Development of a PET module using Silicon Photomultipliers as Photon Detectors

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06 April 2010
Positron Emission Tomography?

- Nuclear Imaging technique often used for medical imaging.
  - $\beta^+$ emitter added to tracer molecule
  - Can be used to study functional processes in the body

- Indirectly measures the 3D distribution of emitted positron radiation.
  - Back-to-Back $\gamma$’s from $e^+e^-$ annihilation are measured
Basics of PET

1. Positron ($\beta^+$ decay) slows down in tissue
2. $e^+ e^- \text{ annihilation} \rightarrow 511 \text{ keV } \gamma \text{ pair}$
3. To measure distribution of annihilation events requires:
   - Coincidence measurement $\gamma$ pair $\rightarrow$ line of response (LOR)
   - Segmented detector ring for 360° or 2 rotating modules

Accept events within coincidence time window
&
Reject events outside coincidence time window
Photon can interact with material in 3 ways:

- **Photo-electric effect** → entire photon energy is absorbed → full energy measured
- **Compton scattering** → photon scatters on $e^-$ & some energy is transferred to $e^-$
- **Pair production** → $\gamma$ interacts with a nucleus & $e^+e^-$ pair is produced (requires $E_\gamma \geq 2 \times 511\text{keV}$) → no issue for PET

**Compton Scattering:**

$E'_\gamma = E_\gamma \frac{1}{1+\epsilon(1-\cos \theta_\gamma)}$ \quad $\epsilon = \frac{E_\gamma}{m_e c^2}$

$E_{\gamma}^{\min} = \frac{E_\gamma}{3}$ for $\epsilon \rightarrow 1$ & $\theta \rightarrow 180^\circ$

$E_{e^-}^{\max} = E_\gamma - E_{\gamma}^{\min} = \frac{2}{3} E_\gamma$ \quad $E^{\max} \approx 340\text{ keV}$
Photon Interaction with Matter

Cross section of $\gamma$ interaction is $Z$-dependent:
- Photo-electric effect (PE) $\propto E^{-3.5} Z^5 \rightarrow$ dominant at low energies BUT strongly dependent on $Z$
- Compton scattering (CS) $\propto Z \ln E/E \rightarrow$ dominant at medium energies & only linearly dependent on $Z$

Carbon $\rightarrow Z=6$

very important for maximizing scintillator efficiency!

Lead $\rightarrow Z=82$
**Fundamental limits of PET**

- **Range effect** → $e^+e^-$ annihilation not at location of $\beta^+$ decay (few mm)

- **Incorrect Line of Response (LOR) effects:**
  - Compton scattering of $\gamma$’s in tissue and material in the path of the $\gamma$ → angular deviation on LOR
  - Random events coupled incorrectly to each other
  - Parallax error when LOR is at edge of transaxial view PET scanner

- $\beta^+$ emitter has to be chosen based on:
  - half-life $t_{1/2}$ → minimise absorbed dose vs good measurement statistics
  - Energy spectrum of $\beta^+$ decay → range

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$ (min)</th>
<th>$E_{av}$ (MeV)</th>
<th>$R_{av}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}\text{C}$</td>
<td>20.4</td>
<td>0.385</td>
<td>1.7</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>10</td>
<td>0.491</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>2</td>
<td>0.735</td>
<td>2.7</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>109.8</td>
<td>0.242</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Why combine MRI scan with a PET scan?
- MRI → tissue identification
- PET → physiological and biochemical tissue activities
- Combine MRI & PET scanners for ease of alignment and increased accuracy

Requires magnetic field (MRI!) insensitive photon detectors
- classical PMT’s (magnetic field, expensive, fragile, power)
- Silicon Photomultipliers (magn. field insensitive, can be cheap, robust, low power)
Use time difference between detection of back-to-back $\gamma$’s:

- **Infinitely sharp timing** $\Rightarrow x = \frac{\Delta t \cdot c}{2}$
- **Detector timing resolution** $\sigma_t \Rightarrow x + \sigma_x = \frac{\Delta t \cdot c}{2} + \frac{\sigma_t \cdot c}{2}$

**Better $\sigma_t \rightarrow$ more accurate position**

- Speed of light 33 ps/cm $\rightarrow$ sub-cm resolution $\rightarrow$ improve spatial resolution

**If $\sigma_x <$ size of emission source:**

- Distance between annihilation events $> \sigma_x \rightarrow$ decouple events
- Distance between annihilation events $< \sigma_x \rightarrow$ decouple events
- Improvement of S/N
PET Module Requirements

- **PET module should consist of:**
  - Scintillator → convert $\gamma$ into light
  - Photon detector to detect the scintillation light

- **Ideal characteristics of PET module:**
  - High stopping power (total absorption of 511 keV $\gamma$)
  - High spatial resolution → detector segmentation
  - Good Energy resolution → rejection of scattered events
  - Inexpensive

- **Additional requirements for components:**
  - Magnetic field insensitive detectors → PET & MRI
  - Very fast detectors (sub-ns range) → ToF to improve S/N
  - Silicon Photomultiplier → promising candidate as photon detector for ToF PET & MRI combination (B-field insensitive, fast, relatively cheap → segmentation, ...)

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SiPM PET Module
Scintillators

- Convert $\gamma$ to visible light:
  - Visible light is easiest to detect (shallow penetration depth)
  - Scintillation crystal has to be clear material

- Production of scintillation light:
  - $\gamma$ interacts with $e^-$ in crystal valence band → creates photo-$e^-$
  - Photo-$e$ collides with $e$ in valence band → multiple $e$ get excited
  - each $e$ in conduction band decays → emits a photon

- A good candidate for ToF PET should have:
  - Fast decay time → ToF information
  - High light yield → energy resolution & ToF
  - High density → high stopping power → small crystals for fine segmentation
  - Preferably non hygroscopic → easy to handle
Physical properties of some scintillator materials often used for PET

<table>
<thead>
<tr>
<th>Scintillator Material</th>
<th>Density ($g/cm^3$)</th>
<th>Absorption length (cm)</th>
<th>Light Yield (% NaI)</th>
<th>Decay time (ns)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>1.04</td>
<td>20</td>
<td>300</td>
<td>480</td>
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<tr>
<td>LYSO</td>
<td>7.10</td>
<td>1.20</td>
<td>75</td>
<td>40</td>
<td>420</td>
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<tr>
<td>NaI:TI</td>
<td>3.67</td>
<td>2.91</td>
<td>100</td>
<td>230</td>
<td>410</td>
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<tr>
<td>GSO</td>
<td>6.70</td>
<td>1.41</td>
<td>20</td>
<td>60</td>
<td>440</td>
</tr>
<tr>
<td>LuAP</td>
<td>8.30</td>
<td>1.05</td>
<td>30</td>
<td>18</td>
<td>365</td>
</tr>
<tr>
<td>PbWO$_4$</td>
<td>8.28</td>
<td>0.85</td>
<td>1</td>
<td>15</td>
<td>440</td>
</tr>
</tbody>
</table>
Solid-state Photon Detectors

- p-doped Si + n-doped Si → depletion region (↑ with $V_{bias}$ ↑)

- Internal Photo-effect converts visible light into an e-h pair ($\sim 1.1 \text{ eV}$ needed)

- Si-Photodiode:
  - Visible light is absorbed within $\sim 1 \mu m$ → very thin p layer
  - High QE (80% $\lambda \approx 700 \text{ nm}$)
  - No gain: single-photon detection

- Avalanche Photodiode:
  - High reverse bias voltage, typically 100-200 V
  - High gain, typically 100-1000

- Very high gain ($\sim 10^5-10^6$) with Avalanche Photodiode operation in Geiger-mode!


** Silicone Photomultiplier**

- Array of Avalanche Photo-Diodes (APD) operating in Geiger Mode
- Geiger discharge $\rightarrow$ dead time of APD $\rightarrow$ 1 photon / APD!
- Array of APD's $\rightarrow$ dynamic range of SiPM, position sensitivity!

**Advantages:**
- Low operation voltage $\sim 10-100$ V
- Gain $\sim 10^6$
- Peak Photon Detection Efficiency (PDE) up to 40% (400 nm)
  \[ \text{PDE} = \text{QE} \times \epsilon_{\text{Geiger}} \times \epsilon_{\text{geo}} \quad (\epsilon_{\text{geo}} \sim \text{dead space between cells}) \]
- Time resolution $\sim 100-200$ ps
- Works in magnetic field

**Disadvantages:**
- Dark Counts $\sim$ several 100 kHz/mm$^2$
- Radiation damage ($p, n$), but not an issue for PET
Digital sampling of electronic signal:
- Switched Capacitor Array (SCA) stores total signal
- Charge on each capacitor is measured → sampled waveform
- Rebuild waveform for testing (slow readout)
- Analyse waveform on FPGA (fast readout)

Very POWERFULL tool because:
- Incorporate waveform analysis algorithms on FPGA for deconvolution of piled-up signals (classic electronics)
- QDC and TDC all in 1 device!
- High density of channels, cheap (VLSI), fast (up to 20 GSa/s), FPGA → flexible, low power
Silicon Photomultiplier: Surface Sensitivity

**Setup for position scan**
- Single photon light intensities → light filters
- Beam expander → parallel light → strong lens for sharp focus
- Focus needs to be < pixel pitch

**Position scan → internal structure of SiPM:**
- Internal SiPM structure determines $\epsilon_{geo}$ which mainly determines PDE of SiPM
- Higher $\epsilon_{geo}$ → better energy resolution → improved S/N
- Full surface scans → overall uniformity of sipm
Linearity of SiPM

- Finite number of SiPM pixels
  - Limited dynamic range
  - Linear behaviour $\propto$ number of pixels
  - Pixel has dead time when it discharges $\rightarrow$ non-linear behaviour when $N_{\text{phot}}$ approaches $N_{\text{pix}}$

- Hamamatsu S10931-100P(X):
  - 900 pixels with 100 $\mu$m pitch
  - Radioactive samples with different decay energies used: $^{22}\text{Na} (511 \text{ keV} \& 1230 \text{ keV } \gamma)$, $^{60}\text{Co} (1173 \text{ keV } \gamma)$, $^{137}\text{Cs} (662 \text{ keV } \gamma)$

\[ \text{ADC} = \text{ADC}_0 (1 - \exp \left( -\frac{E}{E_0} \right)) \]
**SiPM & LYSO Combination**

- **Energy resolution:**
  - LYSO coupled to SiPM
  - Module energy resolution depends on FWHM$_\text{LYSO}$ and FWHM$_\text{SiPM}$
  - LYSO crystals from 2 companies tested (Sinocera & Saint-Gobain)

### Manufacturer Comparison

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Sinocera</th>
<th>Saint-Gobain</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO Intrinsic FWHM</td>
<td>20%</td>
<td>8%</td>
</tr>
<tr>
<td>Light Yield (NaI)</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>Peak Emission Wavelength</td>
<td>428 nm</td>
<td>420 nm</td>
</tr>
</tbody>
</table>

### Peak and Resolution Data

- **STMicroelectronics + Sinocera LYSO**
  - 19% FWHM
  - No correction for non-linear behaviour!

- **STMicroelectronics + Saint-Gobain LYSO**
  - 14% FWHM

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Ruben Verheyden  SiPM PET Module
Single Photon & Back-to-Back Gamma

- **SiPM intrinsic timing limits the coincidence timing of back-to-back γ’s?**
  - Measure intrinsic timing with single photon level
  - Different companies
  - Wavelength dependence of intrinsic timing?

- **Single Photon timing resolution:**
  - Very short pulses $\rightarrow < 40$ ps laser pulse width
  - **Red & Blue** light

<table>
<thead>
<tr>
<th>1mm$^2$ SiPM</th>
<th>S137</th>
<th>H100C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{red}$ (ps)</td>
<td>182</td>
<td>145</td>
</tr>
<tr>
<td>$\sigma_{blue}$ (ps)</td>
<td>151</td>
<td>136</td>
</tr>
</tbody>
</table>

- **Timing resolution of back-to-back γ’s?**
  - Scintillator light used $\rightarrow$ threshold level at several photon
  - Threshold influences back-to-back timing resolution!
  - Preliminary result (Hamamatsu) $\rightarrow \sigma_t = 442$ ps
Positron Emission Tomography:

- Measure 3D distribution of $e^+e^-$ annihilation to determine $\beta^+$ tracer distribution (medical imaging)
- Combine PET & MRI $\rightarrow$ B-field insensitive detectors (SiPM)
- ToF PET $\rightarrow$ improve S/N
- $\gamma$ detection requires:
  - $\gamma$ conversion $\rightarrow$ LYSO scintillator (fast, high light yield)
  - Light detection $\rightarrow$ SiPM as photon detector
- Waveform sampling:
  - Development of waveform analysis was started and shows promising

Simple PET module $\rightarrow$ SiPM + LYSO:

- Different scintillator crystals have been tested $\rightarrow$ production has an influence on energy resolution
- Timing resolution for 2 back-to-back $\gamma$’s in the sub-ns range ($<500$ ps)
- Promising for ToF PET