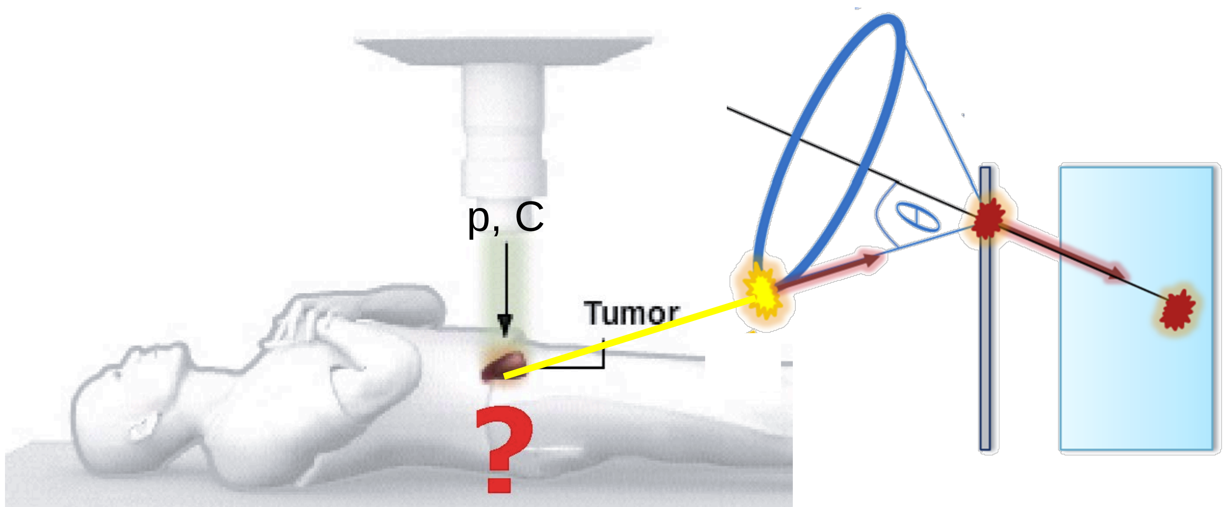
Development of a Compton Camera for Prompt Gamma Imaging

P.G. Thirolf, LMU Munich



- Motivation: need for accurate ion beam range verification
- Method: prompt-γ imaging via Compton scattering kinematics
  R&D on Compton camera (with electron tracking capability)
- Design, setup and characterization of prototype detector system

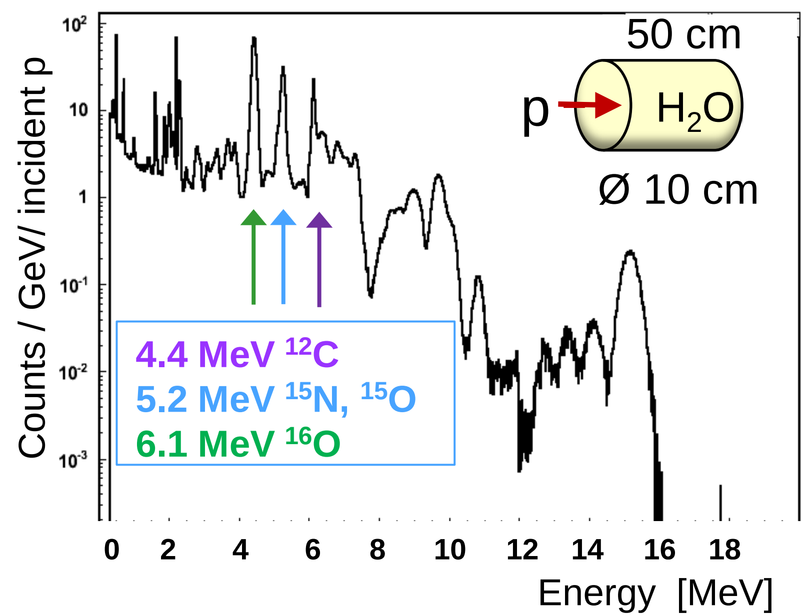
Prompt gamma emission from proton beam on biomedical sample

- key issue in hadron therapy:
  - localization of Bragg peak within patient/sample

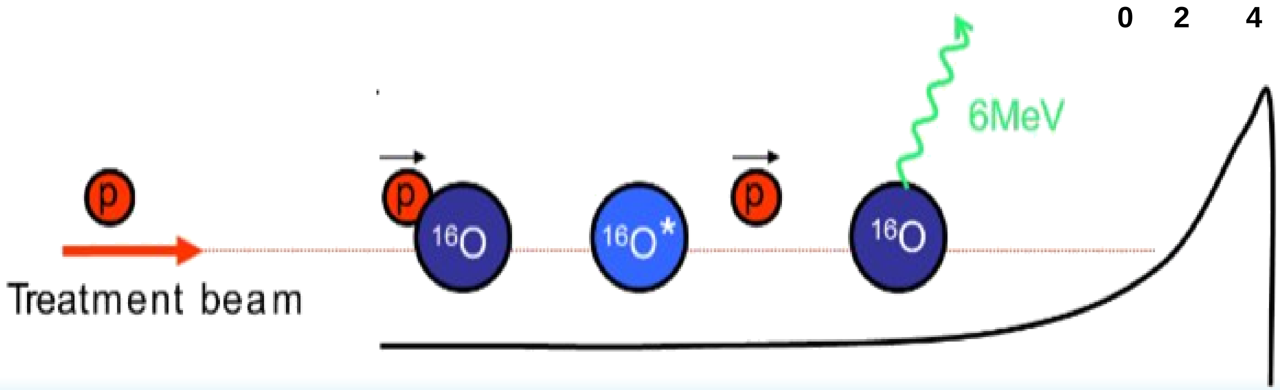
  → range verification of therapeutic proton (or ion) beam

- experimental approach:
  imaging via prompt γ emission from nuclear reactions

- irradiation of water phantom with 100 MeV protons:



(simulation)

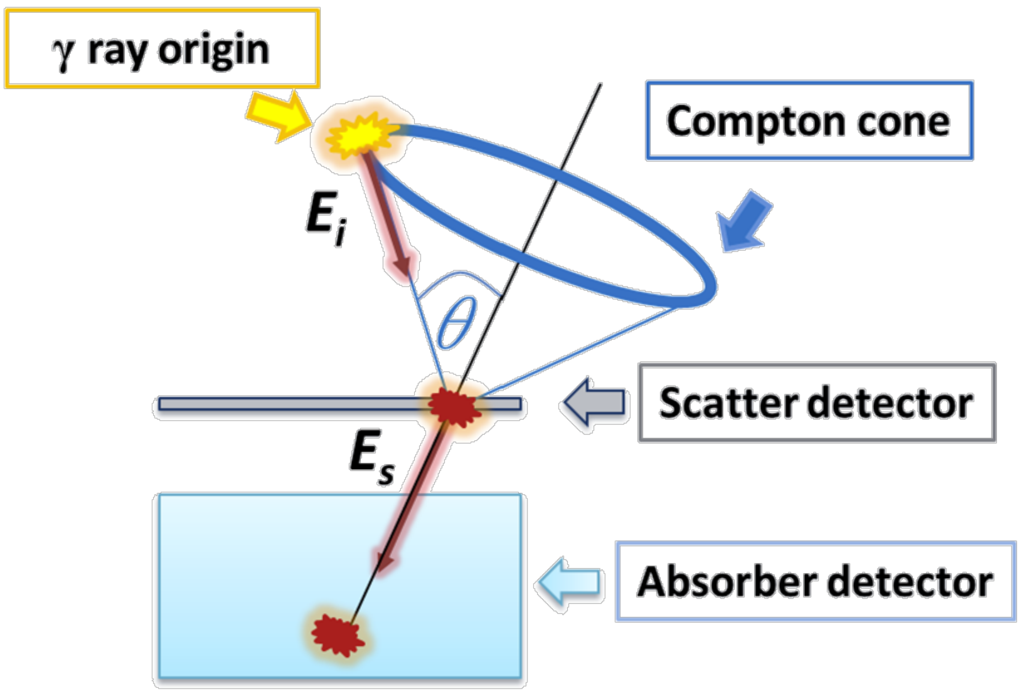


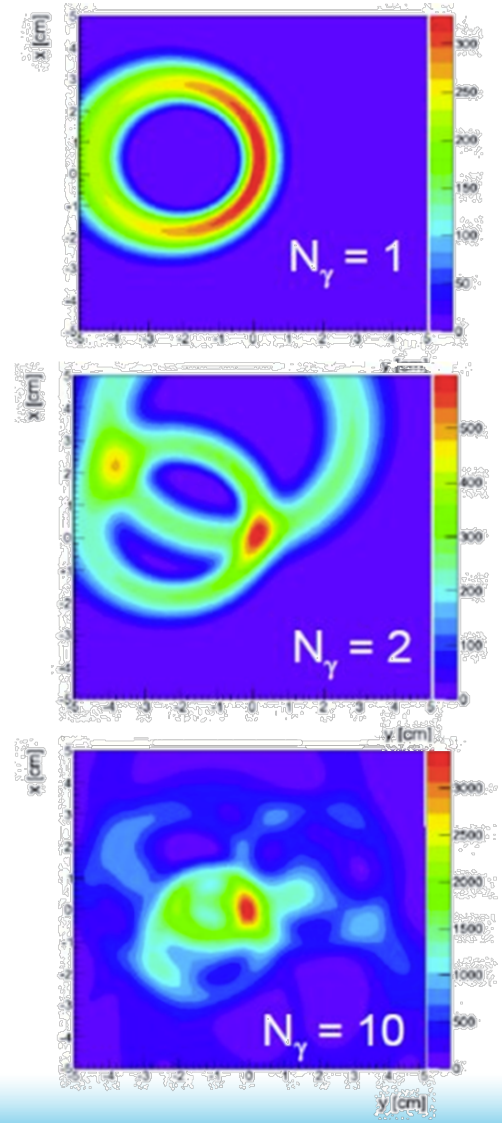
(Prompt) Gamma Imaging: Compton Camera

- exploit kinematics of Compton scattering:

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$

(i) γ tracking:





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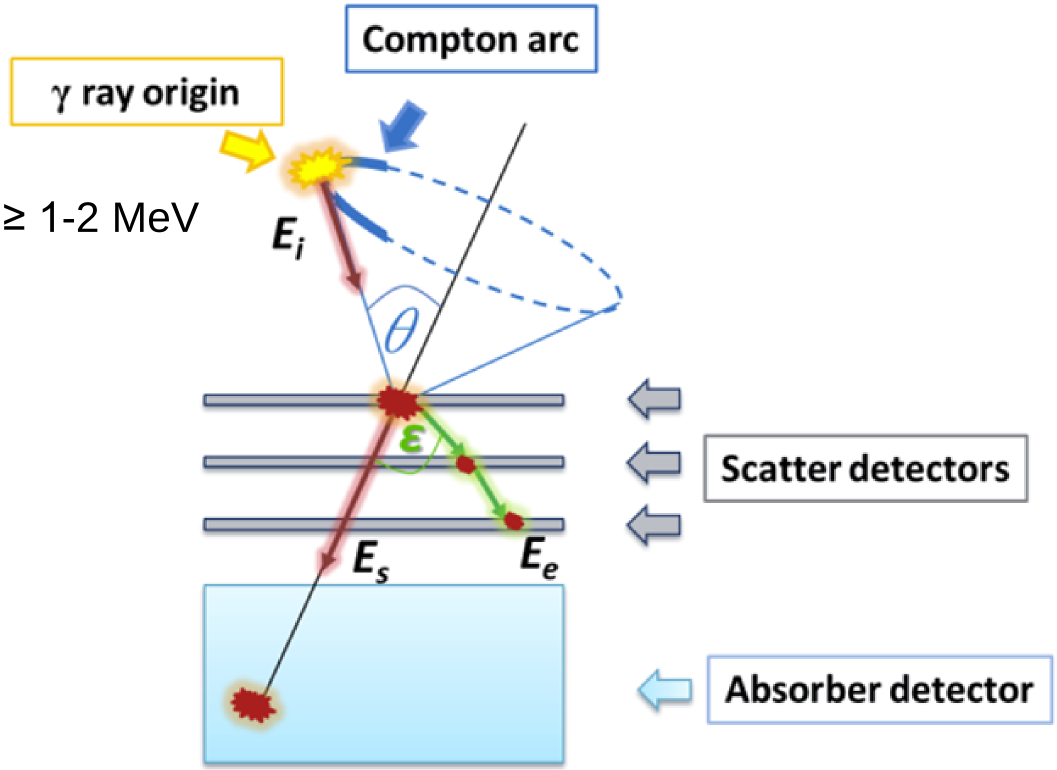
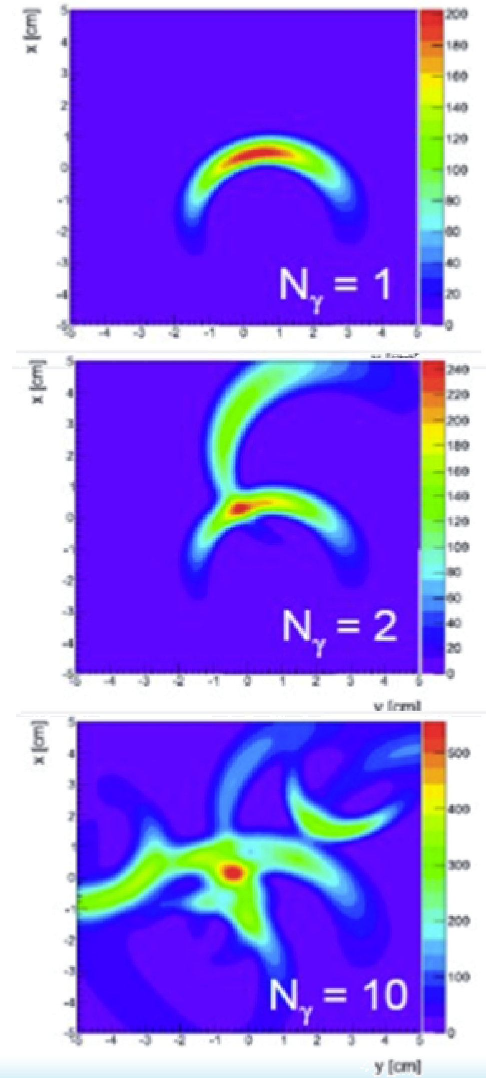
(Prompt) Gamma Imaging: Compton Camera

(ii) electron tracking:

$E_\gamma \geq$ 1-2 MeV





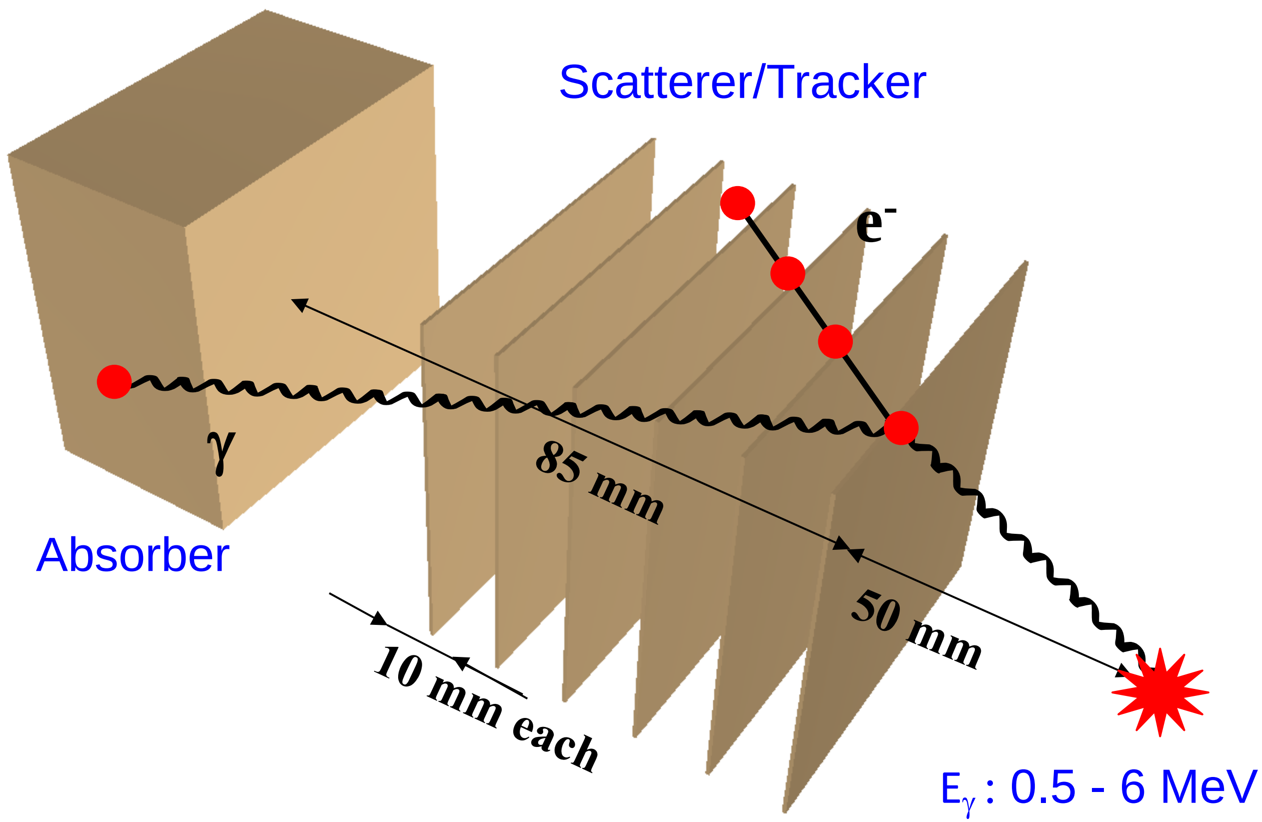
advantage:

- reconstruction of incompletely absorbed events

→ increased reconstruction efficiency

Garching Compton Camera Prototype

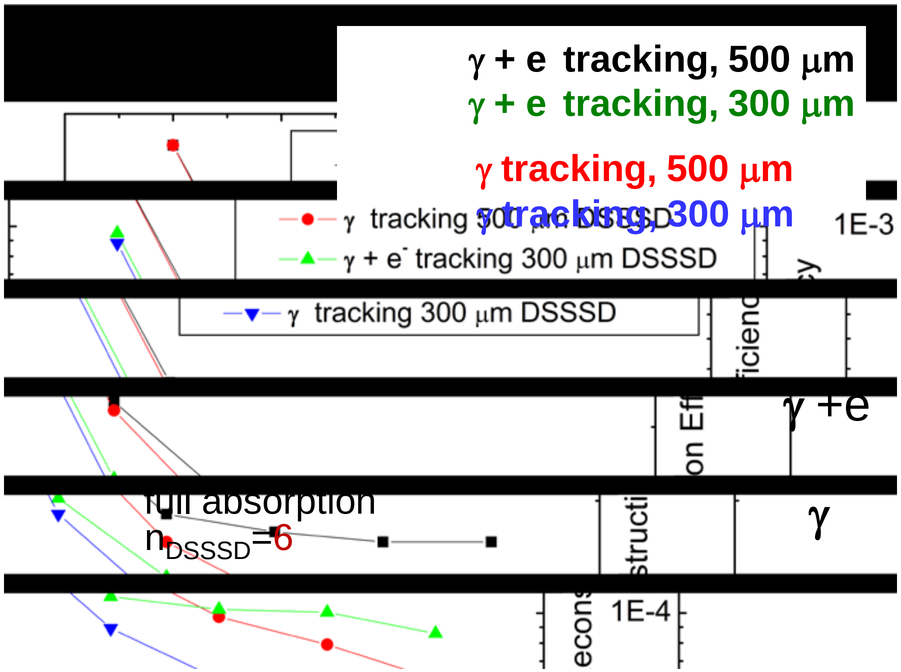
- Compton camera layout:

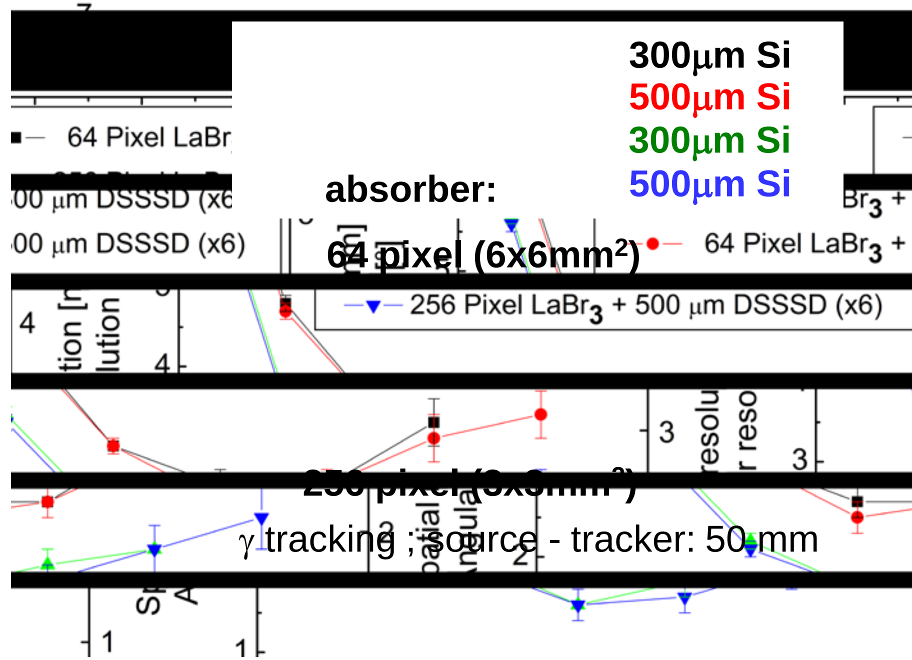


C. Lang et al., JINST 9 (2014) P01008, PhD thesis in preparation

Compton Camera Design Simulations

- simulations for tracker/absorber specifications and expected performance:





- $d=500\ \mu m$ + electron tracking:
  → improved efficiency

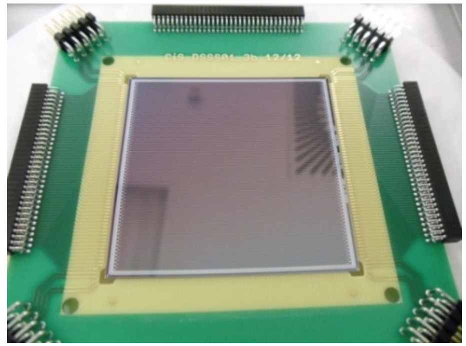
- $6x6\ mm^2$ → $3x3\ mm^2$ pixel:
- spatial resolution improves by ≥50 %

- $\varepsilon \approx 10^{-3} - 10^{-5}$ (@ 1- 5 MeV for optimum resolution)
- angular resolution ≈ $2^o - 2.5^o$ (@ 2-6 MeV)

Compton Camera Prototype: Scatter/Tracker Array

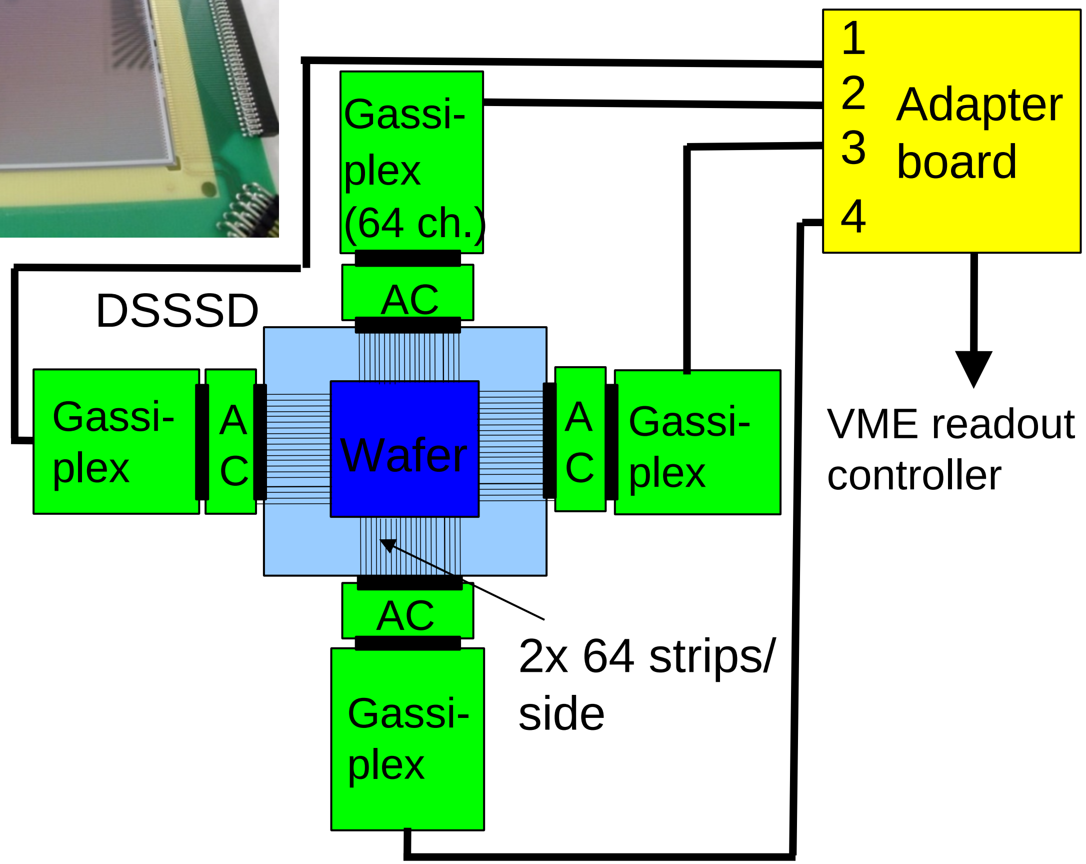
- Scatterer/Tracker Array:

6x double-sided silicon strip detectors (DSSSD)
→ active area 50 x 50 mm^2
→ thickness : 500 μm
→ 128 strips on each side
→ pitch size 390 μm



- DSSSD readout:

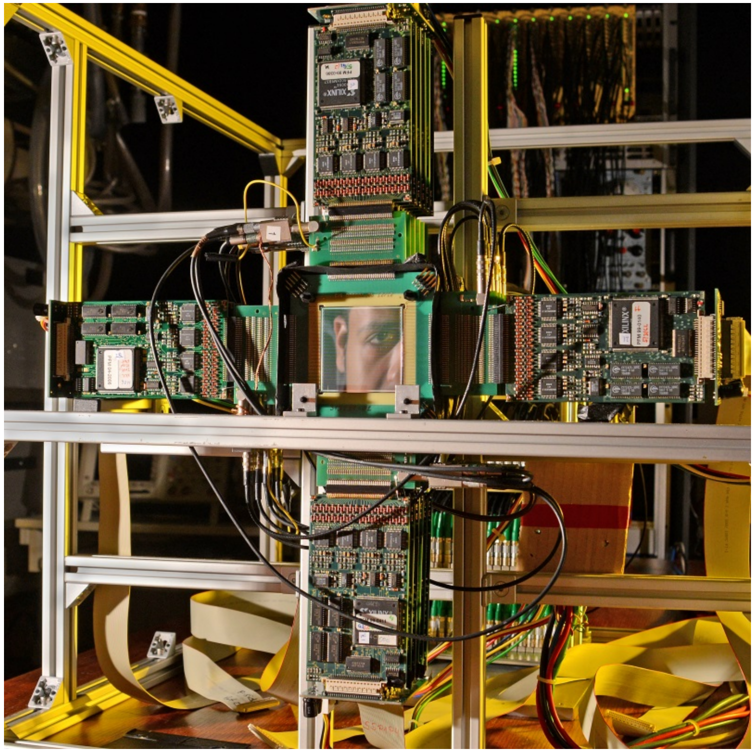
Gassiplex (4x16 ch. ASIC):
→ charge-sensitive preamplifier
→ shaper
→ digital discriminator
→ track & hold-stage
→ multiplexed ADC



→ replacement by modern ASIC desirable: wider dynamics, trigger, more flexibility (monitor)

S. Aldawood, PhD thesis, in preparation

Compton Camera Prototype: Scatter/Tracker Array



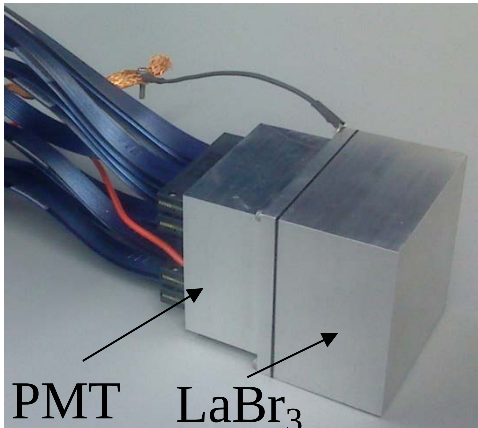
- light tight enclosure
- Faraday cage (+ ventilation, thermal control)

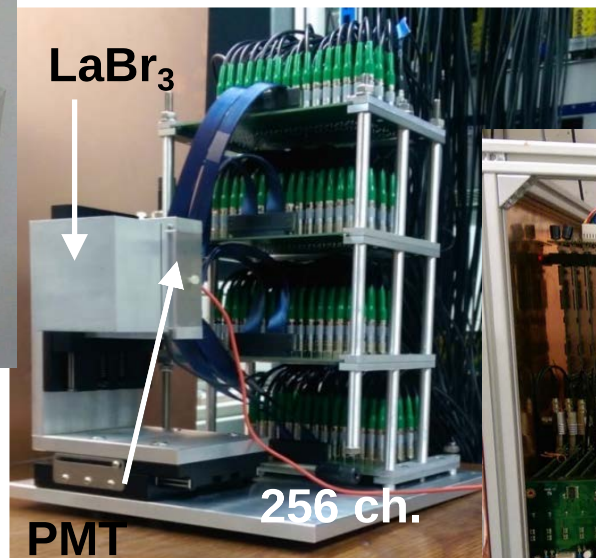
S. Aldawood, PhD thesis, in preparation

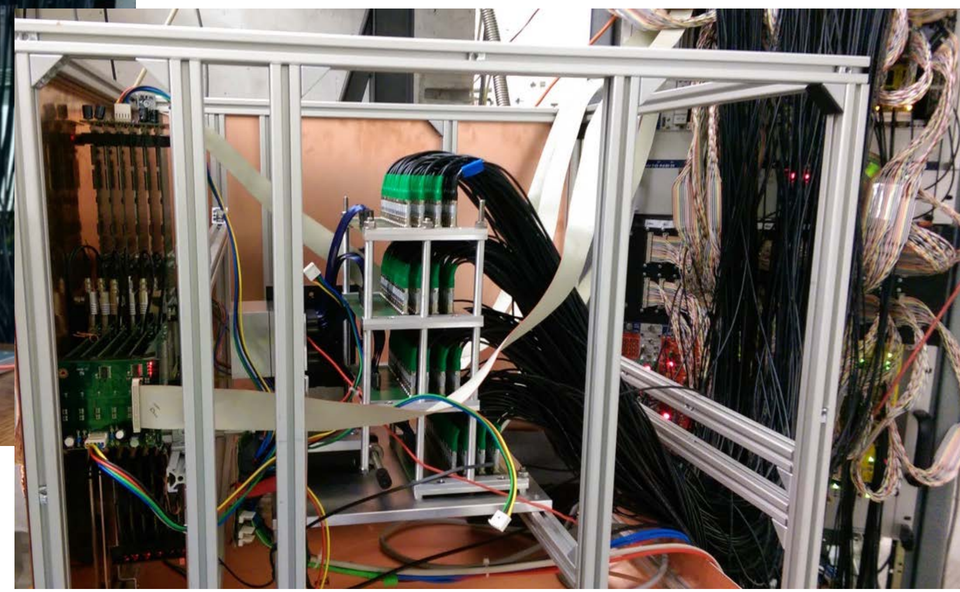
Compton Camera Prototype

- Absorber:

$LaBr_3$ crystal: 50 x 50 x 30 mm^3
PMT: Hamamatsu H9500 (multi-anode: 16x16):







- signal processing:

  - 256 pixel (3x3 mm^2)
  - individual spectroscopy electronics channels

→ fast amplifier + CFD (Mesytec MCFD-16, 16 ch.)
→ charge-sensitive digital converter (Mesytec, 32 ch. VME-QDC)

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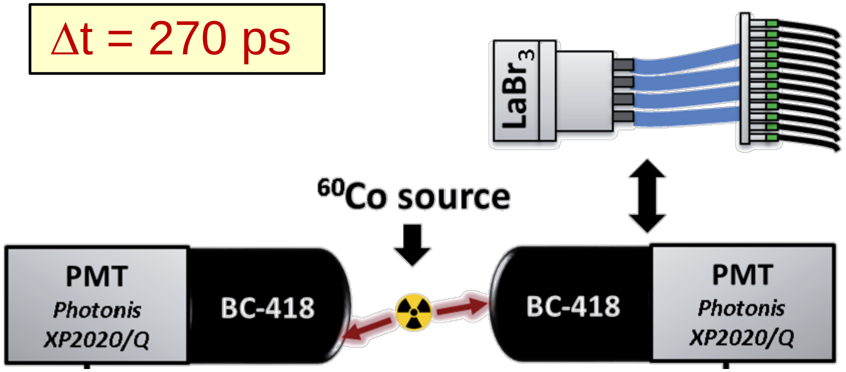
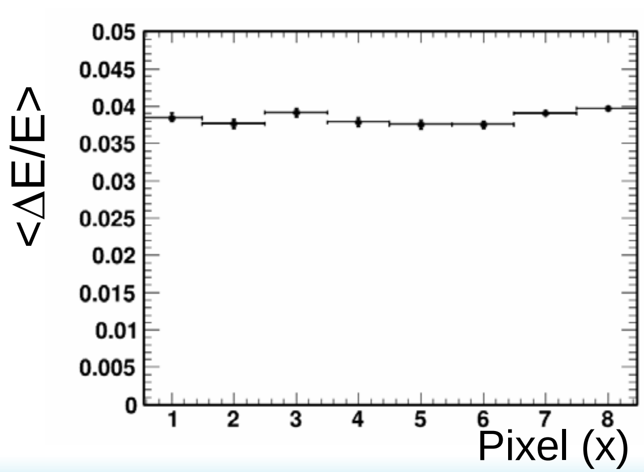
LaBr$_3$ detector properties: energy / time resolution

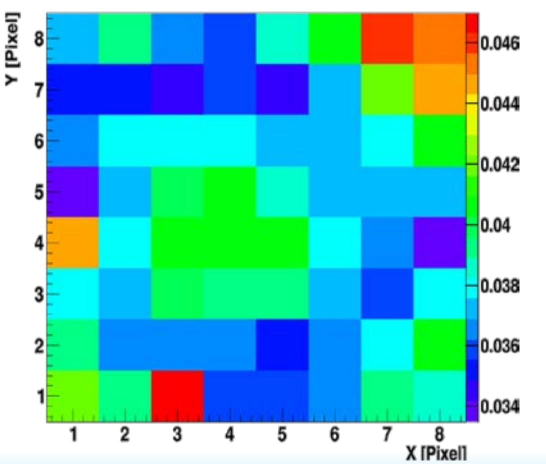
- time resolution: Δt = 270 ps

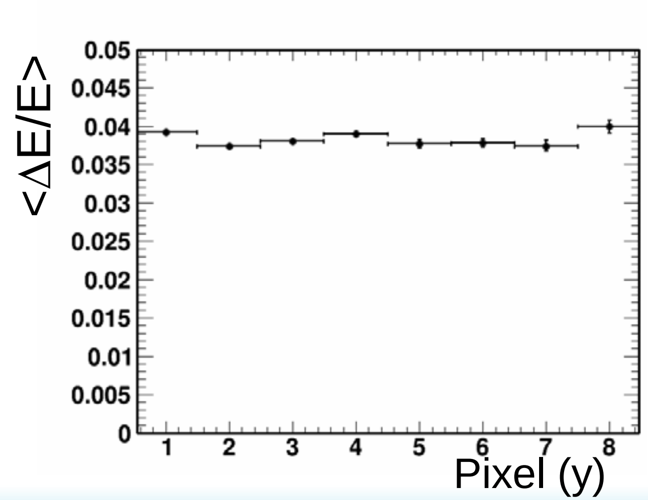


- energy resolution: $\langle \Delta E/E \rangle$ = 3.8% @ 662 keV (^{137}Cs)

H. v.d. Kolff, Master thesis, TU Delft/LMU (2014)

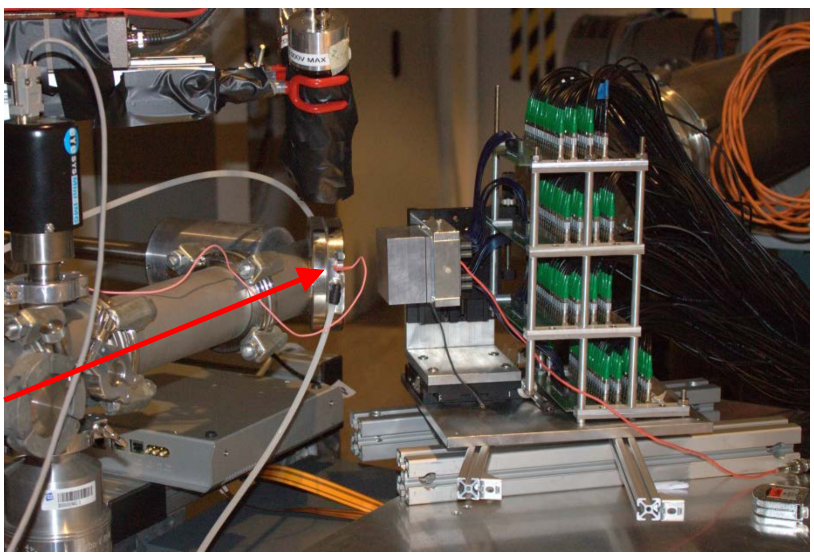




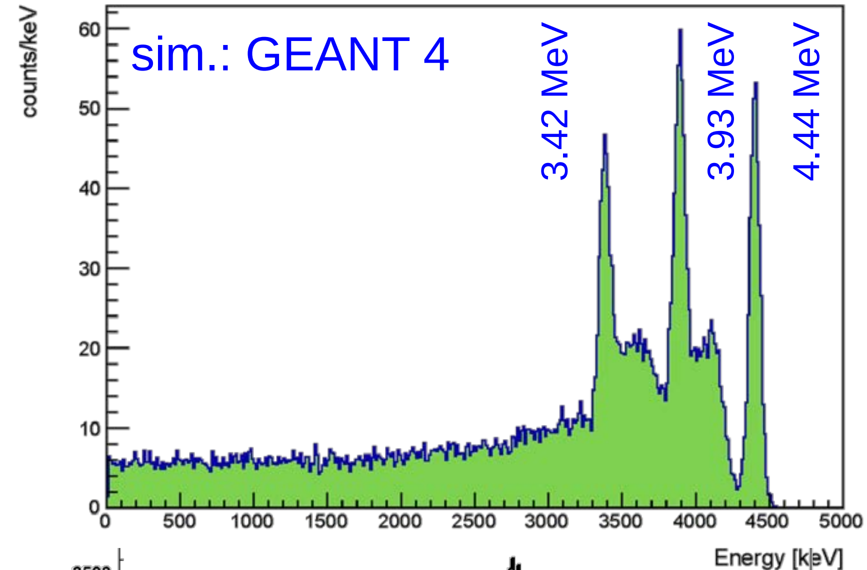


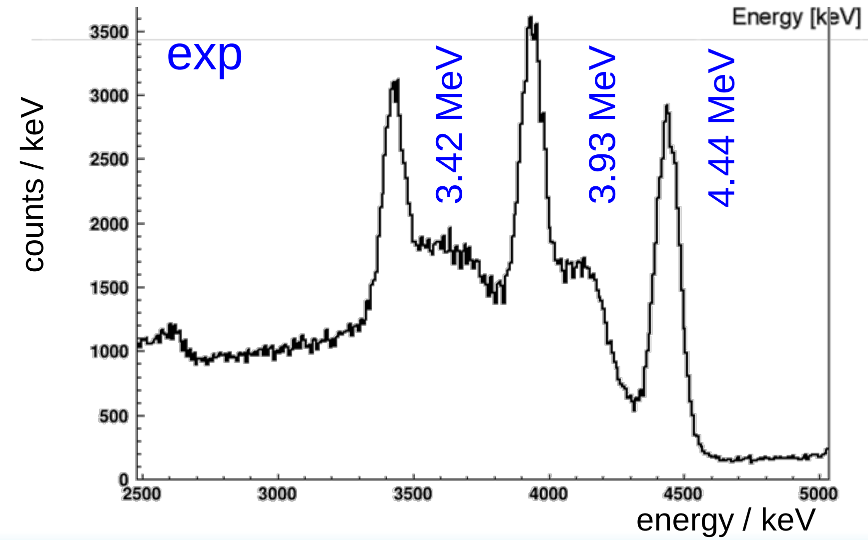
High-Energy Calibration

- Experiment at Tandetron (HZDR, Dresden/Rossendorf):
  - low energy (~1 MeV) protons
  - E_γ =4.44 MeV via $^{15}N(p,\alpha\gamma)^{12}C$



→ validation of MC simulations



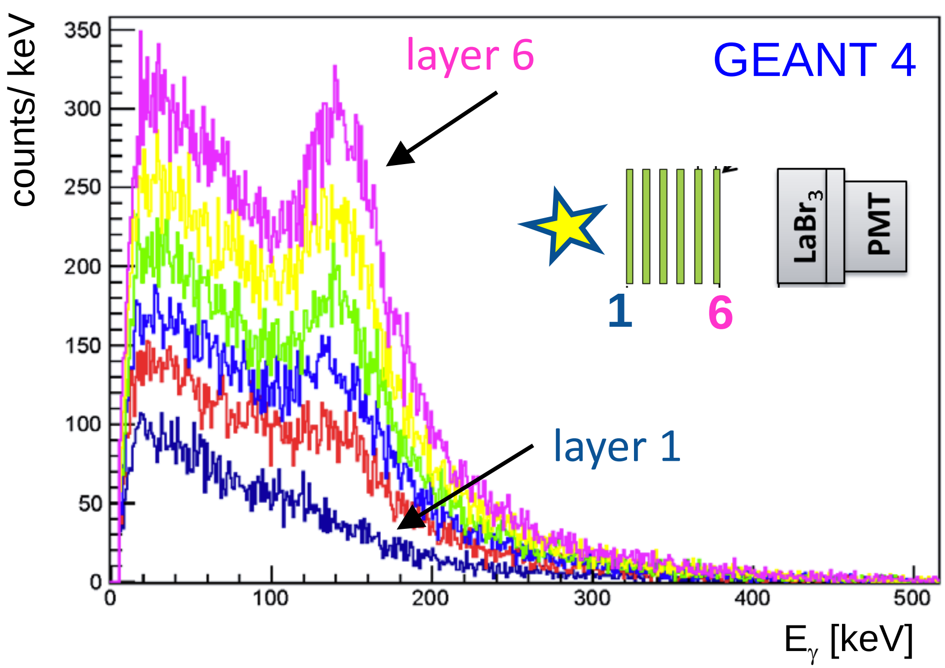


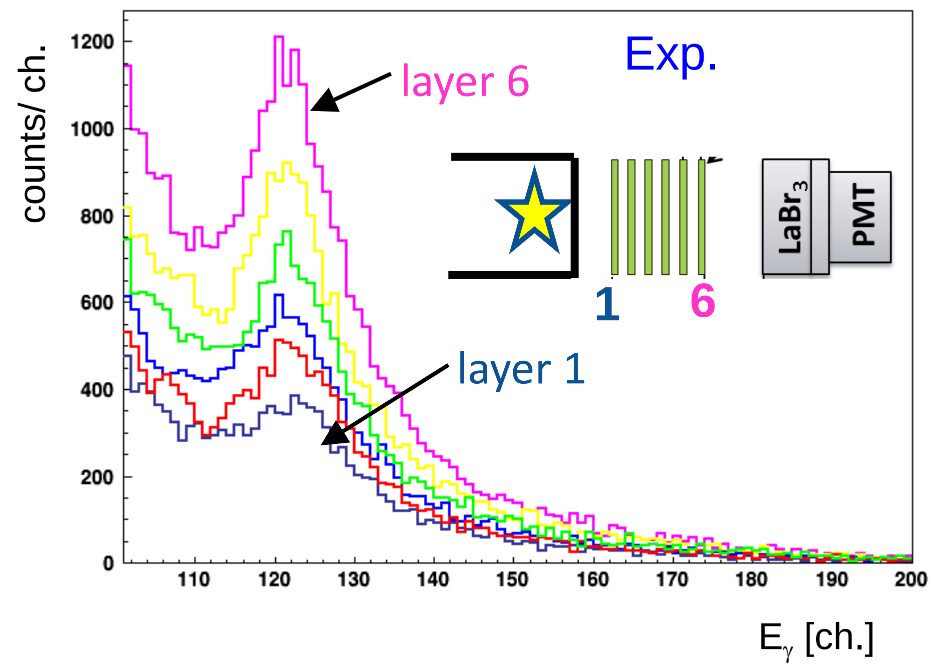
S. Aldawood, PhD thesis, in preparation

Scatter/Tracker Array

- energy deposition in 6 DSSSD layers: E_γ = 4.4 MeV

  - from simulation: increasing yield from front- to backside layers (accumulating contributions from Compton electrons)



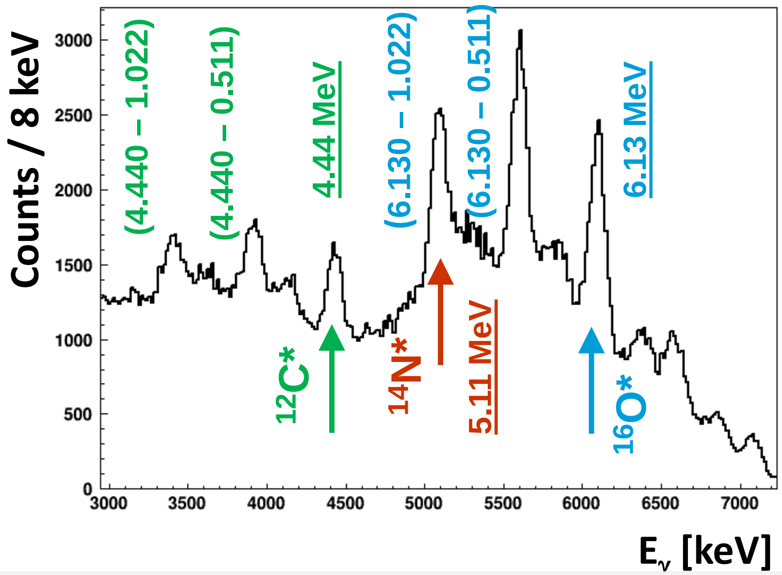


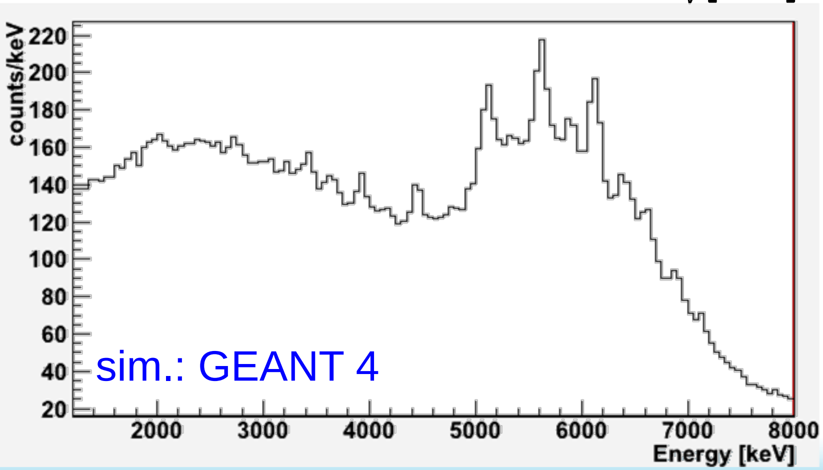
→ simulations verified

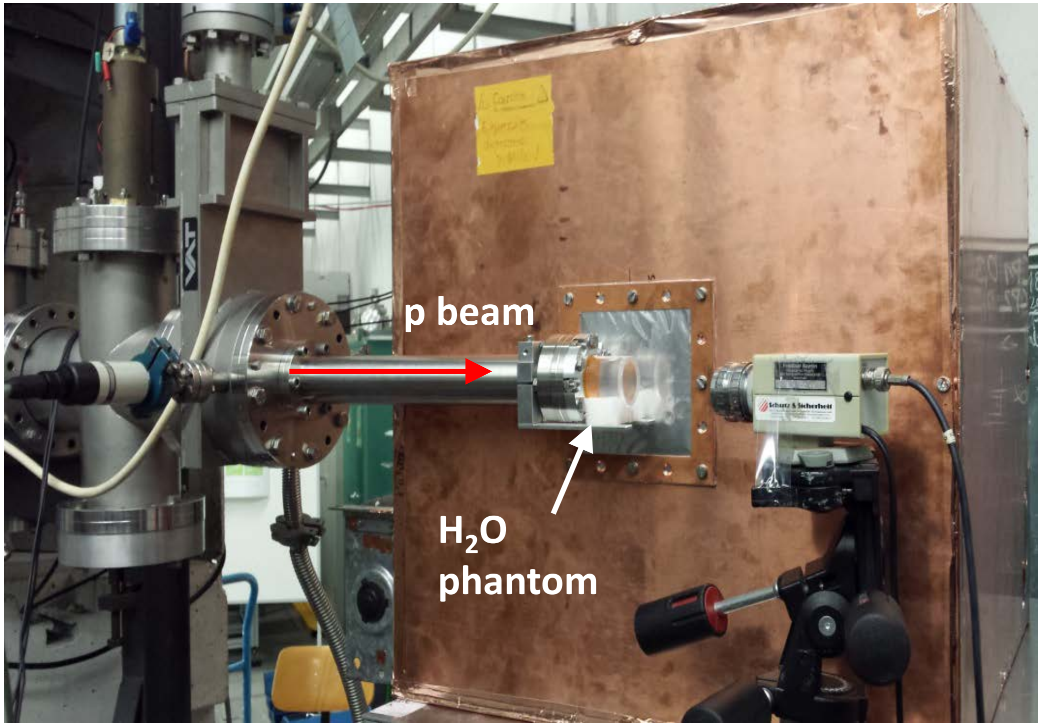
S. Aldawood, PhD thesis, in preparation

Commissioning at Garching Tandem Accelerator

- 20 MeV protons + water phantom: prompt-γ spectrum







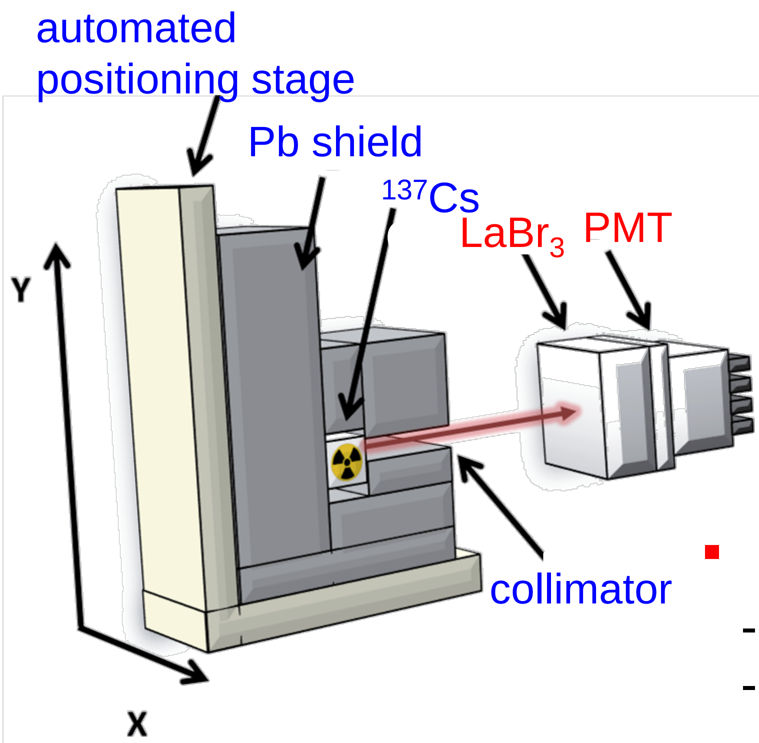
I. Castelhano, Master thesis, U Lisbon/LMU, 2014

$LaBr_3$ detector properties: Spatial resolution

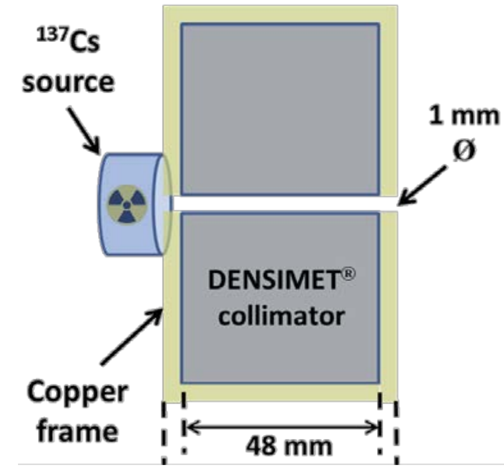
- spatial resolution:

  - collimated γ source (Ø 1 mm): ^{137}Cs (662 keV, ca. 100 MBq)

  → 2D scan of $LaBr_3$



H. v.d. Kolff, Master thesis, TU Delft/LMU (2014)



- data analysis:

  - background correction
  - gain matching/uniformity correction: electronics, PMT

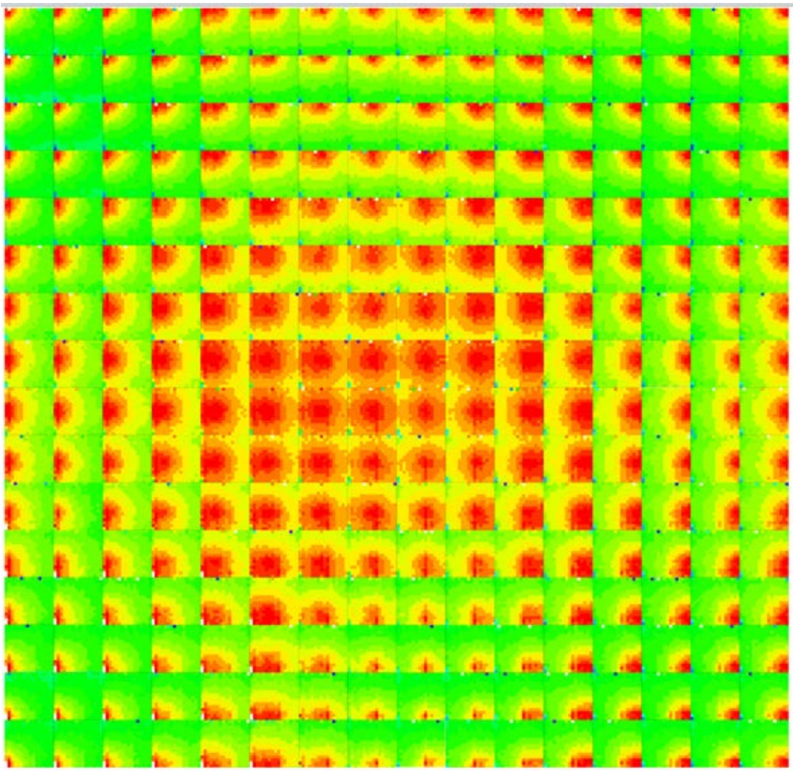
    → "k-nearest neighbour" algorithm (TU Delft)

    → derive position information from monolithic crystal

H.T. van Dam et al., IEEE TNS 58 (2011) 2139

$LaBr_3$ detector properties: Spatial resolution

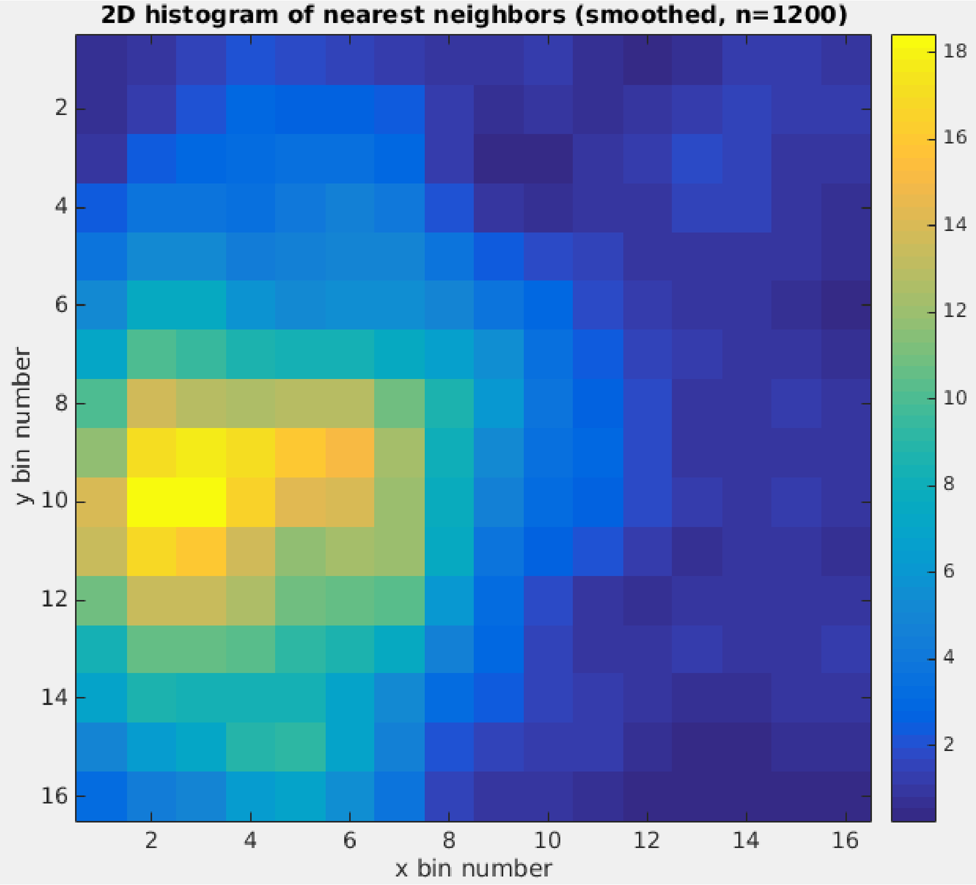
- light amplitude distribution maps:
  - 2D scan with collimated ^{137}Cs source
  - irradiation of 16x16 pixels (3x3 mm^2)



  - goal: 10^4 maps as reference data set (0.5 mm collimation, 0.5 mm step size)

S. Aldawood, PhD thesis, LMU, in preparation

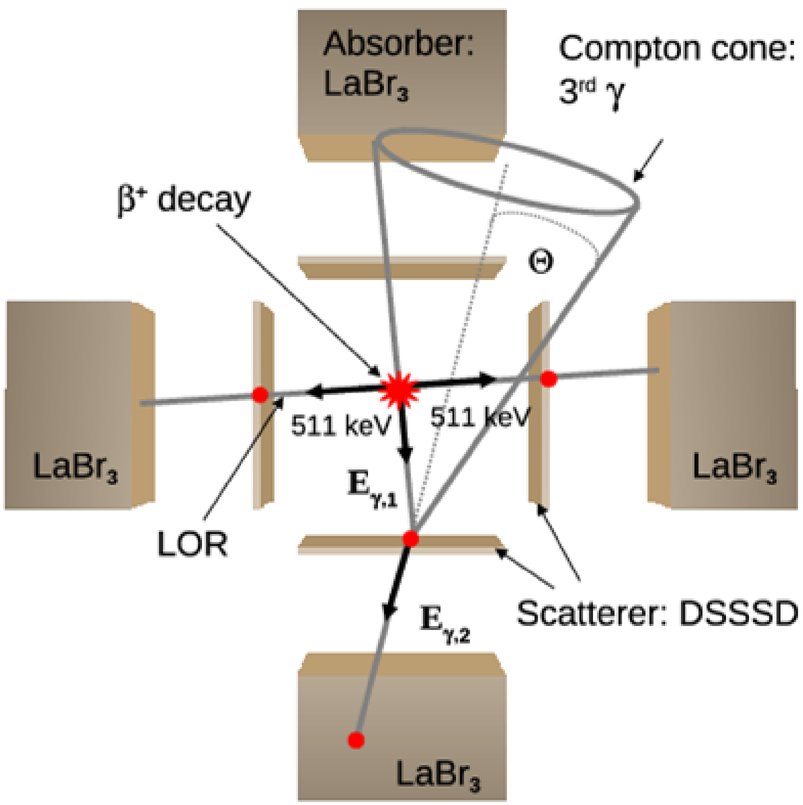
- γ hit position identification via 'k-NN': (preliminary, not yet full resolution)

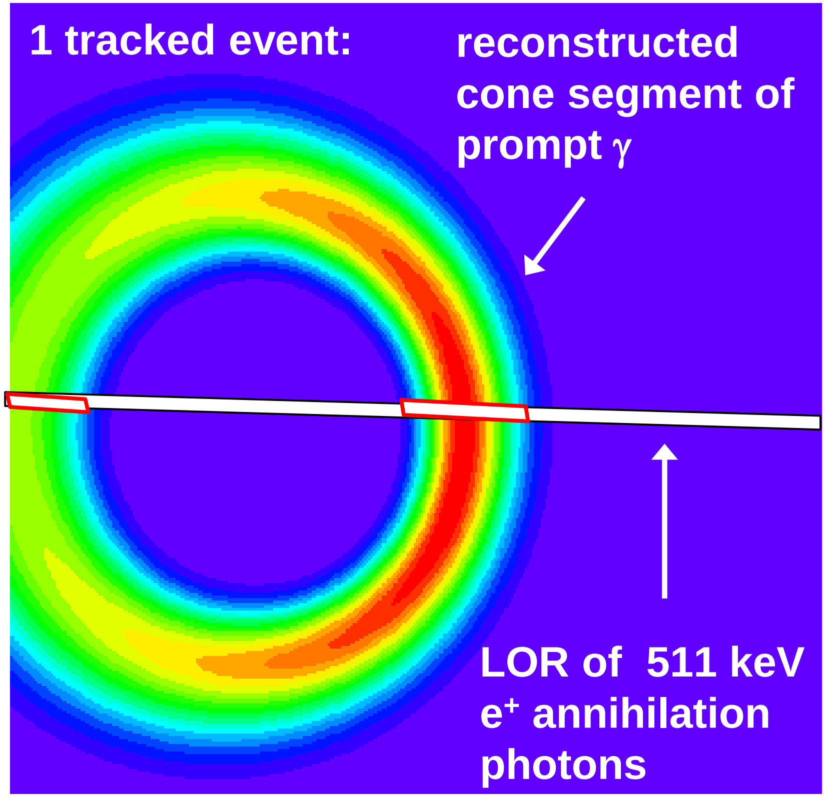


T. Marinšek, Master thesis, LMU, in preparation

Perspective:
'Hybrid Detector' System

- γ-PET technique: reconstruct triple-coincidences from $\beta^+\gamma$ emitters

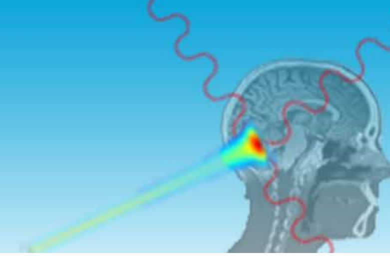




C. Lang et al., JINST 9 (2014) P01008,
PhD thesis in preparation

→ prompt-γ detection during irradiation
→ delayed photons from β^+ (γ) emitters ($^{11,10}C$, $^{15,14}O$, ^{13}N) during irradiation interrupts

Conclusion



- Compton camera prototype for prompt-gamma range monitoring:

  - prototype characterized off- and online:

    - absorber:

      $LaBr_3$ with multi-anode PMT: $\Delta E/E = 3.8\%$, $\Delta t = 270$ ps
      spatial characterization (k-NN method) in progress

      → prerequisite of source reconstruction (MEGAlib)

    - scatterer/tracker:

      6x DSSSD (500 μm, 50x50 mm^2, 2x128 ch.)

    - online characterization: Garching (E_p= 20 MeV), Dresden (E_γ=4.4 MeV)
    - verification of model simulations

- Perspective: hybrid detector system

  - prompt-γ detection during irradiation
  - delayed photons from β^+ (γ) emitters ($^{11,10}C$, $^{15,14}O$, ^{13}N) during irradiation interrupts

Thanks to …

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- TU Munich: L. Maier, M. Böhmer, R. Gernhäuser
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Thank you for your attention !