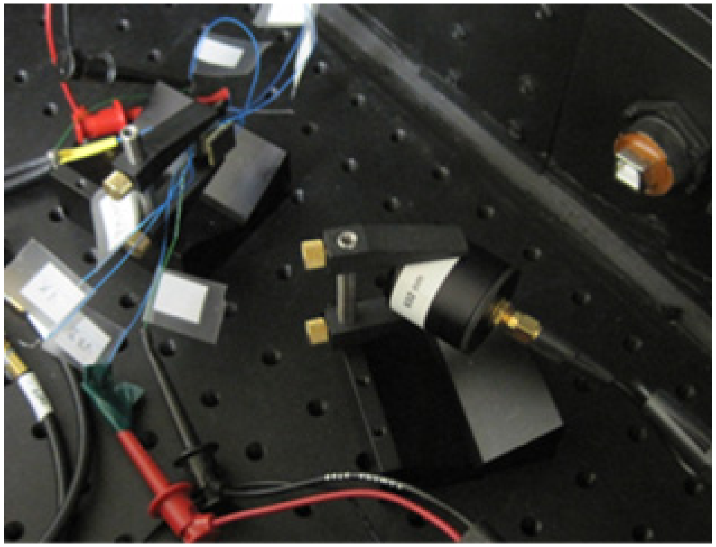
Dig. Pot (MAX5483)

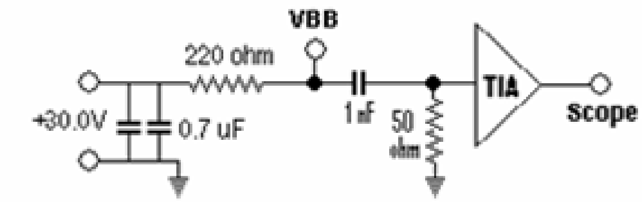
DC/DC (LT1615)

12-bit, 250-MSPS ADC (AD9230)

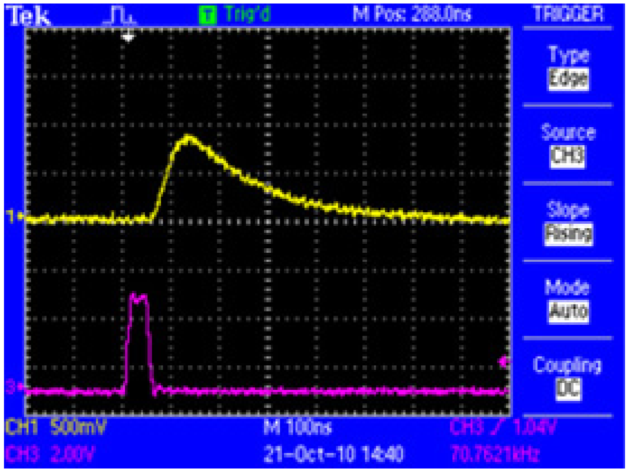
SSPM Connection



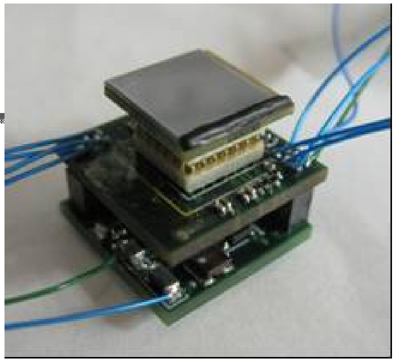




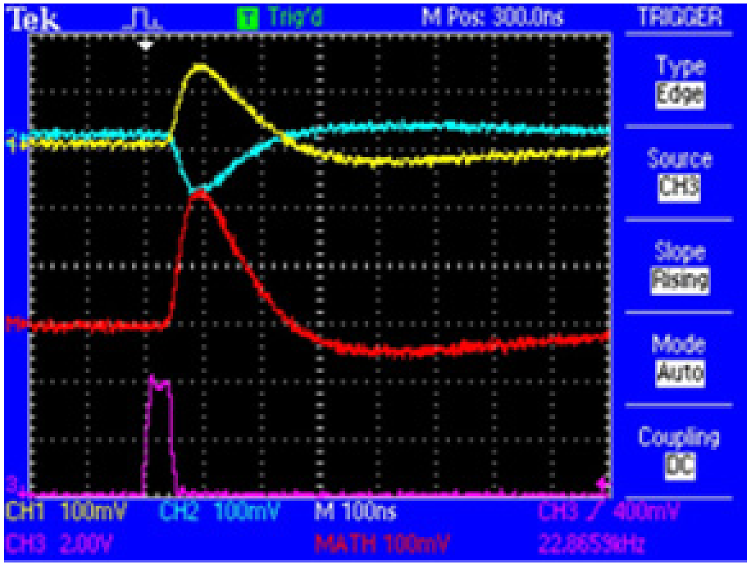
- Evaluated each component of the modular readout boards.
- SSPM connections were tested.
- Simple trans-impedance amp and a light pulse from an LED was used.
- Each photodetector on the device is connected properly.



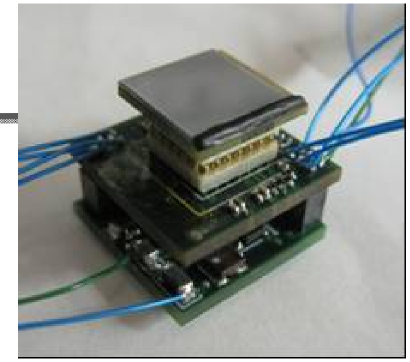
Fast Amplifier



- The fast amplifier used is a 2.2 GHz differential amplifier.
- The signal from the SSPM is readout after the amplifier.
- The output looks good.

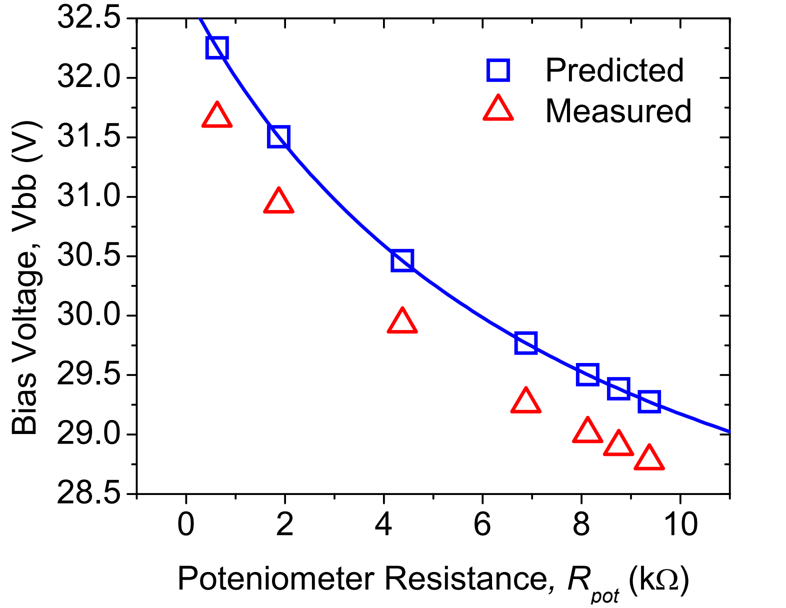


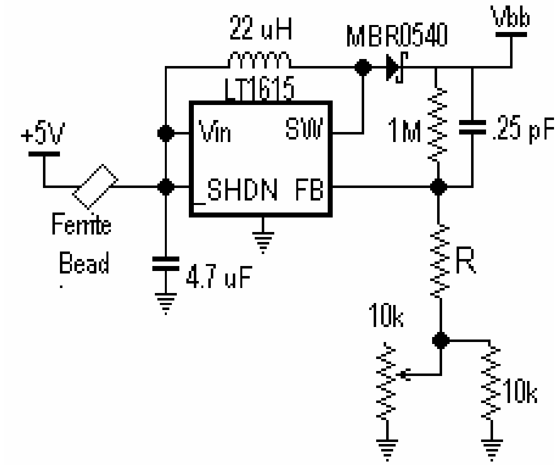
Boost Converter

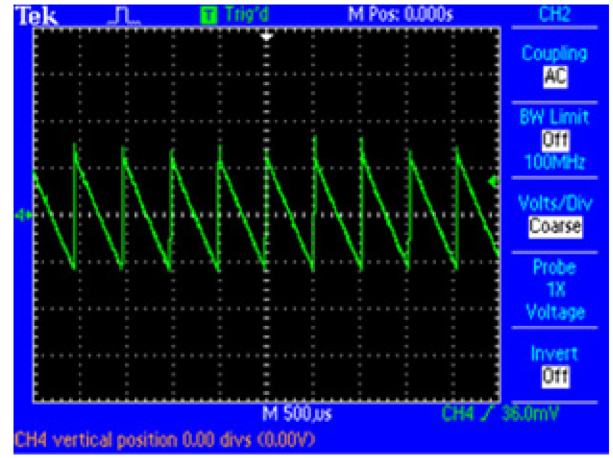


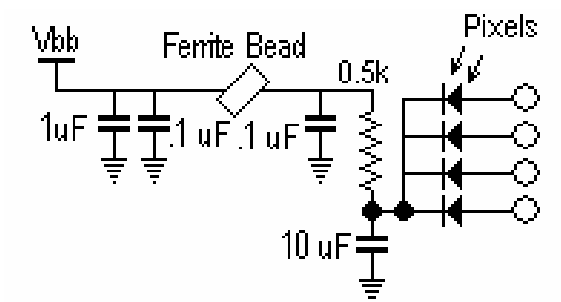
- A DC/DC boost converter is used to power the SSPM.
- The voltage will be controlled through an interface through the FPGA.
- Each circuit will need to be calibrated.
- Filtering is used to remove the switching noise from the converter.

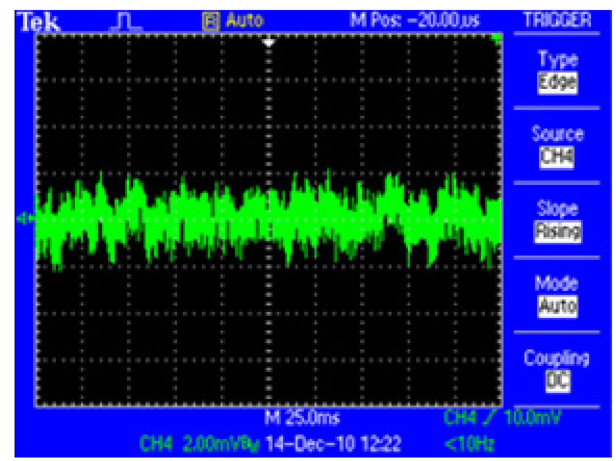
Predicted and actual step-up bias voltages (Vbb)



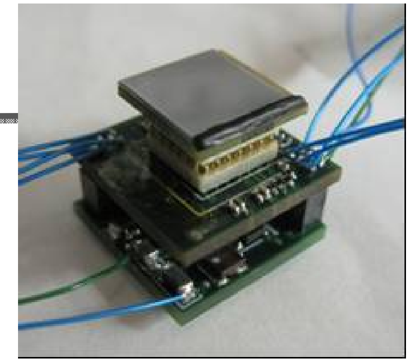


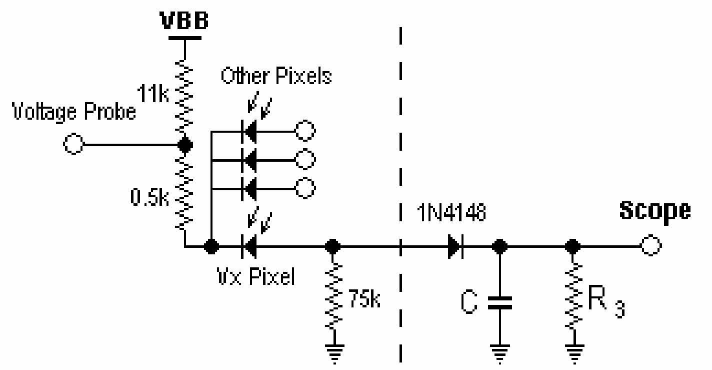




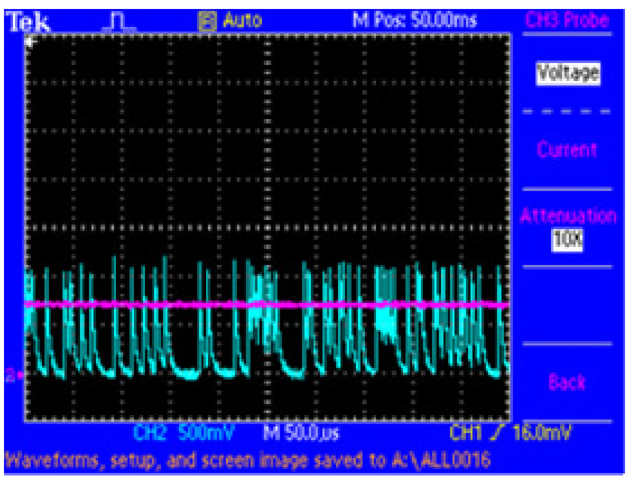


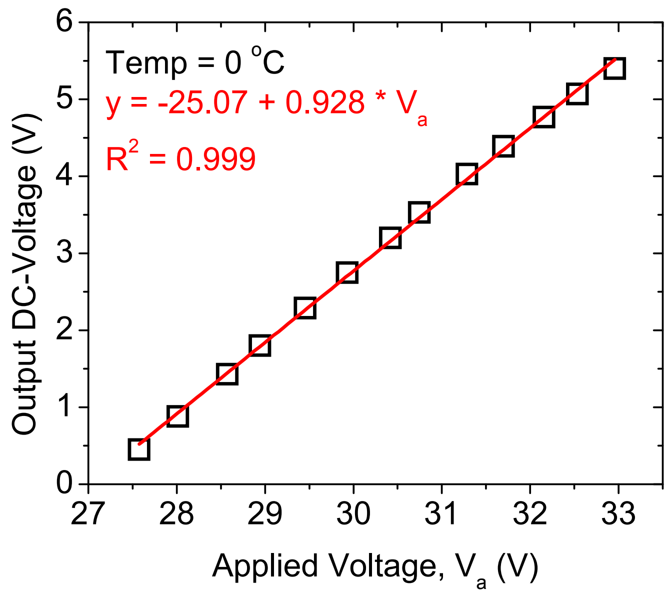
Excess Bias Monitor

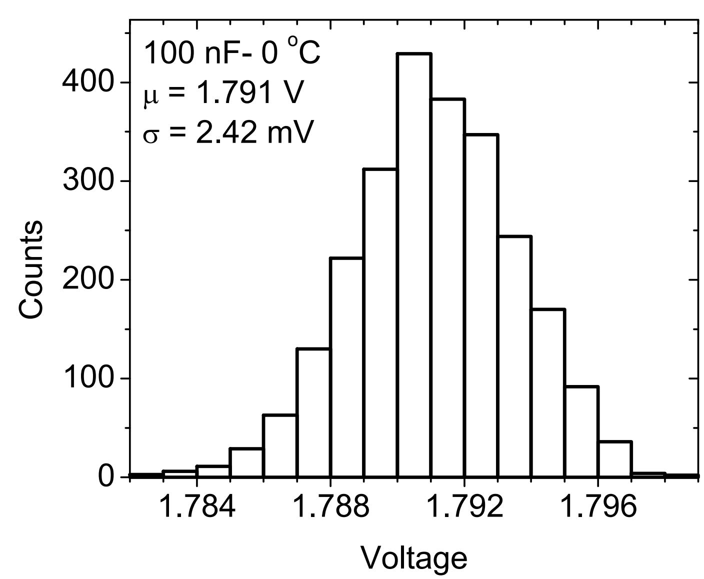




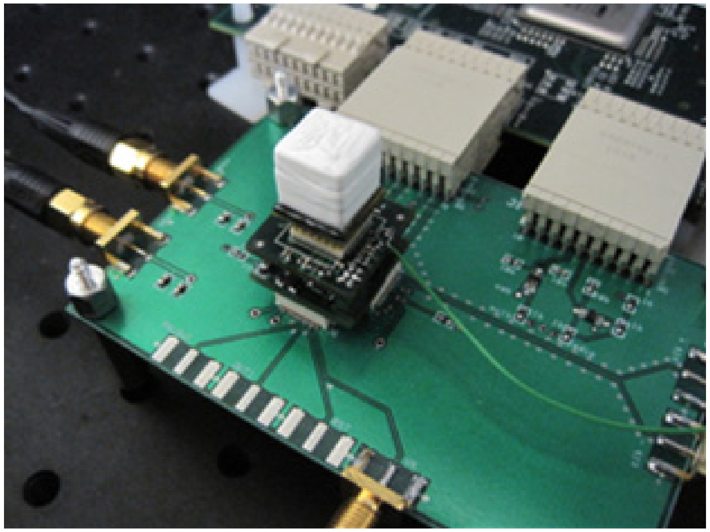
- A large isolated pixel is used to monitor the excess bias.
- The voltage drop across the diode is held by a slow RC circuit.
- The dark current is sufficiently large to keep the voltage stable.
- The response is linear will applied bias over a 5 V swing.
- The offset is accurate to within 2.5 mV.

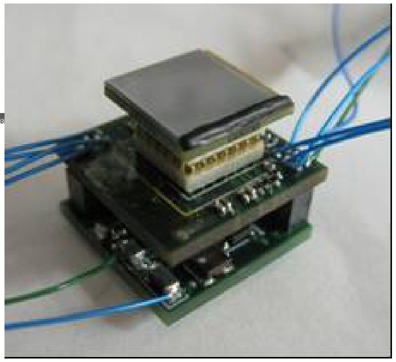


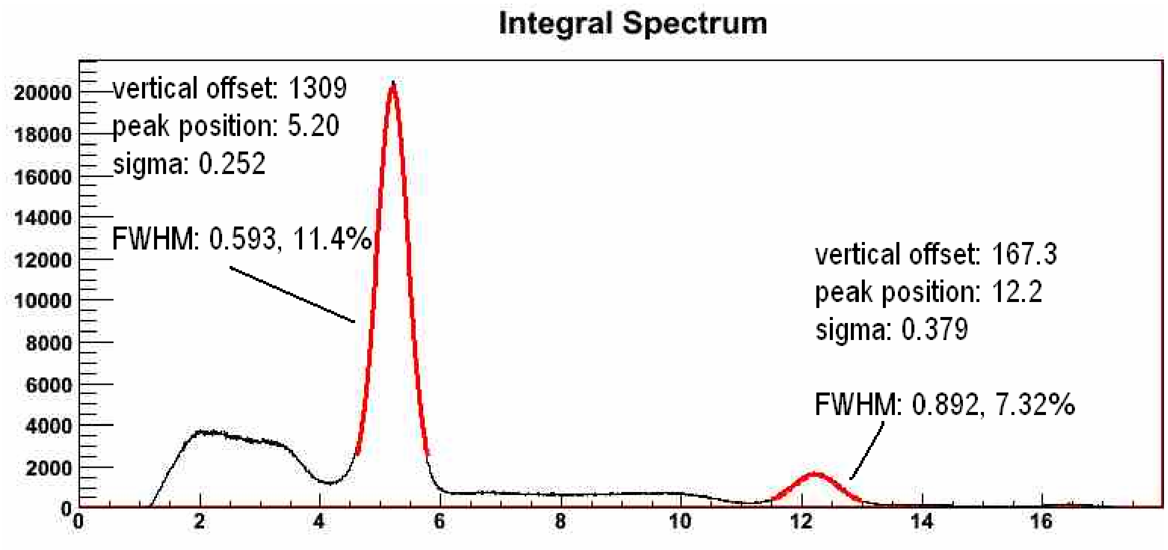




Complete Functionality

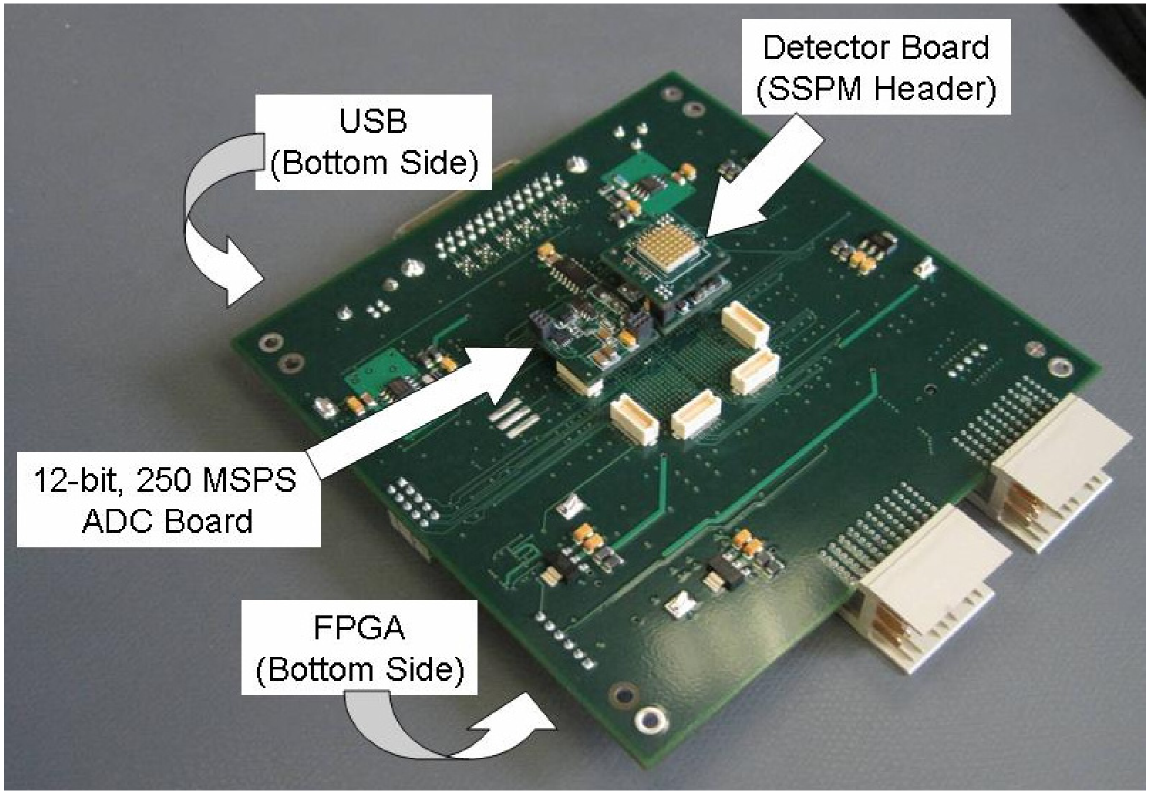






- Coupled to an FPGA evaluation board.
- Placed a LYSO crystal on the SSPM and powered the device through the boost converter.
- The 12-bit word from the ADC was sent into the FPGA and processed.
- The code calculated an integral for each gamma event from a ^{22}Na source.
- The integrals were saved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

Existing Hardware: Four Channel Device

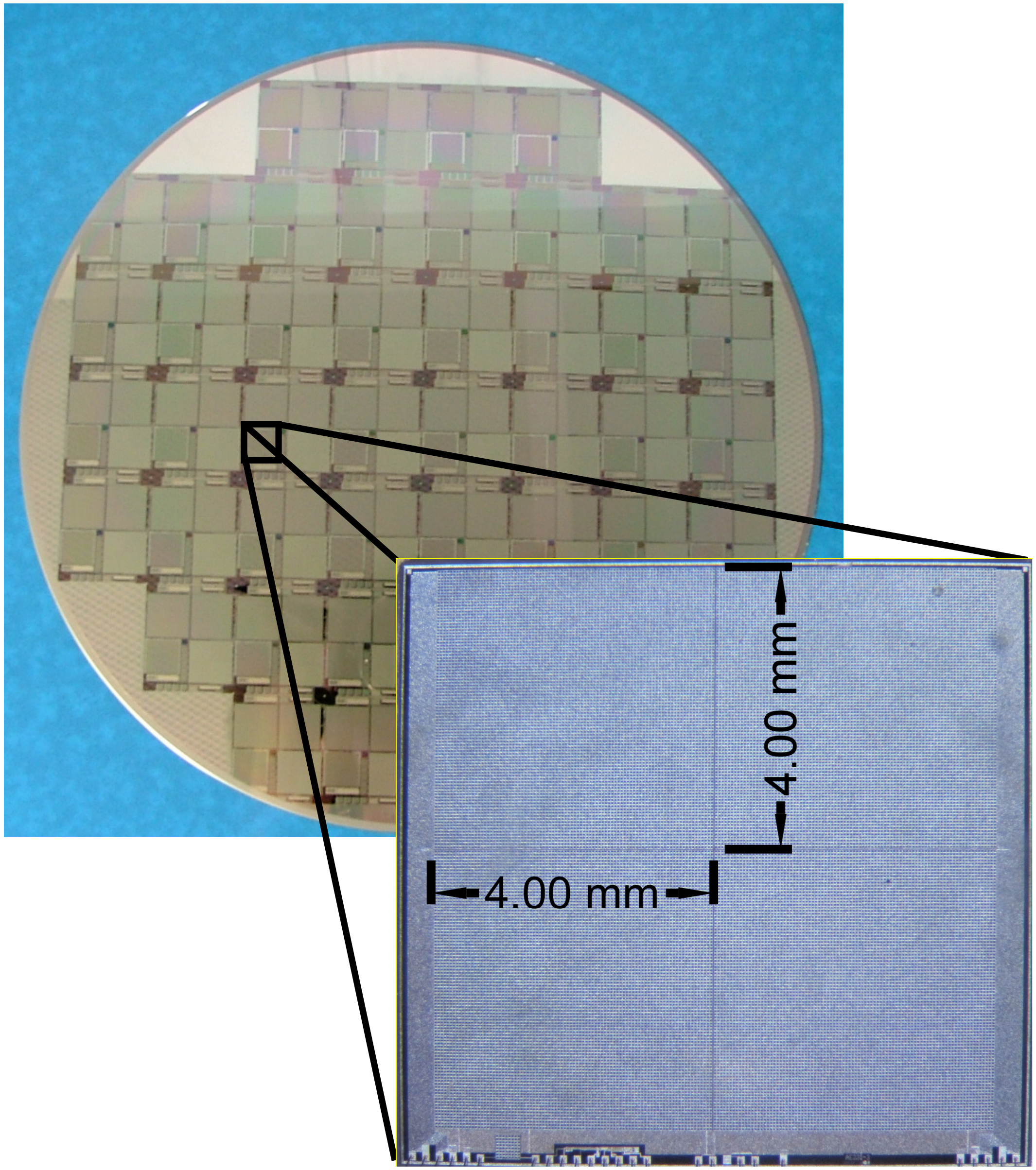


- Design and layout by Don Lydon (UMass)

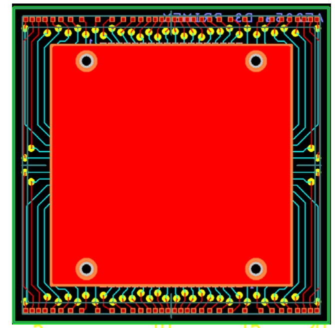
- Based on FPGA evaluation board from Analog Devices for ADCs.
- USB 2.0.
- Connect up four channels.
- Xilinx Virtex 4 (XC4VFX20-10FFG672C)
- Four channels for gain monitors.
  - Voltage followers.
  - ADC with MUX (AD7888)
- 12-channel I/O through D-sub connection.

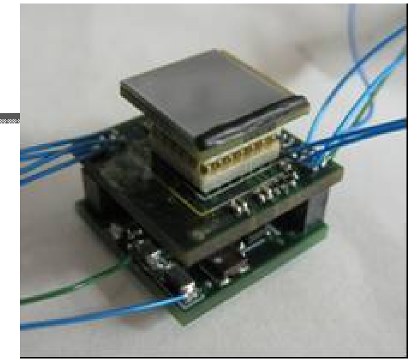
1st Generation SSPMs Status Review and Work Plan

- Conducted Engineering Run.
  - 6 wafers.
  - 44 reticles printed per wafer.
  - 264 PrimEx prototype die have been fabricated.
  - Explored a post-processing option to improve the QE.
- Status:
  - Packaged 12 die into large ceramic packages.
  - Simple resistive load test, showed 3 die not functional.
  - Previous yields have been closer to 100%.
  - Packaging or post processing on the die might be the issue.
  - V_{BD} = 27.18 ± 0.01 V (3 die).
  - I_d (V_x = 1 V) = 10 ± 1 Hz/μm^2

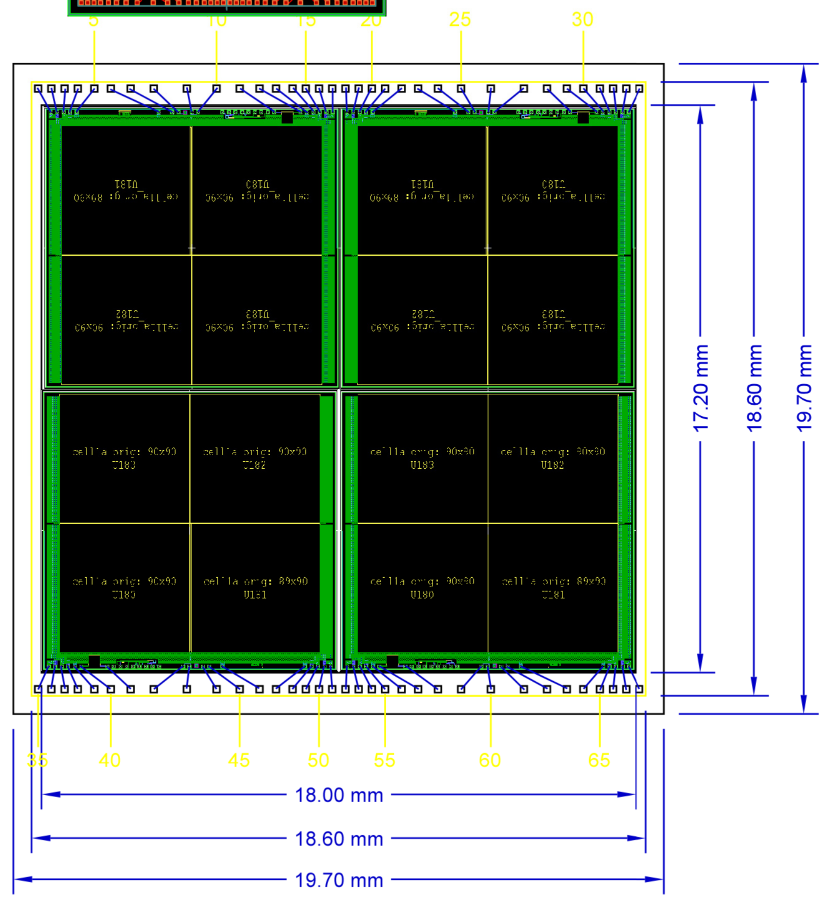


Readout Status Review and Work Plan

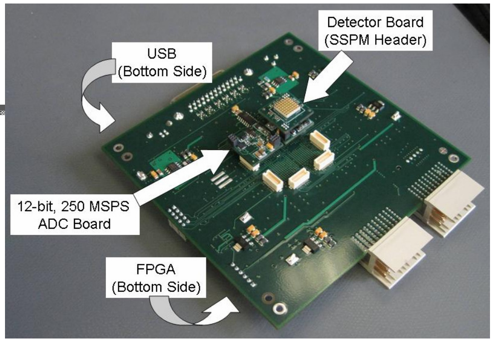




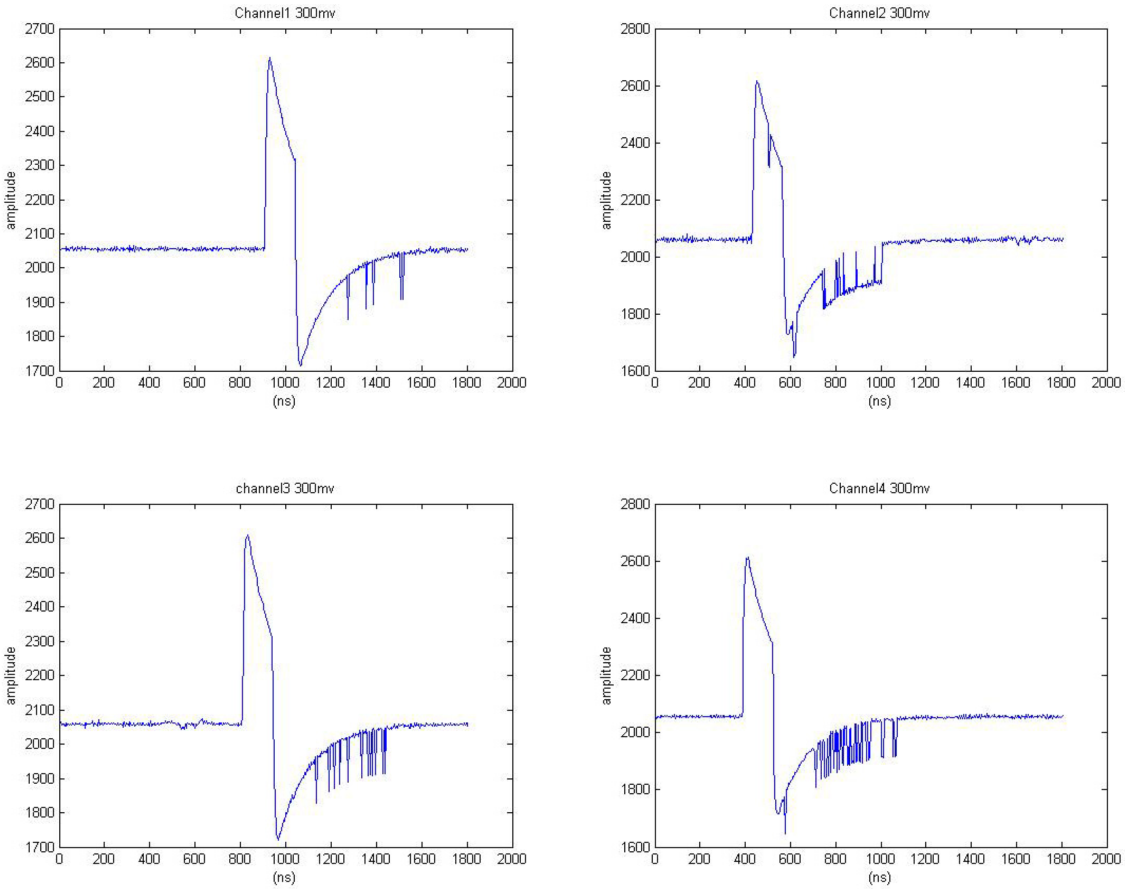
- SSPM Package
  - Design and layout complete.
    - FR4 PCB substrate.
    - 2 alternating board-to-board connectors.
  - Bonding wire protection considerations.
    - Epoxy boarder.
    - Frame.
  - Requesting quote and approval.
  - Submission soon.
- Amplifier Board
  - Slight redesign to account for change in header.
  - Add in circuitry for gain monitoring.
  - Change board to board connections to ADC board.
  - Design and layout are being worked on at this point.
  - Quick-turn readout board for new SSPM package.
  - Considering a quick-turn board using existing headers.
  - Considering developing a prototype board for a low input impedence amplifier for faster recovery.
  - Increase size to 19.7 mm x 19.7 mm.
- ADC Board
  - Design and layout for better board to board connectors.
  - Increase size to 19.7 mm x 19.7 mm.



FPGA DAQ Status Review and Work Plan

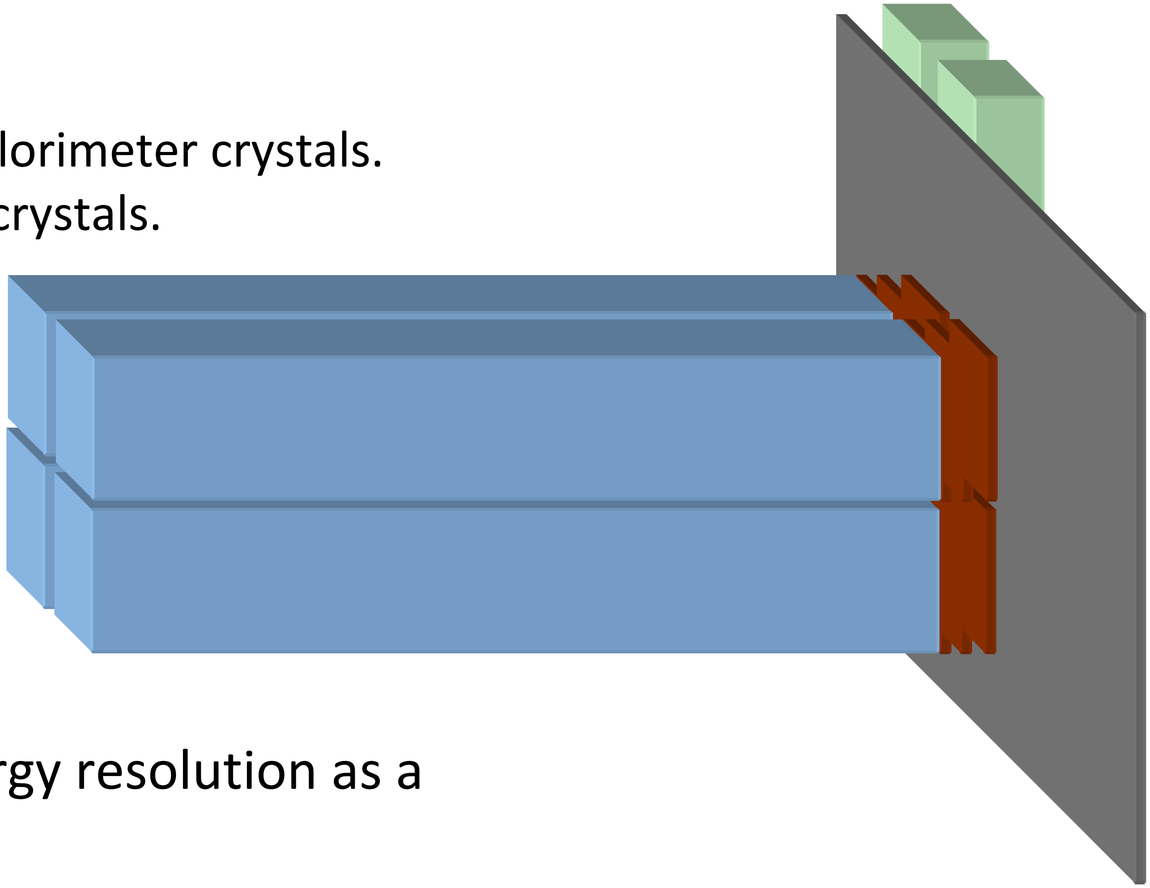


- Development of HDL code for data capture.
- Started with the code for the single channel board.
- Clock management is now done through the FPGA.
- The signal baseline should be at VCC/2.
  - VCC is the input voltage to the ADC.
  - Baseline should be around 2048 ADC channels.
- Channels are not synchronized at this point, but each channel is responsive.
- Work Plan:
  - Clean up the data capture.
  - Implement VCM (common mode) correction, SPI interface with ADC.
  - Synchronize all four channels.
  - Develop prototype code for bias control; digital potentiometer on ADC Board.
  - Develop prototype code for data capture of gain monitor.



Testing at Jefferson Lab

- Test with four $PbWO_4$ crystals.
  - Size should be close to actual calorimeter crystals.
  - Validate the expectation of the crystals.
- Beam conditions:
  - 100+ MeV photons.
  - Multiple beam energies; should characterize with no less than five different energies.
- Default: Measure waveforms.
- Ideal: Measure energy and time.
- Goal: Generate a plot of the energy resolution as a function of energy deposited.
- Timing:
  - Need a reference time.
  - Implement code to capture reference time signal and process.



Schedule

Work Task	30-Jul	6-Aug	13-Aug	20-Aug	27-Aug	3-Sep	10-Sep	17-Sep	24-Sep	1-Oct	8-Oct	15-Oct	22-Oct	29-Oct
1st Gen. SSPM														
Eval.														
Dice														
Package Dev.														
Review														
Fabrication														
Package														
Amp Dev.														
Schematic														
Layout														
Review														
Fabrication														
ADC Dev.														
Schematic														
Layout														
Review														
Fabrication														
Amp Eval. Boards														
Test Multiple Amps														
Quick-Turn Low-Z Board														
Eval. Low-Z Board														
Quick-Turn SSPM Pack.														
Eval. SSPM Pack.														
FPGA Code Dev.														
1-channel Data Capture														
VCM enable														
Synch 4-channels														
Bias Control														
Gain Mon. Capture														
User Interfacing														
Integral and Timing														
Temp. Feedback Enable														
GUI: Data Monitor														
GUI: Bias Control														
GUI: Data Control														
Jlab Test Prep														
Acq. Materials.														
Setup at RMD														
Eval. each chan.														
Travel to Jlab.														

Note on Cost

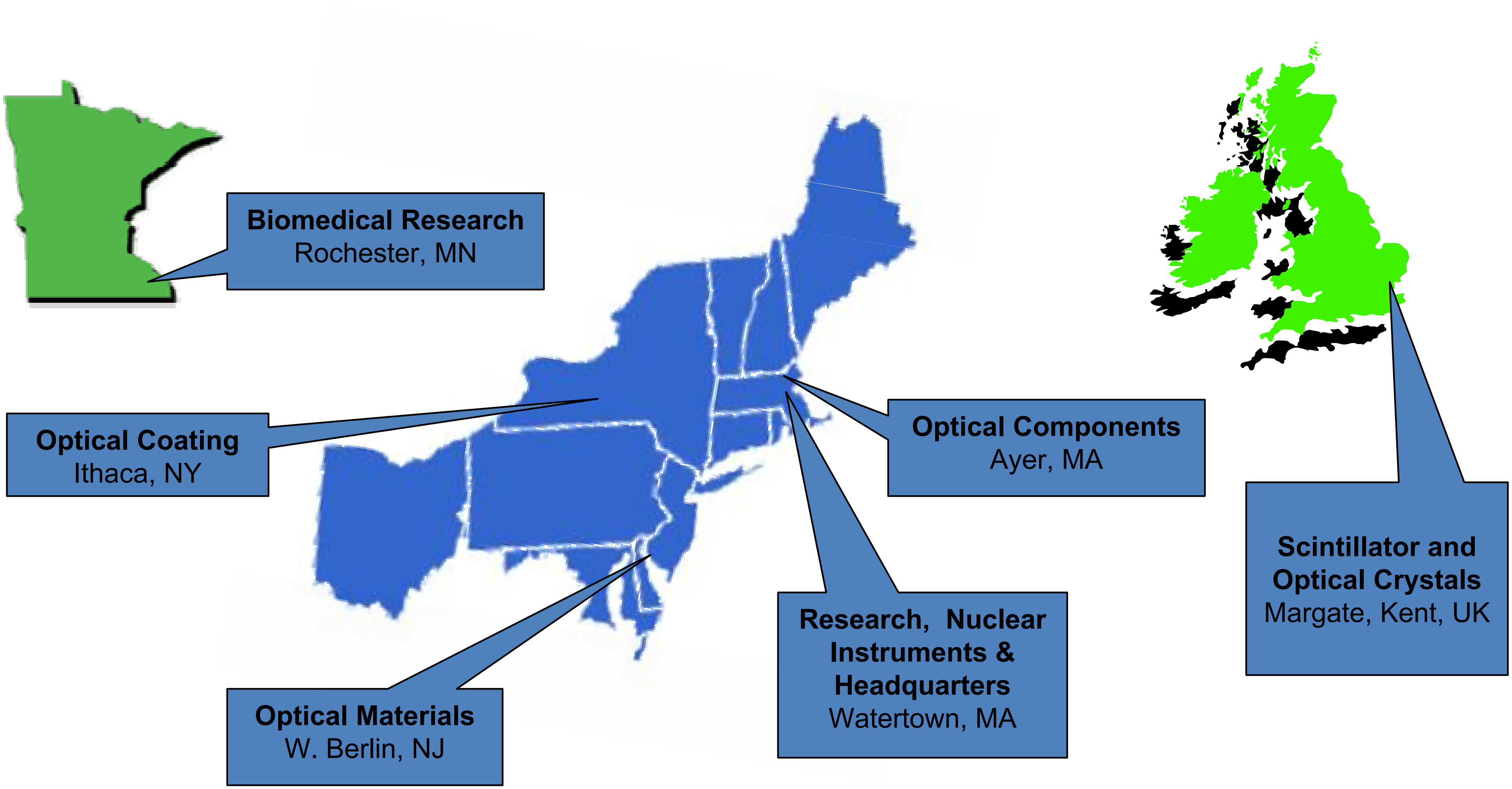
- Material cost of CMOS based instruments scale per area.
- There is a NRE for each new mask set.
  - Defines the structures to be built in the silicon.
  - Layout costs and materials.
- Estimate 65 reticles per wafer (equivalent to 65 detectors).
- PrimEx Calorimeter will need no less than 56 wafers.
  - Full production of wafers will be implemented.
  - This will reduce the cost significantly.
- Packaging is not trivial because of the size.
  - The device causes a more expensive, non-commercial packaging.
  - I'm working on a simple FR4 (standard PCB) package.
- As final parts are built, I will have a better idea of the cost and will be able to provide a better price.
- Estimated Price: $100 - $800 for each SSPM.
- The AD9230 is $100 per ADC for large orders.

Questions

- Will an external ADC be used?
- Will you need an amplifier connected to the SSPM?
- Will a digitally controlled DC/DC boost converter be useful?
- Will the gain monitor signal be useful?

- If you are seriously considering using off-detector (modular) components, we can accelerate our schedule for testing at JLab if a DAQ system is available.
  - A revision of the pcb package is available.
  - Silicon die are available.
  - Package up detectors within a couple of weeks.
  - Layout and fabrication of an interconnect board with an amplifier is quick.
  - We would just need to know what our output should be (differential, signal ended, voltage swing, etc.).
  - Is this what is needed?

Dynasil: Current Facilities & Products



What Does RMD Research Do?

We perform research and development in:

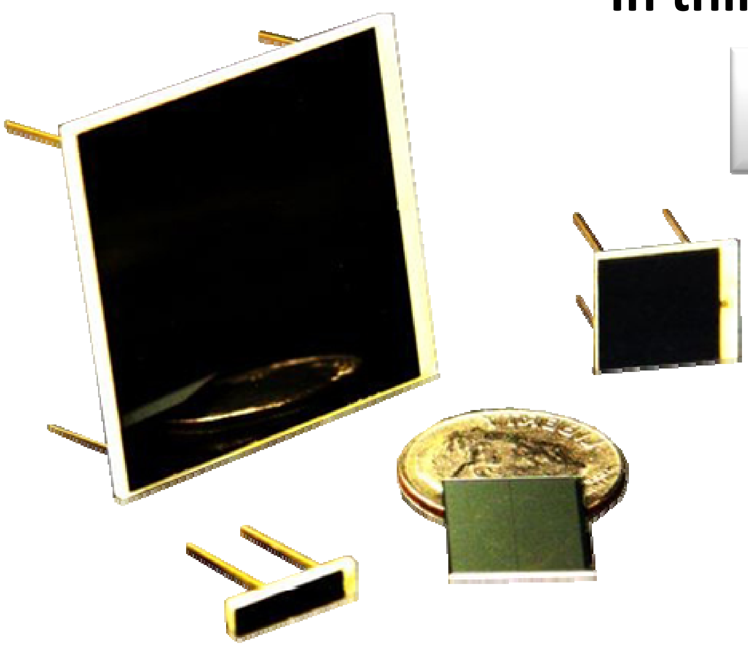
Materials   Sensors   Instruments (Proof-of-concept)

In things that detect, use or measure:

Radiation   Light   Magnetism   Sound

For use in/by:

Homeland security
Military & “First Responders”
Medical diagnosis & treatment
Industry
Other research organizations



Solid-state light detectors

Enabling Technologies in Multiple Growth Markets

Detector Type	Medical Diagnostics	Border Security Police & Military	Industrial	*RMD Advantages*
X-Rays	Flat Panel Detectors Computed Tomography Dosimeters (Medical)	Baggage Scanners Container Scanners	Product Testing Product Inspection	Brighter & Faster Thin Film & Ceramic Scintillators
Gammas	PET SPECT MRI+PET Surgical Probes	Nuke Pagers/HH/Portals Container Scanners Dosimeters	Oil Exploration Non destructive testing; others	High-Performance Crystals Lower-Cost Ceramics Dual-Mode Crystals Solid-State Light Detectors IC-Based Dosimeters
Neutrons	Emerging Techniques	Nuke Pagers/HH/Portals Container Scanners Dosimeters	Oil Exploration Non destructive testing; others	
Magnetic			Aircraft Inspection Power Plant Inspection Steel Hardening	Novel Eddy-Current Sensor Technology
Key Drivers	Lower Radiation Doses Higher Thru-put Lower Initial / LT Costs Multi-mode Diagnostics	More Sensitive Replacing Helium-3 More Compact More Robust	Higher Resolution More Sensitivity Higher Thru-put Lower Cost	

Partners and Agencies

- New technology helps drives new physics experiments.
- Scientific community provides a valued proving ground for new technology.

ANL
Brookhaven
Edgewood
Fort Monmouth
INL
JPL
JSFC
LANL
LBNL
LLNL
MSFC
NASA Goddard
NRL
ORNL
PNNL
ROME
Sandia
WPAFB

Arizona State University
Boston University
Brandeis
CUNY
Duke
Fisk University
Georgia tech
Harvard
Johns Hopkins
Kansas State
LSU
Mayo Clinic
MGH
MIT
Northeastern
Penn State
Purdue
Roswell Park Cancer Center
Stanford
Tufts
U AZ
UC Berkely
UC Davis
UCLA
UCSF

U Mass
U Mich
U Oklahoma
UNH
U Penn
USC
WSU
Yale

Army
Air Force
DNDO
DOC
DOE
DTRA
EPA
HSARPA
HUD
Marines
NASA
Navy
NIH
NIST
NSF
US Customs

Analogic
AS&E
BTI
Canberra
Conoco
General Atomic
General Electric
General Motors
ICX
Raytheon
Schlumberger
Thompson CSF
Titan
Tyco
US Surgical
Varian
Xerox