Poster M-08-113 (# 3467)

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Characterization of a Compton Camera setup with monolithic $LaBr_3$(Ce) absorber and segmented GAGG scatter detectors

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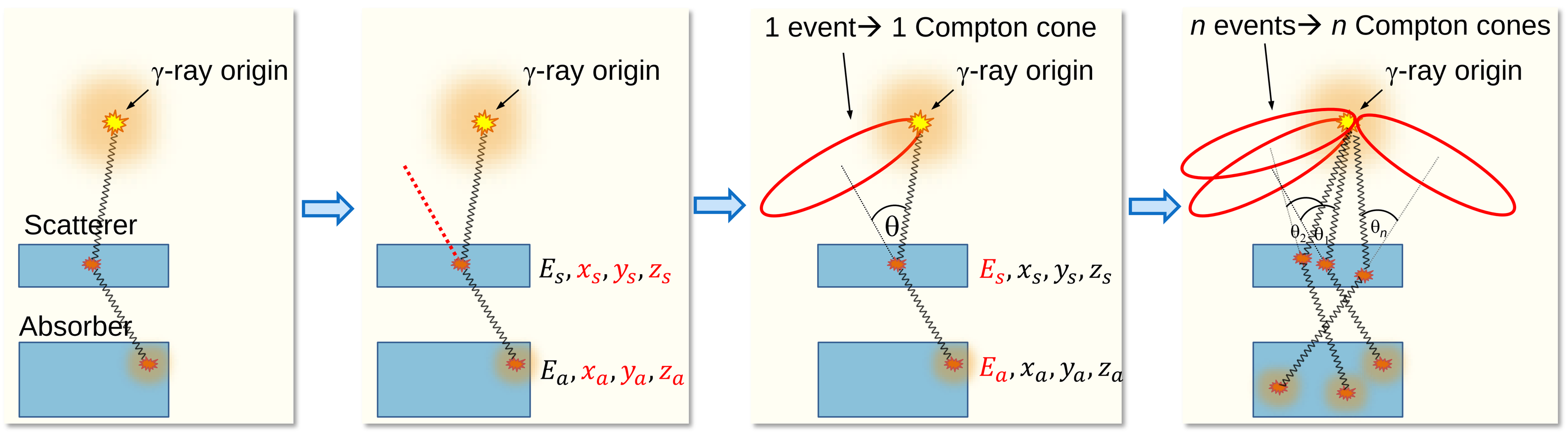
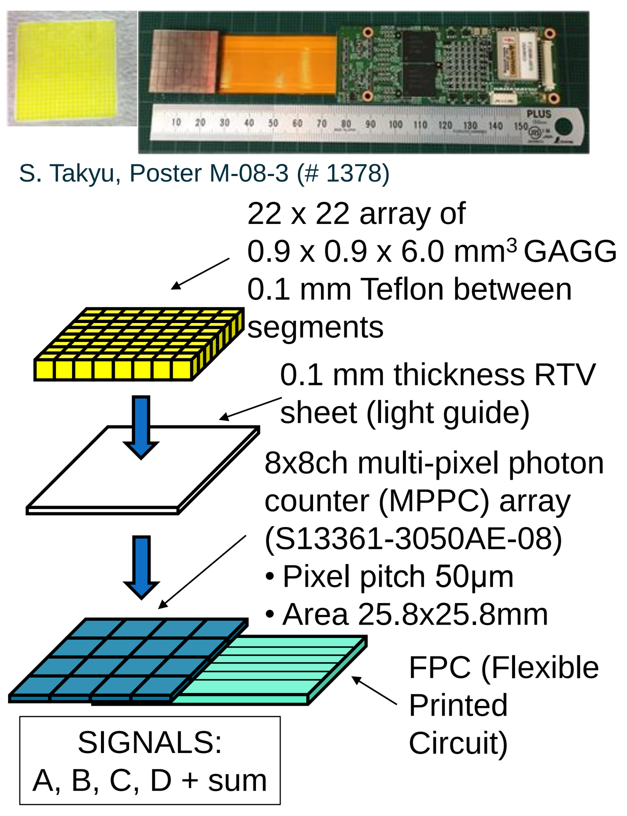
Purpose

- Particle beams offer accurate tumor targeting thanks to their rising dose distribution culminating in the **Bragg peak**.
- The accuracy is partially hampered by particle beam **range uncertainties**.
- The need for **(in-vivo) beam range verification** of particle beams via the localization of the Bragg peak is the key issue of particle therapy.
- A **Compton Camera** (CC) system can provide an in-vivo proton / ion beam range monitoring via detecting **secondary prompt-γ rays** (PG) emitted from nuclear reaction of the particle beam with biological samples [1] and correlated to the Bragg peak position.
- Exploiting **Compton kinematics**: $\cos\vartheta = 1 - m_e c^2\left[\frac{1}{E_a} - \frac{1}{E_s}\right]$, the **PG image** can be reconstructed (figure on the right).
- A proof of principle study is presented for a **Compton Camera system** composed of a scatterer component consisting of a **pixelated GAGG crystal** and an absorber consisting of a **monolithic $LaBr_3$(Ce) crystal**.



Materials and Methods

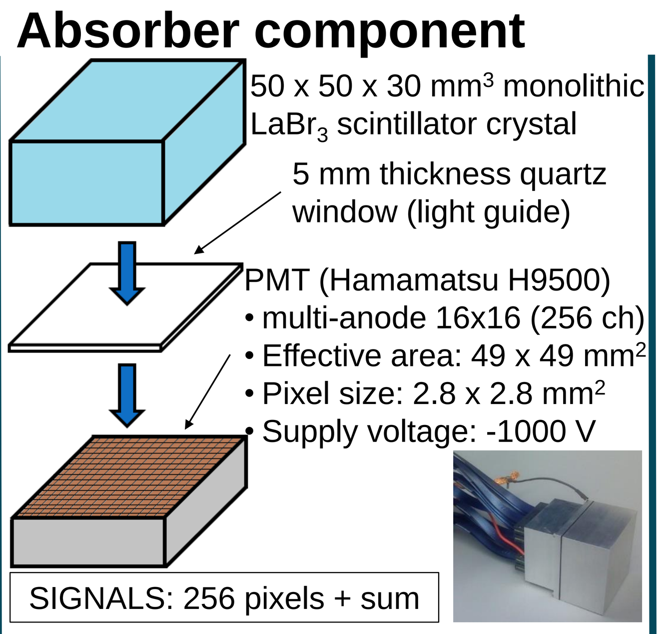
Scatterer component



Crystal specifications	GAGG
Decay time [ns]	92
Light output [photons / MeV]	~ 56000
Emission wavelength [nm]	520
Density [g / cm³]	6.63
Internal radioactivity	no

Detector specifications	GAGG
Energy resolution	6.3% @ 662 keV (from simulations)
Spatial resolution	1 mm
Spatial information	Anger-logic calculation

Absorber component

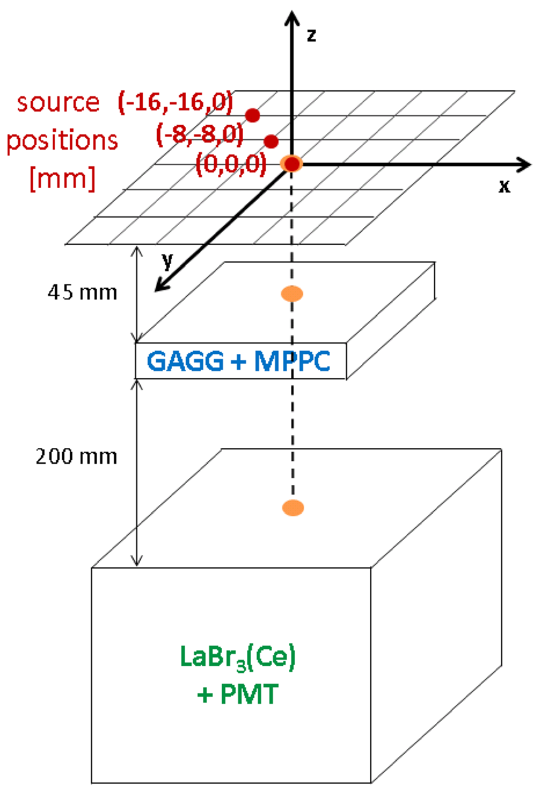


Crystal specifications	$LaBr_3$
Decay time [ns]	16
Light output [photons / MeV]	~ 63000
Emission wavelength [nm]	380
Density [g / cm³]	5.08
Internal radioactivity	yes

Detector specifications	$LaBr_3$
Energy resolution [3]	3.8% @ 662 keV (measured)
Spatial resolution [5]	4.4(1) mm
Spatial information	kNN / CAP algorithm [2]

Energy [MeV]	Categorical Average Pattern (CAP) [mm]	K-Nearest-Neighbours (kNN) [mm]
0.662	4.4(1)	4.7(1)
1.17	3.0(2)	3.1(2)
1.33	2.9(1)	2.9(1)

Compton Camera system



SOURCE
- Cs-137 source
- Calibration source (non collimated)
- $A_{(Jan2017)}$=233,6 kBq

READOUT SYSTEM
- Individual spectroscopy (NIM+VME) electronic, digitizing energy and time signals

IMAGE RECONSTRUCTION
- MEGAlib toolkit [6], based on the List-Mode Maximum-Likelihood Expectation-Maximization (LM-ML-EM) algorithm

- Signal processing and data acquisition
  - Acquisition via PPC RIO in VME crate – Marabou software [4].
  - Hardware trigger: sum signal of $LaBr_3$ (absorber).
  - CFD, QDC modules (MCFDs and MQDCs - Mesytec). Thresholds applied in CFD modules.
  - Corrections: gain matching, pedestal cut, PMT non-uniformity.
- Selection of data (Compton data)
  - Graphical cut applied on 2D energy plot (= coincidence events) → Extract the data contained in this energy window.
  - Creation of text files must contain (for both detectors):
    - Total energy deposited in each detector
    - x, y, z position coordinates (z = fixed to middle of crystal)
      - $LaBr_3$: kNN / CAP algorithm applied: An unknown photon event is compared to a light amplitude Reference Library [2]. In *Fig.1* an example of an event reconstructed using the CAP algorithm (an improved version of the kNN algorithm) is shown.
      - GAGG: Anger logic calculation (from 4 single signals):

$$X = \frac{-(A+C)+(B+D)}{A+B+C+D} \qquad Y = \frac{-(A+B)+(C+D)}{A+B+C+D}$$

  - Only physical angles to be selected:

$$\underbrace{\cos\theta = 1 - m_e c^2\left(\frac{1}{E_{abs}} - \frac{1}{E_{abs}+E_{scatt}}\right)}$$

$$\boxed{0 < m_e c^2\left(\frac{1}{E_{abs}} - \frac{1}{E_{abs}+E_{scatt}}\right) < 1}$$

→ Keep only physically meaningful Compton events

- MEGAlib requirements for reconstruction
  - energy$_s$, x_s, y_s, z_s (scatterer)
  - energy$_a$, x_a, y_a, z_a (absorber)

  for each event

- Image reconstruction and evaluation
  - Experimental data
  - Simulated data
    - Scatterer = pixelated detector
    - Absorber = Anger camera

  → Evaluation using 2D Gaussian fit of image

Results

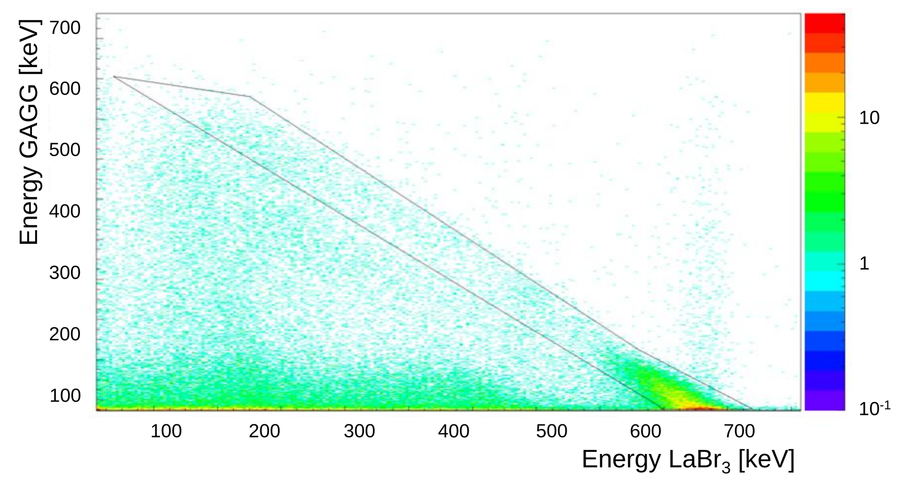


Fig.1 Example of a graphical cut applied on the 2D energy plot of the experimental data, acquired in 4 hours, for the (0,0) [mm] source position.

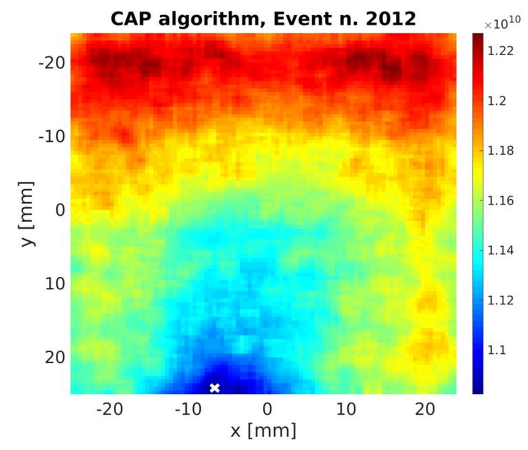
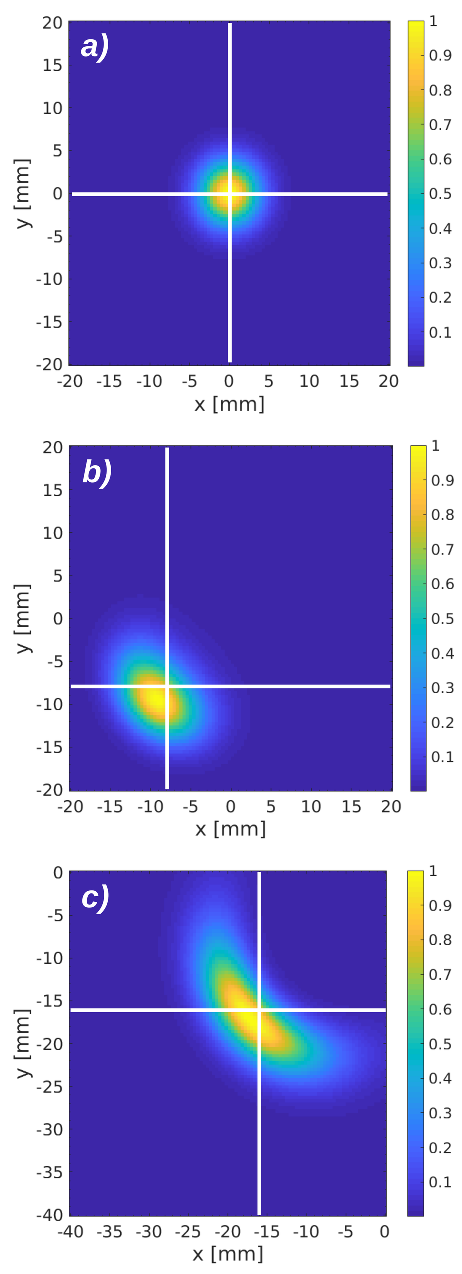


Fig.2 Example of position reconstruction using CAP algorithm for one event in the monolithic $LaBr_3$(Ce) scintillator. The white cross at the lower border indicates the calculated position of the photon source.

Source position reconstruction

Simulated data



a) 2D Gaussian fit

Parameter	Value
Δx	0,17 mm
Δy	0,20 mm
σ_x	2,6 mm
σ_y	3,7 mm
ARM	5,97°

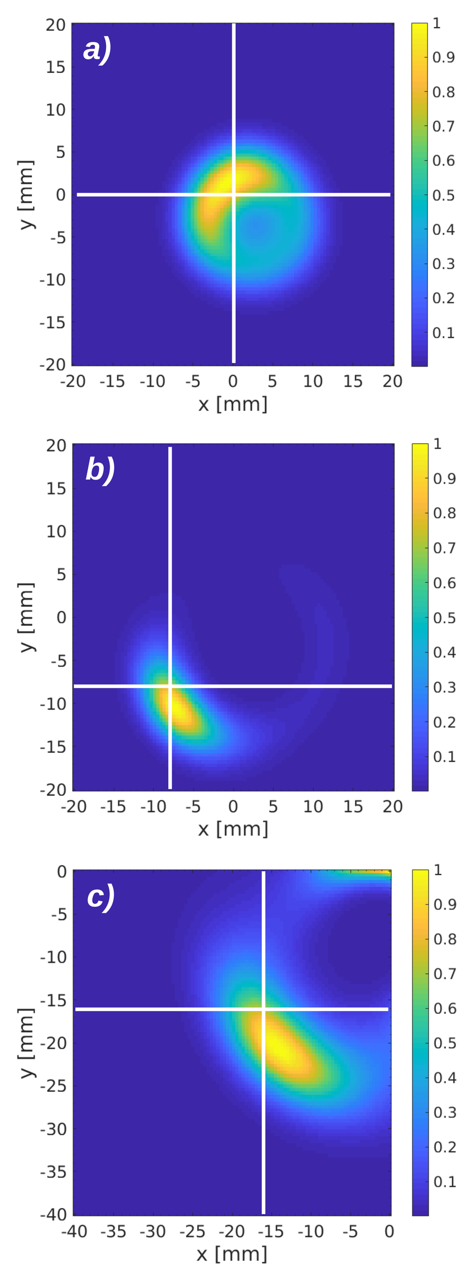
b) 2D Gaussian fit

Parameter	Value
Δx	-0,84 mm
Δy	-0,84 mm
σ_x	3,4 mm
σ_y	4,7 mm

c) 2D Gaussian fit

Parameter	Value
Δx	-0,70 mm
Δy	-0,52 mm
σ_x	6,9 mm
σ_y	3,9 mm

Experimental data



a) 2D Gaussian fit

Parameter	Value
Δx	-0,34 mm
Δy	0,76 mm
σ_x	4,8 mm
σ_y	7,2 mm
ARM	13,21°

b) 2D Gaussian fit

Parameter	Value
Δx	0,24 mm
Δy	-0,82 mm
σ_x	2,5 mm
σ_y	4,5 mm

c) 2D Gaussian fit

Parameter	Value
Δx	0,32 mm
Δy	-6,95 mm
σ_x	4,2 mm
σ_y	7,0 mm

Fig.3 Source image reconstruction for ***a)*** the (0,0) [mm] source position: from simulated data (left) and experimental data (right). ***b)*** the (-8,-8) [mm] source position: from simulated data (left) and experimental data (right). ***c)*** the (-16,-16) [mm] source position: from simulated data (left) and experimental data (right). For all the recostructed images around 15000 events were used and 20 iterations of the algorithm have been performed.

Conclusions and Outlook

- Successfully merged datastream from two different data acquisition chains.
- The photon interaction position in the monolithic $LaBr_3$(Ce) scintillator was determined with data analysis using the CAP algorithm.
- Spatial resolution for the monolithic $LaBr_3$(Ce) scintillator using the CAP algorithm is calculated to be 4.4(1) mm, with the perspective of an improvement at higher energies .
- Given the energies and positions information, the image reconstruction was performed using MEGAlib, a toolkit based on the MLEM algorithm. Around 15000 events were used for the reconstruction.
- Experimental data are in good agreement with simulations and the different source positions could be resolved.

Next steps
- Further measurements in different geometrical scenarios.
- Further measurements at higher photon energies.
- Comparison of GAGG - $LaBr_3$(Ce) Compton camera setup with alternative Compton Camera setup using pixelated absorber.

References :

[1] J. Krimmer et al.: Prompt-gamma monitoring in hadrontherapy: A review, *Nuclear Inst. And Methods in Physics Research, A*, 2017.
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Acknowledgment : This work is supported by the NIRS International Open Laboratory, the DFG Cluster of Excellence Munich Centre for Advanced Photonics (MAP), King Saud University (KSU).