Efficiency of a Cherenkov based PET module with an array of SiPMs

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Outline

- Time-of-flight (TOF) positron emission tomography (PET)
- Use of Cherenkov radiation for TOF PET
- Previous experiments
  - microchannel plate photomultipliers (MCP PMT) as photodetectors
  - silicon photomultipliers (SiPM) as photodetectors
- 16 channel Cherenkov PET module
  - measurements of detection efficiency
- Summary
Positron emission tomography (PET)

- medical physics modality, enabling in-vivo imaging of biological processes via coincident detection of 511 keV annihilation $\gamma$ rays

Time-of-flight (TOF)

- measurement of arrival times of the two $\gamma$ can be used to limit the reconstructed position of annihilation
- improves the quality (contrast-to-noise ratio) of reconstructed images

\[ \Delta x = \frac{c_0 \cdot \Delta t}{2} \]

Phils Gemini TF PET/CT, TOF resolution of 600 ps

[PET Center of Excellence Newsletter, Vol.3 Issue 3 (2006)]
Use of Cherenkov Light in TOF PET

- γ detectors in traditional PET: scintillator crystal + photodetector

<table>
<thead>
<tr>
<th></th>
<th>BGO</th>
<th>LSO</th>
<th>LaBr₃(Ce)</th>
<th>PbF₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>7.1</td>
<td>7.4</td>
<td>5.1</td>
<td>7.77</td>
</tr>
<tr>
<td>μ₅₁₁keV (cm⁻¹)</td>
<td>0.96</td>
<td>0.87</td>
<td>0.43</td>
<td>1.06</td>
</tr>
<tr>
<td>Photofraction for 511 keV (*)</td>
<td>0.41</td>
<td>0.32</td>
<td></td>
<td>0.46</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>300</td>
<td>40</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>Light yield (/511 keV)</td>
<td>3,000</td>
<td>15,000</td>
<td>30,000</td>
<td>10 (‡)</td>
</tr>
</tbody>
</table>

(*) [XCOM: Photon Cross Sections Database] (‡) in 250-800 nm wavelength interval

- Lead fluoride (PbF₂) crystal
  - exclusively Cherenkov light produced (prompt)
  - excellent properties for stopping 511 keV annihilation γ
  - excellent light transmission (down to 250 nm)
  - low cost
  - low light yield - single photon detection
Previous results (MCP PMT)

- Two detectors in back-to-back configuration
- Cherenkov radiators
  - 25x25x5 or 25x25x15 mm$^3$ PbF$_2$
- Photodetectors
  - microchannel plate photomultiplier tubes (MCP PMTs)
  - single photon timing ~ 50 ps FWHM
  - active surface 22.5x22.5 mm$^2$

- TOF (coincidence) resolution:
  - 71 ps FWHM (5 mm thick, black painted PbF$_2$)
  - 95 ps FWHM (15 mm thick, black painted PbF$_2$)

- Low efficiency ~ 6% (single side)
  - traditional scintillation detectors ~ 30%

NIM A 654 (2011) 532
**Previous results (SiPM)**

- Two detectors in back-to-back configuration
- Cherenkov radiators: 5x5x15 mm$^3$ PbF$_2$
- Photodetectors: 3x3 mm$^2$ silicon photomultipliers
  - cooled to -25°C (SiPM dark counts)

**TOF (coincidence time) resolution:**
- 306 ps FWHM (AdvanSiD, black paint)

**Efficiency:**
- 30% single side (SensL-J, Teflon wrapped)

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![Graphs showing single side detection efficiency and coincidence timing](image-url)
Summary of previous results

- Excellent TOF PET timing achievable using exclusively Cherenkov light:
  - 95 ps FWHM coincidence timing with 15 mm thick PbF$_2$ (~ $\gamma$ stopping power of 20 mm of LSO)
  - Cherenkov considered for the goal of 10 ps TOF PET [P. Lecoq]
- Very few (single) photons
  - efficiency an issue
- Silicon photomultipliers
  - Cherenkov PET efficiency competitive to scintillators (~30% single side)
  - timing an issue (especially with configuration optimized for efficiency)
- Cost of PbF$_2$ ~ 20% of LSO (cost of scintillator ~ 50% of PET scanner)
  - lower cost PET scanners
  - total-body PET scanners [S. Cherry]
- Our next step
  - PET module, optimized of efficiency and price

[Cherry et al., The Journal Of Nuclear Medicine, Vol. 59, No. 1 (2018)]
[Lecoq et al., IEEE TRPMS, Vol. 1, No. 6 (2017)]
16 channel PET module

- **Cherenkov radiators**
  - 4x4 array of 3x3x15 mm$^3$ PbF$_2$
    
    [Shanghai SICCAS High Technology Corporation]
  - white reflector (black paint where noted)

- **Photodetectors**
  - 4x4 array of 3x3 mm$^2$ SiPM
  - Hamamatsu MPPC S13361-3075AS-04
    - 75 μm pixels (1600 / 3x3 mm$^2$)
    - peak sensitivity ~ 50% PDE @ 450 nm
    - breakdown voltage ~ 53 V
    - dark count ~ 0.5 Mcps (/ 3x3 mm$^2$), crosstalk prob. ~ 7%
      (overvoltage $V_{ov} = 3$ V)

- **Custom connector board**
- **3D printed crystal supports**
- **SiPM bias provided by readout module - EASIROC**
• **EASIROC chip [OMEGA group]**
  - Extended Analogue Silicon pm Integrated Read Out Chip
  - 32 channel ASIC dedicated to read-out of SiPM detectors
    - Internal input 8-bit DAC for individual SiPM gain adjustment
    - Individually addressable calibration injection capacitance
    - Energy measurement: 14-bit dynamic range
    - Trigger output

• **EASIROC module [Osaka, KEK]**
  - 2 x 16 channels per module
  - **SiPM bias supply**, adjustable by 4.5V for each channel
  - **ADC**, 12bit, dual range
  - **LVDS trigger** outputs (for external TDC)
  - possibility to perform TDC in FPGA (~1ns resolution)
  - Ethernet connection to PC
Efficiency of a Cherenkov based PET module with an array of SiPMs

Experimental setup

- Cherenkov detector:
  - 4x4 array of 3x3x15 mm³ PbF$_2$
  - 4x4 array of 3x3 mm$^2$ SiPM
- Reference detector
  - 3x3x30 mm$^3$ LYSO scintillator
  - 3x3 mm$^2$ SiPM
- Annihilation $\gamma$ source
  - $^{22}$Na point source (D = 0.3 mm)
  - activity = 0.6 MBq
- Temperature: -25°C (SiPM dark counts)

* ch.0 next to ground - more noisy; ch.15 TDC not connected
Laser calibration

- Laser illumination instead of reference scintillation detector
  - ~1 mm laser spot scanned over each SiPM array channel center (w/o PbF$_2$ crystals)
  - gain ~ (ADC 1 p.e. peak) - (ADC noise peak)
  - adjusted for each channel
Detection efficiency estimation

- Geometrical collimation of coincidences - reference detector further away from the source

- When the reference scintillation detector is hit with one 511 keV \( \gamma \), the other annihilation \( \gamma \) hits the Cherenkov detector
  - reference detector hit: event cut within \( \pm 1\sigma \) of 511 keV photopeak
    - corrected for estimated 1275 keV \( \gamma \) (\(^{22}\text{Na}\)) Compton contribution
  - Cherenkov detector hit: TDC within 30 ns
    - corrected for noise, estimated from constant fit in off-time window

\[
\text{Efficiency} = \frac{N_{TDC/PP} - N_{\text{noise}}}{N_{\text{photopeak}} - N_{1275\text{keV}}}
\]
Results: source position on channel / off channel

Channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>ADC CH.1 POS.14</th>
<th>ADC CH.1 POS.2</th>
</tr>
</thead>
</table>
| 13 | 14 | 12 | 12 | 15 | 0 | 3 | 11 | 8 | 7 | 4 | 10 | 9 | 6 | 5
| 0 | 1 | 2 | 3 | 14 | 15 | 8 | 9 | 10 | 11 | 4 | 5 | 6 | 7 |

Position

<table>
<thead>
<tr>
<th>Position</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

Cherenkov detector (when reference within ±1σ) ADC

TDC CH.1 POS.14

white reflector; T = -25°C; V_{ref} = 5 V

Reference detector charge

ADC Ref. POS.14

ADC Ref. POS.2

Efficiency of a Cherenkov based PET module with an array of SiPMs
Results: efficiency map

- Efficiency of each channel when collimated with the source
  - average = 28.4% (previous single ch. result ~ 25% - 30%)

* ch.0 next to ground - more noisy; ch.15 TDC not connected
Results: cross talk

- Efficiency of channel 7, for all 16 source positions
  - nearest neighbors average 26% crosstalk
  - diagonal neighbors average 7% crosstalk

- Sources of crosstalk:
  - miss-collimation
  - optical leakage between channels
  - Compton scattering

Efficiency of a Cherenkov based PET module with an array of SiPMs
Results: cross talk - miss-collimation

- When reference detector moved further away
  - nearest neighbors average 22% crosstalk
  - diagonal neighbors average 5% crosstalk

Channel:

<table>
<thead>
<tr>
<th>13</th>
<th>14</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>15</td>
<td>0</td>
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</tr>
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<td>11</td>
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</tr>
<tr>
<td>10</td>
<td>9</td>
<td>6</td>
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</tbody>
</table>

Position:

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<thead>
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<th>12</th>
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<th>14</th>
<th>15</th>
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<tbody>
<tr>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Efficiency of a Cherenkov based PET module with an array of SiPMs
Results: cross talk - optical leakage between channels

- **Crystal array black painted** instead of white reflector
  - nearest neighbors average 11% crosstalk
  - diagonal neighbors average 0% crosstalk

![Graph showing efficiency of a Cherenkov based PET module with an array of SiPMs](image)
Results: efficiency map for black painted array

- Efficiency of each channel when collimated with the source
  - average = 6.9% (previous single ch. result ~ 5% - 8%)
  - much less homogeneous results
    - lower quality of crystal array assembly

![Efficiency Map](image)

```
<table>
<thead>
<tr>
<th>Channel</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4</td>
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<td>9</td>
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<tr>
<td>Position</td>
<td>12</td>
<td>13</td>
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<td>15</td>
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<tr>
<td>11</td>
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<td>8</td>
<td>7</td>
<td>4</td>
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<tr>
<td>10</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
```

black paint; $T = -25^\circ C$; $V_{ov} = 5 V$
Results: cross talk

- Source scanned over one column of SiPM array

<table>
<thead>
<tr>
<th>Channel</th>
<th>1D scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>13, 14</td>
<td>1, 2</td>
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<td>12, 15</td>
<td>0, 3</td>
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<tr>
<td>11, 8, 7</td>
<td>4, 4</td>
</tr>
<tr>
<td>10, 9, 6</td>
<td>5, 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Efficiency</th>
<th>Cross section 3x3 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH.6</td>
<td>69%</td>
<td>13%</td>
</tr>
<tr>
<td>CH.7</td>
<td>56%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Reference detector crossection 3x3 mm²

CH.6 fraction of events: 13% 59% 24% 4.4% 0.8%
CH.7 fraction of events: 2% 19% 56% 18% 4%
**Results: cross talk**

- Source scanned over one column of SiPM array - black painted array

```
<table>
<thead>
<tr>
<th>Channel</th>
<th>13</th>
<th>14</th>
<th>12</th>
<th>15</th>
<th>0</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH.6</td>
<td>15%</td>
<td>76%</td>
<td>9%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH.7</td>
<td>2%</td>
<td>12%</td>
<td>71%</td>
<td>13%</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>
```

**Note:**
- Most crosstalk due to optical leakage.
Results: efficiency vs. SiPM overvoltage

- Average efficiency over all (15 connected) channels
Summary

- Use of Cherenkov light in PET
  - TOF resolution <100 ps FWHM (limited efficiency)
  - efficiency 30% single side (limited TOF resolution)

- Low cost of PbF$_2$
  - reduce cost PET of scanners (limited TOF, but still competitive performance)
  - total-body PET scanners

- 16 channel PET module
  - 4x4 array of 3x3 mm$^2$
    - PbF$_2$ Cherenkov radiator + SiPM photodetector
  - efficiency 28% single side
  - good uniformity
  - optical crosstalk between channels should be reduced

- Next steps
  - 2-4 modules in coincidence
  - study effects of Compton events