Towards Reconstructionless 3D Imaging of Positron-Emitting Radiotracers using Cerenkov Radiation
Disclosures

Research Agreements
Canon Medical Research Unit
United Imaging Healthcare

UC Davis has a revenue sharing agreement with
United Imaging Healthcare
State-of-the-Art PET/CT

- 3-4 mm spatial resolution
- Detection sensitivity 5-10%
- Timing resolution: 200-500 ps
• Speed of light is
  – $3 \times 10^8$ m/s
  – 30 cm/ns

• Current state of the art is
  ~250 psecs - localizes signal to ~3.75 cm

• 20 psecs timing would localize event to 3 mm

\[ \text{noise reduction } \sim \sqrt{\frac{2P}{c \Delta t}} \]
Current work with Scintillators

Monolithic LYSO, double-sided dSiPM

L(Y)SO pixels, FBK NUV SiPM

Scintillation is a (relatively) slow process

Courtesy Dennis Schaart (TU Delft)

Courtesy Paul Lecoq (CERN)
Cerenkov Radiation in Scintillators

511 keV Gamma ray

Scintillator

10^{-16} sec

Energetic electron

10^{-9} sec

Scintillation photons

Cerenkov photons

Photodetector (PMT or SiPM)
Using Cerenkov Radiation for Time-of-Flight PET

Needs:

- Dense materials with high index of refraction and high transparency in blue/UV
- Photodetectors with high blue/UV sensitivity and low noise

\[
\frac{dN}{dx} \propto \left(1 - \left(\frac{c}{n \times v}\right)^2\right) \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2}
\]

## Scintillators

<table>
<thead>
<tr>
<th>Property</th>
<th>NaI(Tl)</th>
<th>BGO</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
<th>CsI(Tl)</th>
<th>LuAP(Ce)</th>
<th>LaBr$_3$(Ce)</th>
<th>Plastic*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
<td>7.13</td>
<td>7.40</td>
<td>6.71</td>
<td>4.51</td>
<td>8.34</td>
<td>5.3</td>
<td>1.03</td>
</tr>
<tr>
<td>Effective atomic number</td>
<td>50</td>
<td>73</td>
<td>66</td>
<td>59</td>
<td>54</td>
<td>65</td>
<td>46</td>
<td>12</td>
</tr>
<tr>
<td>Decay time (nsec)</td>
<td>230</td>
<td>300</td>
<td>40</td>
<td>60</td>
<td>1000</td>
<td>18</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Photon yield (per keV)</td>
<td>38</td>
<td>8</td>
<td>20-30</td>
<td>12-15</td>
<td>52</td>
<td>12</td>
<td>61</td>
<td>10</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.85</td>
<td></td>
<td>1.82</td>
<td>1.85</td>
<td>1.80</td>
<td>1.97</td>
<td>1.9</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>2.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Slightly</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Peak emission (nm)</td>
<td>415</td>
<td>480</td>
<td>420</td>
<td>430</td>
<td>540</td>
<td>365</td>
<td>358</td>
<td>Various</td>
</tr>
</tbody>
</table>
ToF PET with Bismuth Germanate?

\[
\frac{dN}{dx} \propto \left( 1 - \left( \frac{c}{n \times v} \right)^2 \right) \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2}
\]

For BGO, \( n = 2.15 \)
Generation of Cerenkov Photons in BGO

(a) 3D representation of electron and Cerenkov photons in BGO crystal with dimensions 3 x 3 x 20 mm$^3$.

(b) Graph showing the count of photons for different energy levels:
- Total
- PE
- Compton-Captured
- Compton-Escaped

Y-axis represents energy levels (0K, 33K, 17K, 0K) and the x-axis represents the number of produced Cerenkov photons per event.
Time of Flight PET with BGO

Microchannel Plate Photomultipliers

Single photon time resolution (SPTR) is critical for very fast timing

<table>
<thead>
<tr>
<th>Photosensor</th>
<th>SPTR (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (R9800)</td>
<td>270</td>
</tr>
<tr>
<td>FBK NUV-HD SiPM</td>
<td>91</td>
</tr>
<tr>
<td>MCP-PMT (R3809)</td>
<td>25</td>
</tr>
</tbody>
</table>

BGO coupled to MCP-PMT

FWHM 2066 ps
Dual-Ended Readout

FWHM = 66 ps

FWTM 394 ps
MCP-PMTs with Integrated Cerenkov Radiator

Ota et al, Phys Med Biol 2019; 07LT01
MCP-PMTs with Integrated Cerenkov Radiator

In collaboration with Ryosuke Ota and Tomohide Omura

Cerenkov radiator (lead glass) Photocathode

CRI MCP-PMT

Photocathode

SiPM

Cerenkov radiator (lead glass) Photocathode

CRI MCP-PMT

Count (a.u.)

46 ps FWHM

Count (a.u.)

28 ps FWHM
Acknowledgements

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R35 CA197608
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R01 EB029633