monolithic absorber detector performance:
- spatial resolution: k-NN algorithm vs. Convolutional Neural Network
- influence of multi-hit interactions
alternative component studies: CeBr$_3$ compared to LaBr$_3$(Ce)
SiPM compared to MA-PMT
pixelated GAGG scatter array
optical alignment system
- exploit kinematics of Compton scattering for medical imaging:

\( \gamma \) tracking:

\[ E_s = \frac{E_i}{1 + \frac{E_i}{m_0c^2}(1 - \cos \theta)} \]

Idea already in 1974:
Todd, Nightingale, Everett:
(Nature 251, 132-134):
“A proposed gamma camera”

\( \gamma \) + electron tracking:
**LMU Munich**

**Compton Camera Prototype**

- **Garching Compton camera layout:**
  - Scatterer/Tracker Array: (double-sided)
  - Si-strip detector (DSSSD)

  **Absorber:**
  - Scintillator crystal (LaBr$_3$:Ce + PMT, CeBr$_3$ + PMT)

  - **Scattered $\gamma$**
  - **Prompt $\gamma$**
  - **Compton $e^-$**

  **6x DSSSD**
  - active area 50 x 50 mm$^2$
  - thickness: 500 $\mu$m
  - 128 strips on each side
  - pitch size 390 $\mu$m

  - **50 x 50 x 30 mm$^3$**
  - 64/256-seg. MA-PMT (Hamamatsu)

  - **$E_\gamma$: 0.5 - 6 MeV**

---

P.G. Thirolf et al., EPJ Web of Conf. 117, 05005 (2016)


P.G. Thirolf, LMU Munich
Experimental setup for collimated source scan

- spatial resolution: based on 2D detector response
- collimated $\gamma$ source (Ø 1 mm): $^{137}\text{Cs}$ (662 keV, 72 MBq)
  $^{60}\text{Co}$ (1.17/1.33 MeV, 20 MBq)

→ 2D scan of LaBr$_3$ (mounted on translational stage)
2D Light Amplitude Distributions

2D light amplitude reference library

- 1 mm collimation
- 0.5 mm step size (x,y)
- $10^4$ irradiation position
- 400 – 800 photopeak events/position

$^{60}\text{Co} (1.3 \text{ MeV})$
here: 3 mm step size in (x,y)

Interaction position reconstruction:
Conventional method: k-nearest neighbour (kNN) algorithm
variant: Categorical Averaged Pattern (CAP)
Machine learning approach: Convolutional Neural Network (CNN)

8x8 ch. light distribution, single event
Convolutional Neural Network Architecture

Much better explanations in Poster Session by Maria Kawula

M. Kawula, MSc thesis, LMU 2019 (in preparation)
spatial resolution reached physical limit for CeBr₃ @ 60Co energies:

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>Spatial resol. CAP [mm]</th>
<th>Spatial resol. Neural Netw. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr₃</td>
<td>CeBr₃</td>
<td>LaBr₃</td>
</tr>
<tr>
<td>0.662</td>
<td>3.4(1)</td>
<td>2.7(1)</td>
</tr>
<tr>
<td>1.17</td>
<td>2.9(1)</td>
<td>2.6(1)</td>
</tr>
<tr>
<td>1.33</td>
<td>2.9(1)</td>
<td>2.6(1)</td>
</tr>
</tbody>
</table>

- CNN outperforms k-NN algorithm (CAP version)
- CNN allows for drastic reduction of computational costs (prerequisite for in-vivo application)
- sub-1.5 mm resolution reached in large monolithic crystals

→ Still open: behaviour at higher photon energies?

M. Kawula, MSc Thesis LMU 2019 (in preparation)
Ongoing Studies

- **Can spatial resolution < 1 mm be reached?**
  - use of 0.6 mm collimator:
    - not feasible with LaBr$_3$:Ce
      (SNR reduction due to internal activity)
    - but: promising results with CeBr$_3$

- **Can DOI information be retrieved via Neural Network reconstruction?**
  - extend collimated crystal scan from 2D to 3D:
    - sample light amplitude distributions from 2 opposite side surfaces
  - libraries have been acquired, analysis is in progress
How do double-hit interactions affect the interaction position reconstruction?

- \( \gamma + \gamma (^{137}\text{Cs}, ^{60}\text{Co}) \) & \( \gamma + e \ (^{204}\text{Tl}: E_e = 764 \text{ keV}) \)

- direct combined irradiations will not provide sufficient coincidence rate
- combinatoric summation of \( \gamma-\gamma \) and \( \gamma-e \) events from individual collimated irradiations
- \( \text{CeBr}_3 \) crystal used (+ H12700 64-ch. PMT)
**Multi-Hit Interactions in Absorber Crystal**

- **Example: Photon + Photon (^{137}Cs, ^{60}Co):**

  - ^{60}Co at r = 0
  - ^{137}Cs at r = 10 mm
  - ^{60}Co + ^{137}Cs

- **Results:**

  - ^{60}Co
  - ^{137}Cs
  - CAP
  - CNN

  - ^{60}Co + ^{137}Cs
  - ^{60}Co + ^{60}Co
  - ^{60}Co + ^{204}Tl

G. Vinci, MSc Thesis LMU 2019
Comparative Scintillator SIPM Readout Studies

Study any combination of:

**Detector:** LaBr$_3$:Ce CeBr$_3$

**Photosensor:**
- KETEK SiPM array:
  - 8x8 ch., 3x3 mm$^2$, cell size 15/25/50 $\mu$m
- Hamamatsu SiPM array:
  - 8x8 ch., 3x3 mm$^2$, cell size 50 $\mu$m
- Hamamatsu MA-PMT:
  - 8x8 ch., H8500, H12700

**Readout/signal processing electronics:**
- PETsys (ASIC based)
- Mesytec (individual components)

SIPM-based Scintillator Readout

- **Energy resolution:**

  **LaBr$_3$:Ce** (50x50x30 mm$^3$) crystal coupled to:
  - 256-fold PMT (Hamamatsu H9500)
  - 64-fold PMT (Hamamatsu H8500)
  - 64-fold PMT (Hamamatsu H12700)

- 256 ch. SiPM array:
  4 x KETEK PA3325WB-0808 (cell: 25 μm)

- 64 ch. SiPM array
  KETEK PA3325WB-0808/PA3350WB-0808 (25/50 μm)

  **CeBr$_3$:** coupled to a 64-fold PMT (H12700) and 256 ch. SiPM array
  (4 x KETEK PA3325WB-0808)

- Low light amplitude levels per channel deteriorate the energy resolution
- SiPM with high gain/ PDE and large active areas, provides comparable energy resolution as PMT (H12700 in red)

<table>
<thead>
<tr>
<th>Energy resolution (@ 662 keV):</th>
<th>PMT</th>
<th>SiPM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.4%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

Much more information in **Poster Session by Tim Binder**


MediNet Final Meeting Wiener Neustadt, Austria 7-9.10.2019
Optical Alignment System

- alignment of absorber relative to scatter component:
  - motorized (x,y,z) translation stages
  - laser diode attached to scatter detector frame
  - photosensor: SiPM pixel (final: 0.5x0.5 mm$^2$, tests with 3x3 mm$^2$) attached to absorber detector frame
  - control/readout via Arduino micro-processor

→ allows for relative alignment to ≤ 0.5 mm
→ allows for variation of distance between scatterer and absorber
Pixelated (GAGG) Scintillation Scatterer

16x16: 1.45 x 1.45 x 6 mm³  25.8 mm, 8x8 ch., 3x3 mm²

GAGG crystals

RTV sheet

MPPC

collaboration with QST-NIRS (Chiba/Japan)

60Co, reconstruction with MEGAlib:

- 2 mm (x,y) shift → resolved in all geometrical configurations
- σₓ, σᵧ: simulation: < 3 mm, experiment: < 6 mm

Summary

- **Spatial resolution:**
  - drastic improvement (resolution & computational) by neural network
  - further improvement possible (0.6 mm collimation) ?
  - 3D extension for DOI ?
  - influence of double hits ($\gamma+\gamma$, $\gamma+e$): g-g has the larger impact

- **Study alternative components:**
  - SiPM readout vs PMT readout
    - cross-comparison of crystals, photosensors, signal processing
  - CeBr$_3$ vs LaBr$_3$:Ce
  - pixelated GAGG scatter array

- **Technical progress:**
  - optical alignment system
Thanks to …

- **TU Munich:** L. Maier, M. Böhmer, R. Gernhäuser
- **OncoRay/ HZDR, Dresden:** G. Pausch, K. Römer, J. Petzoldt, F. Fiedler, T. Werner
- **QST-NIRS (Chiba/Japan):** S. Takyu, F. Nishikido, T. Yamaya
- **C&A corporation (Japan):** K. Kamada
- **TU Delft:** D.R. Schaart

Supported by DFG Cluster of Excellence MAP (Munich-Centre for Advanced Photonics) and the QST-NIRS International Open Laboratory

Thank you for your attention!