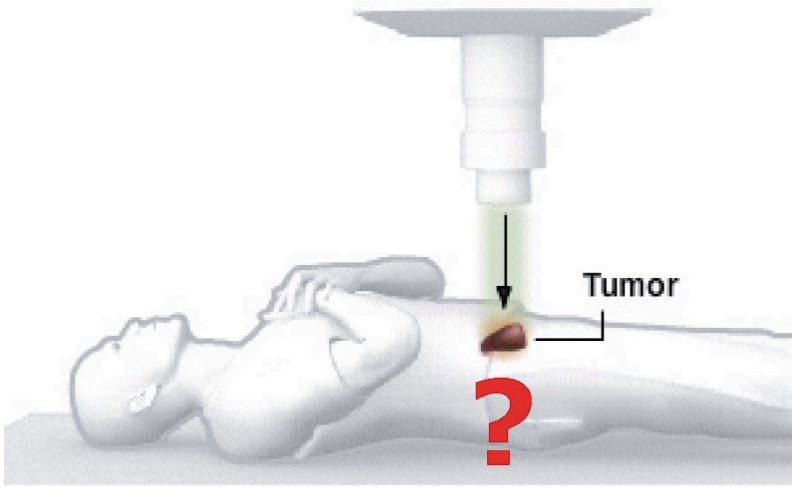
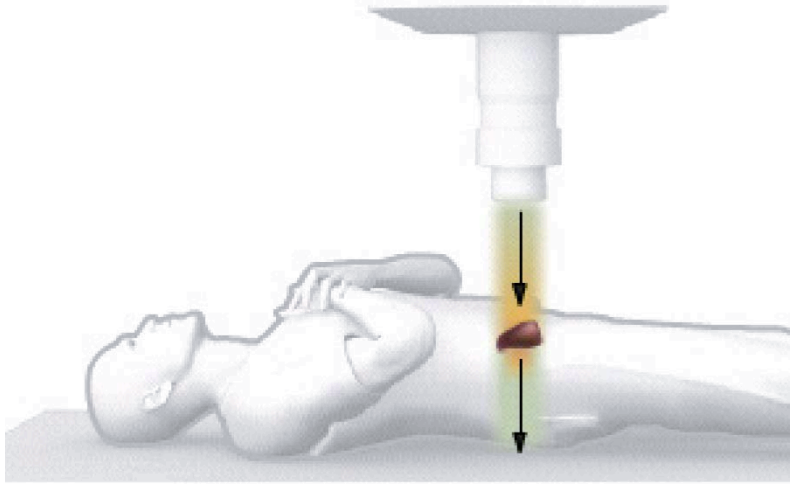
Novel Detectors for Range Assessment in Particle Therapy

P.G. Thirolf, LMU Munich



particle therapy (p, C)



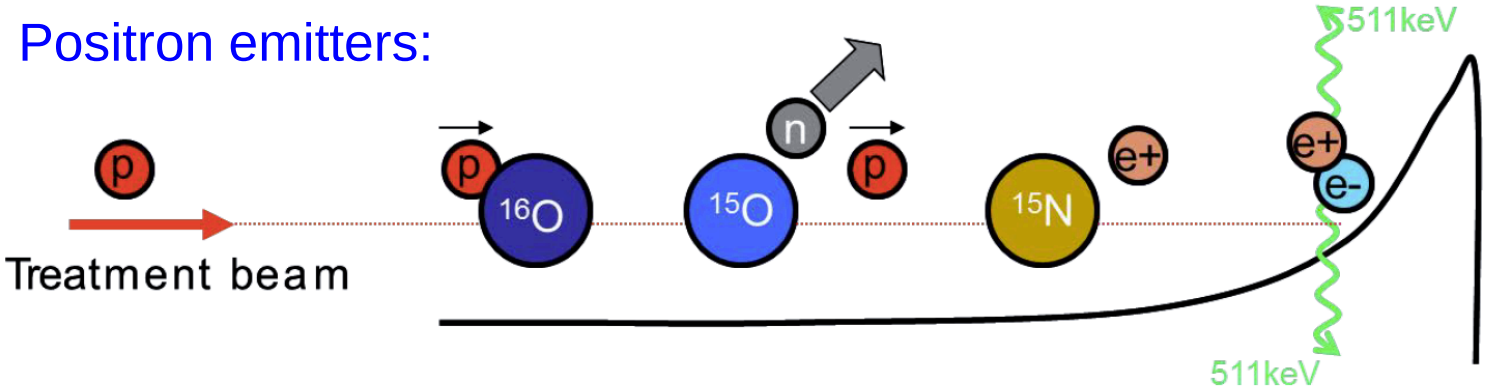
conventional radiotherapy (X-ray)

- need for accurate ion beam range assessment
- gamma imaging: technological improvements
  prompt-γ imaging
- charged particle imaging
- multimodal approaches

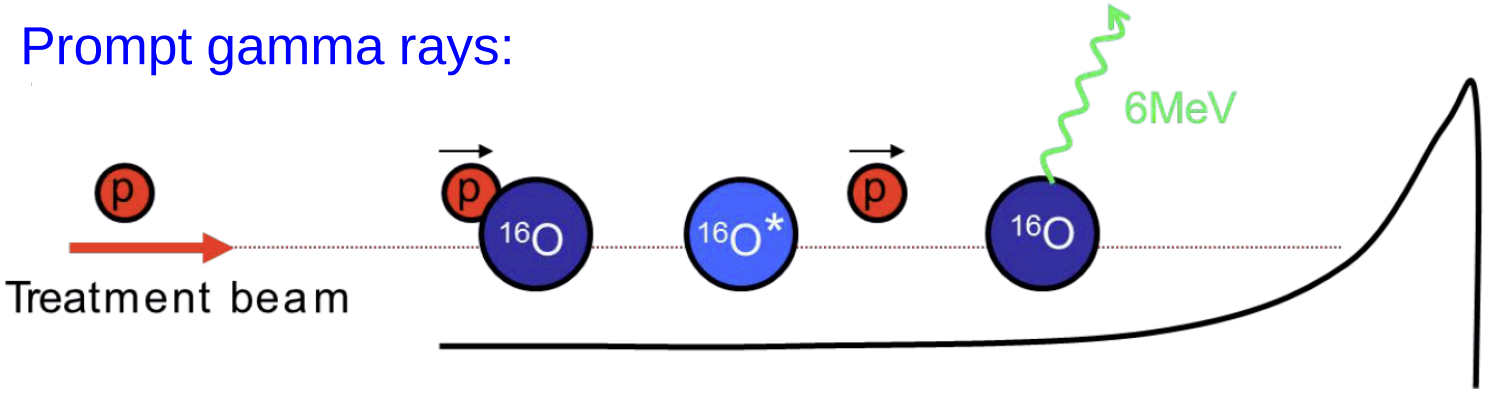
Signatures for Photon Imaging

- human body: > 90% oxygen, carbon, hydrogen, nitrogen

Positron emitters:

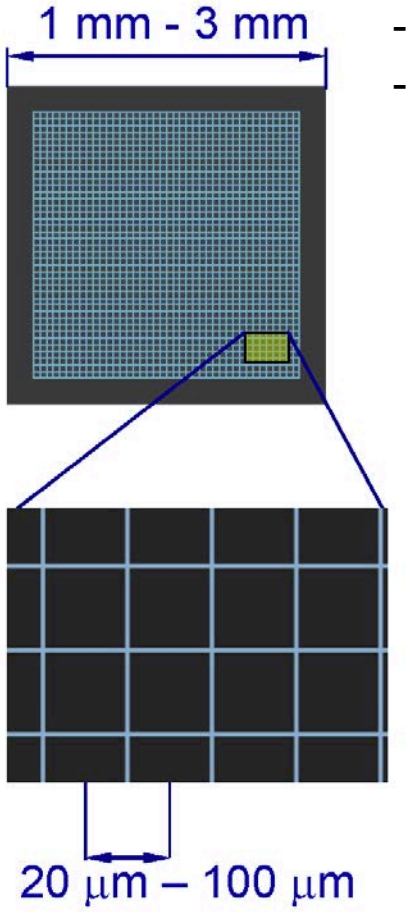


Prompt gamma rays:



Technological Improvements for Photon Detection

- **Silicon Photomultiplier** (SiPM) based photon detection:



courtesy: D.R. Schaart (TU Delft)

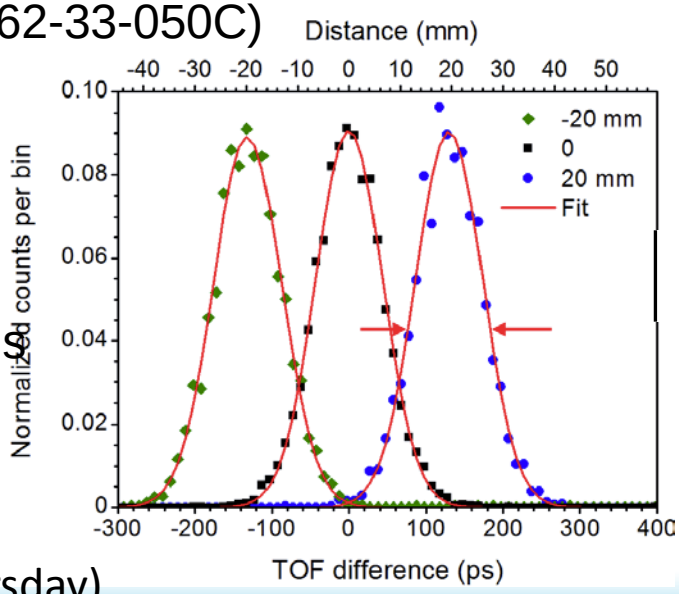
- array of many self-quenched Geiger-mode APDs (microcells)
- increasingly interesting as PMT replacement:
  → high gain (~10^6), high PDE, fast response (ns), magn. insensitive

- fast coincidence timing in PET applications:

→100 ps barrier (CRT) has been broken in laboratory:
2 small $LaBr_3$:Ce (5%) crystals (3x3x5 mm^3)
SiPM: Hamamatsu (MPPC-S10362-33-050C)
digital signal processing

- digital SiPM:
direct on-chip counting
negligible electronic noise
highly suited for monolithic crystals

~ 95 ps FWHM
~ 15 mm FWHM

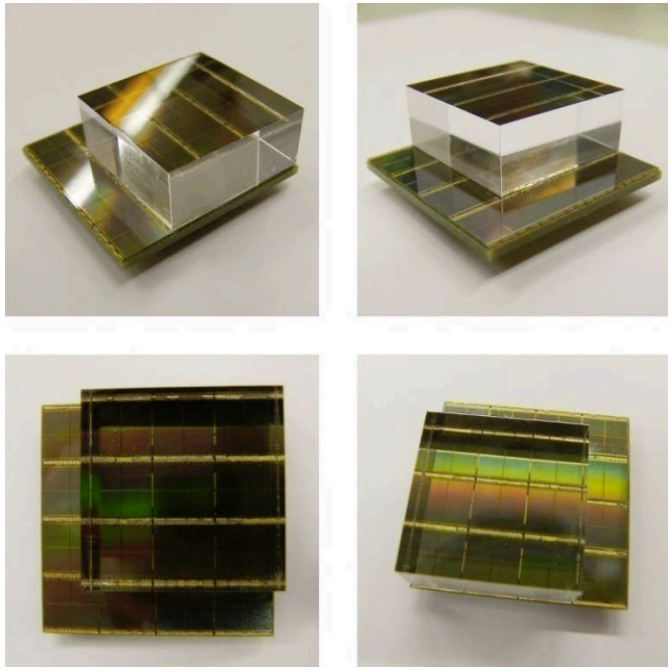


→ talk: D. Schaart (Thursday)

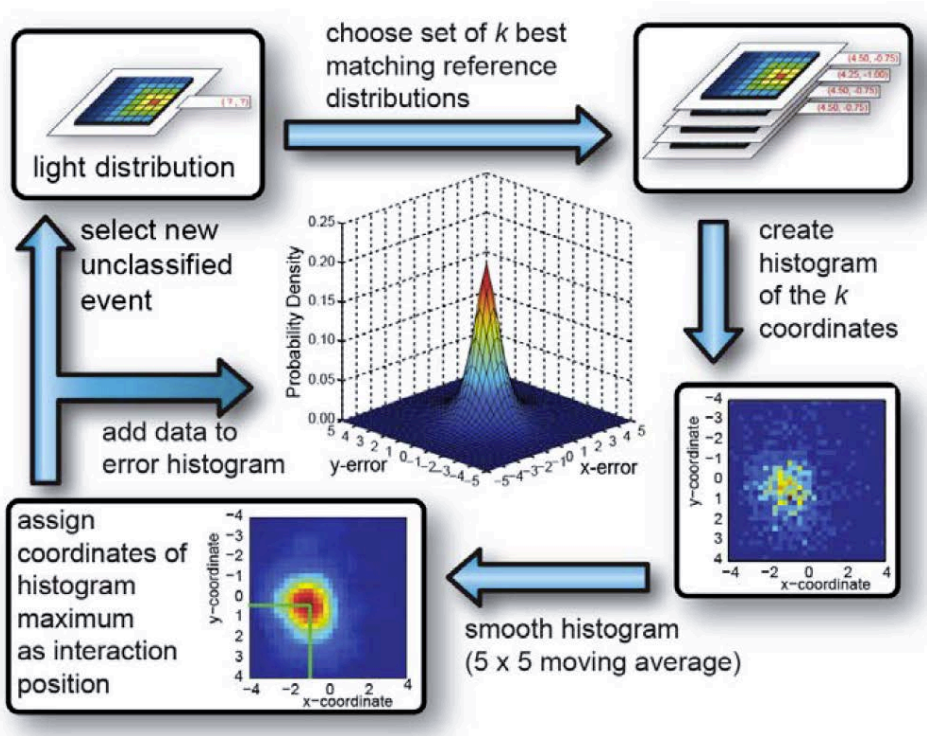
TU Delft
S. Seifert et al., IEEE Trans. Nucl. Sci. 59 (2012) 190

Spatial resolution from monolithic scintillators

- 24 x 24 x 10 (20) mm³ LSO:Ce,Ca scintillator on digital SiPM array:



- fast & accurate nearest neighbour algorithm:



- sub-2 mm spatial resolution:

crystal size [mm³]	average FWHM (mm)	
	x	y
24 x 24 x 10	**1.08**	**1.06**
24 x 24 x 20	**1.61**	**1.64**

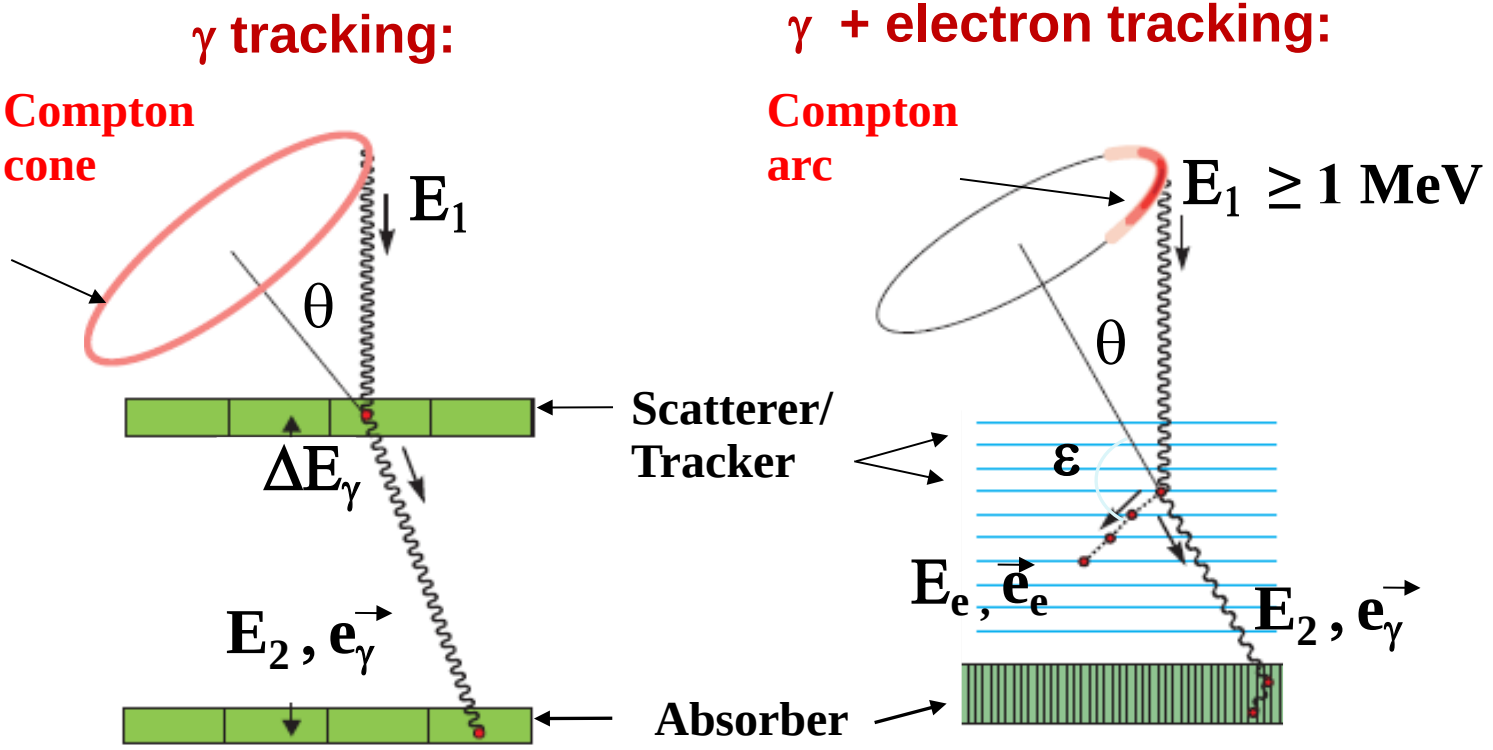
courtesy: D.R. Schaart (TU Delft)

H.T. van Dam et al., IEEE TNS 58 (2011) 2139
S. Seifert et al., PMB 58 (2013) 3061

(Prompt) Gamma Imaging: Compton Camera

- exploit kinematics of Compton scattering:

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

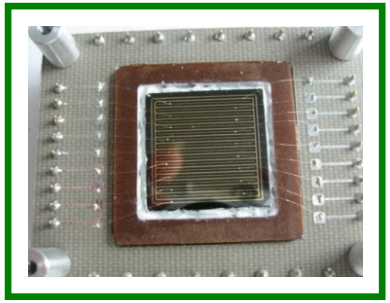


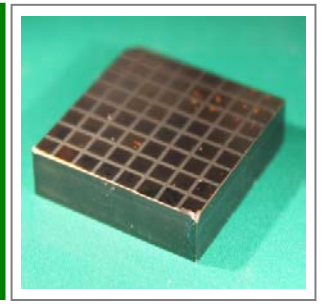
Compton Camera project at OncoRay/HZDR

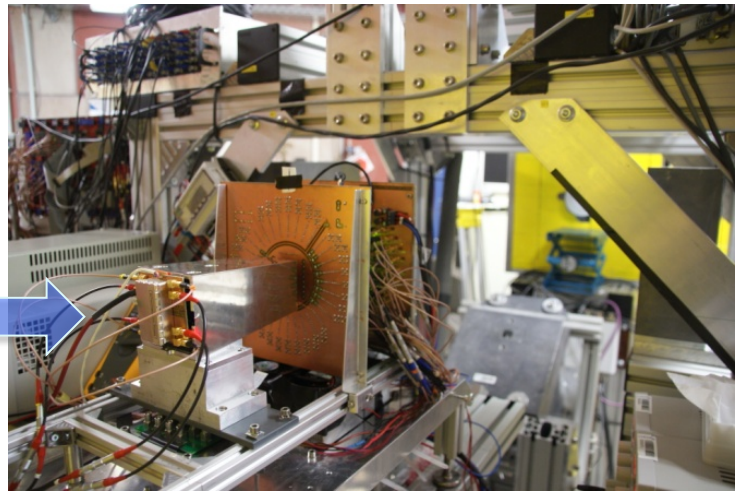
- Dresden groups: W. Enghardt, F. Fiedler, G. Pausch et al.:
  hardware R&D, modelling/image reconstruction

- translational research :
  new proton therapy facility in Dresden

- Compton camera development:
  scatter plane:
  (1) CZT Cross-strip detectors
  (2) CZT pixel detectors
  absorber plane:
  (1) LSO PET block detectors
  (2) dSiPM-based scintillation detectors







- Challenge: energy range of 2-8 MeV
  - no adequate γ sources in the lab
  - high expense of detector calibration
  - low probability of full absorption complicates image reconstruction

Prompt Gamma Imaging (OncoRay/HZDR)

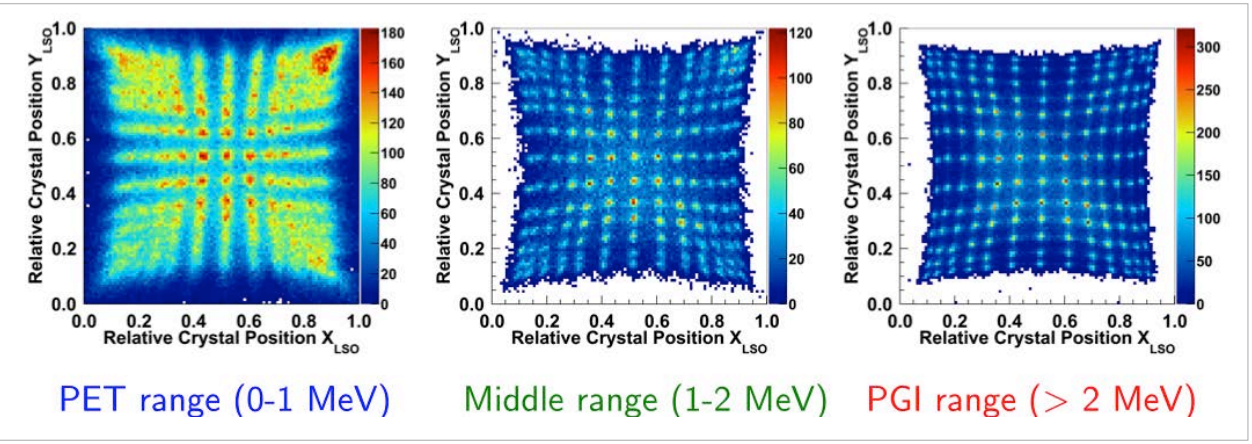
- Experiments: complementary facilities and techniques

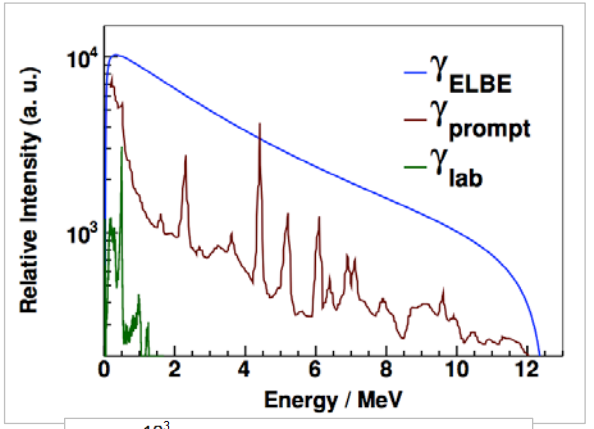
(1) ELBE (HZDR) 13 MeV electrons
point source of Bremsstrahlung
continuous spectrum, excellent timing

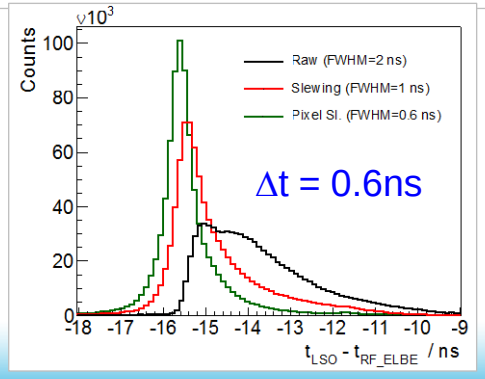
→ spatial & time resolution of scatter and absorber detectors

exemplary results for the LSO PET block:
- excellent spatial resolution in PGI range
- excellent time resolution in PGI range

if slewing and individual pixel corrections are applied:







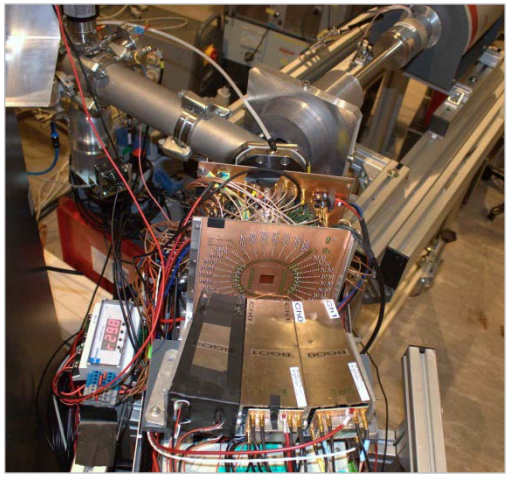
Prompt Gamma Imaging (OncoRay/HZDR)

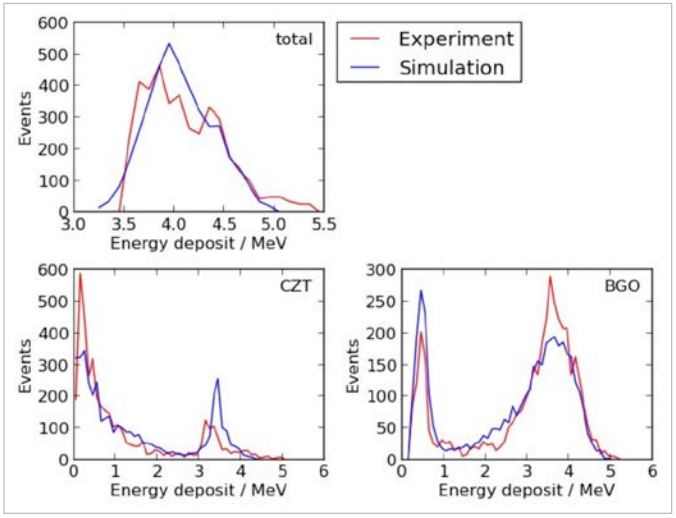
- Experiments: complementary facilities and techniques

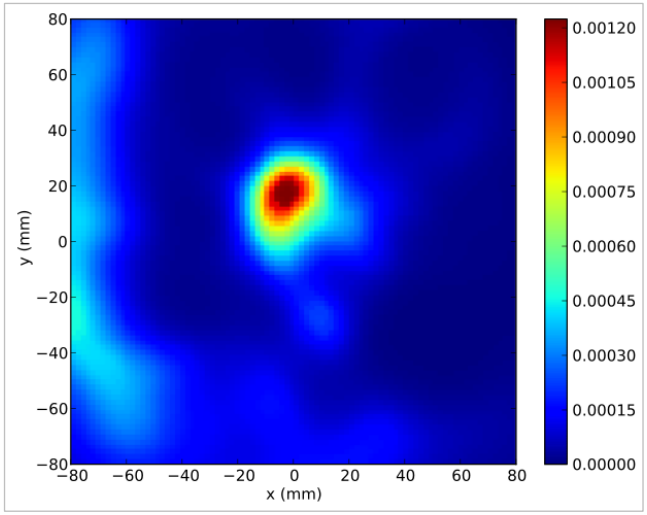
  (2) Tandetron (HZDR) low energy (1 MeV) protons
  4.44 MeV (and other) gammas
  via resonance capture reactions

→ verify imaging and modeling with MeV γ's:

- radiation field: E_γ= 4.44 MeV via $^{15}N(p,\alpha\gamma)^{12}C$
- imaging setup: 2 CZT cross-strip detectors
  3 BGO PET block detectors



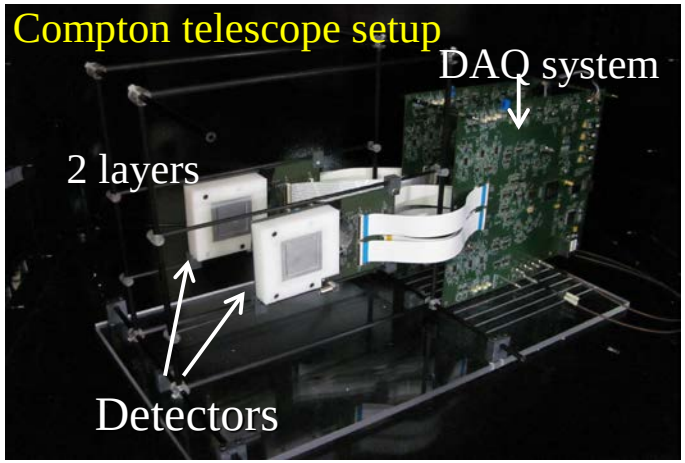




T. Kormoll et al., IEEE NSS/MIC 2013, M21-11
S. Schöne et al., IEEE NSS/MIC 2013, NPO2-64
H. Rohling et al., DGMP-Jahrestagung 2013, P 97

Compton Telecope @ Valencia

- based on continuous $LaBr_3$ crystals + SiPM:

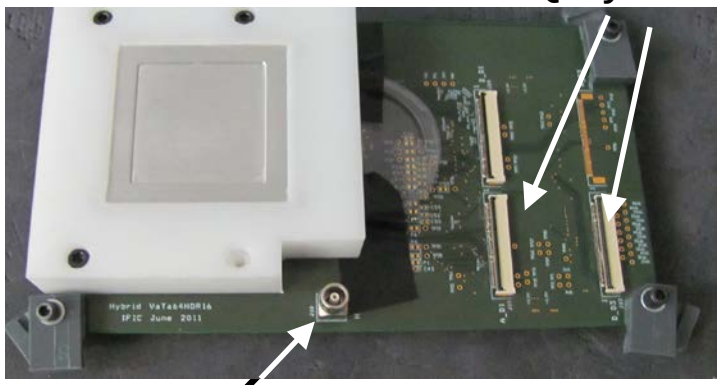


- **MPPC arrays:**
  placed in customized hybrid board
  - mechanical support, bias
  - ASIC: VATA64HDR16
    (Gamma Medica – Ideas)

- **SiPM:** MPPC array from Hamamatsu
  - 16 pixel of 3x3 mm^2
  - 50 μm microcell size
  in 4.05x4.05 mm^2 pitch (S11064-050PXI)

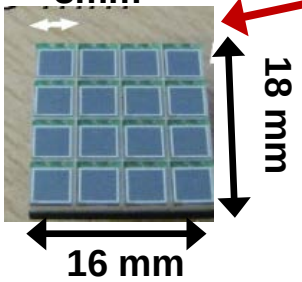
32 x 36 mm^2 $LaBr_3$:

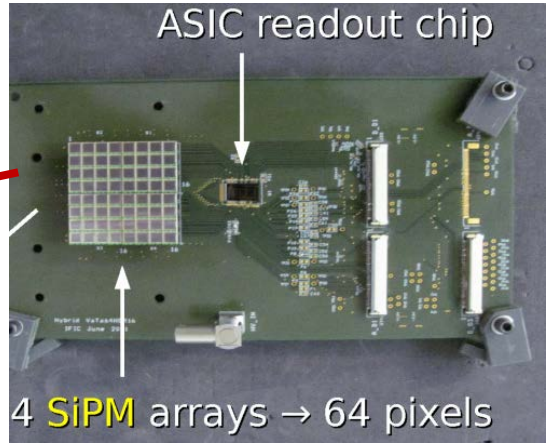
connection to DAQ system



high voltage

1 array:



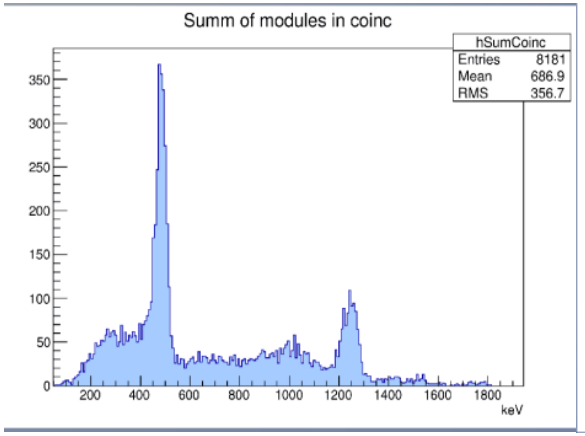


→ talk: P. Solevi

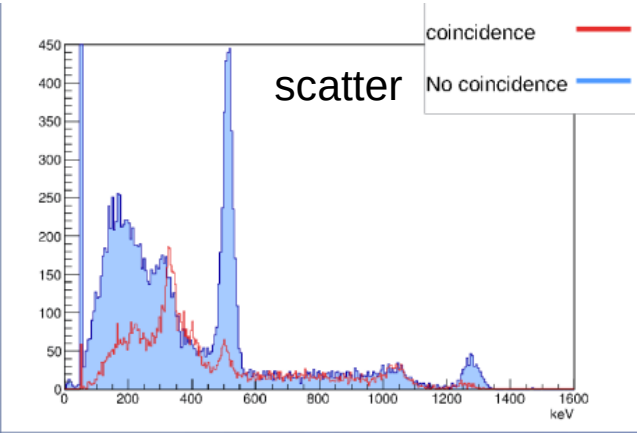
Characterization with ^{22}Na source

- coincidence test: 2 ($LaBr_3$) detectors in time coincidence

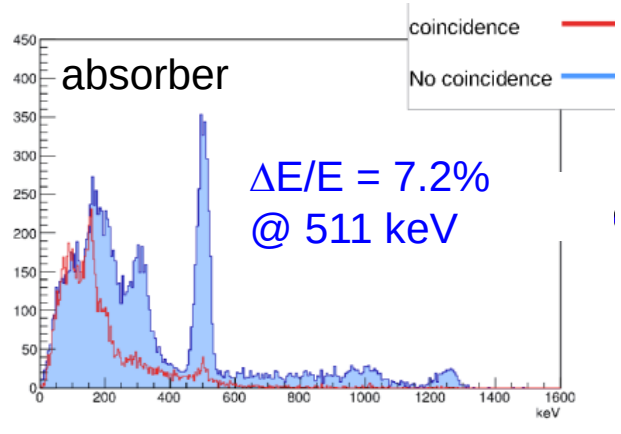
  → collect ^{22}Na photons: Compton scattered in Det. 1, absorbed in Det. 2



coincident energy sum

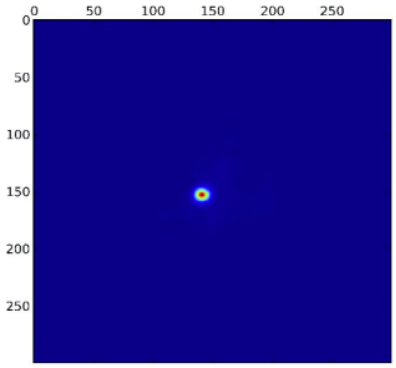


Det. 1: SiPM + 5 mm $LaBr_3$

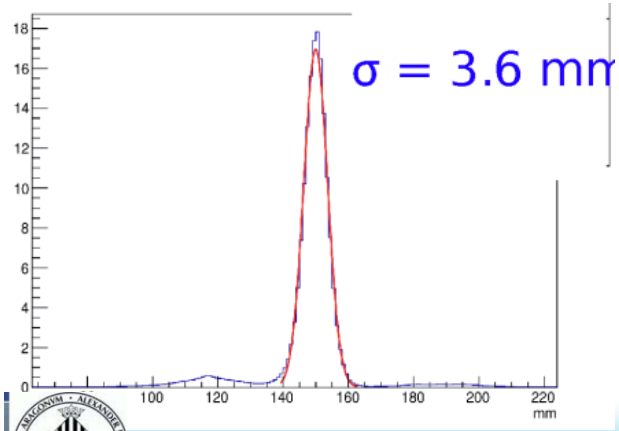


Det. 2: SiPM + 10 mm $LaBr_3$

- image reconstruction:
  - ^{22}Na point source:
  - ML-EM algorithm

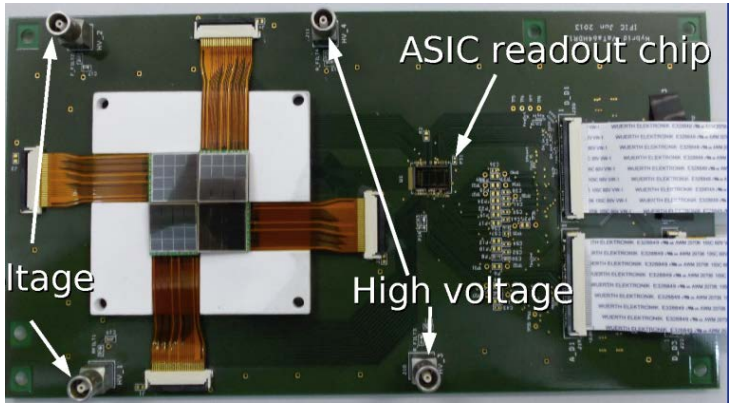


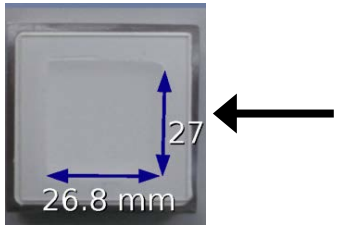
- spatial resolution:

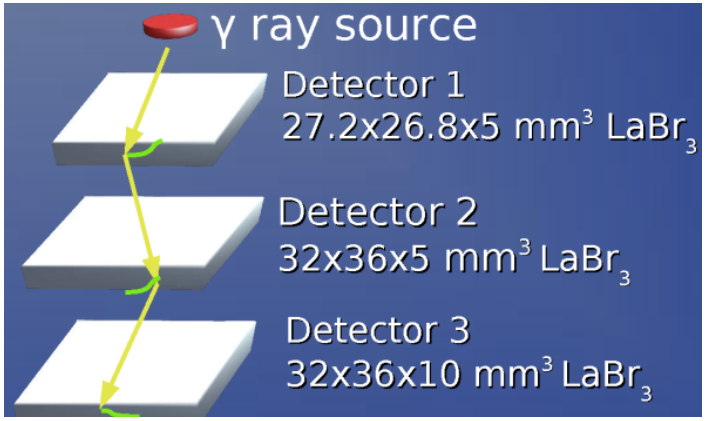


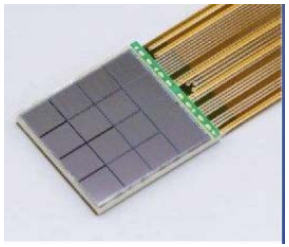
Compton telescope: 3rd Detector Layer

- new version of PCB hybrid:
  individual biasing of each MPPC array
- new type of SiPM array with increased
  active area (elements gap: 0.2 mm instead 1.5 mm)
- improved energy resolution: 6.4% @ 511 keV



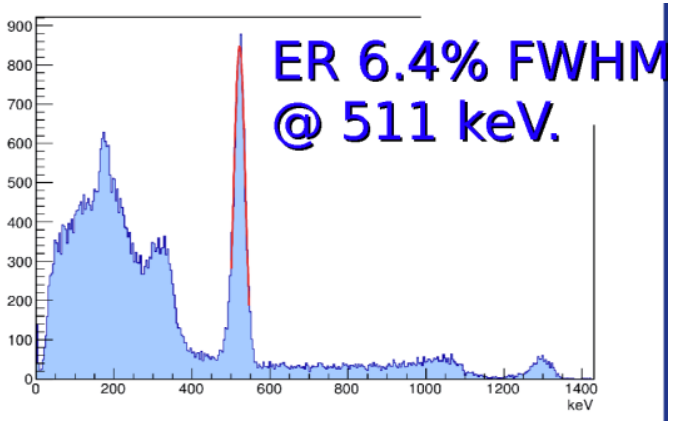






Hamamatsu
4x4 MPPC array
(S11830-3344MF)

- requires:
  ≥ 3 Compton interactions
  or 2 Compton interactions + photo-absorption
- 3rd layer ready to operate

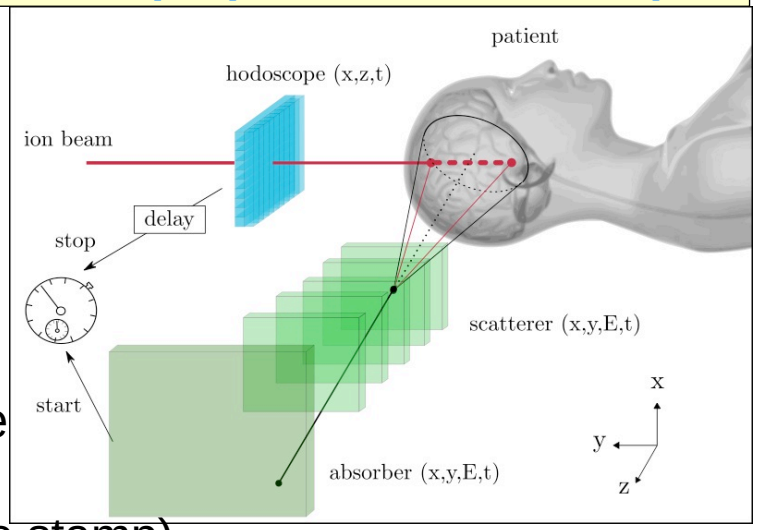


^{22}Na energy spectrum from
27.2 x 26.8 x 5 mm^3 $LaBr_3$

Time-Of_Flight Compton Camera (IPN Lyon)

→ **scatterer (7 DSSSD) + absorber (100 BGO) + hodoscope (2x128 scint. fibers)**

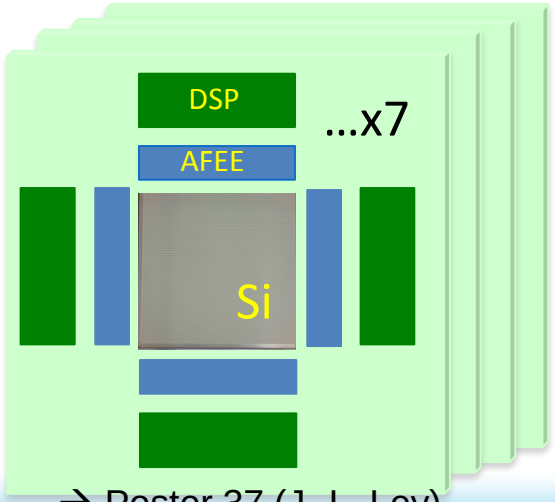
R&D ongoing: electronics, mechanics



- **scatterer:**
  - 7 silicon layers of 9 x 9 x 0.2 cm^3
  - 2 x 64 strips

  dedicated analog electronics:

  ASIC (8 ch.):
  - charge sensitive pre-amplifier for P- and N-side
  - slow shaper: 1 µs (energy)
  - multigain fast shaper & comparator: 15 ns (time stamp)
  - electronic noise expected: 120 e^- rms
- **absorber:**
  - size : 40 x 40 cm^2, 400 PMTs channels
  - development at LPC Clermont-Ferrand
- **data acquisition system:**
  - high-rate µTCA data acquisition system (45 Gbps)
  - development at CPPM-Marseille (Poster C. Abellan)

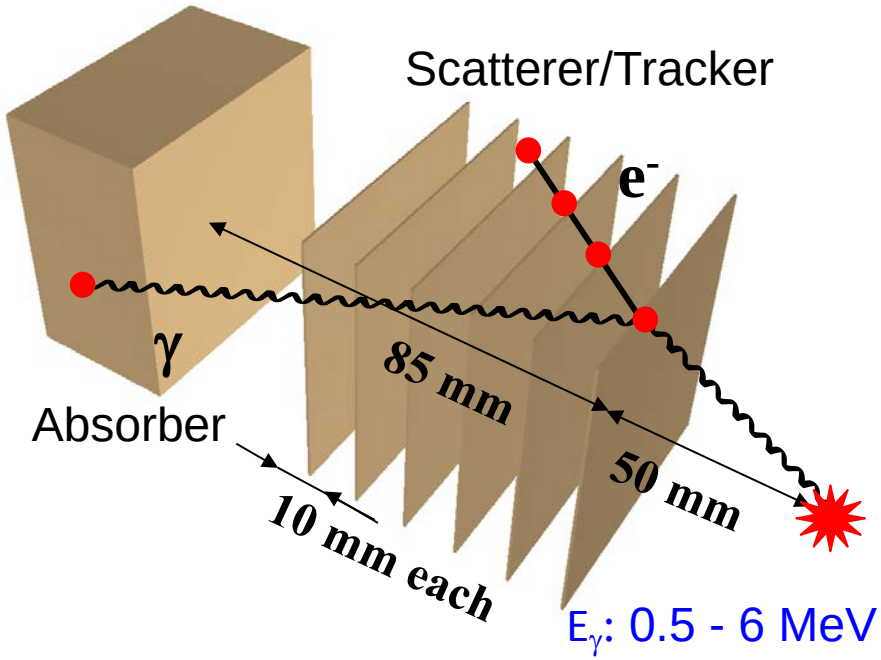


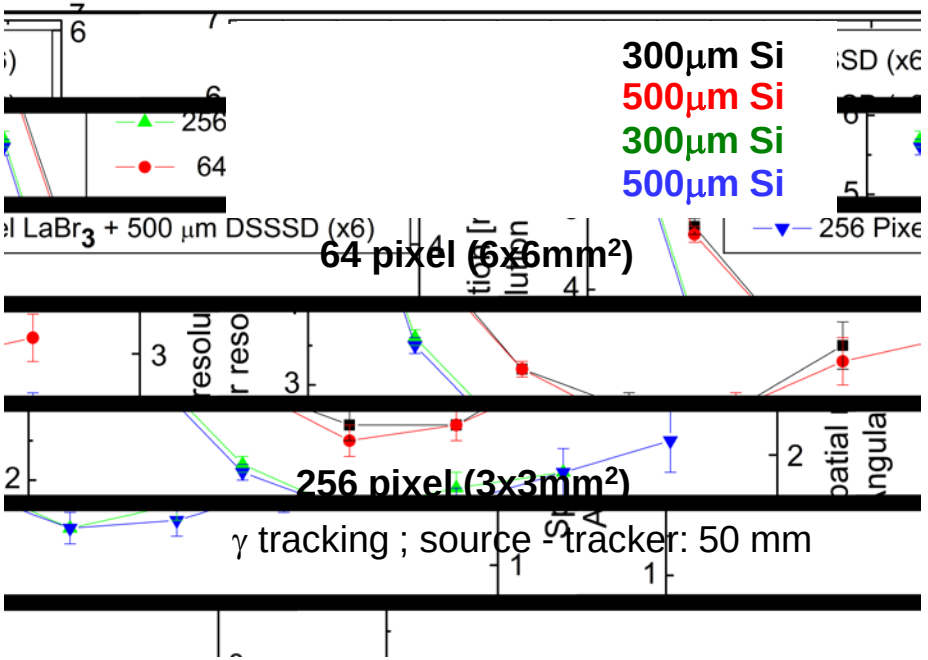
→ Poster 37 (J.-L. Ley)

courtesy: D. Dauvergne, IPN Lyon

Garching Compton Camera

- Goal: range verification of laser-accelerated protons
- Method: prompt γ imaging with Compton camera (with electron tracking)

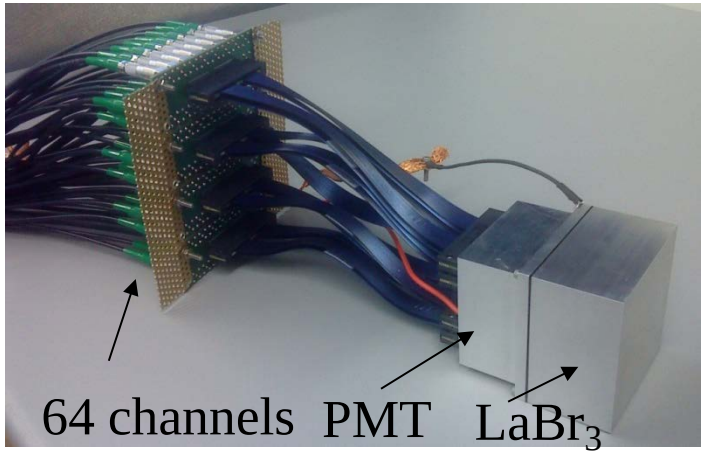




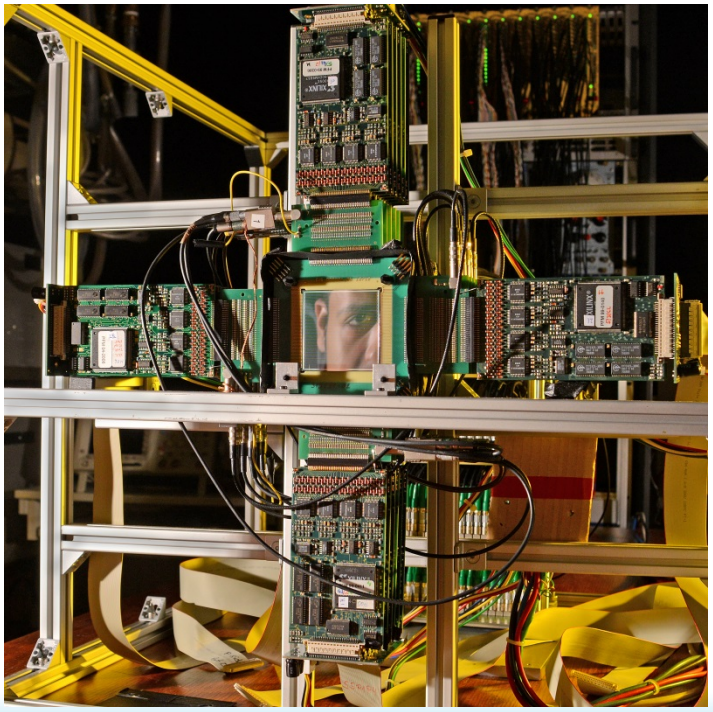
- Simulation/reconstruction tool: MEGAlib
  - → Monte Carlo simulation (based on Geant4)
  - → event reconstruction
  - → image reconstruction (LM-ML-EM algorithm)

C. Lang et al., JINST 9 (2014) P01008

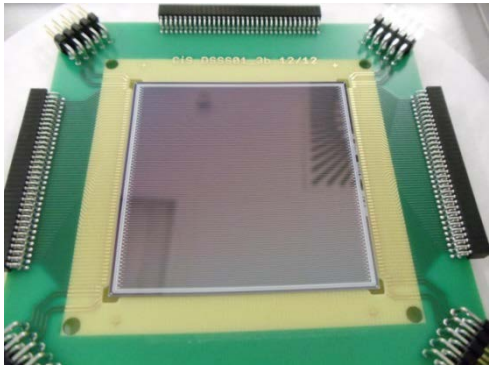
Compton Camera Project in Garching



- Absorber:
  $LaBr_3$ crystal: 50 x 50 x 30 mm^3
  PMT: Hamamatsu H9500 (multi-anode: 16x16)
  start version: 64 pixel (6x6 mm^2)
  upgrade: 256 pixel (3x3 mm^2)
  individual spectroscopy electronics channels



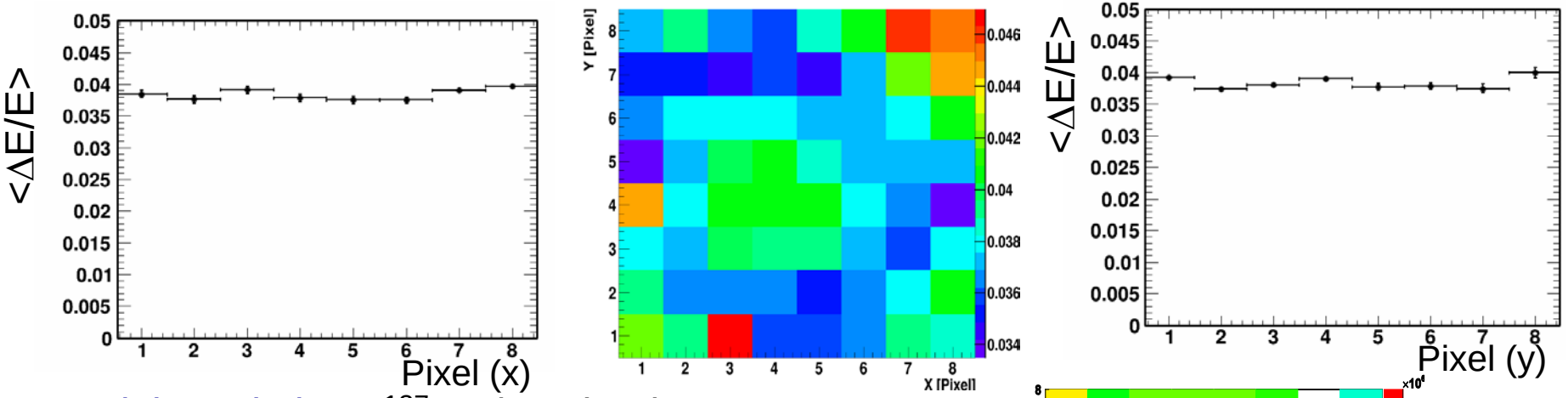
- Scatterer/Tracker:
  6x double-sided silicon strip detectors (DSSSD)
  → active area 50 x 50 mm^2
  → thickness : 500 μm
  → 128 strips on each side
  → pitch size 390 μm



- DSSSD readout:
  - each side: 2x64 ch. ASIC boards (GASSIPLEX)
  - VME readout controller

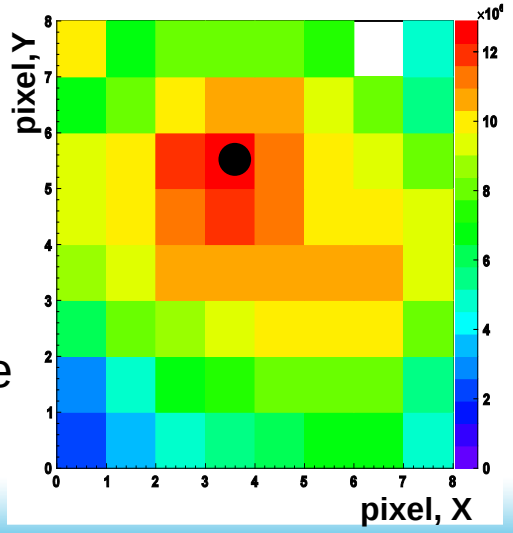
$LaBr_3$ detector properties

- time resolution: Δt = 270 ps
- energy resolution: $\langle \Delta E/E \rangle$ = 3.8% @ 662 keV (^{137}Cs)



- spatial resolution: ^{137}Cs (662 keV),
  - collimated source (Ø 1 mm)
    (background corrected, gain matching:
    electronics, uniformity correction:
    PMT, crystal)
  - analysis in progress: Ø 0.5 mm collimation/step size

→ point-spread function for 256 PMT pixel:
k-nearest neighbour algorithm (Delft group)



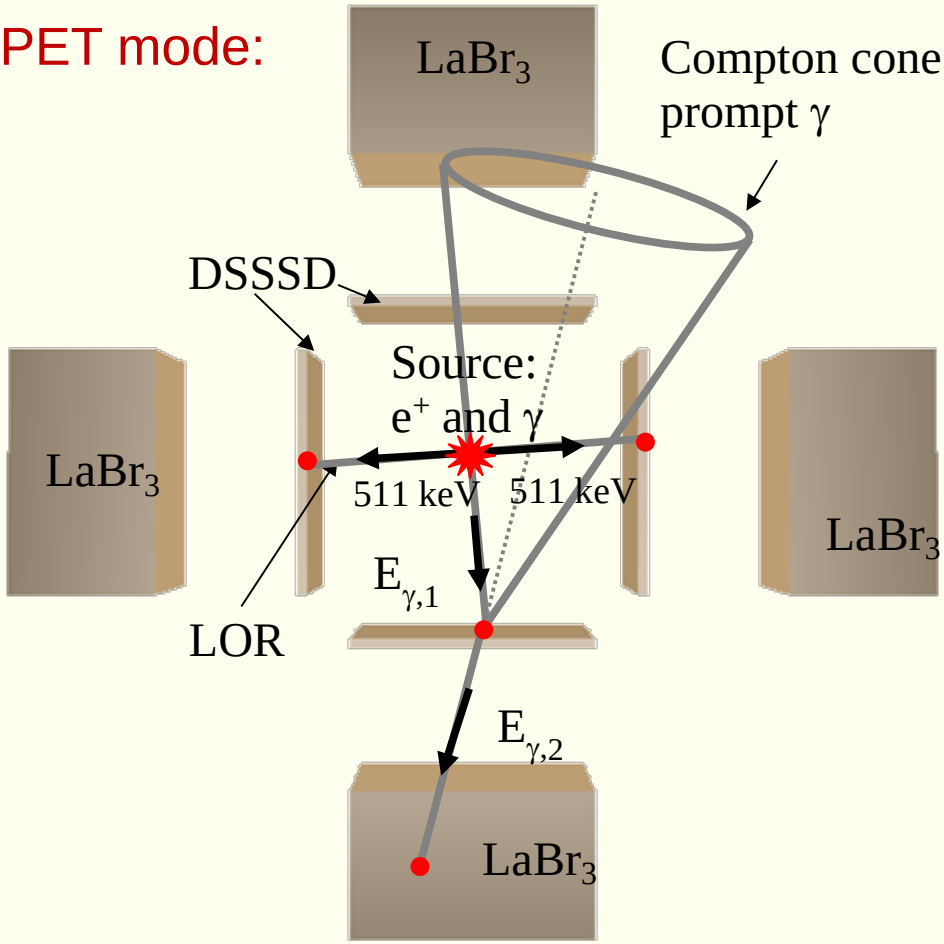
●: source position

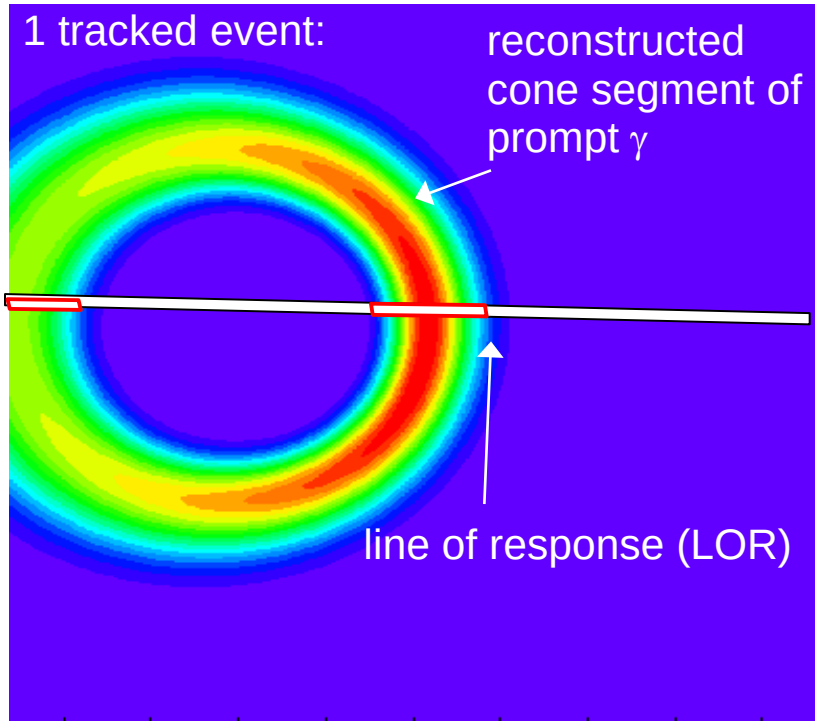
H. v.d. Kolff, Master thesis, in preparation (2014)

Perspective: Hybrid detector system

(i) prompt γ detection: during therapy irradiation
(ii) delayed γ detection ((γ–)PET, 511 keV): during irradiation interrupts

γ-PET mode:





enhanced sensitivity via γ-PET mode:
→ intersection of LOR + prompt γ in individual event

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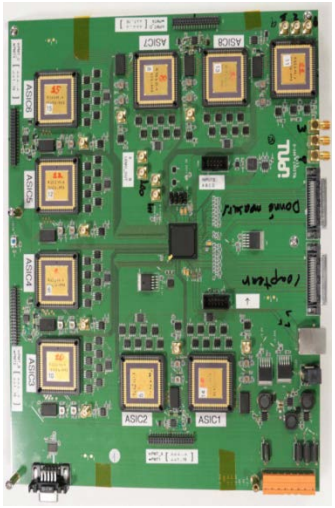
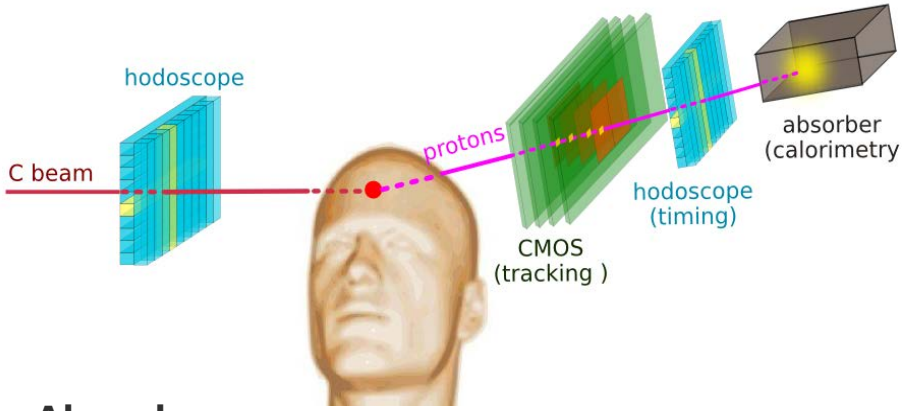
Proton Interaction Vertex Imaging for carbon therapy quality control

Hodoscope system:

2 x 32 scintil. fibers (1mm)
4 x MA-PMT (H8500)



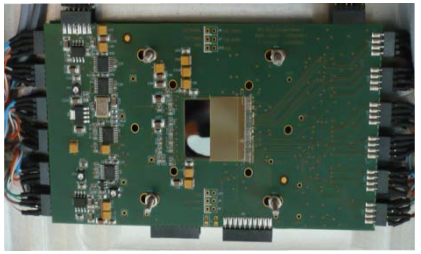
8 ASICs: (fast comparators)
1 FPGA: (400 MHz)



Absorber:

2" x 3" Lanthanum Bromide scintillator
ΔE/E ~ 3% @ 662 keV, Δt < 1 ns

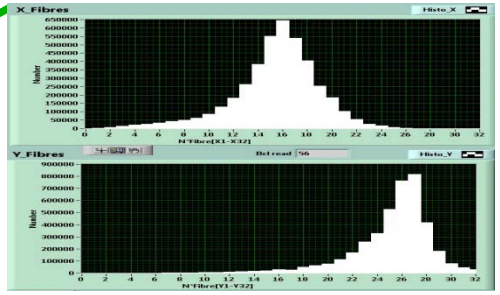
CMOS Tracker:



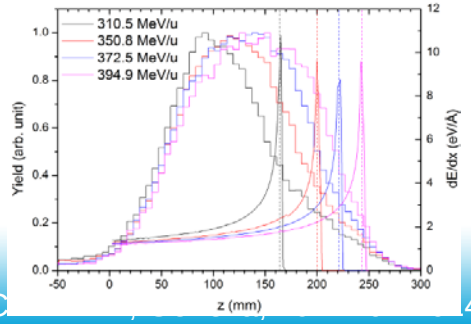
8 x Mimosa 26 ASICs

1152 x 576 pixels
negligible dead time
115.2 µs integration time

Beam Profile:



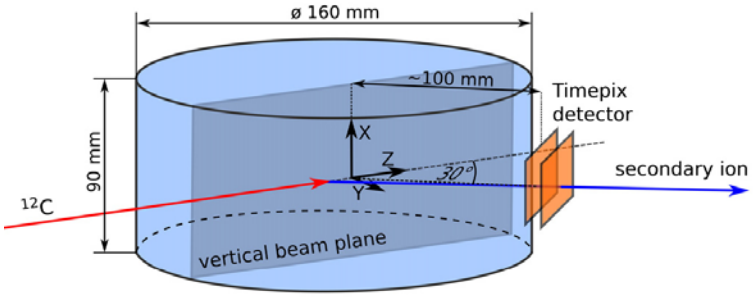
Vertex distributions:
(Talk R. Rescigno)

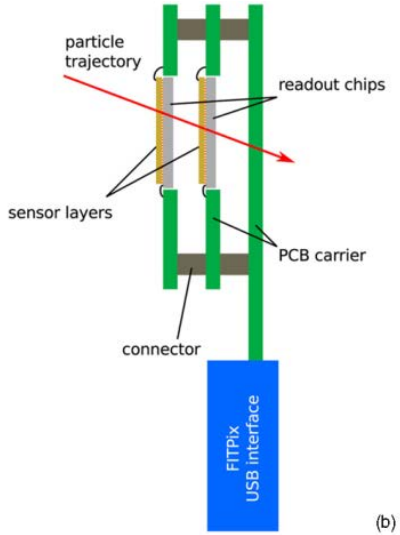


courtesy: D. Dauvergne, IPN Lyon

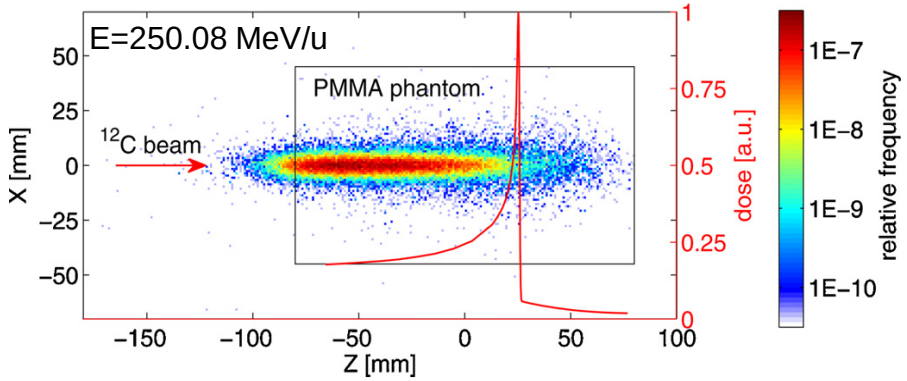
Range Monitoring via Secondary Ions

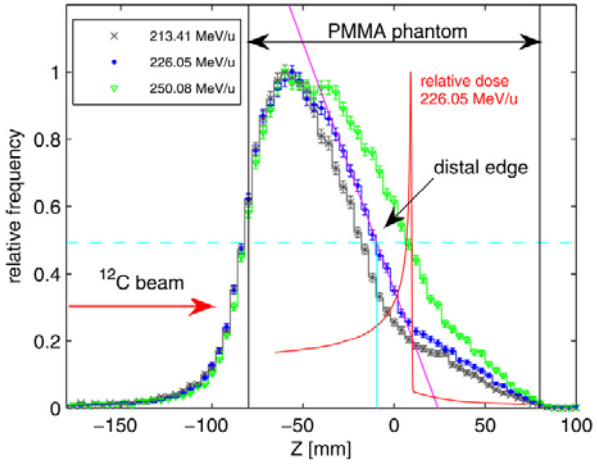
- double-layer Timepix detector: tracking





- back-projected secondary particle tracks:





- detectable:

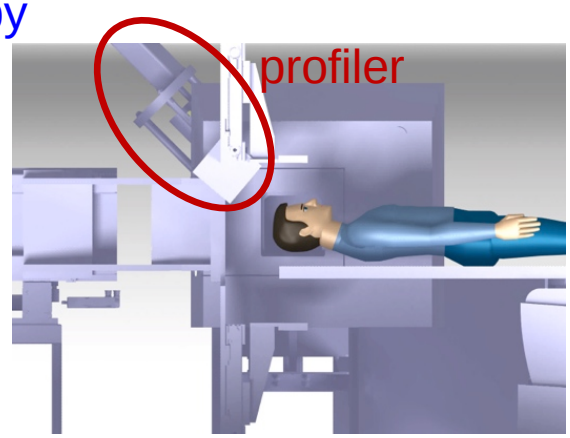
beam range: Δ~ 1.3 mm ; beam width: Δ~0.9 mm ; (lateral) beam position: Δ< 1mm

Heidelberg- group, K. Gwosch et al., PMB 58 (2013) 3755

The INSIDE project @ CNAO

- **In**novative **S**olutions for **I**n-beam **D**osim**e**try in Hadrontherapy

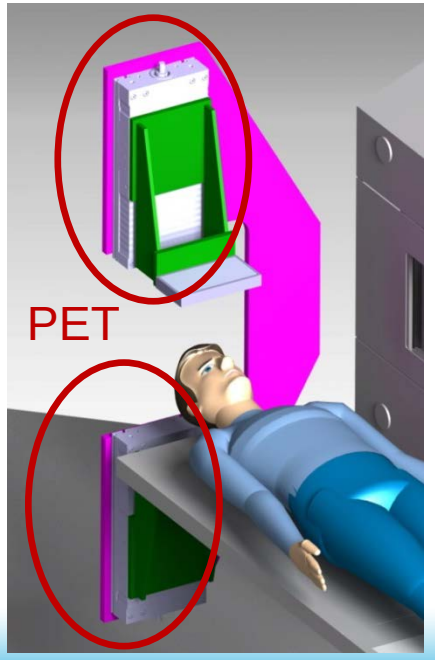
  (Bari, Pisa, Roma, Torino Univ., Milano LNS, INFN Torino)



→ In-beam multimodal dose profiling by **PET-induced activities** and **charged secondaries** detection.

→ Mechanics and operation optimized to be inserted in the CNAO work-flow

- PET: 2 planar panels: each 10 cm x 20 cm wide.
  each panel: made by 2 x 4 detection modules



- each module: composed of pixelated LYSO scintillator matrix:

  → 16 x 16 pixels, 3x3 mm^2 crystals, 3.1 mm pitch
  → total sensitive area of 5x5 cm^2

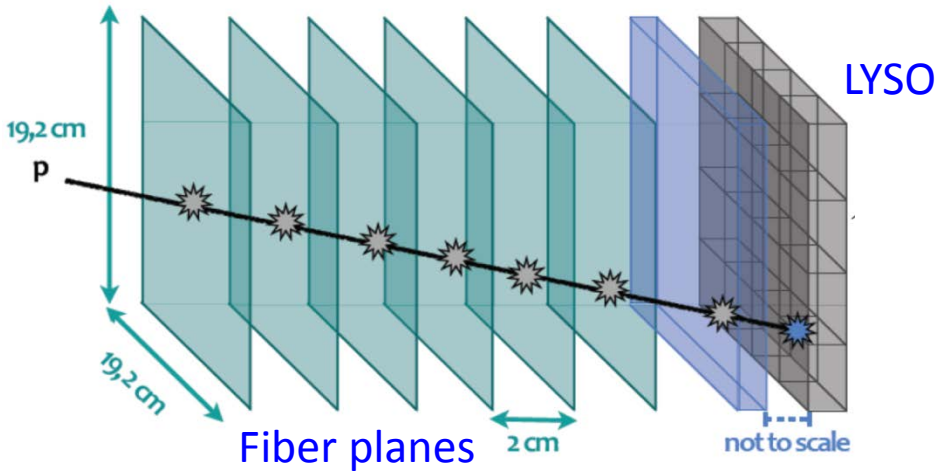
- 1 SiPM array (16x16 pixels) coupled 1:1 to each LYSO matrix

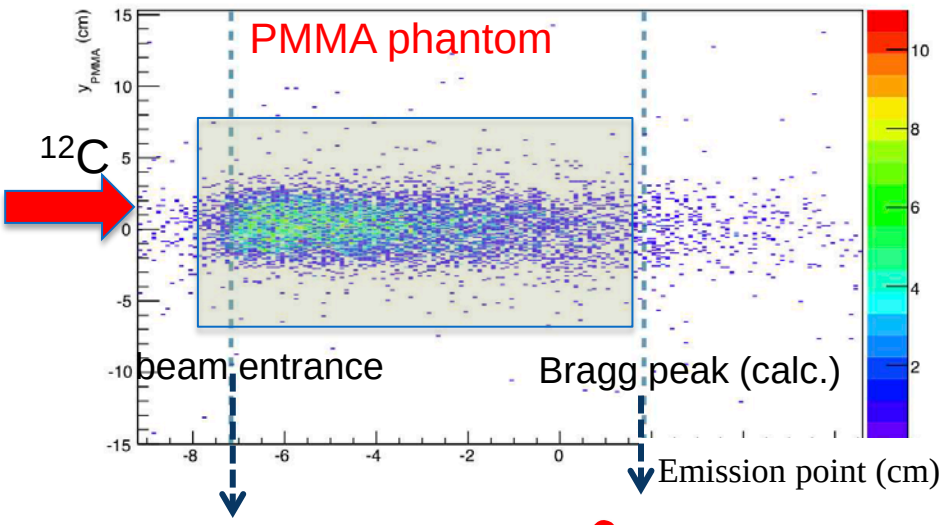
- DAQ: sustains annihilation and prompt photon rates during the beam irradiation

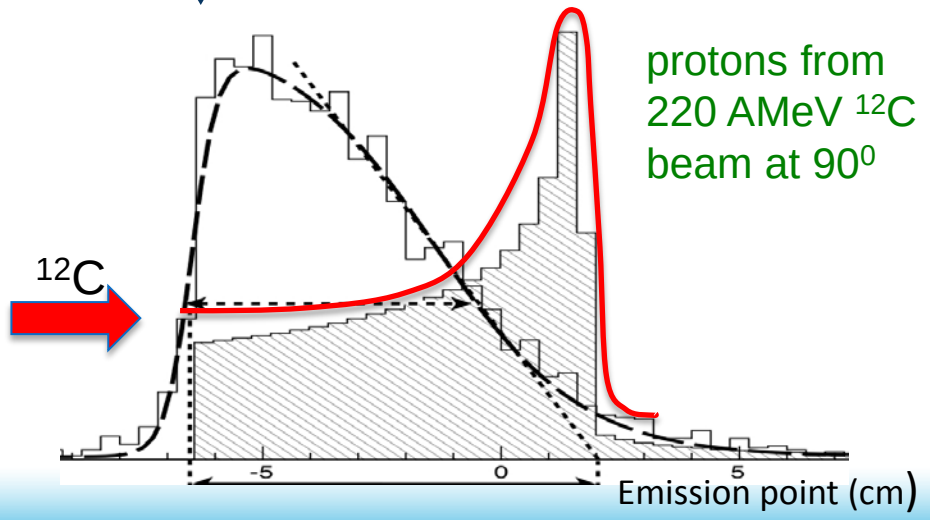
The INSIDE charge profiler

- charged secondaries vs. γ's: higher detection efficiency compensates lower yield

Profiler: - six 20x20 cm^2 XY planes of scint. fibers coupled to 1 mm^2 SiPM
- energy measured by array of LYSO crystals







- charged (mainly protons) emission point distribution gives info on beam profile
- pencil-beam geometry can be reconstructed via backpointing of charged track to beamline

courtesy: V. Patera

Summary

- Broad spectrum of ongoing efforts all over Europe on ion beam range assessment:
  - new technologies:
    - new readout techniques
    - improved algorithms: simulation, reconstruction
    - new scintillators
  - prompt gamma imaging (Compton cameras)
  - charged particle imaging
  - multi-modal approaches

- not covered here: iono-acoustics signal for Bragg peak assessment
  → talk by K. Parodi

Credits …

Thanks for valuable input and comments:

- D.R. Schaart (TU Delft)
- G. Pausch (OncoRay Dresden/HZDR)
- D. Dauvergne (IPN Lyon)
- V. Patera (Univ. 'La Sapienza' Rome)
- P. Solevi, M. Trovato, M. Rafecas (IFIC / Univ. Valencia)
- LMU Munich: C. Lang, S. Aldawood, H. v.d. Kolff, W. Assmann, D. Habs, S. Reinhardt, R. Lutter, J. Bortfeldt, K. Parodi
- TU Munich: L. Maier, M. Böhmer, R. Gernhäuser

Thank you for your attention !