Digital SPAD Scintillation Detector Simulation Flow to Evaluate and Minimize Real-Time Requirements

Marc-André Tétrault, Audrey Corbeil Therrien, William Lemaire, Réjean Fontaine, Jean-François Pratte
Outline

• Short overview for PET and time of flight PET
  ▪ Basic PET principles and why real-time matters
  ▪ Review detector chain towards time of flight

• High timing resolution detector design
  ▪ Photodetector
  ▪ DAQ
  ▪ Compromises for real-time embedded microsystem
Positron Emission Tomography

• Molecular Imaging Modality
  ▪ Tracer distribution (positron emitter)
    o Hot spot on the left side
  ▪ Positron Annihilation
  ▪ Collinear 511 keV particles
  ▪ Line of response

• Invited speaker tomorrow
Image Quality Figures of Merit

- Contrast to Noise Ratio from detector’s
  - Spatial resolution
  - Energy resolution
  - Timing resolution
- Sensitivity or Noise Equivalent Counts
  - Detector dead time
  - Optimized with real-time processing
Image improvement avenue

- Spatial resolution limit is positron range
  - About 0.5 mm for mainstream tracers
- Improve contrast with time of flight

1.5 mm on the LOR needs **10 ps FWHM** in coincidence
- Real time image reconstruction (no iterative engine required)
• Scintillator-based detectors
Factors affecting timing

- Light yield
- $T_{\text{rise}}$, $T_{\text{decay}}$
- Crystal size/length

Fast TOF Scintillators

- LSO, LuAG, LuAP, LaBr$_3$

With an ideal photodetector the 1$^{\text{st}}$ photon has best timing

- LSO 1$^{\text{st}}$ photon has theoretically $\sim 35$ ps FWHM in coincidence

Weber et al, NIM 2004; Mikhailin et al, NIM 2002

1- Derenzo et al, PMB 2014
2- Gundacker et al, NIM 2016
3- Conti et al, TNS 2009
Photodetectors

- **PMT**
  - ☀ High gain, fast timing
  - ☹ block detector, many pixels, medium count rate
  - ☹ Bulky, sensitive to magnetic fields

- **APD**
  - ☀ High PDE, immune to magnetic fields
  - ☀ Pixelated detector, high count rate
  - ☹ noisy, limited gain, average timing

- **SiPM (Geiger-mode APD, MPPC)**
  - Array of Single Photon Avalanche Diodes (SPAD)
  - ☀ High gain, very fast timing
  - ☀ Single photon sensitivity
  - ☀ Pixelated, high count rate, immune to magnetic fields
### Where are we?

#### Experimental measurements with LYSO

<table>
<thead>
<tr>
<th>Systems</th>
<th>Table setups</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT</td>
<td>473 ps FWHM (1)</td>
</tr>
<tr>
<td>APD</td>
<td>6.6 ns FWHM (2)</td>
</tr>
<tr>
<td>Analog SiPM</td>
<td>385 ps FWHM (3)</td>
</tr>
<tr>
<td>Digital SiPM Frach et al, 2009</td>
<td>212 ps FWHM (4)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1- Wong et al, TNS 2015  
2- Bergeron et al, TNS 2009  
3- Levin et al, TMI 2016  
4- Degenhardt et al, NSS-MIC 2012  
5- Peng et al, TNS 2013  
6- Leroux et al, TNS 2009  
7- Nemallapudi et al, PMB 2015  
8- Somlai-Schweiger et al, J. Inst. 2015  
9- van Dam et al, PMB 2013
• Analog front-end
  ▪ Adapted to photodetector
  ▪ Typically fast and low-noise preamplifiers
    o Anghinolfi et al, TNS 2004
    o Olcott et al, TNS 2005
    o Callier et al, NSS-MIC 2009
    o Powolni et al, TNS 2011
    o De Medeiros Silva et al, TCS 2014
    o ... and many more
• Real Time Data Acquisition
  ▪ Trigger-based generation systems
    o Lecomte et al, TNS 1990, Young et al, NSS-MIC 1999
  ▪ Modern systems:
    o Hybrid ADC and TDC: Wang et al, Real Time 2009
• Going forward, the key DAQ component for timing
  ▪ Time to Digital Converters (Henzler, S., Springer, 2010)
    o Low power with 45 ps resolution → Perenzoni et al, Elec. Lett. 2015
Towards 10 ps time of flight

• 1.5 mm on the LOR needs 10 ps FWHM in coincidence
  ▪ Scint : High light yield, fast rise and decay times
  ▪ Opto : High photodetection efficiency
  ▪ DAQ : Single-shot timing with ps resolution and low jitter $\rightarrow \sigma(t)$
  ▪ DSP : Individual photon distinction would enable better signal processing

• Excellent measurements with SiPM photodetector
  ▪ Why?
• With non-ideal detector, first few photons have best timing information
  ▪ SiPM can see that!

• Detection efficiency $\propto$ Bias
• Noise $\propto$ Bias
Analog vs Digital SiPM

**Passive quench SiPM**
- Very simple
- Variable cell response

**Active quench SiPM**
- Noise suppression
- Temp. invariant signal
- Uniform cell response

**Digital SiPM**
- No external analog front-end

---

**Generic devices, many companies**

**Nolet et al, NSS-MIC 2014**

**For PET:**
- Frach et al, 2009
- Braga et al, 2014
- Schaart et al, 2016
Detection efficiency $\propto$ Optical Fill Factor

Analog or digital? Same timing with same SPAD arrays

- Gundacker et al, NIM 2015
Vertical Integration for Digital SiPM

• Back-side illumination
  ▪ Infra-red wavelengths
  ▪ Zou, Bronzi, 2014, SOI on CMOS
  ▪ Pavia et al, JSSC 2015, Dual-CMOS

• Front-side illumination
  ▪ Tétrault et al, TNS 2015
    - Test chip in assembly
    - Prelim results at NSS-MIC 2016
Digital SiPM microsystem design

• Implementation boundaries
  ▪ 1 TDC per scintillator
    o First observed photon to reach TDC
    o No post-processing required, excellent real-time performance
  ▪ 1 TDC per cell (400 cells per mm²)
    o Maximum Likelihood Estimator (MLE)

• Is there a middle point providing the best of both worlds?
Digital SiPM Microsystem Model

- Light generation
- Light transport

Optoelectronic
- Array of SPADs
- Quenching Circuit
- Digital trigger

Acquisition and signal processing
- Analog Sum
- Threshold Trigger
- TDC
- TDC Sharing
- Signal processing

Crystal

Photon Statistics
- Light Transmission
- Efficiency

Geant4 toolkit,
Wrapper courtesy of
Marco Pizzichemi, CERN

Geant4 toolkit,
Wrapper courtesy of
Marco Pizzichemi, CERN

Fill factor
- Quantum efficiency
- Avalanche probability
- Noise not considered
- QC dead time

QC jitter

Skew and jitter for
- Clock tree
- Trigger tree

TDC LSB
TDC Jitter
TDC Sharing

Single TDC
Multi-TDC + MLE

Therrien et al, TNS 2014

*This work, Python models
Simulation parameters

**LYSO**
- 40,000 / MeV
- 1.1 x 1.1 x 3 mm³
- $T_{\text{rise}} = 70$ ps
- $T_{\text{decay}} = 40$ ns

**SPAD array**
- Effective PDE = 18% @ 420 nm
- 1.1 x 1.1 mm²
- 484 cells, 50 micron pitch
- Dalsa CMOS HV doping profile
- 20 ns quench/recharge dead time

**TDC**
- Programmable precision
- Programmable resolution
- Programmable SPAD:TDC ratio

Many parameters to consider, needs deep knowledge of entire detector to fully configure
Simulation Outcomes (LYSO)

- What is the coincidence timing resolution (CTR) lower limit?
- What is the performance gain between one and many TDCs?
- How many TDCs are actually needed?
  - Will determine real-time load and silicon real-estate for TDCs
  - Faster real time $\rightarrow$ lower dead time $\rightarrow$ better sensitivity

- Subset of full simulation results
  \[
  \sigma(t)_{\text{Cell}}^2 = \sigma(t)_{\text{SPTR}}^2 + \sigma(t)_{\text{QRC}}^2
  \]
  \[
  \sigma(t)_{\text{Cell}} = 30 \text{ ps FWHM}
  \]
  \[
  \sigma(t)_{\text{TDC}} = 30 \text{ ps FWHM or variable}
  \]
  TDC resolution : 1 to 50 ps LSB
  Figure of merit : coincidence timing resolution (CTR)
Full TDC array LYSO results

1- Lower limit
2- Multi-TS improvement

$\sigma_{\text{Cell}} = 30$ ps FWHM
TDC LSB = 1 ps

~90 ps FWHM

10-35%
Impact of sharing TDC LYSO

How many TDC?

- 1:4 Ratio
- 1:1 Ratio

\[ \sigma_{\text{Cell}} = 30 \text{ ps FWHM} \]
\[ \sigma_{\text{TDC}} = 30 \text{ ps FWHM} \]

\[ \text{MLE CTR (ps FWHM)} \]

Number of TDCs in array

50 ps LSB
20 ps LSB
10 ps LSB

20th IEEE NPSS Real Time Conference, Padova, 2016
How to reach 10 ps?

- 10 ps beyond current scintillator limit
- Crystal designers have ideas
  - Improve prompt photon yield
    - Cherenkov
    - Intra-band luminescence
    - Nano crystals
    - Cqwells
      - Lecoq et al, TNS 2016
  - Expected light yield
    - Unknown
  - Model approximation
    - Second scintillation component
    - Light Yield = 1000 / MeV
    - $T_{\text{rise}} = 0.1$ ps
    - $T_{\text{decay}} = 5$ ps
  - Observed time-stamped prompts
    - About 25 in photopeak events
• What is the timing lower limit?
• What is the performance gain between one and many TDCs?
• How many TDCs are actually needed?
  ▪ Will determine real-time load and silicon real-estate for TDCs
  ▪ Faster real time → lower dead time → better sensitivity
• Subset of full simulation results

\[
\sigma(t)_{\text{Cell}}^2 = \sigma(t)_{\text{SPTR}}^2 + \sigma(t)_{\text{QRC}}^2
\]

\[
\sigma(t)_{\text{Cell}} = 15 \text{ ps FWHM}
\]

\[
\sigma(t)_{\text{TDC}} = 10 \text{ ps FWHM or variable}
\]

TDC resolution: 1 to 5 ps LSB
Full TDC array Prompts results

1- Lower limit
2- Multi-TS improvement

\[ \sigma_{\text{Cell}} = 15 \text{ ps FWHM} \]

\[ \text{TDC LSB} = 1 \text{ ps} \]

~11-14 ps FWHM
How many TDC?

- 1:4 Ratio
- 1:1 Ratio

\[ \sigma_{\text{Cell}} = 15 \text{ ps FWHM} \]
\[ \sigma_{\text{TDC}} = 10 \text{ ps FWHM} \]
Outcomes

Current Scintillators
• Not likely to reach 10 ps FWHM CTR
• Moderate gain from multi-TDC MLE
  ▪ Need only a few TDCs to be effective
• Use real-estate to embed other real time tasks
  ▪ MLE calculation
  ▪ Energy discrimination
  ▪ Crystal identification

Future Detector Crystals
• Can theoretically reach 10 ps FWHM CTR
• Good gain from multi-TDC MLE
  ▪ Needs several TDCs for optimal timing
• Compromise between embedded real time features and number of TDCs
  ▪ Simulation flow can guide designers
Conclusion

• To reach 10 ps timing resolution
  ▪ Crystal light output major player
  ▪ Jitter and precision are important, but not sufficient
  ▪ The number of TDCs per pixel also major player

• The real time microsystem complexity is dependant on the potentially reachable timing resolution

• The simulation tool can help predict the overdesign threshold
  ▪ Reduce un-needed real-time burden
  ▪ Dedicate otherwise redundant real-estate to other real-time tasks