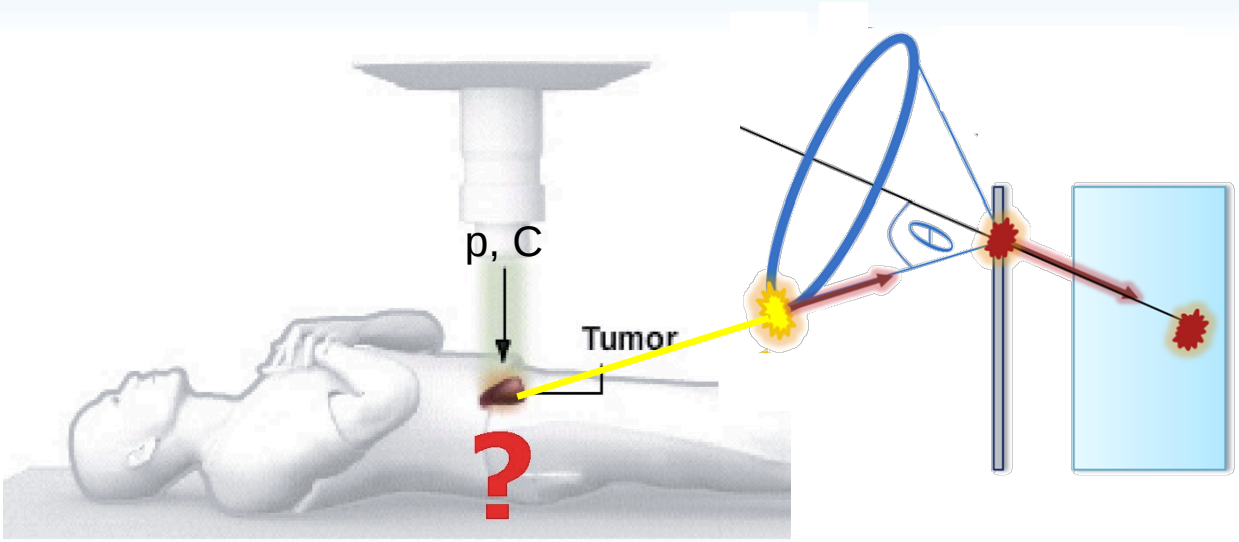
Development of a Compton Camera for Prompt-Gamma Medical Imaging

P.G. Thirolf, LMU Munich



- Motivation: need for accurate ion beam range verification in hadron therapy
- 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

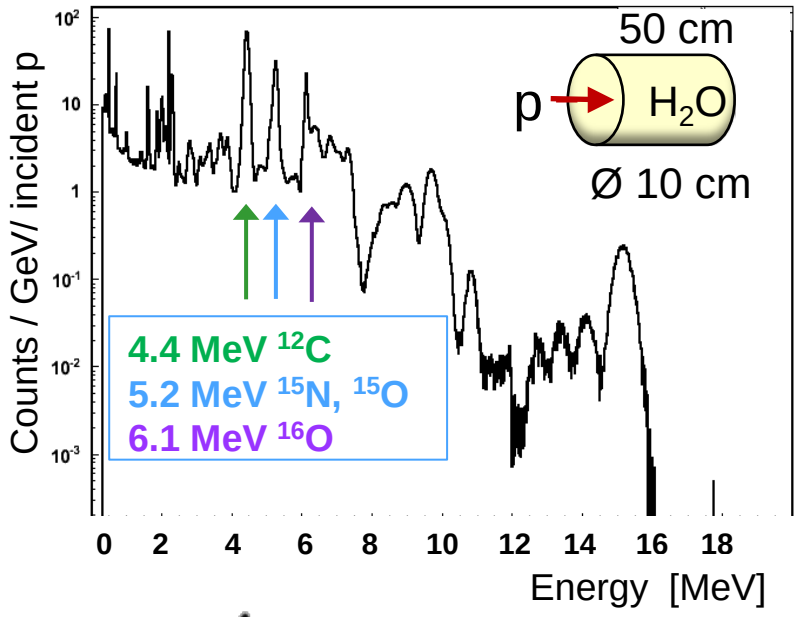
Prompt gamma emission from proton beam on biomedical sample

- key issue in hadron therapy:

  - localization of Bragg peak within patient/sample

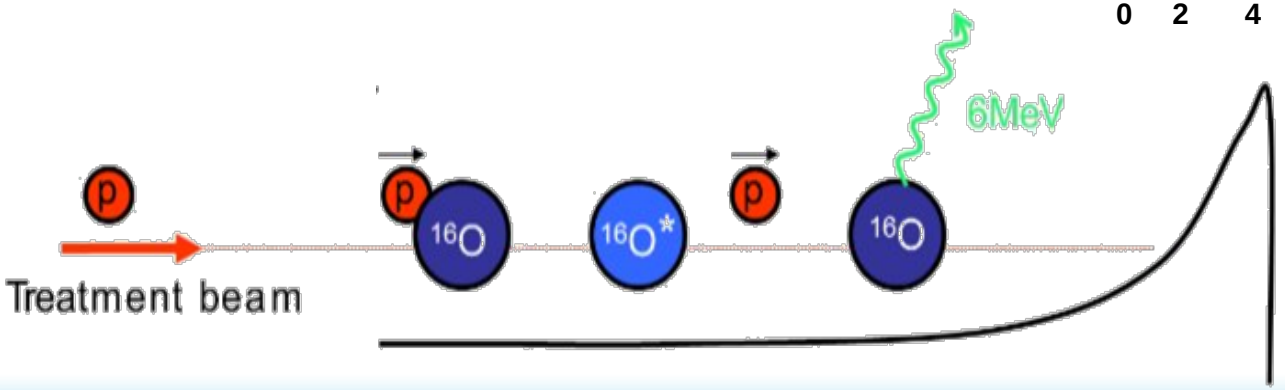
  → range verification of therapeutic proton (or ion) beam

- irradiation of water phantom with 100 MeV protons:



(simulation)

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

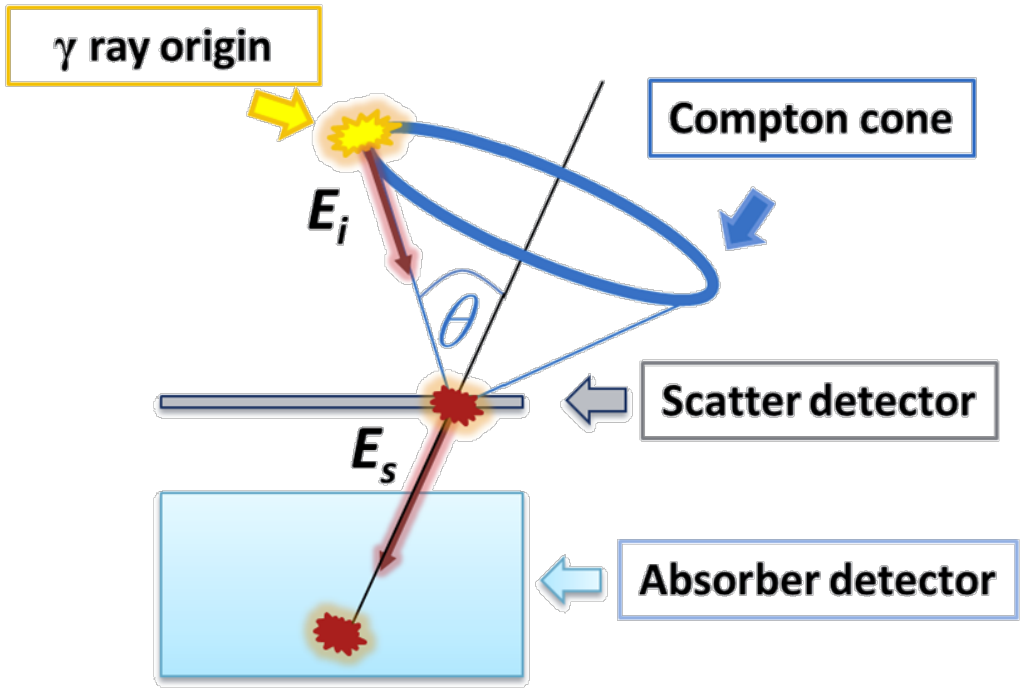


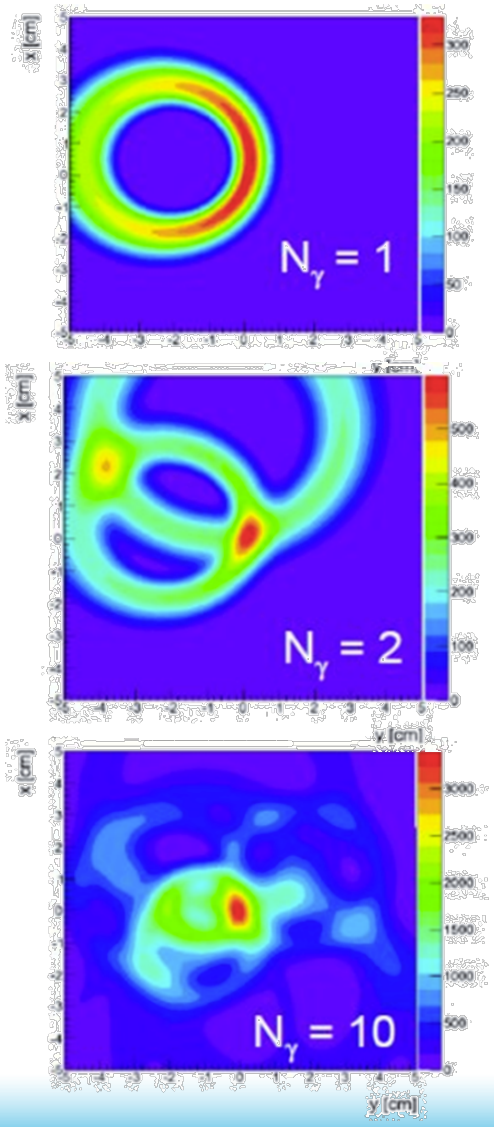
(Prompt) Gamma Imaging: Compton Camera

- exploit kinematics of Compton scattering:

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

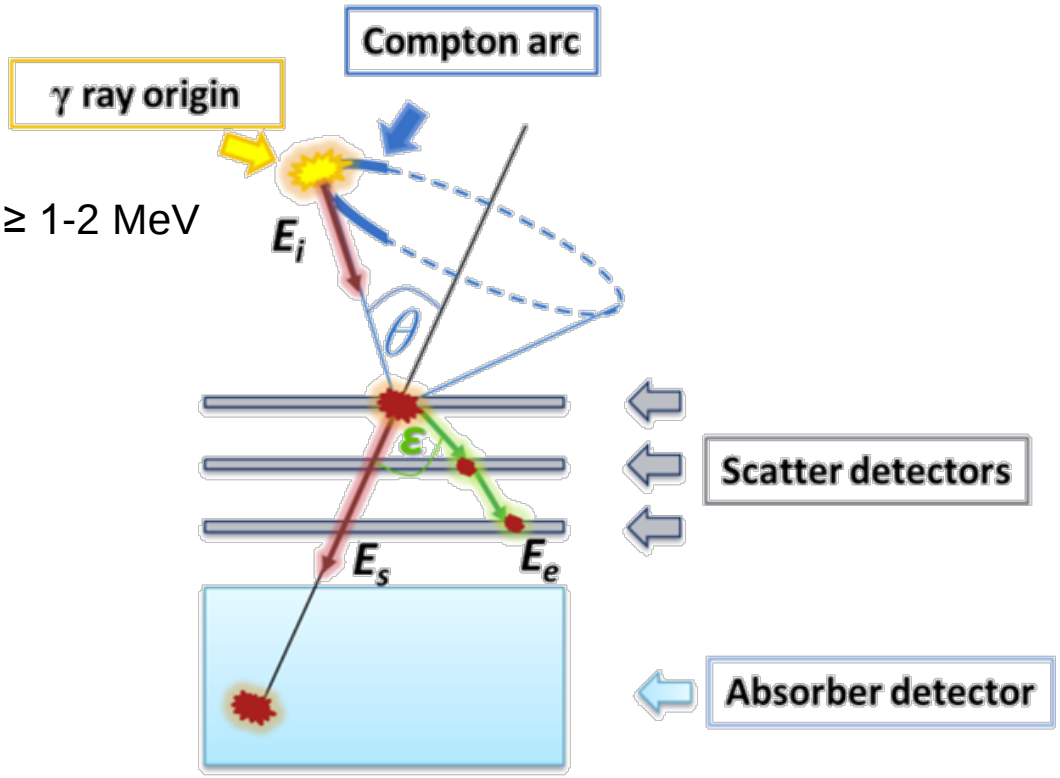
(i) γ tracking:

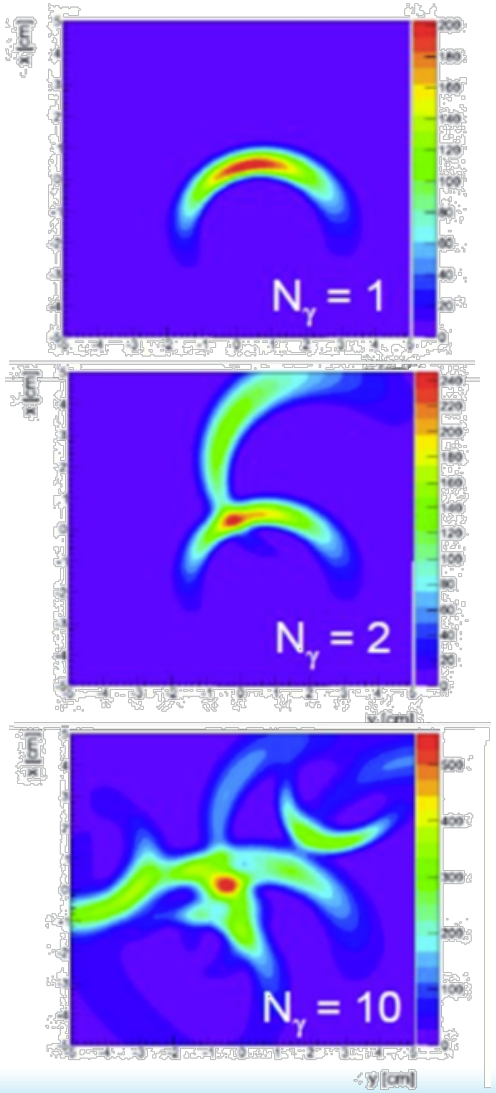




(Prompt) Gamma Imaging: Compton Camera

(ii) electron tracking:





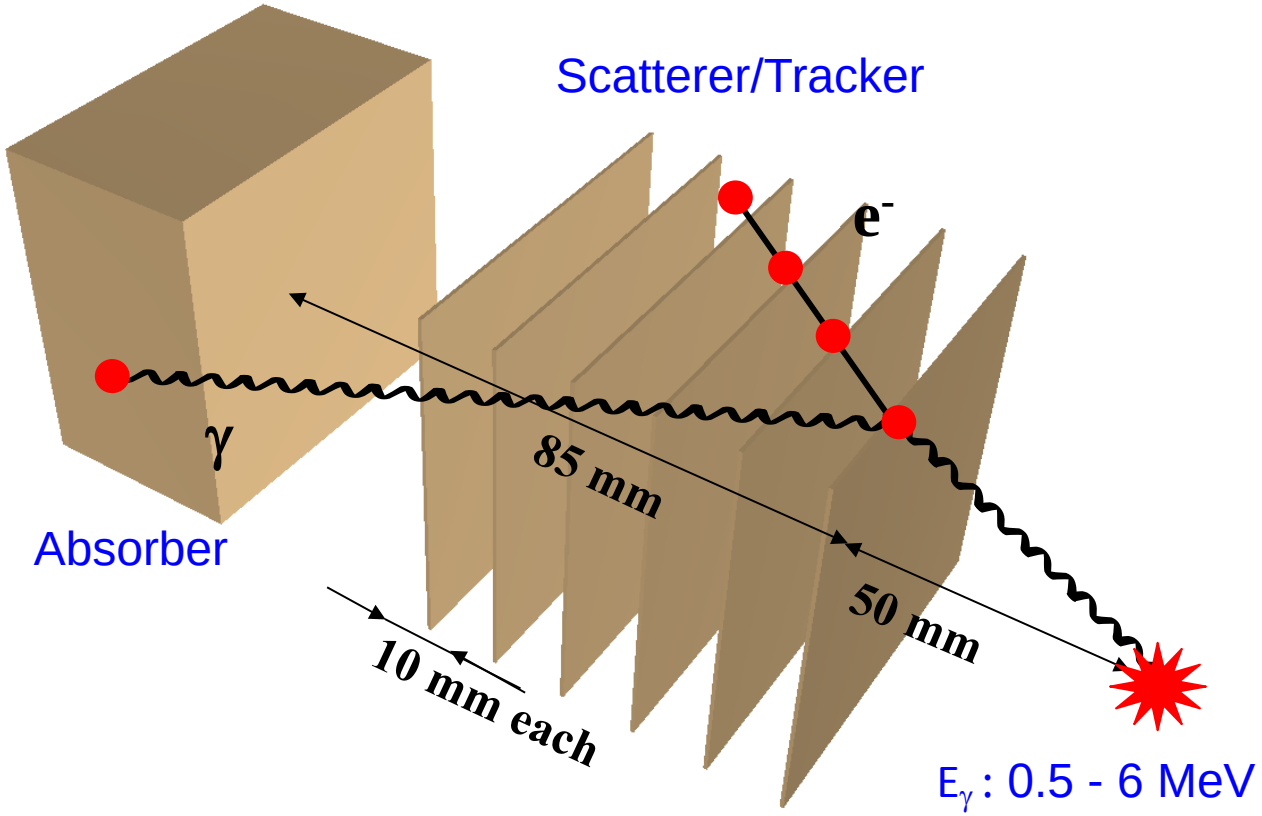
advantage:

- reconstruction of incompletely absorbed events

→ increased reconstruction efficiency

Garching Compton Camera Prototype

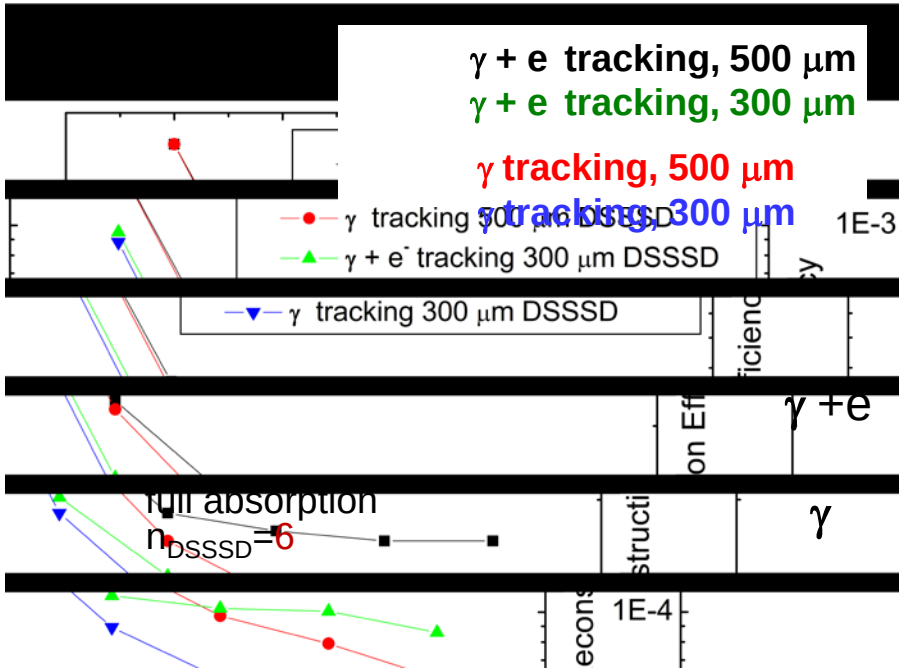
- Compton camera layout:

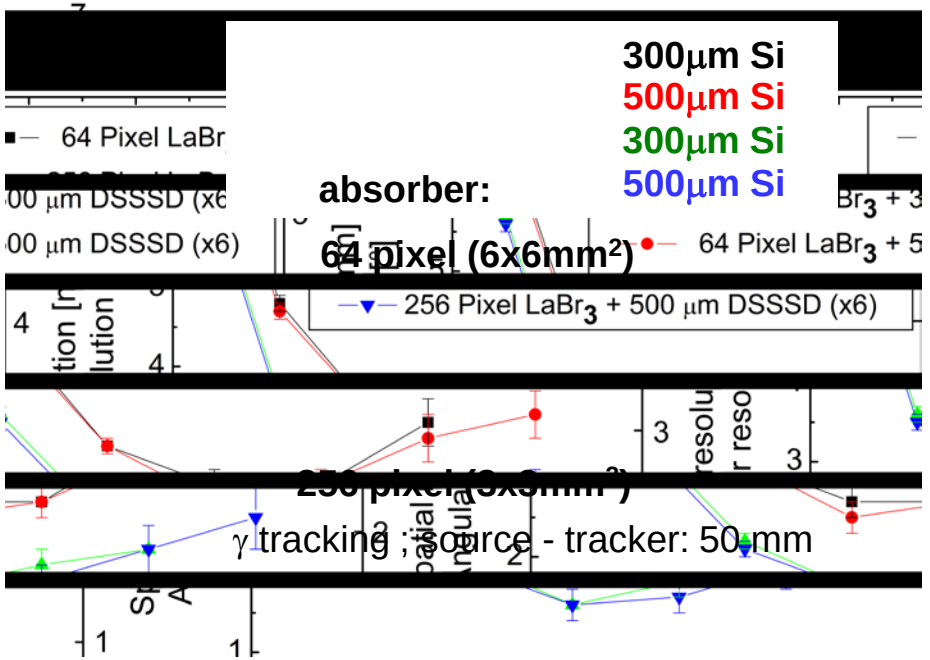


C. Lang et al., JINST 9 (2014) P01008, PhD thesis (LMU, 2015)

Compton Camera Design Simulations

- simulations for tracker/absorber specifications and expected performance:





- d=500 μm + electron tracking:
  → improved efficiency

- 6x6 mm² → 3x3 mm² pixel:
- spatial resolution improves by ≥50 %

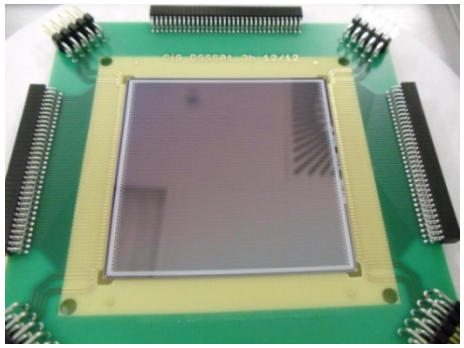
- $\varepsilon \approx 10^{-3} - 10^{-5}$ (@ 1- 5 MeV for optimum resolution)
- angular resolution ≈ 2° – 2.5° (@ 2-6 MeV)

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
→ resistivity > 10 kΩcm

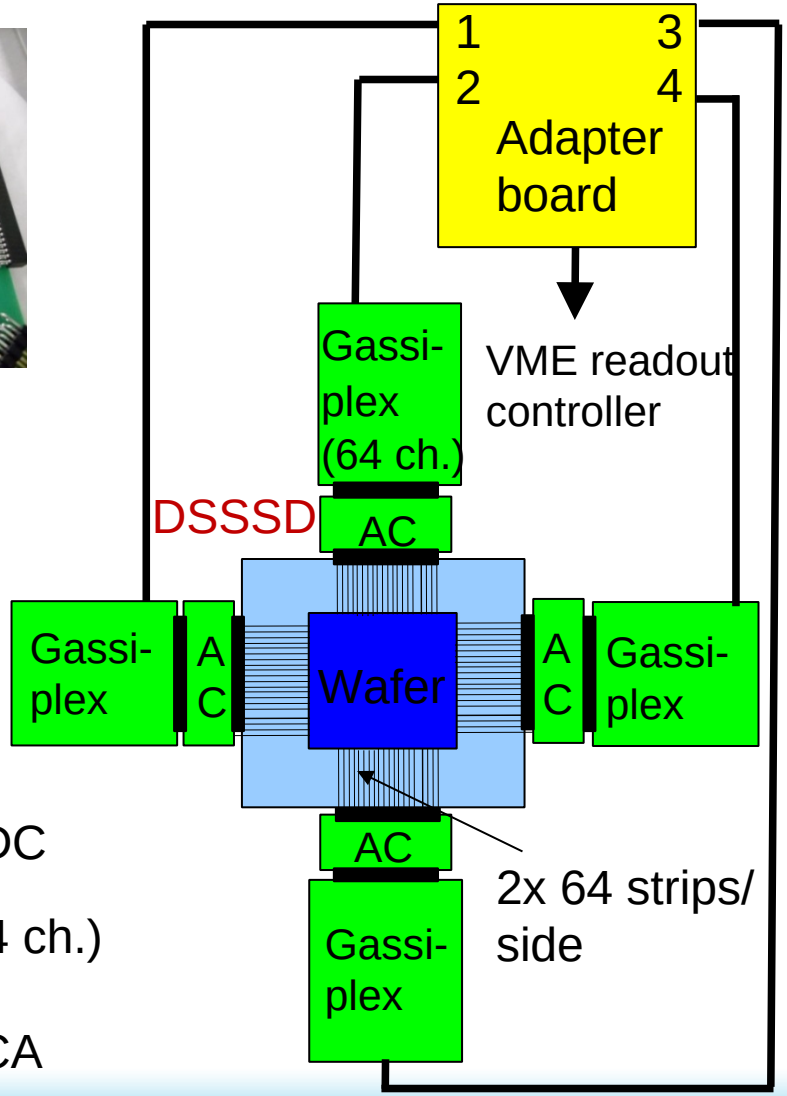


- DSSSD readout:

now: Gassiplex-ASIC (4x16 ch.):

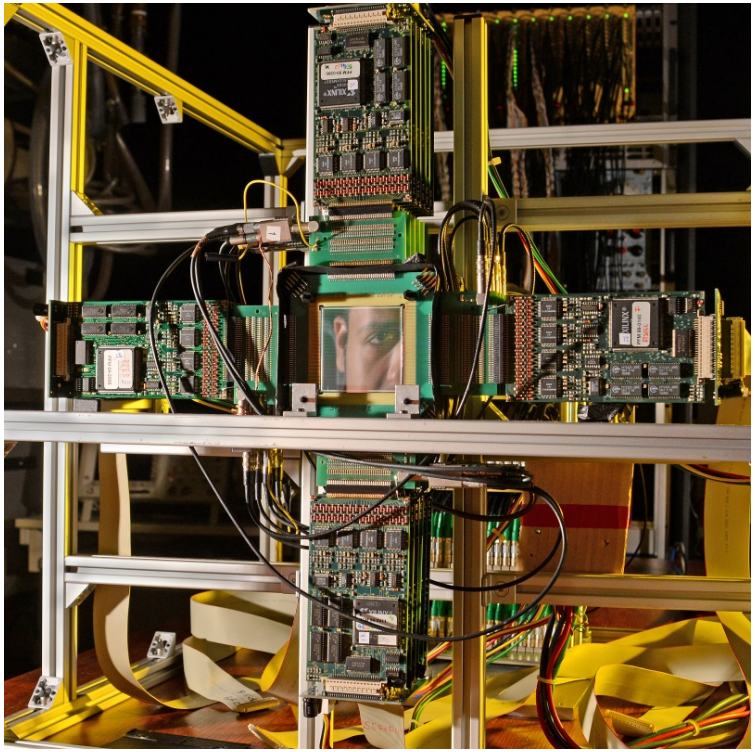
→ charge-sensitive preamp.
→ shaper (τ = 500 ns)
→ digital discriminator
→ multiplexed amplifier, (10-bit) ADC

upgrade: based on GET-ASIC (64 ch.)
- both polarities, trigger, 12 bit, variable shaping, monitor, μ-TCA

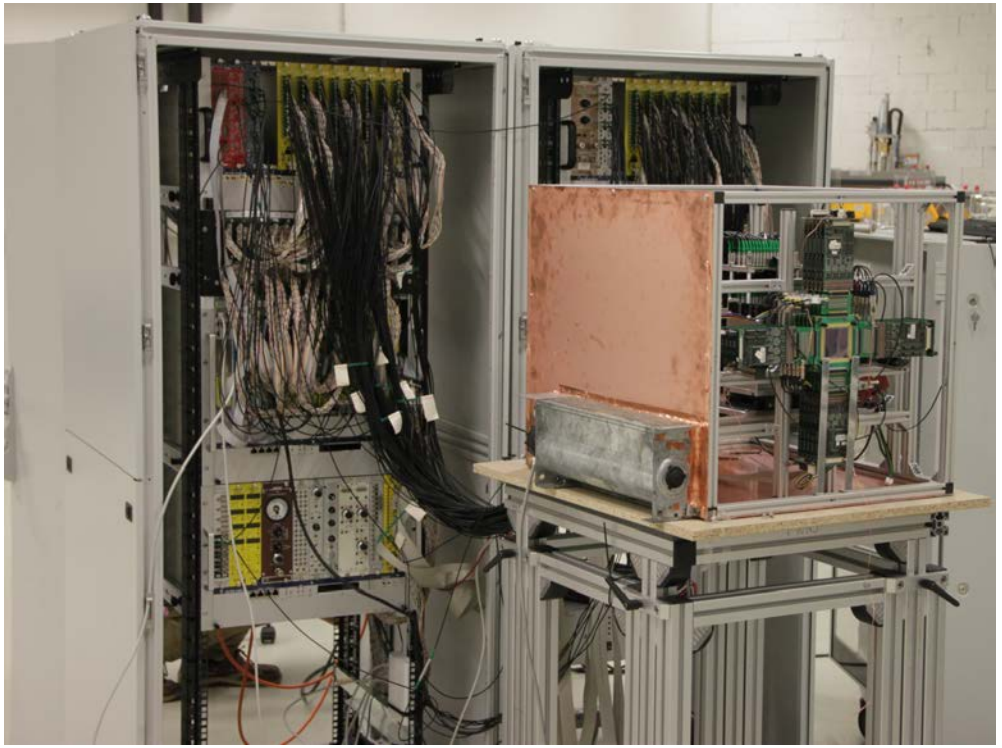


Compton Camera Prototype

scatterer/tracker array:



camera with signal processing:



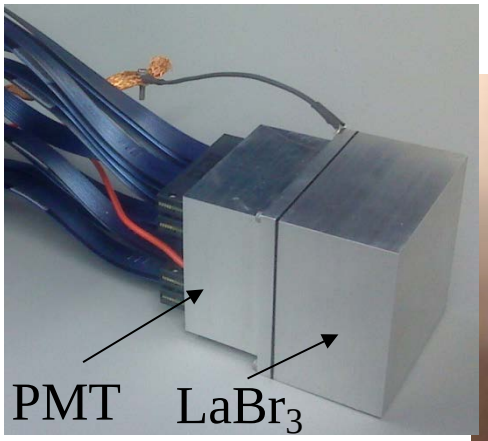
- light tight enclosure
- Faraday cage (+ ventilation, thermal control)

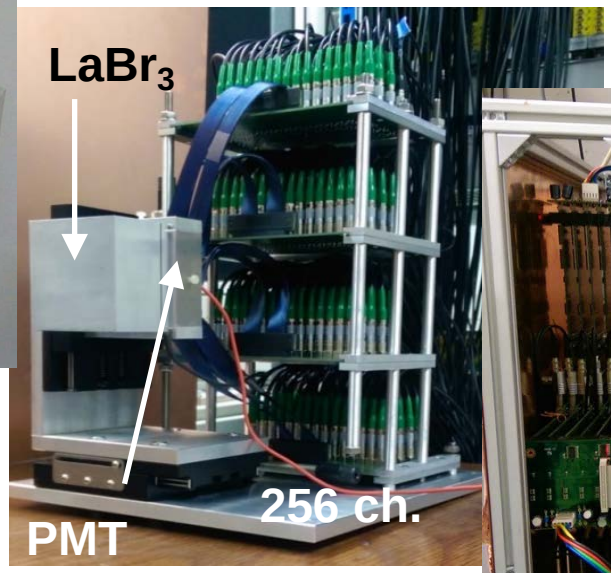
S. Aldawood, PhD thesis, in preparation

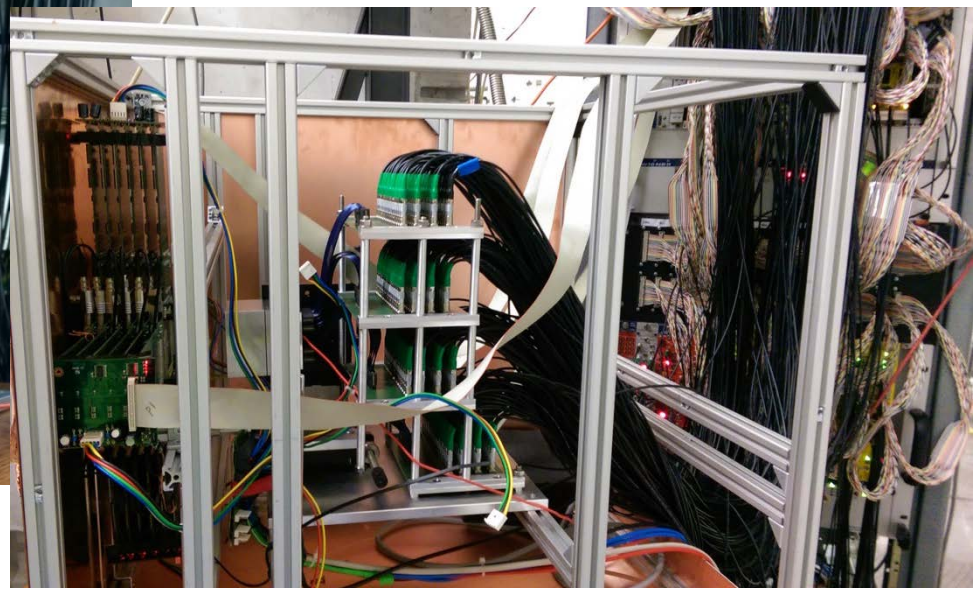
Compton Camera Prototype

- 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 for E, t

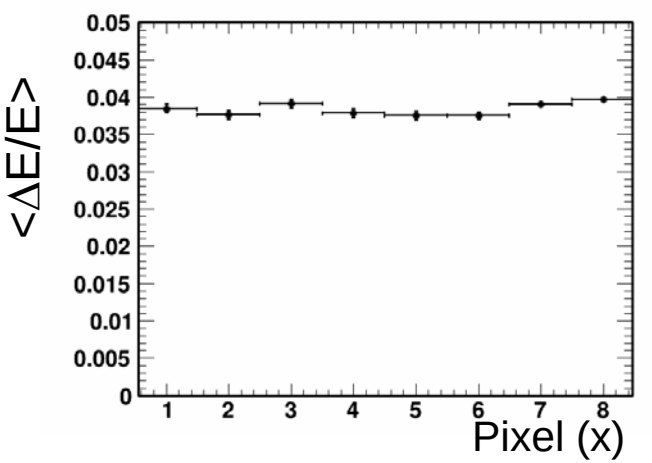
→ fast amplifier + CFD (Mesytec MCFD-16, 16 ch.)
→ energy: charge-sensitive digital converter (Mesytec, 32 ch. VME-QDC)
→ time: (multi-hit) TDC (Mesytec, 32 ch. VME)

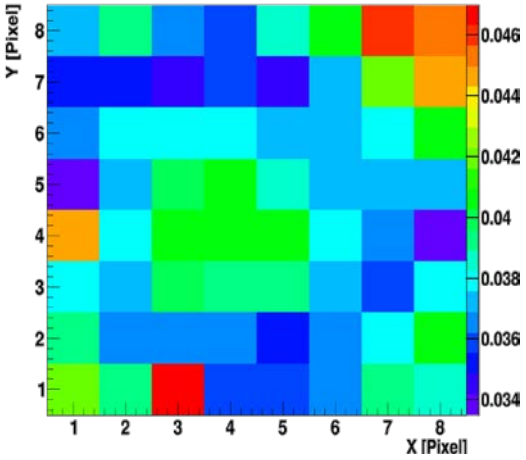
S. Aldawood, PhD thesis, in preparation

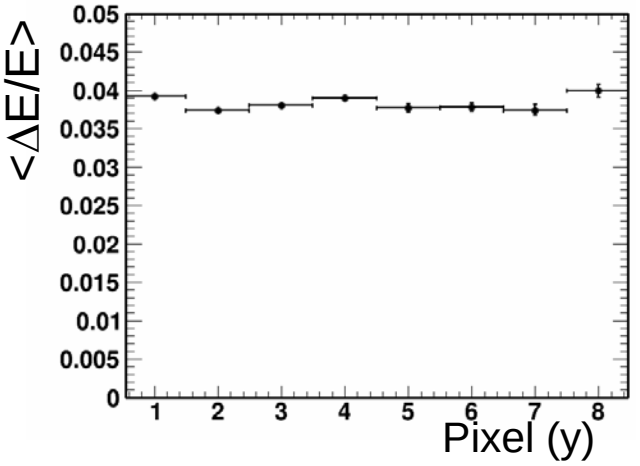
$LaBr_3$ detector properties: energy / time resolution

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

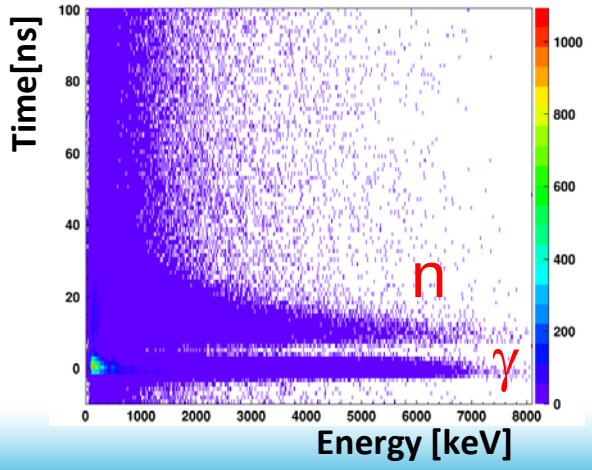
H. v.d. Kolff, Master thesis, TU Delft/LMU (2014)

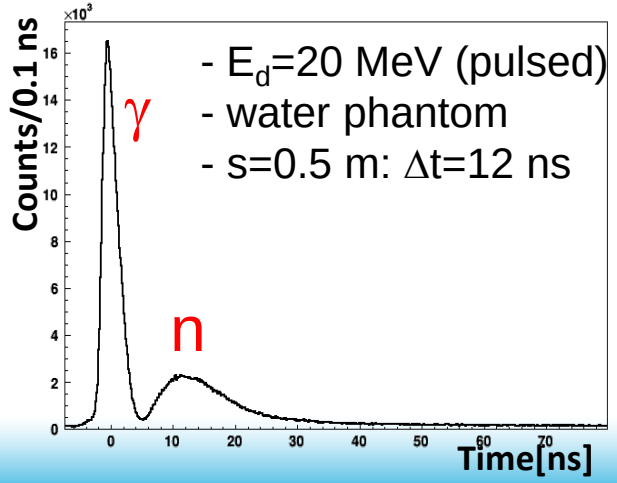


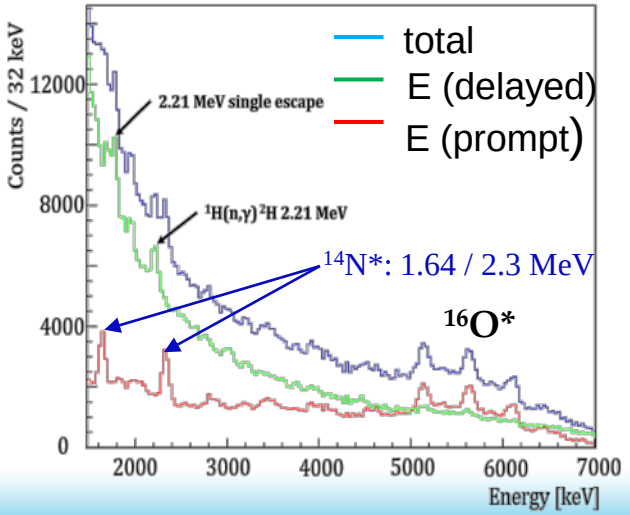




- time resolution: ^{60}Co source: $\Delta t \sim 270$ ps

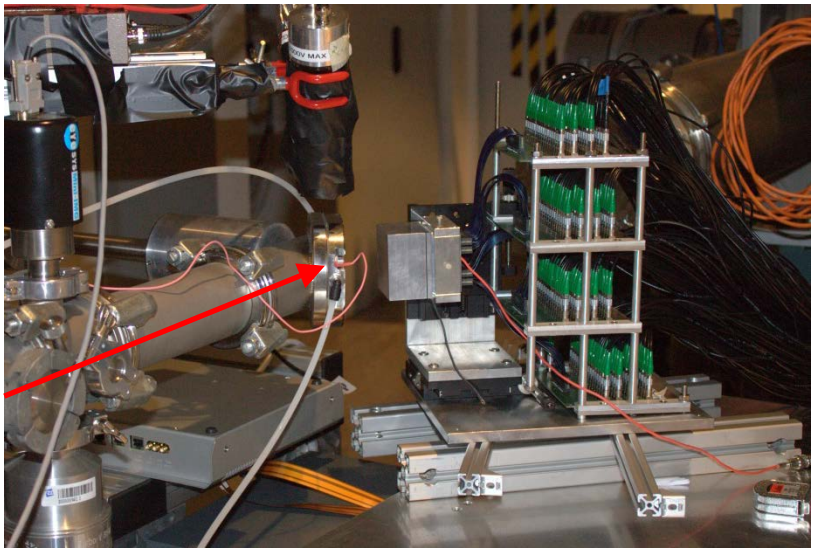






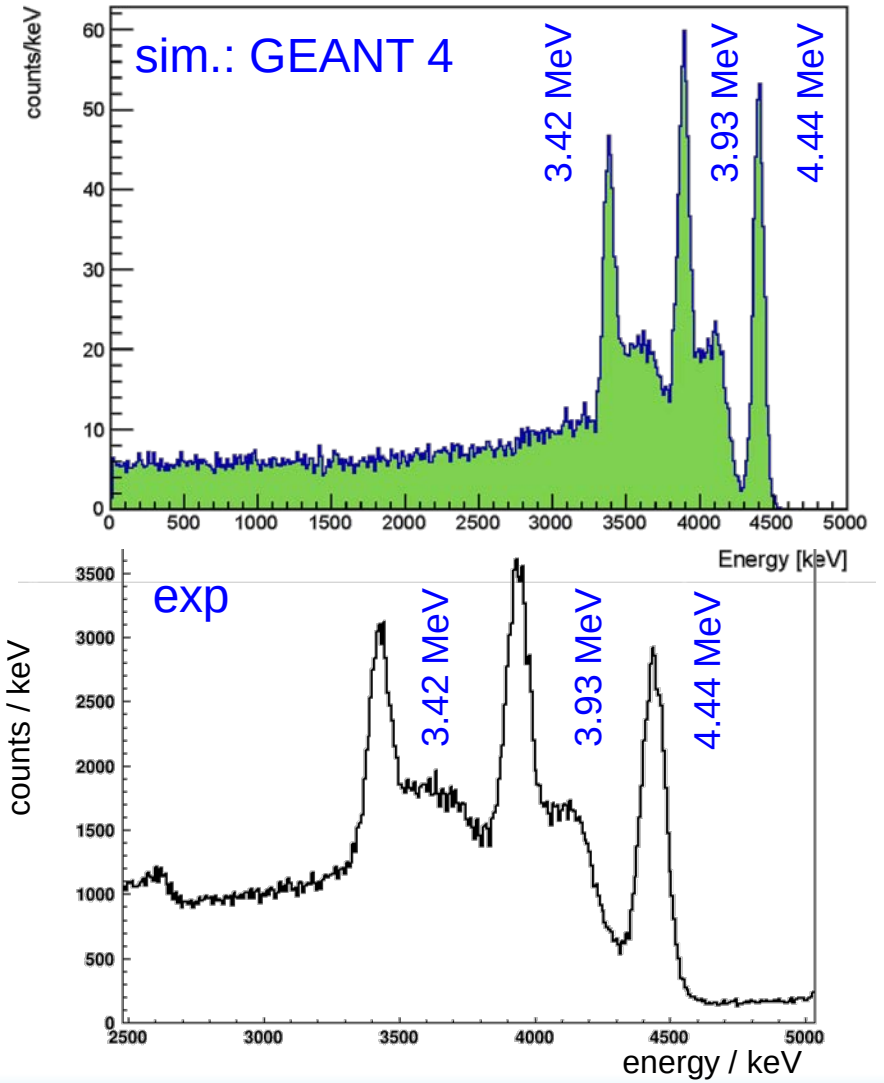
High-Energy Calibration

- 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

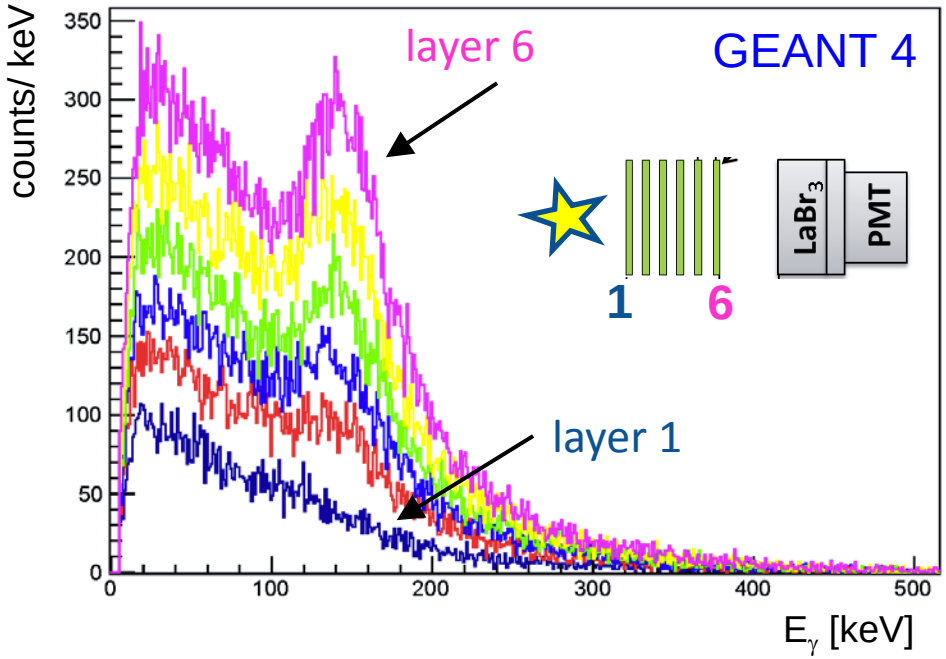
S. Aldawood, PhD thesis, in preparation

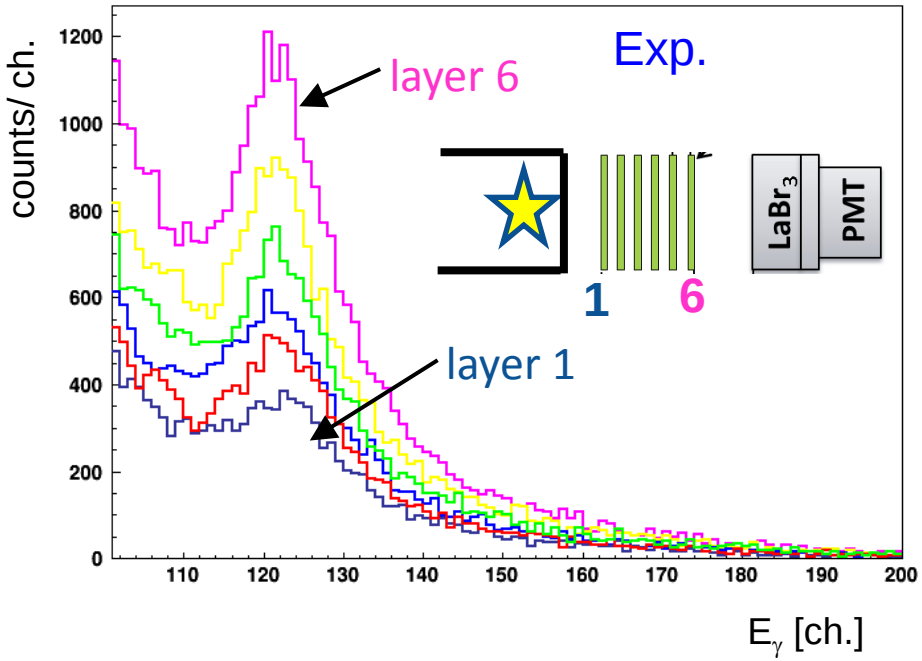


Scatter/Tracker Array

- 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)



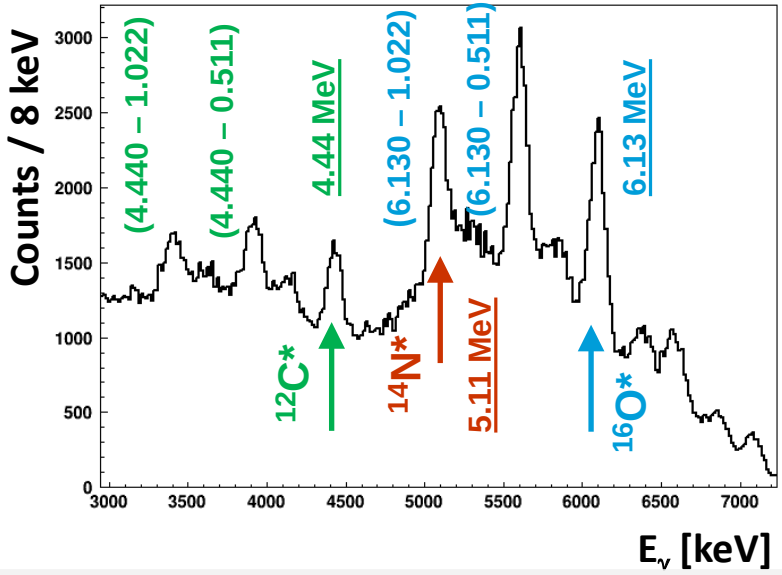


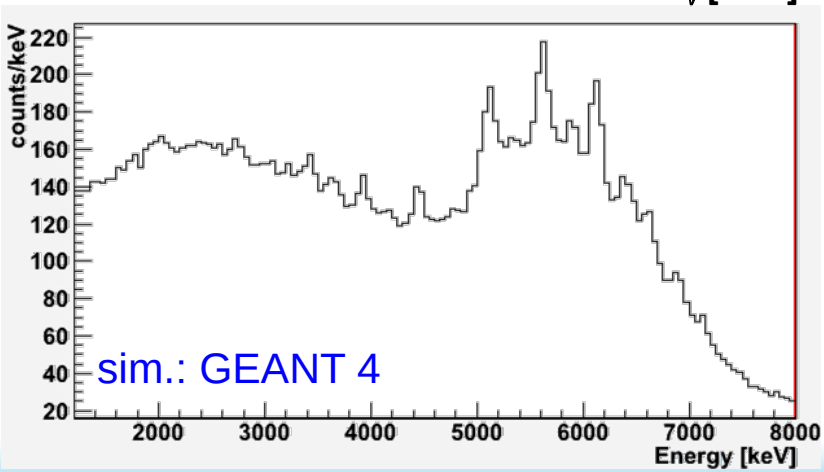
→ simulations verified

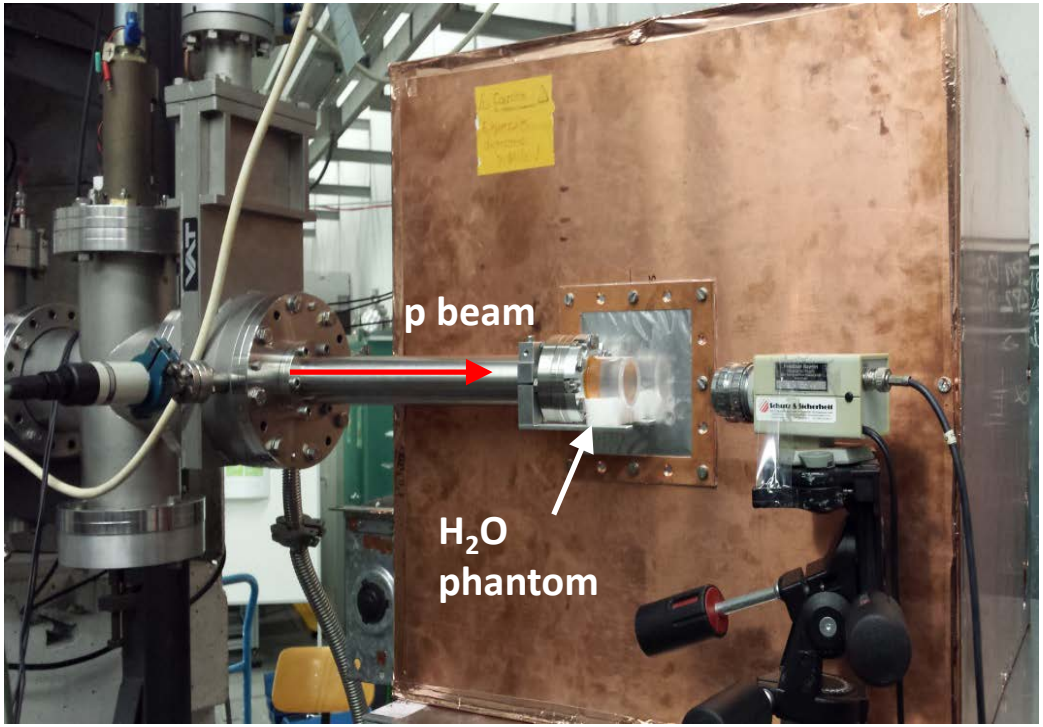
S. Aldawood, PhD thesis, in preparation

Commissioning at Garching Tandem Accelerator

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







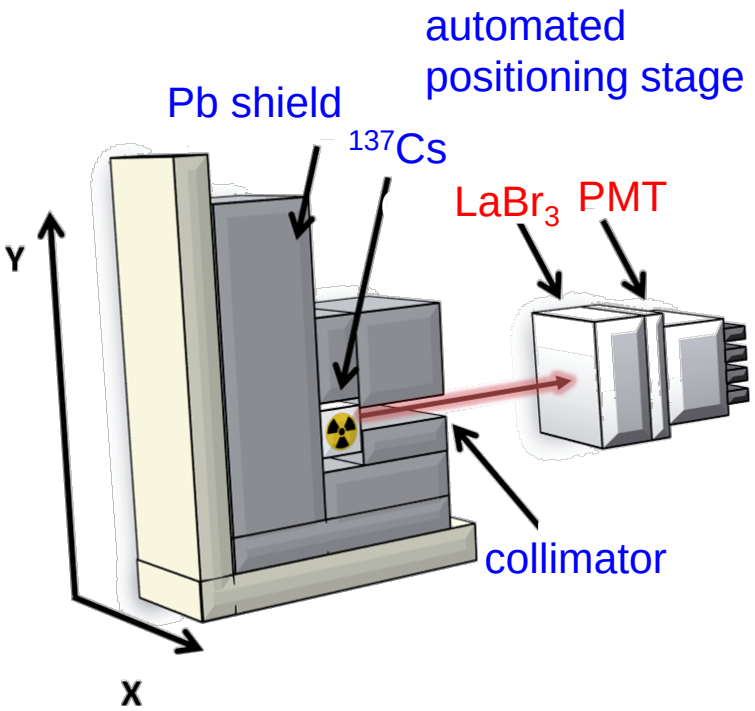
I. Castelhano, Master thesis, U Lisbon/LMU, 2014

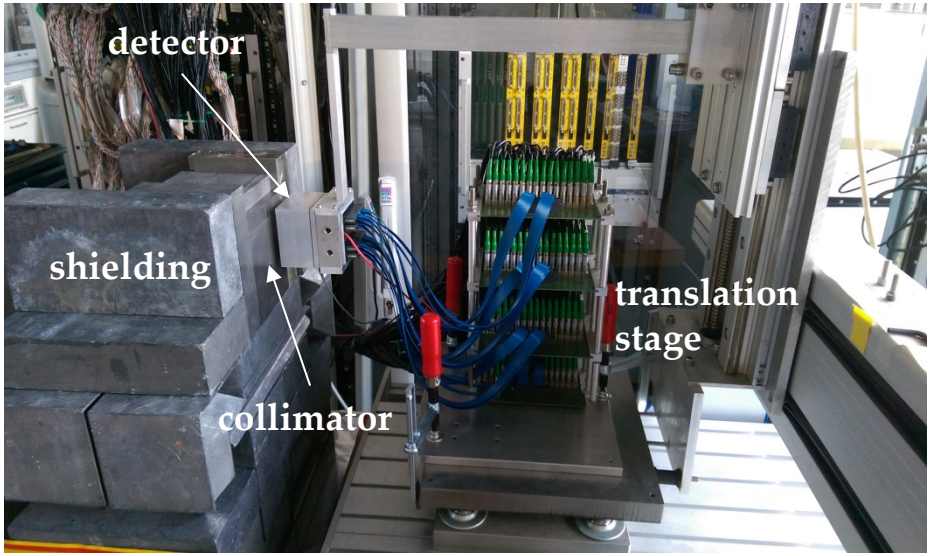
$LaBr_3$ detector properties: Spatial resolution

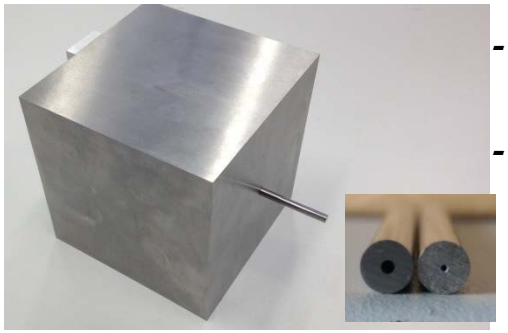
- spatial resolution:

  - collimated γ source (Ø 1 mm):
    ^{137}Cs (662 keV, ca. 80 MBq)
    ^{60}Co (1.17/1.33 MeV, 20 MBq)

  → 2D scan of $LaBr_3$





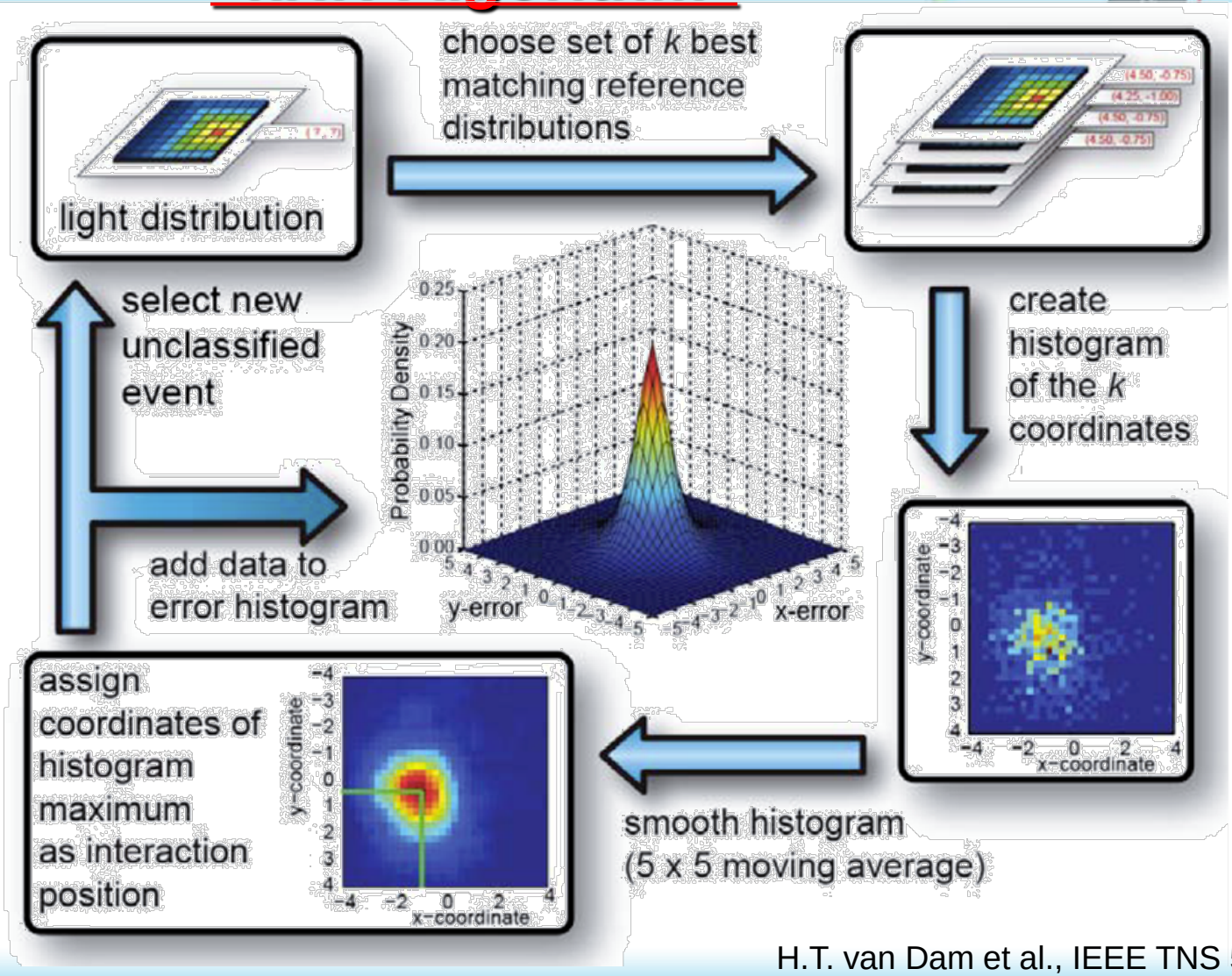


- 100x100x100 mm^3 Densimet shielding
- exchangable WC tube: diameter 1 mm, 0.6 mm

A. Miani, Master thesis, LMU, in preparation

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

Spatial Resolution from Monolithic Scintillator: "kNN-Algorithm"



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

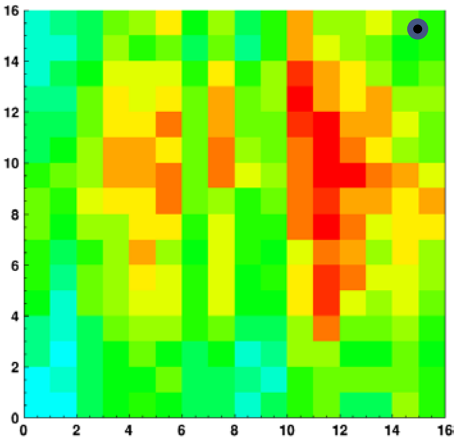
Hit position determination in the absorber detector

- **correction steps:**

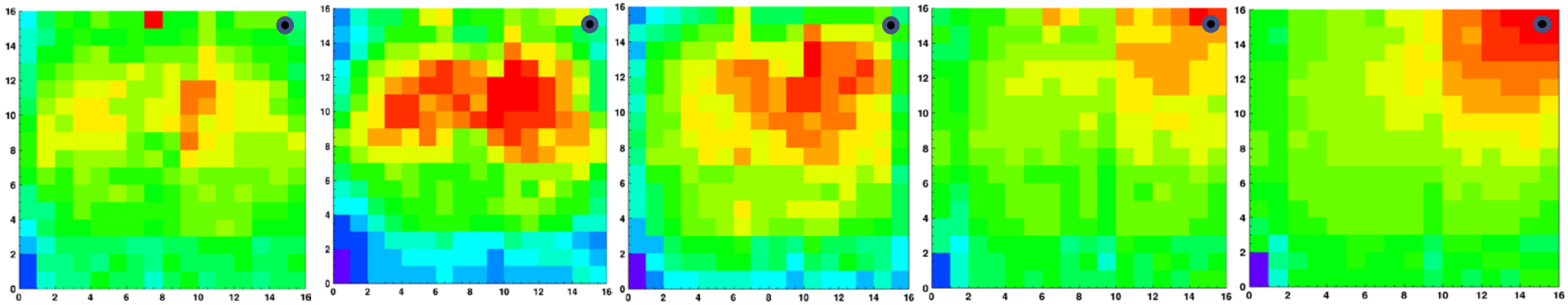
1. gain matching (pulser)
2. pedestal subtraction
3. PMT non–uniformity [provided by manufacturer]
4. spatial homogeneity of light amplitude distribution
5. gating at the region of interest (662 keV ± 5%)

- source position

raw data

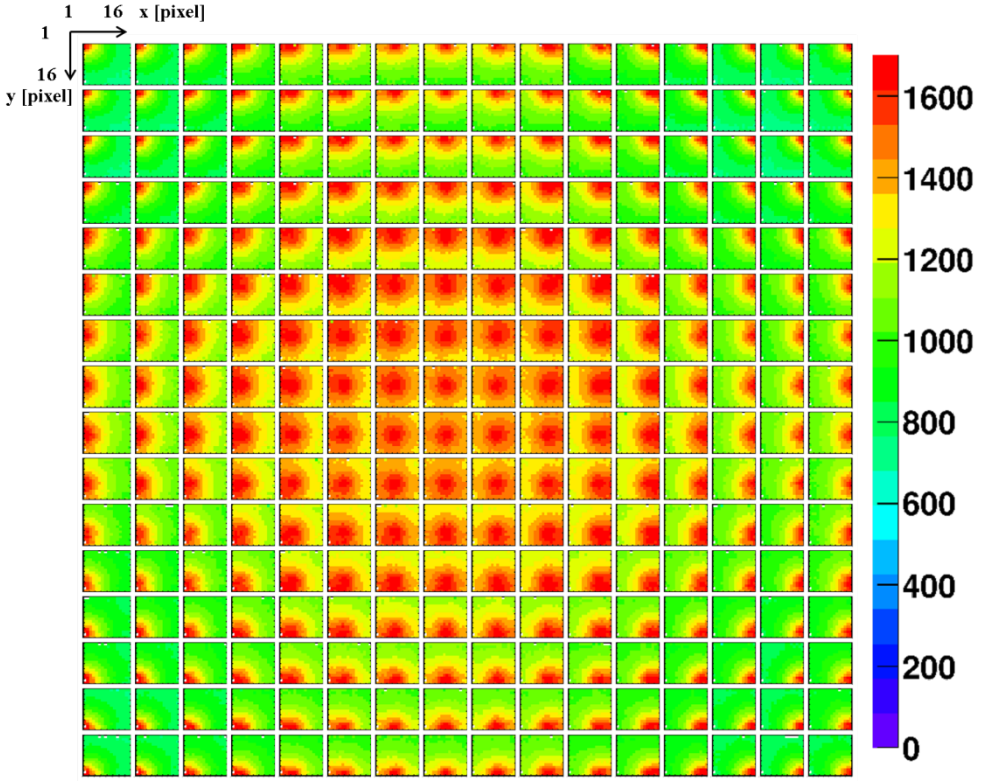


1 2 3 4 5



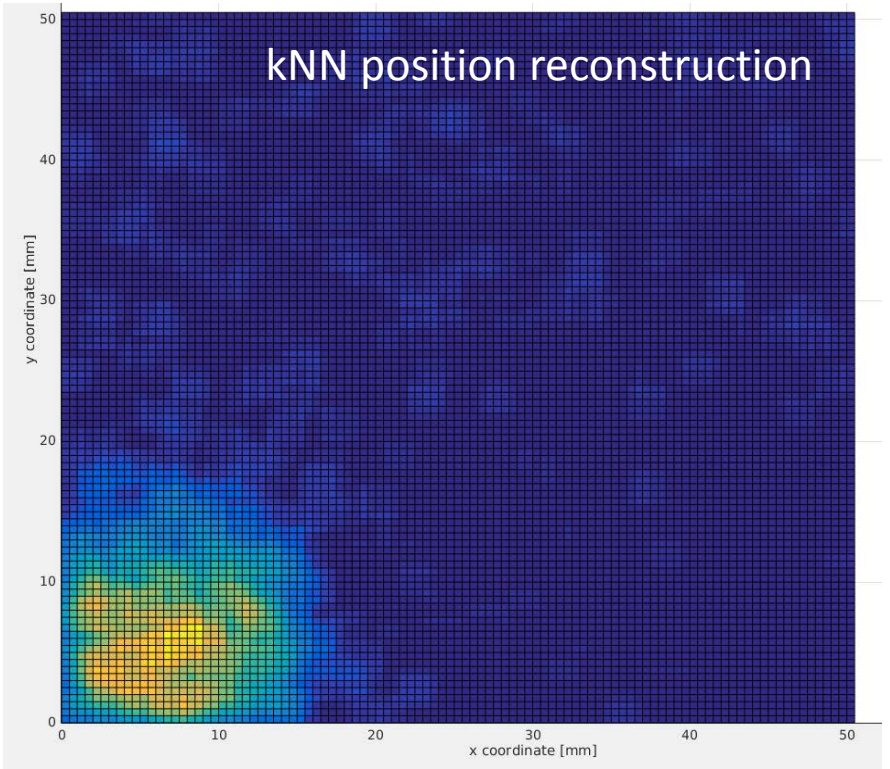
$LaBr_3$ detector properties: Spatial resolution

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



- 10^4 maps as reference data set (1.0/0.6 mm collimation, 0.5 mm step size)

- kNN method (1 mm collimator)
  - irradiation of 102 x102 positions (grid: 0.5 mm)
  - 50 events / position; k=2000:



T. Marinšek, Master thesis, LMU, 2015

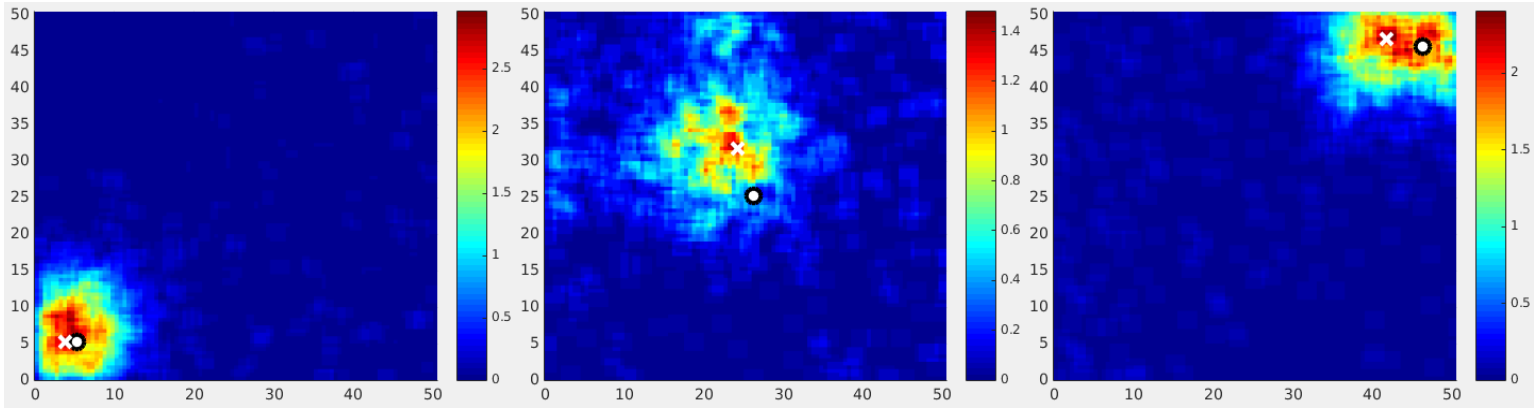
S. Aldawood, PhD thesis, LMU, in preparation

Spatial resolution of monolithic scintillator

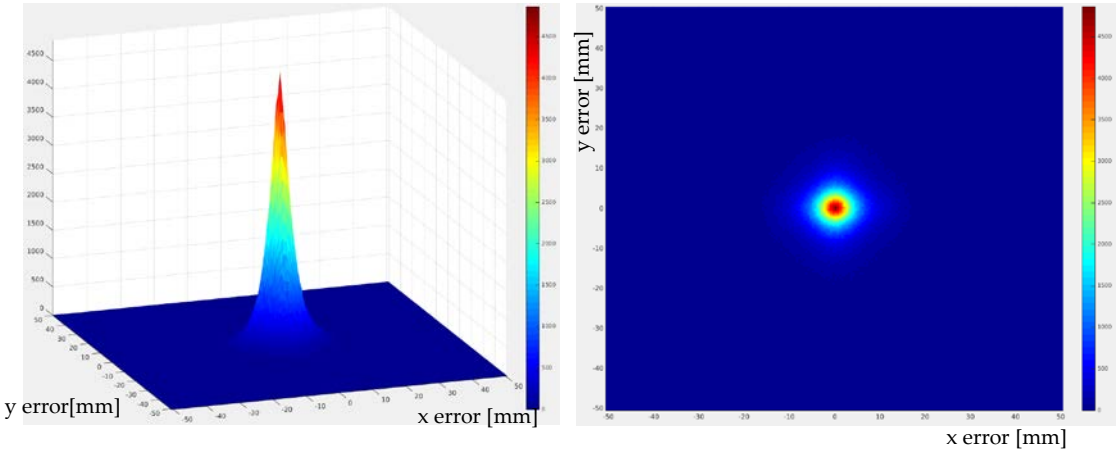
- **k – NN algorithm in action:**

  ‘leave-one-out’-method (k= 4000):

Real interaction position
Calculated interaction position



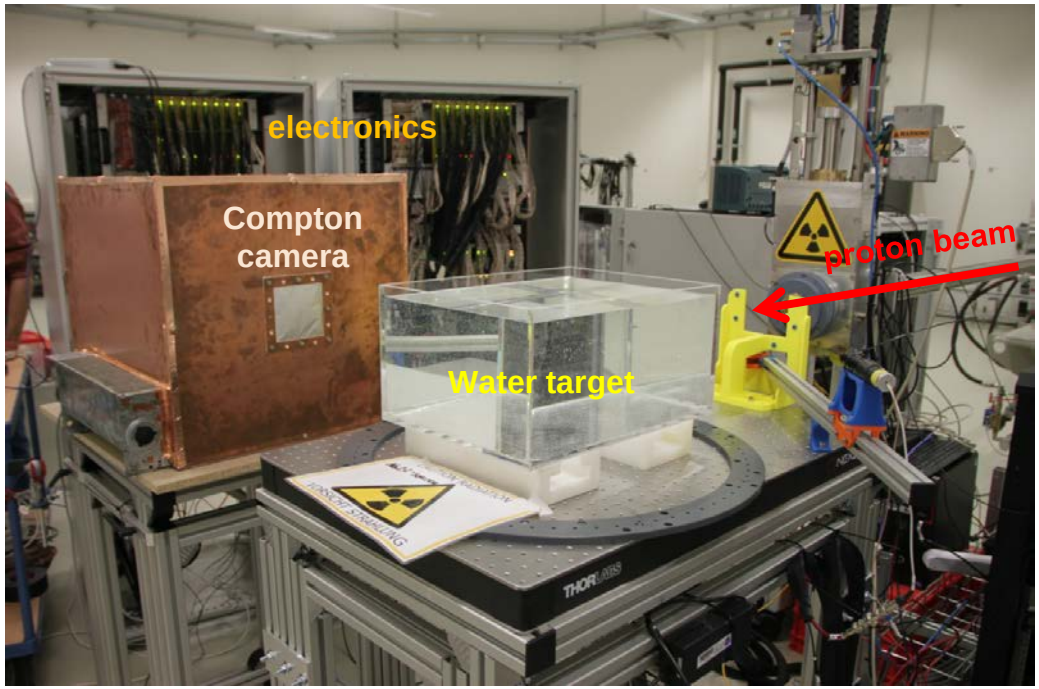
$(\Delta x_1, \Delta y_1)$
$(\Delta x_2, \Delta y_2)$
$(\Delta x_3, \Delta y_3)$
$\vdots$
$(\Delta x_{n_{tot}-1}, \Delta y_{n_{tot}-1})$



- **spatial resolution:** $\mathbf{FWHM = 5.0(1)\ mm}$ at n_{epp}= 400 using CAP k-NN algorithm

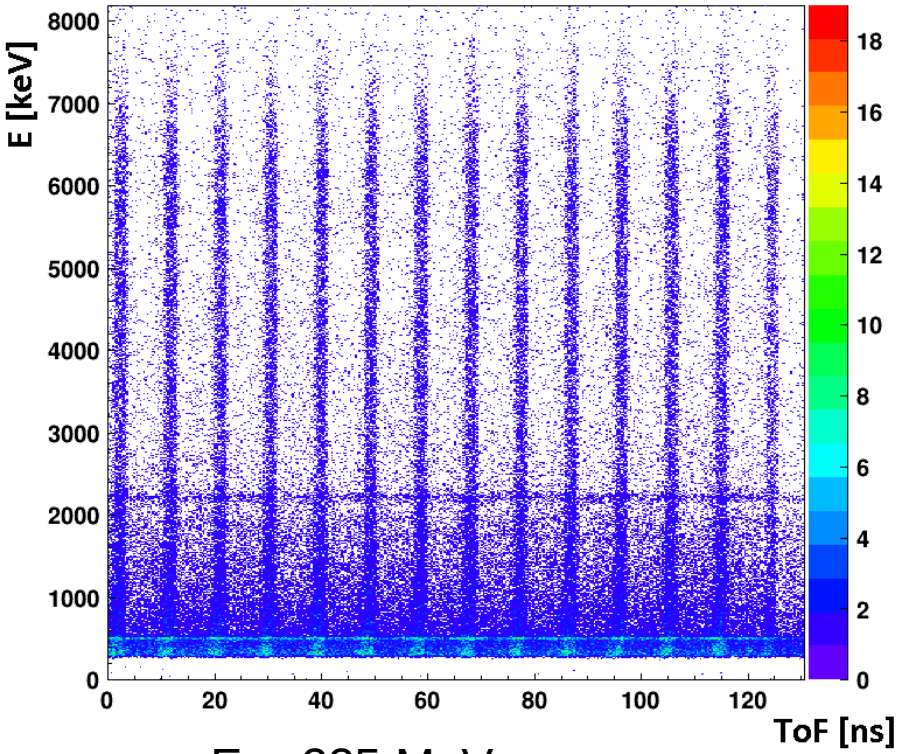
Commissioning at Clinical Proton Beam Facility

- OncoRay (Dresden): National Center for Radiation Research in Oncology
  - E_p= 100, 160 and 225 MeV
  - cyclotron RF: 106 MHz (Δt = 9.4ns)
  - tissue-equivalent targets:
    water phantom
    PMMA phantom ($C_5O_2H_8$)



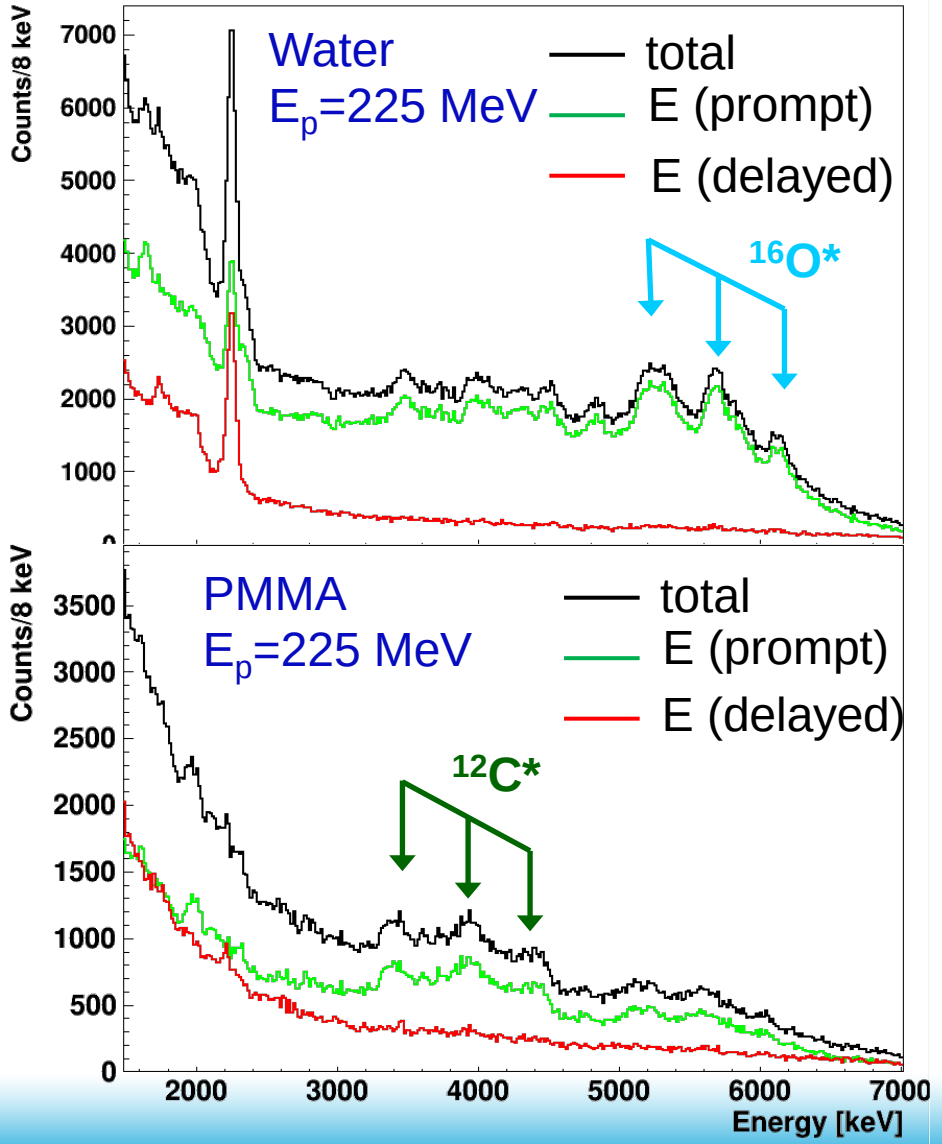
proton penetration depth in water:
E_p = 225 MeV : ~ 32 cm

Prompt γ spectra



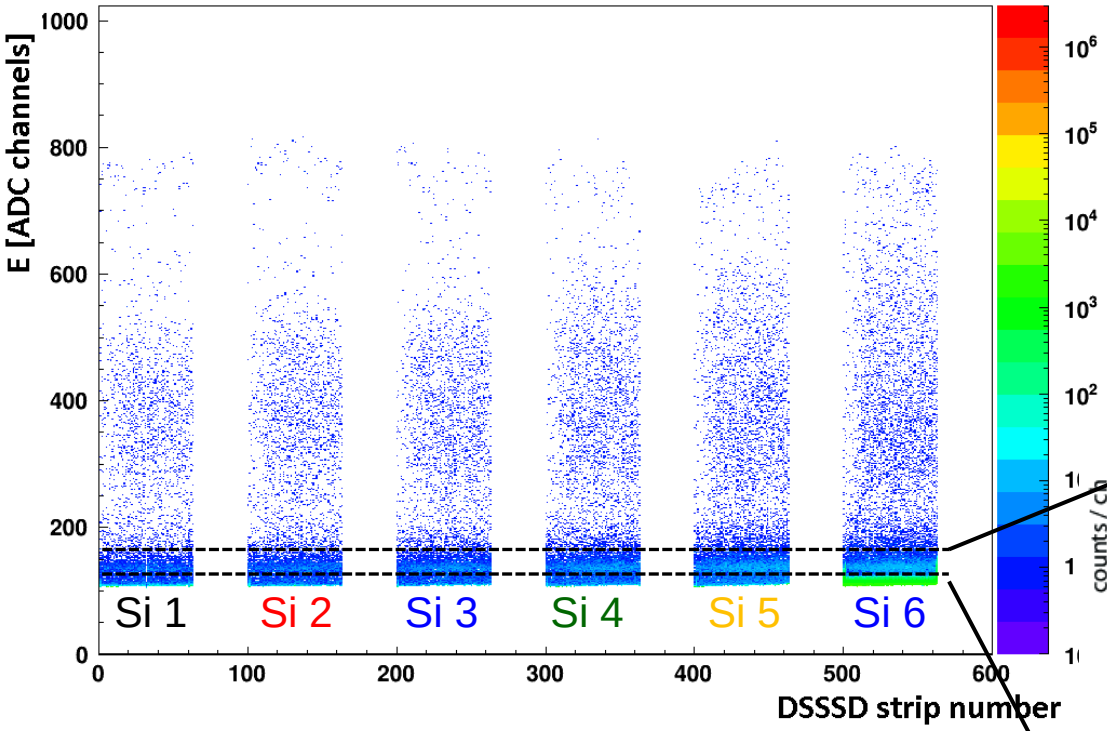
- E_p= 225 MeV
- Δt = 9.4ns

→ neutron suppression using ToF



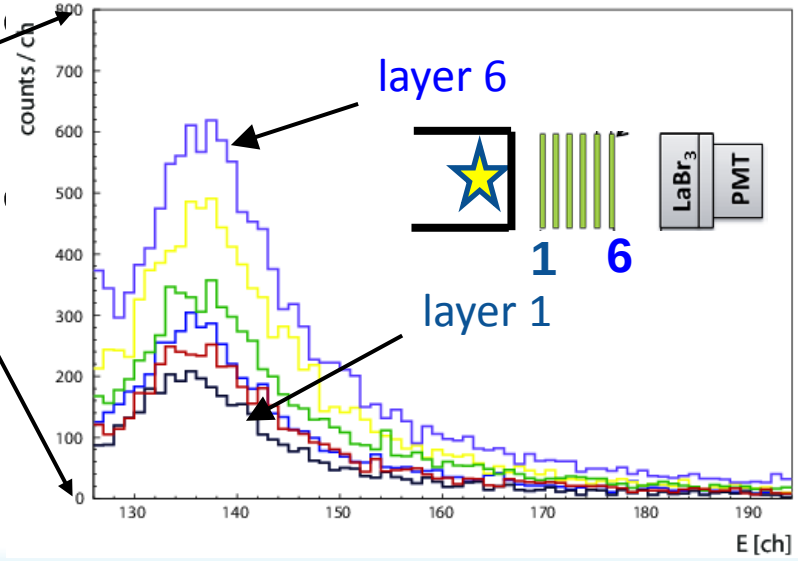
Commissioning at Clinical Proton Beam

- Strip detectors:



here: p-sides, each 64 odd strips
225 MeV, water target

- Compton electron energy deposition:



S. Liprandi, PhD thesis (in preparation)

Summary

- exploiting full potential of hadron therapy:
  - requires (online) verification of ion beam stopping range
- prompt-gamma range monitoring:
  - Compton camera provides (prompt-γ) imaging capabilities
  - development of prototype with electron tracking capability ongoing
    - absorber: $LaBr_3$ scintillator
    - scatterer/tracker: array of double-sided Si-strip detectors
- prototype characterization:
  - offline: energy and time resolution, photopeak efficiency
  - online: 4.4 MeV photons
    20 MeV protons/deuterons (Garching Tandem)
    100/160/225 MeV protons (clinical cyclotron)
  - ongoing: position determination in monolithic scintillator
- next steps:
  - source position image reconstruction
  - upgrade of readout electronics: new ASIC (and μ-TCA-) based

Thanks to …

- LMU Munich: C. Lang, S. Aldawood, I. Castelhano, H. v.d. Kolff, S. Liprandi, T. Marinsek, A. Miani, M. Pocevicius, B. Tegetmeyer, G. Dedes, R. Lutter, J. Bortfeldt, K. Parodi
- TU Munich: L. Maier, M. Böhmer, R. Gernhäuser
- OncoRay/ HZDR, Dresden: G. Pausch, C. Golnik, F. Hueso-Gonzalez, T. Kormoll, K. Römer, J. Petzoldt, F. Fiedler
- TU Delft: D.R. Schaart

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Thank you for your attention !