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

Traditional Scintillator Detector

- 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 FPGA

- 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 π⁰ life time provides evidence that the QCD theories are valid at these low energies.
  - It provides 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 times.
  - η and η’ are produced by the Primakoff Effect
    - 10-GeV photons incident on Liquid Hydrogen
    - Photon and virtual photon interaction yields neutral pseudo-scalars, such as η and η’.
  - They decay into two photons with energies > 1 GeV.
  - The PRIMEX experiment will house a PbWO₄ calorimeter for measuring the total energy of the decay photons to within 1%.

- Experimental Setup with 11 GeV Photon Tagger
  - Bremst. Rad.
  - First C-Dipole
  - Second C-Dipole
  - Pb Shielding Wall
  - LH/LHe Targets
  - PbWO4 Calorimeter
  - Veto scint.
  - Tagger Focal Plane
  - Detectors

[Diagram showing experimental setup]
The PRIMEX PbWO₄ Calorimeter

- Planned Calorimeter
  - 60 x 60 element array of PbWO₄
  - <1% energy resolution for 4.5 GeV
  - ~ 1 mm position resolution
  - 2.125 x 2.125 x 21.5 cm³

- PbWO₄ Parameters
  - Fast Decay: ~10 ns
  - Density: 8.3 g/cm³
  - 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

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

PbWO Crystals
5x5 Array

SSPM
Integrated Signal Processing

Interface
ADC ≥250MSPS

FPGA
DSP
Position Time
Pulse Height
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.

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

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

Large Gain: $\sim 10^6$ (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.

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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.
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

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

- 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.

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<td>Q3</td>
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<tr>
<td>Far</td>
<td>Small</td>
<td>Q4</td>
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Cross Talk Multiplier vs. Excess Bias (V)

Afterpulse Multiplier vs. Temperature (K)

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.

Use a tail pulse generator.
Collect dark events.

Use a tail pulse generator.
Collect dark events.

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

- 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.


Fit and bin data.

Look at events within a small window.

Generate dark spectrum and bin data.

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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.

$$\begin{align*}
M &= \frac{\mu_{\text{meas}}}{\mu_{\text{dark}}} \\
F &= \frac{\sigma^2_{\text{meas}}}{\sigma^2_{\text{dark}}}
\end{align*}$$

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.
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.

![Graph showing charge output from pixel](image)

![Graph showing excess noise factor and crosstalk-afterpulse multiplier](image)
Non-linear Effects

Triggered Pixels

\[
\langle n_t \rangle = n_{\text{eff}} \exp\left( -P_g(V_x, \lambda, \text{FF, QE}, L) \right)
\]

SSPM Non-linear Behavior

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

The large-area SSPM benefit from large pixel numbers.

441-pixel SSPM

Excess Bias: 2V

5.5 x 5.5 x 5.5 mm³ LYSO
Large-area SSPM
Room Temperature

\[ n_{\text{eff}} = 43011 \]

Excess Bias: 3V

ADC Channels (pixels triggered)

Light Yield (photons)

Mean from incident gamma rays
Noise terms and $\tau$–scaling

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

- 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 PbWO₄ 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 thorough 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.

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.

![4300-pixel SSPM with integrated circuitry]

3 mm
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

- Sensor head will be directly coupled to the PbWO₄ 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 PbWO₄ Crystals and high energy gamma rays.
- The prototype has recently been assembled for testing.

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<thead>
<tr>
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<tbody>
<tr>
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<td>ADC Data</td>
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<tr>
<td>Com to DC-DC Supply</td>
<td>Gain Monitor Signals</td>
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<tr>
<td>Clock</td>
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<tr>
<td>+1V</td>
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Data Capture for Characterization

Input

Baseline Correction

Trigger

Timing

Output

Energy

Waveform Output

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## Schedule

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<tr>
<th>Task</th>
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<td>Evaluate Existing CMOS Designs</td>
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<td>Simulate Detector Modules for Optimal Design</td>
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<td>Dec 2010</td>
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<tr>
<td>Design and Construct Prototypes for a Large Area SSPM</td>
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<tr>
<td>Construct an Apparatus for High-Energy Gamma Interactions</td>
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<td>Sep 2010</td>
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<td>Design and Simulate CMOS SSPMs with Integrated Signal Processing</td>
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<td>Construct CMOS SSPMs for Calorimeter Application</td>
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<tr>
<td>Design Interconnect Board for Digitization</td>
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<td>Construct a PRIMEX Calorimeter Cluster Module</td>
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<td>Evaluate Cluster Module at an Accelerator Facility</td>
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<td>Jul 2011</td>
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<tr>
<td>Provide Phase-II Progress Reports</td>
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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.