Radiation Detection in Particle Therapy Developments & Needs at LMU Munich

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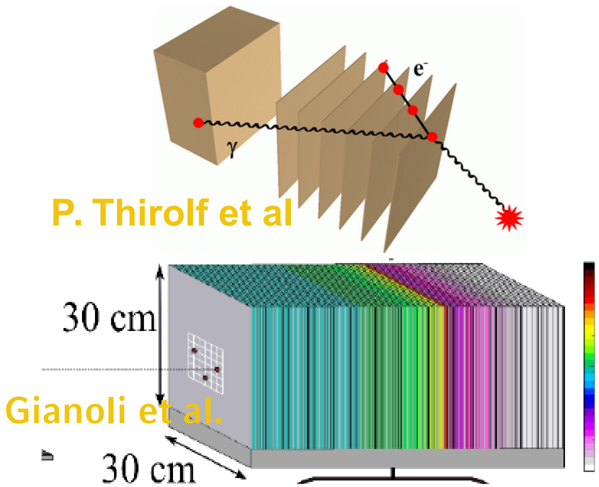
Medical Physics – Chair Parodi, Ludwig Maximilian University Munich, Germany & CERN, Geneva, Switzerland

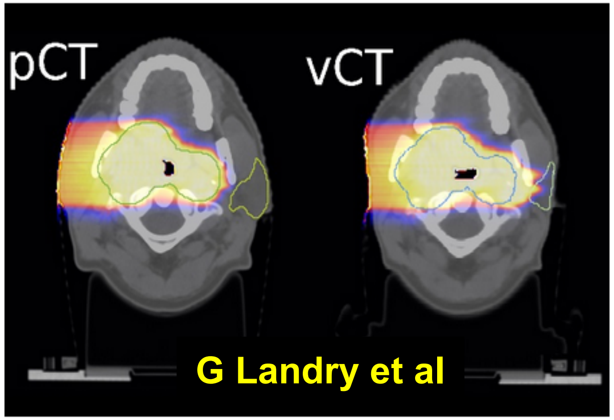
Radiation Detection in Medical Physics Workshop, Aarhus
May 3rd & 4th 2018

LMU Medical Physics Department: Katia Parodi et al.

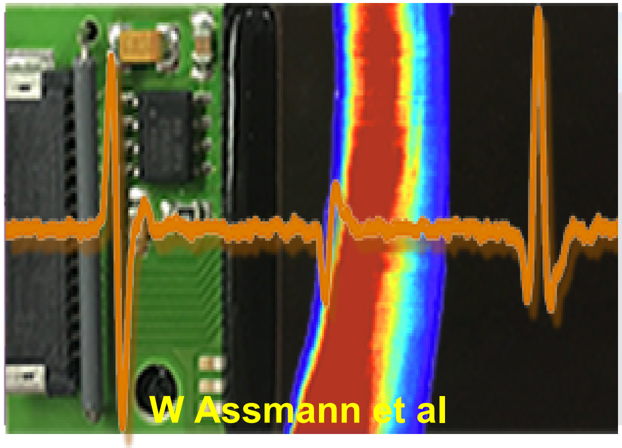
Medical Imaging



Treatment Planning and Plan Adaptation



Dosimetry and Beam Monitoring



Monte-Carlo Simulations

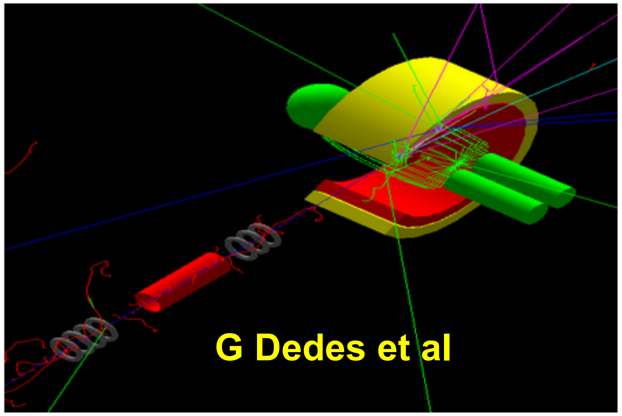
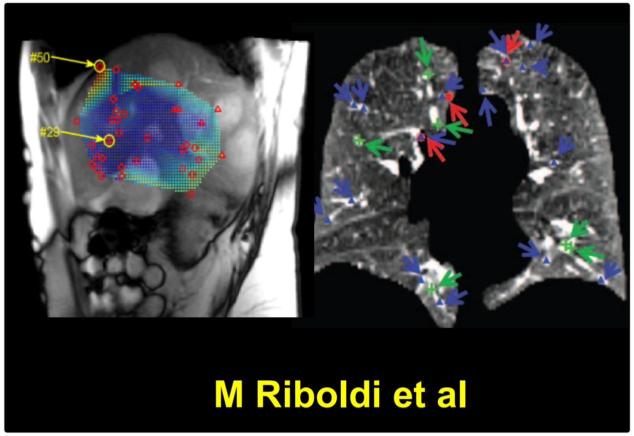
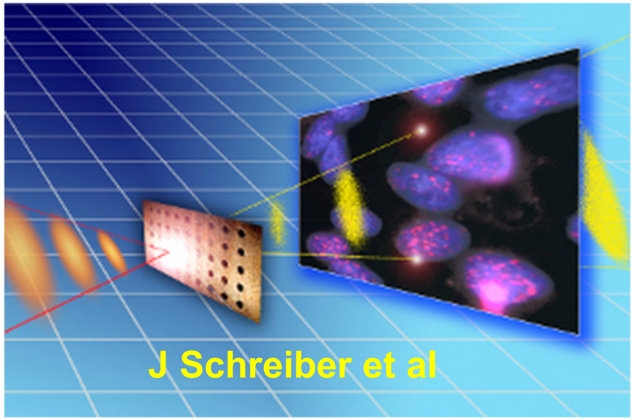


Image-guided Radiotherapy

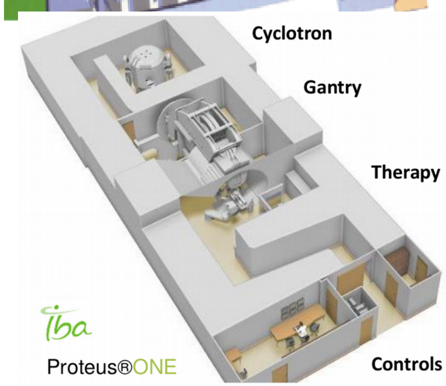


Laser Ion Acceleration

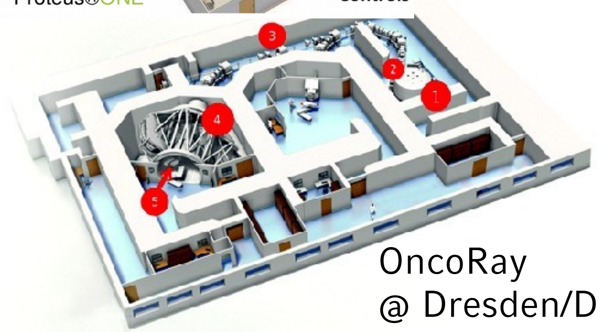


Detectors & Applications at Different Facilities

Beams at Clinical Energies



CAL
@ Nice/F



OncoRay
@ Dresden/D

Beams at Pre-Clinical Energies

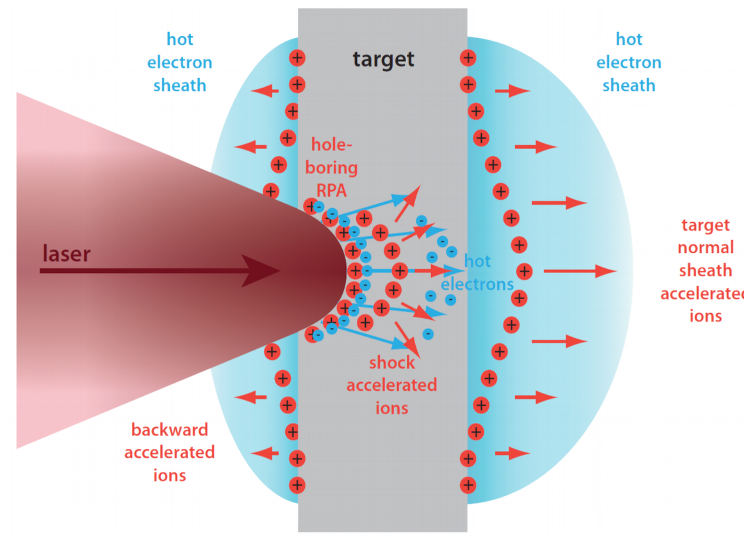
SIRMIO

erc
European Research Council
Established by the European Commission

small animal irradiator setup

development of prototype
- precision, image-guided small animal proton irradiation
- integration in experimental beamlines of clinical facilities

Laser-Accelerated Particle Beams



CALA

Center for Advanced Laser Applications, Garching/D
- poly-energetic proton spectra < 15MeV
- high flux: $>10^7$ cm^{-2}
- short pulses: <1ps

Overview: Detector Related Activities

- medical imaging
  - ion range radiography & tomography
    - integrating particle range detector
    - single particle imaging systems
  - image guided radiotherapy
- medical ion beam irradiation: range verification
  - ionoacoustic range detection
  - promt gamma detection – Compton camera
  - PET
- detection of laser accelerated particles
  - radiography with poly-energetic beam
  - ionoacoustic detection: signal shape analysis
  - time-of-flight with “Bridge” micro-dosimeter
  - magnetic spectrometer + CMOS pixel chip
  - multi-layer scintillator stack + CMOS pixel ship
  - ...

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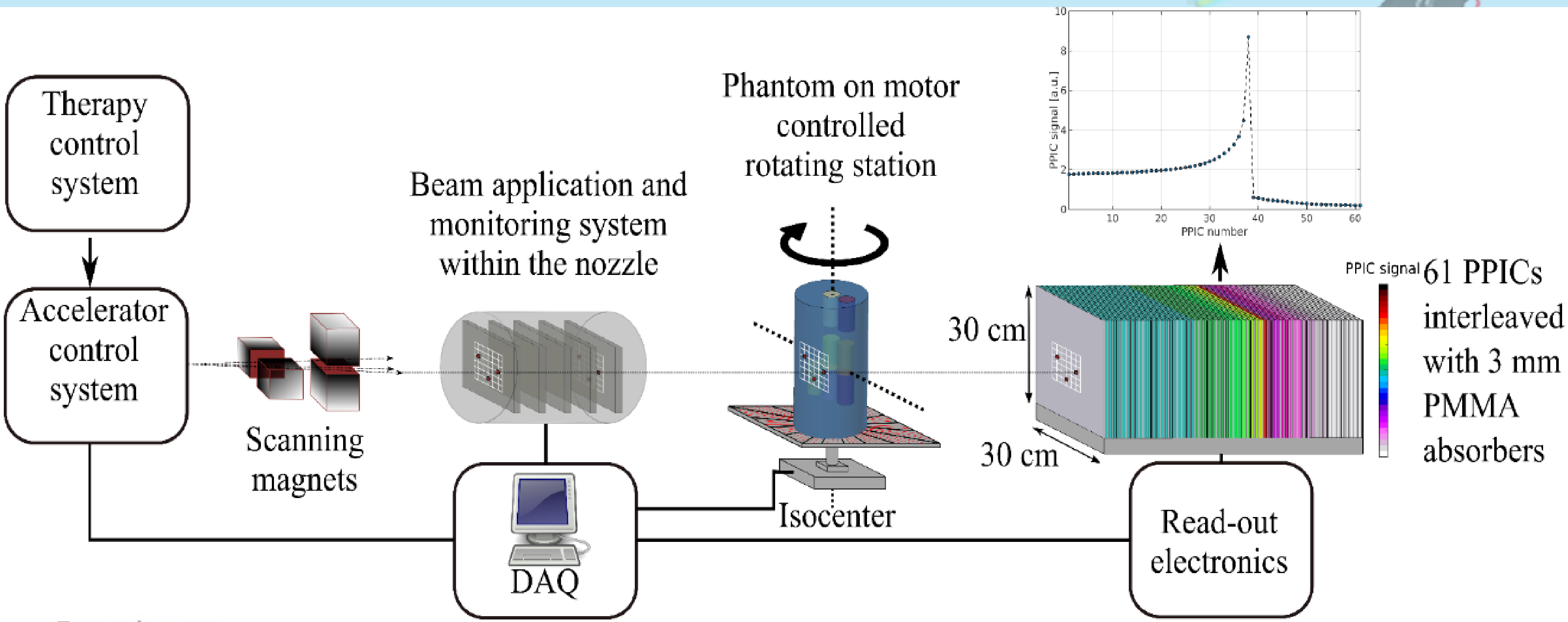
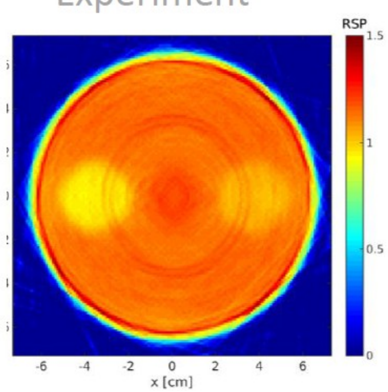
  - ...

Integrating Carbon Ion Radiography/CT Prototype @ HIT



Experiment

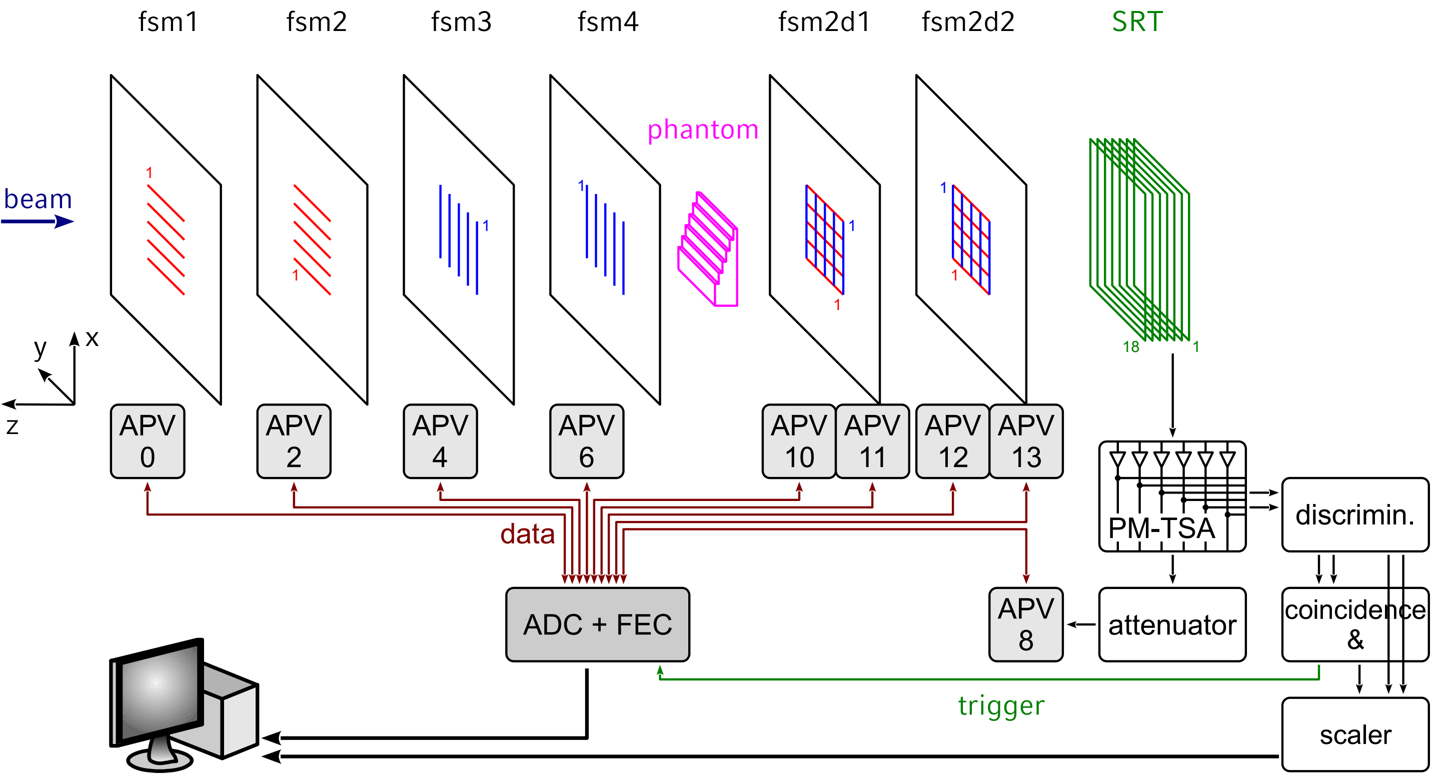


- 61 ionization chambers: 6mm air gap + 3mm PMMA absorber
- ^{12}C, p and ^{4}He beams, **scanned pencil beams**
- position: beam position from beam delivery system
- residual range: Bragg peak location from layer current measurement
  → water equivalent thickness of phantom (per raster point)
- ~10^3 ions/raster point, 150 x 150 raster points/projection & 180 projections/tomography → 50 to 300mGy per tomography

→ relatively simple detector and readout electronics but considerable improvements by higher granularity, lower noise & improved electronics possible

Rinaldi, ..., Parodi, PMB 2014, 2014b, Meyer...Parodi PMB 2017, Magallanes, PhD Thesis LMU 2017

Micromegas + Scintillator Radiography Prototype @ LMU



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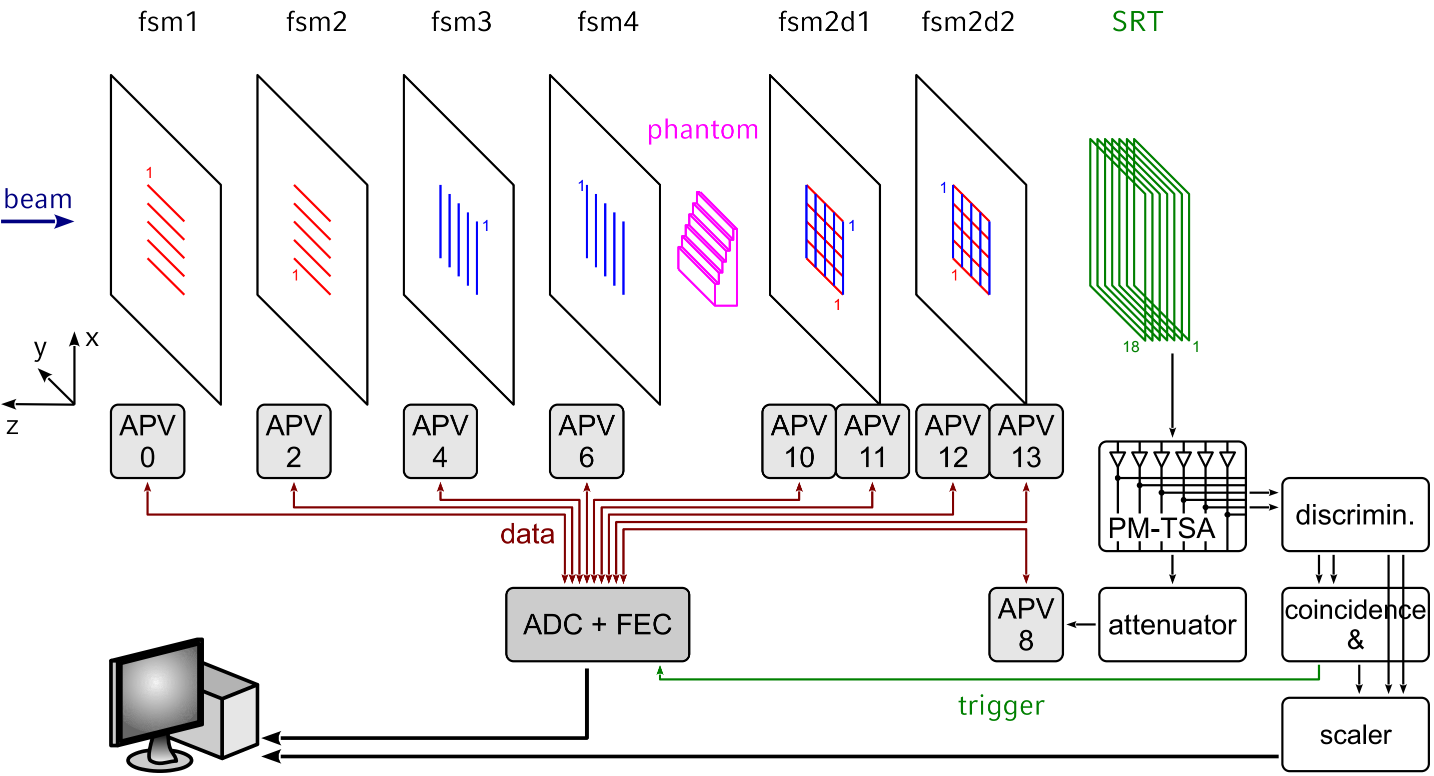
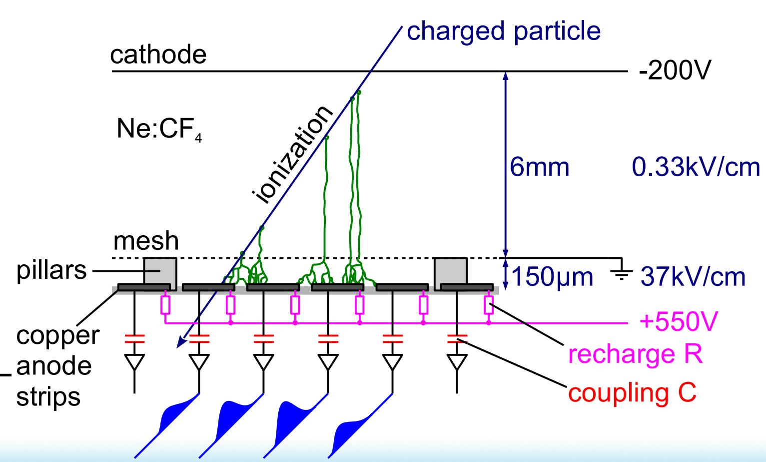


6 floating strip Micromegas

- active area: 64x64mm^2
  128 strips, 0.5mm pitch
- x-y-readout in 2 detectors
- very thin: ≤0.4mm WET
- single particle tracking up to 7MHz/cm^2
- spatial resolution O(100μm)
- timing O(7ns)



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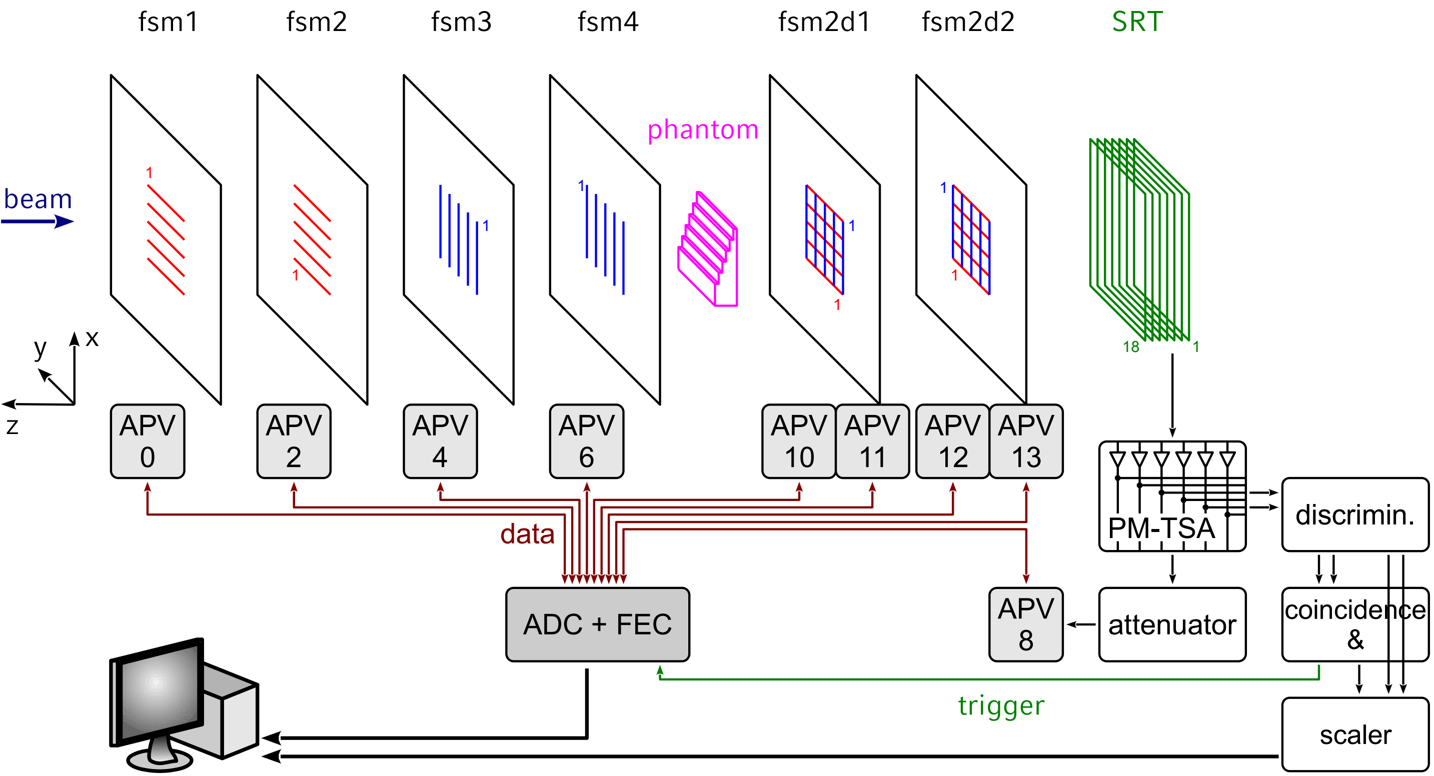

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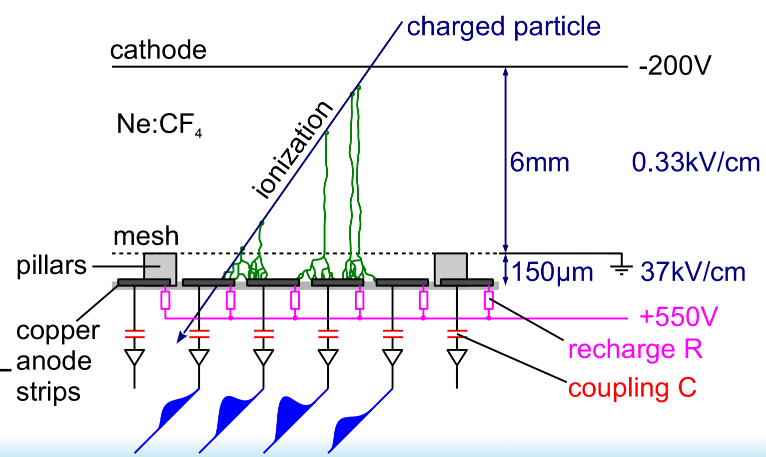
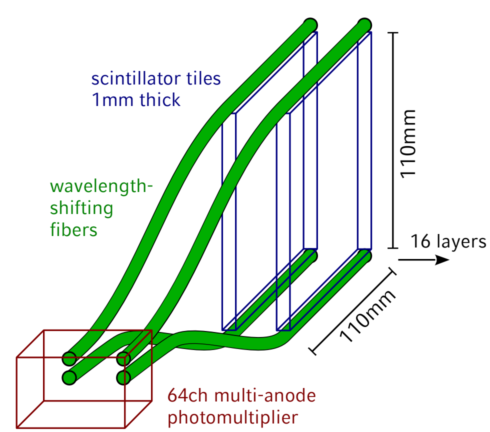
scintillator range telescope

- 18 layers, 1mm each
- 2 WLS fibers/layer
- 64ch multi-anode PMT



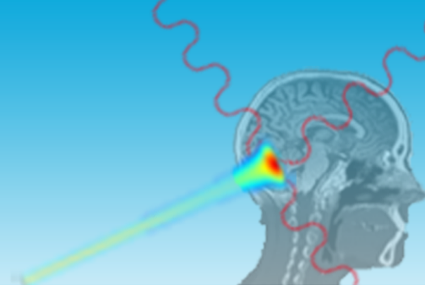


APV25 SRS electronics

- for Micromegas & SRT
- custom amplifiers for SRT
- particle rate ~2MHz but readout rate O(kHz)

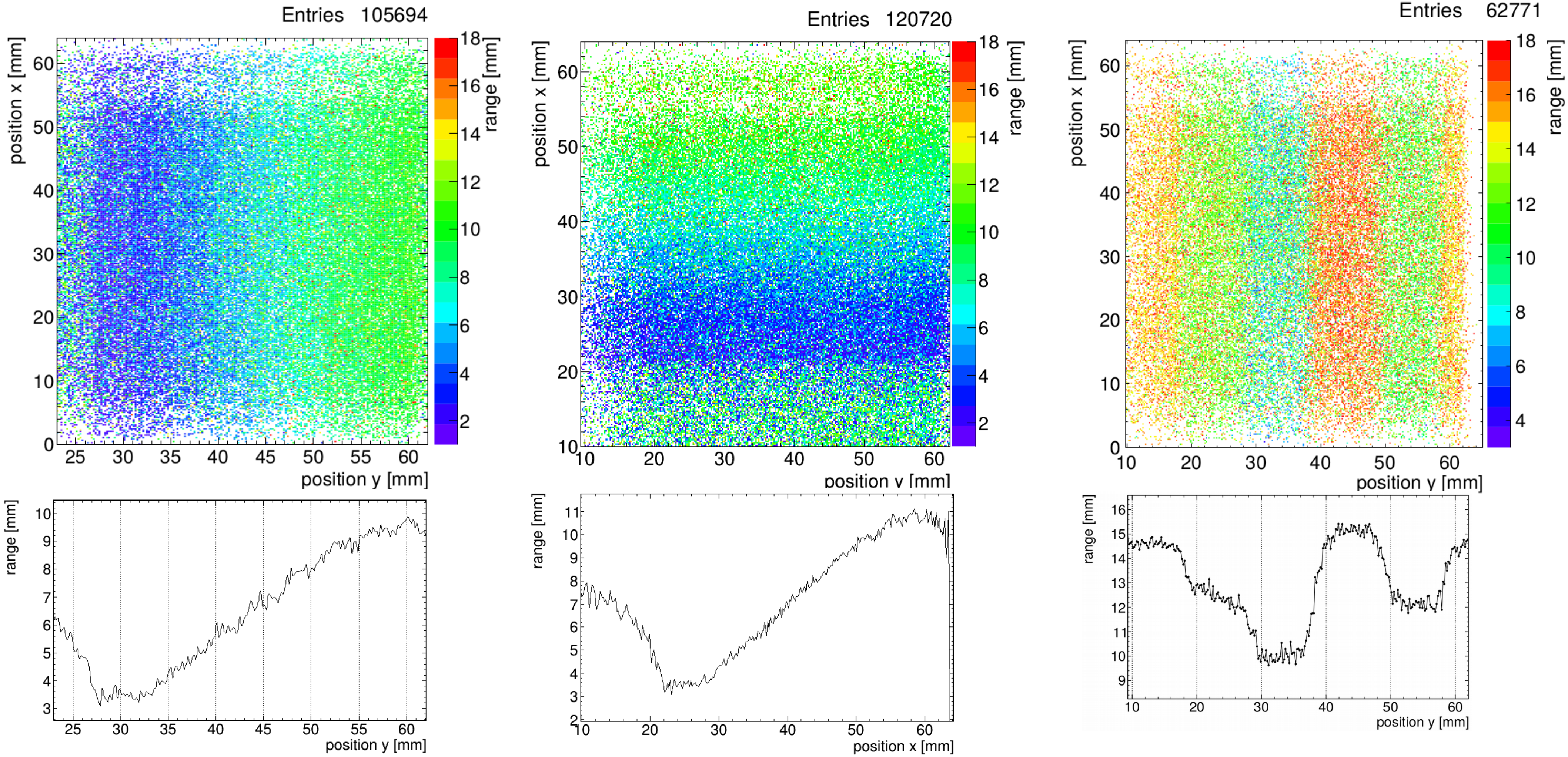
Bortfeldt et al, NPPP, 2016 &
Bortfeldt et al, NIM A, 2017

Micromegas + SRT: ^{12}C Beam Results



PMMA step phantom – vertical & horizontal

tissue-equivalent slab phantom



→ **spatial resolution** in y-direction: **O(1mm)** & in x-direction: **O(1.5mm)**

→ linear range behavior

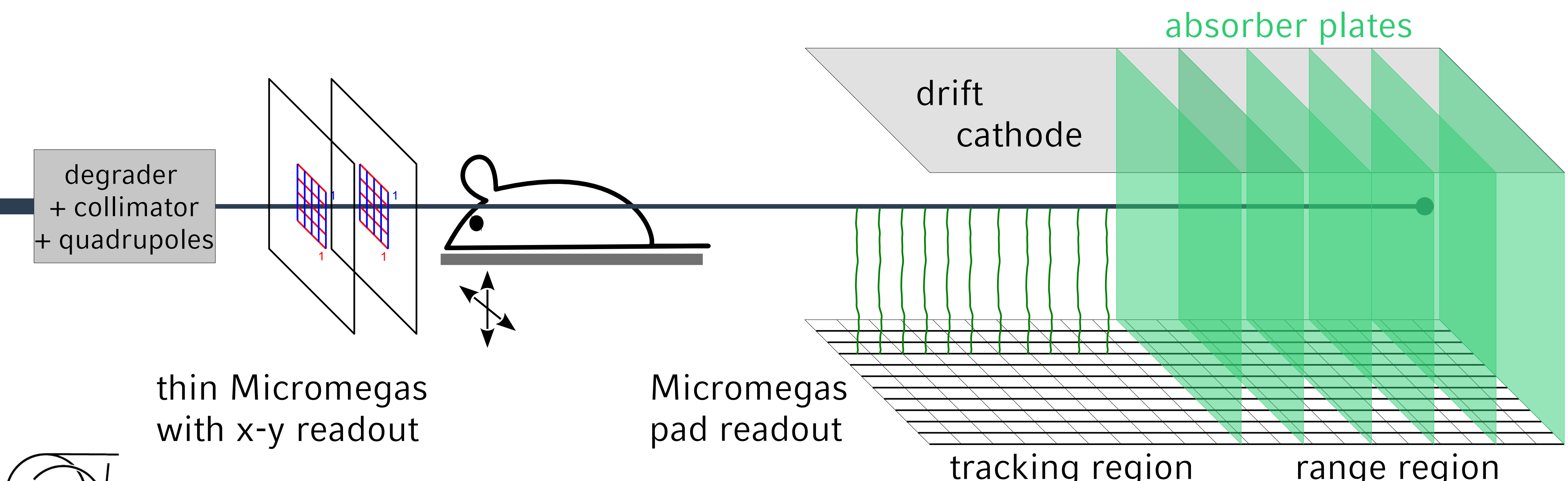
Further Plans with Micromegas Based Detectors

new readout electronics: VMM3 ASIC (ATLAS New Small Wheel readout chip) + RD51 Scalable Readout System

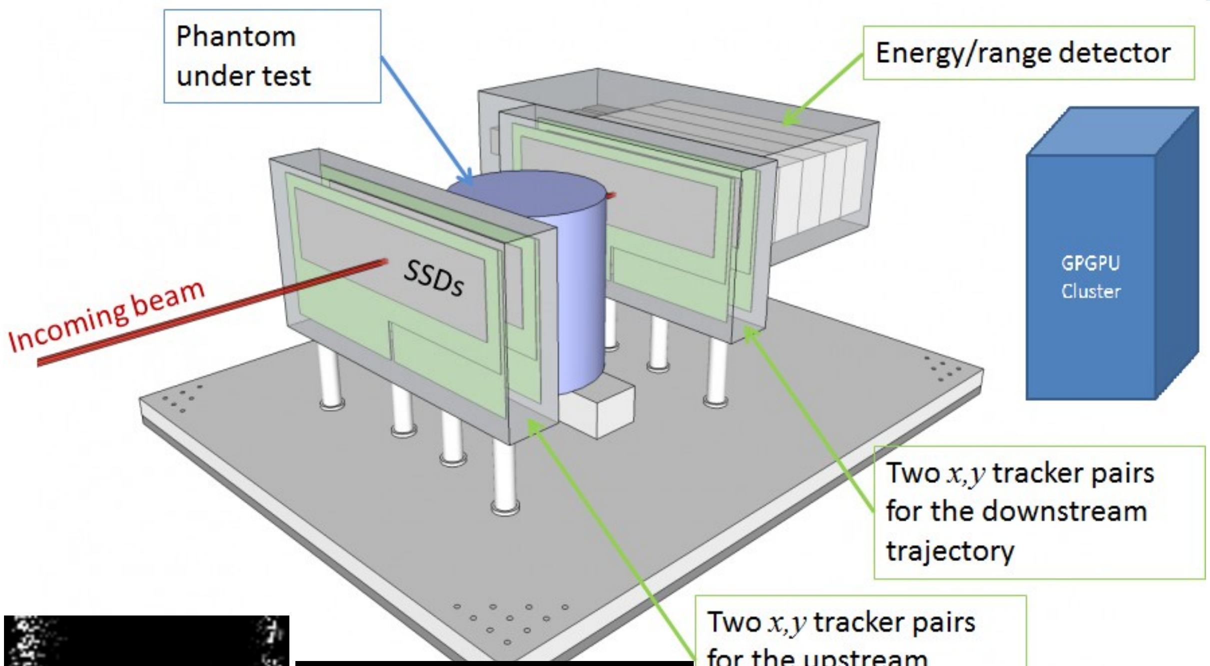
- readout rate ~ 2MHz
- self-triggerable

→ exploit excellent high-rate capability, spatial resolution and granularity of detectors

possible proton radiography system for SIRMIO (small animal irradiator setup): R&D on a Time Projection Chamber with floating pad Micromegas readout



Proton CT Scanner Prototype @ Loma Linda & UCSC



V.A. Bashkirov et al Med Phys 2016, V. Giacometti… Parodi…et al Med Phys 2017, Tomographies: G. Dedes

two tracker modules
- 4 layers silicon strip detectors/module
- 2 layers in x- & 2 in y-direction
- four sensors/layer: 89.5x89.5mm^2, 0.4mm thick, 0.228mm strip pitch

residual energy detector
- 5 layers plastic scintillators, each: 100x400x52mm^3
- binary hit info + energy deposition in last hit layer
  → range resolution ~ 3mm

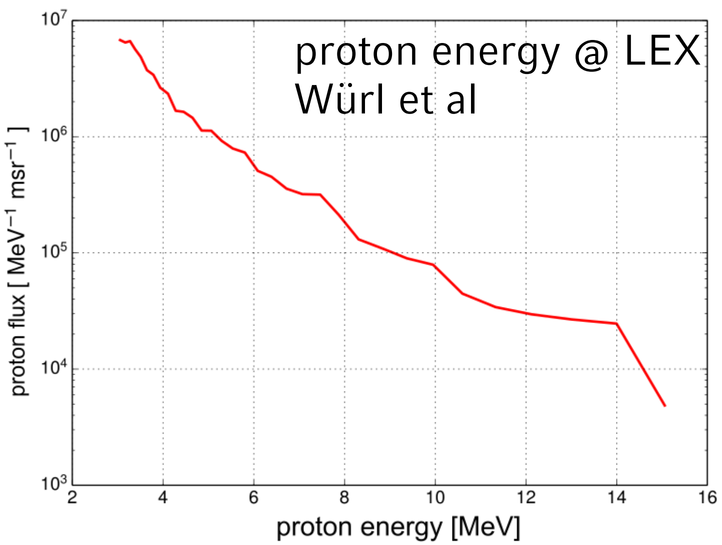
custom readout electronics
- readout rate 1.2MHz

pCT reconstruction
- 1 to 5mGy/tomography
- fluence modulated pCT (Dedes & Landry) → further reduction to <1mGy

possible improvements
- further increase readout rate & field of view
- machine learning algo for WEPL calc

laser-accelerated proton beams
→ poly-energetic spectrum, monotonically decreasing

Zygmanski, 2000: for known spectrum
→ monotonically increasing signal amplitude vs thickness of traversed object
→ determine WET, based on calibration of detector signal



Proton Radiography with Polyenergetic Beam @ LMU

laser-accelerated proton beams
→ poly-energetic spectrum, monotonically decreasing

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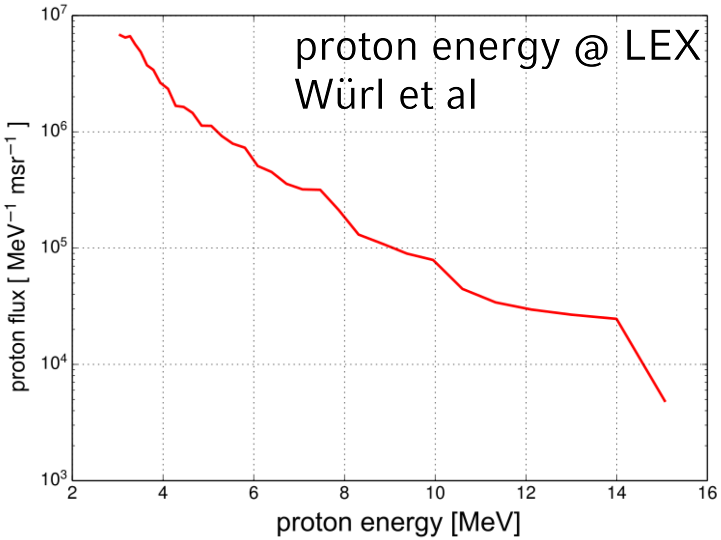
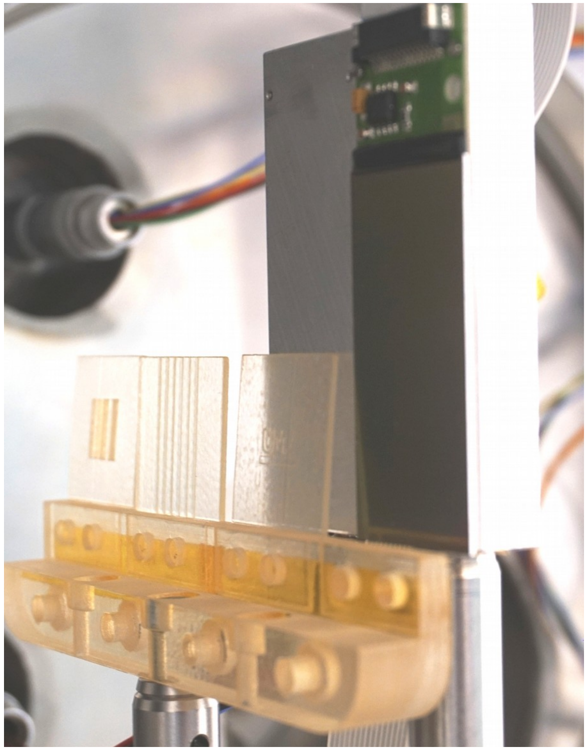
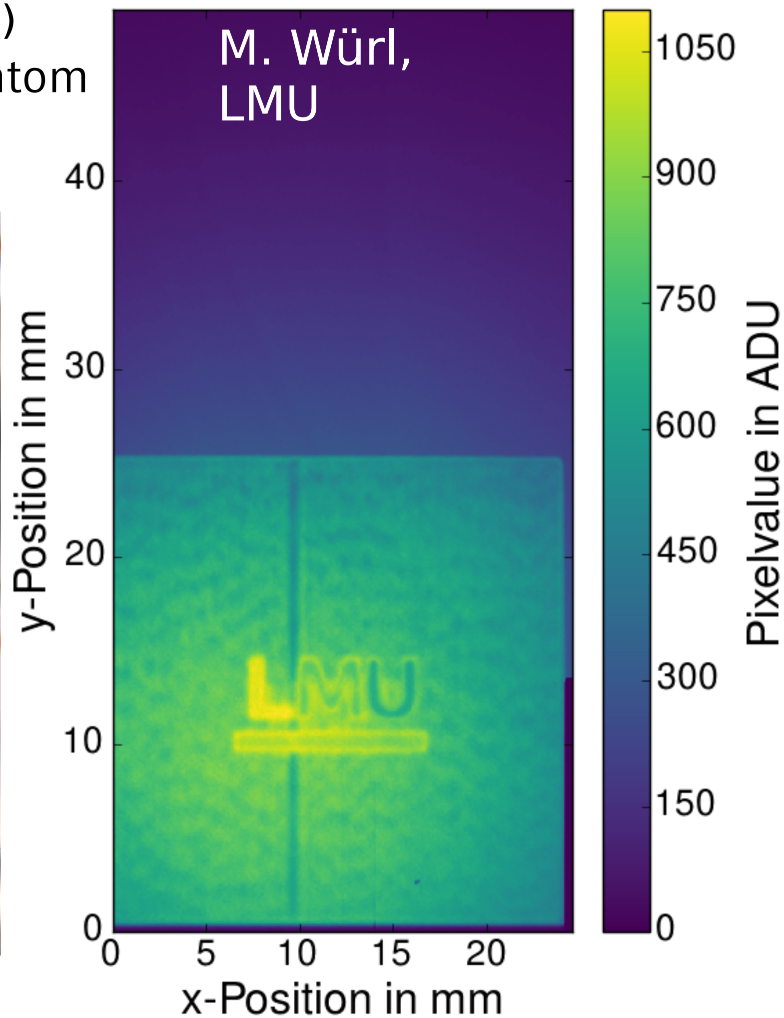


test @ Tandem/Garching: degraded 20MeV p beam on plastic phantom

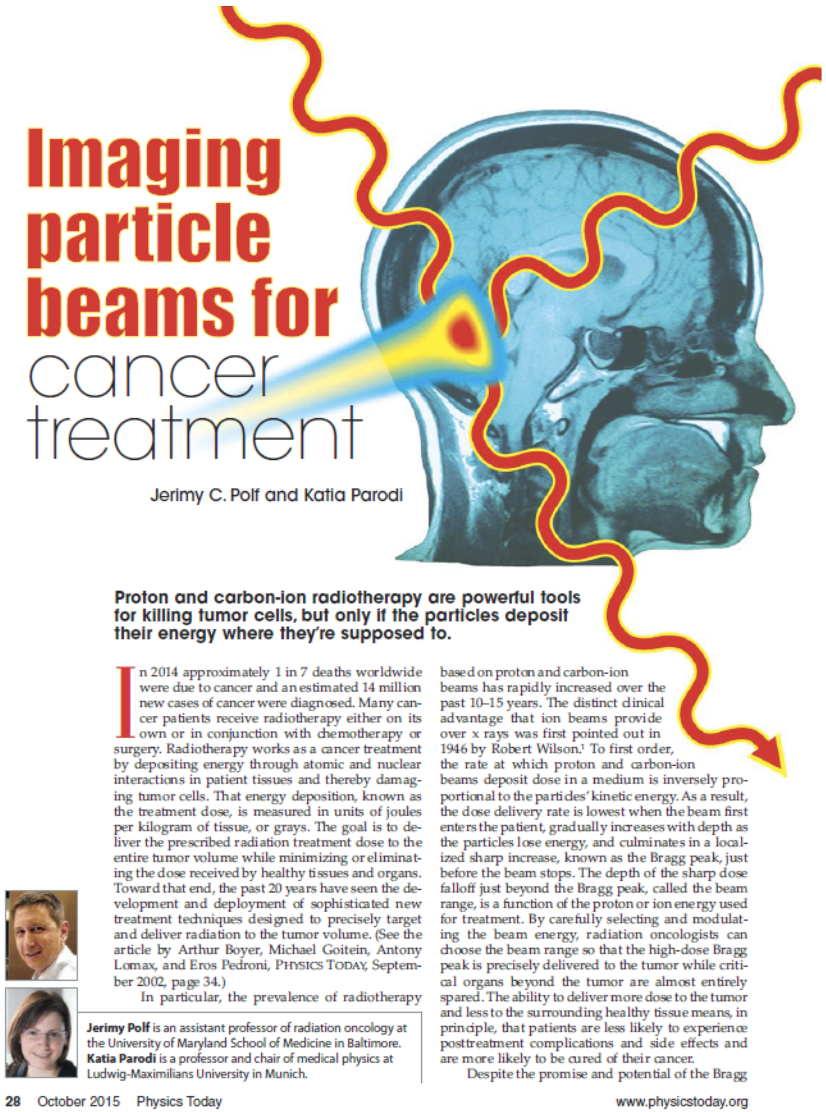
→ RadEye sensor (1024x512 pixel, 48x48μm^2, 2μm sensitive thickness)
~ 3mm behind the phantom

→ clearly visible





Medical Ion Beam Irradiation: Range Verification



Imaging particle beams for cancer treatment

Jerimy C. Polf and Katia Parodi

Proton and carbon-ion radiotherapy are powerful tools for killing tumor cells, but only if the particles deposit their energy where they're supposed to.

In 2014 approximately 1 in 7 deaths worldwide were due to cancer and an estimated 14 million new cases of cancer were diagnosed. Many cancer patients receive radiotherapy either on its own or in conjunction with chemotherapy or surgery. Radiotherapy works as a cancer treatment by depositing energy through atomic and nuclear interactions in patient tissues and thereby damaging tumor cells. That energy deposition, known as the treatment dose, is measured in units of joules per kilogram of tissue, or grays. The goal is to deliver the prescribed radiation treatment dose to the entire tumor volume while minimizing or eliminating the dose received by healthy tissues and organs. Toward that end, the past 20 years have seen the development and deployment of sophisticated new treatment techniques designed to precisely target and deliver radiation to the tumor volume. (See the article by Arthur Boyer, Michael Goitein, Antony Lomax, and Eros Pedroni, PHYSICS TODAY, September 2002, page 34.)

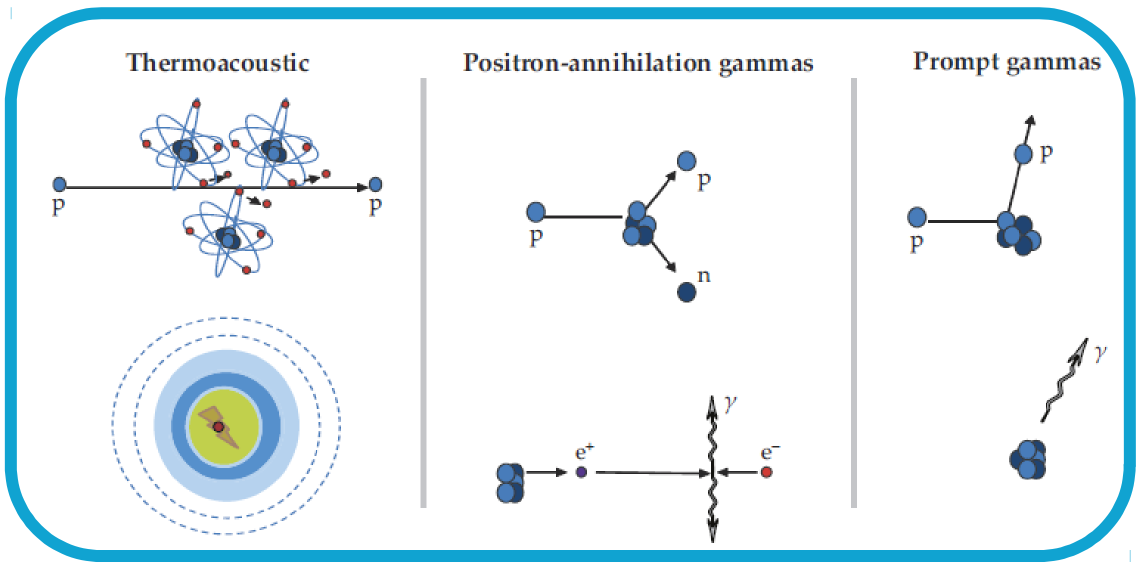
In particular, the prevalence of radiotherapy based on proton and carbon-ion beams has rapidly increased over the past 10–15 years. The distinct clinical advantage that ion beams provide over x rays was first pointed out in 1946 by Robert Wilson.[1] To first order, the rate at which proton and carbon-ion beams deposit dose in a medium is inversely proportional to the particles' kinetic energy. As a result, the dose delivery rate is lowest when the beam first enters the patient, gradually increases with depth as the particles lose energy, and culminates in a localized sharp increase, known as the Bragg peak, just before the beam stops. The depth of the sharp dose falloff just beyond the Bragg peak, called the beam range, is a function of the proton or ion energy used for treatment. By carefully selecting and modulating the beam energy, radiation oncologists can choose the beam range so that the high-dose Bragg peak is precisely delivered to the tumor while critical organs beyond the tumor are almost entirely spared. The ability to deliver more dose to the tumor and less to the surrounding healthy tissue means, in principle, that patients are less likely to experience posttreatment complications and side effects and are more likely to be cured of their cancer.

Despite the promise and potential of the Bragg

Jerimy Polf is an assistant professor of radiation oncology at the University of Maryland School of Medicine in Baltimore. **Katia Parodi** is a professor and chair of medical physics at Ludwig-Maximilians University in Munich.

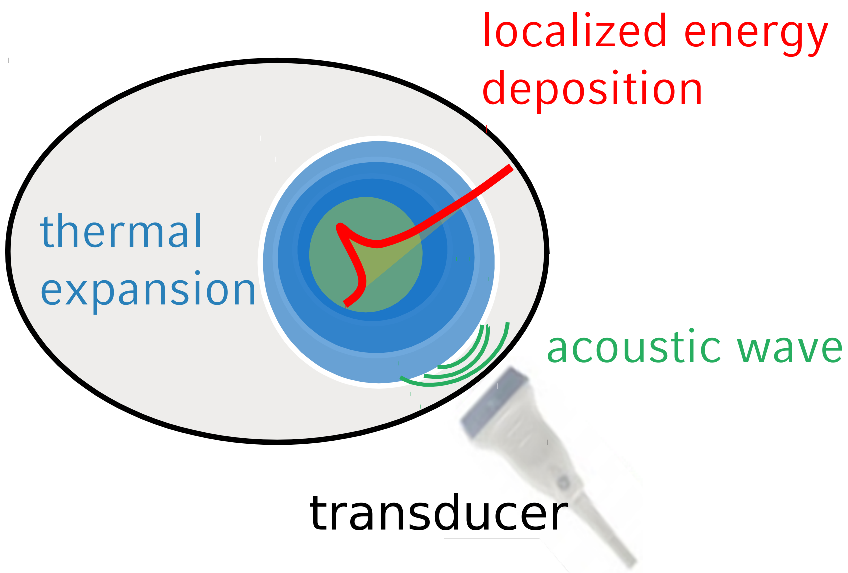
28 October 2015 Physics Today www.physicstoday.org

signal generation mechanisms



Ionoacoustic Beam Detection: The Principle

the principle



1Gy dose → ΔT ~ 0.25mK & Δp ~ 2mbar

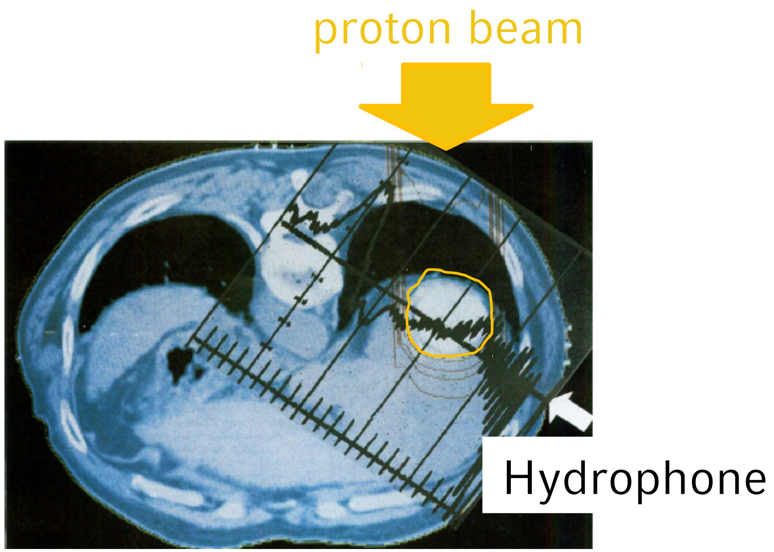
spatial and temporal localization of beam → strong influence

advantageous:

- pencil beam scanning
- short pulse duration

Acoustic Pulse Generated in a Patient During Treatment by Pulsed Proton Radiation Beam

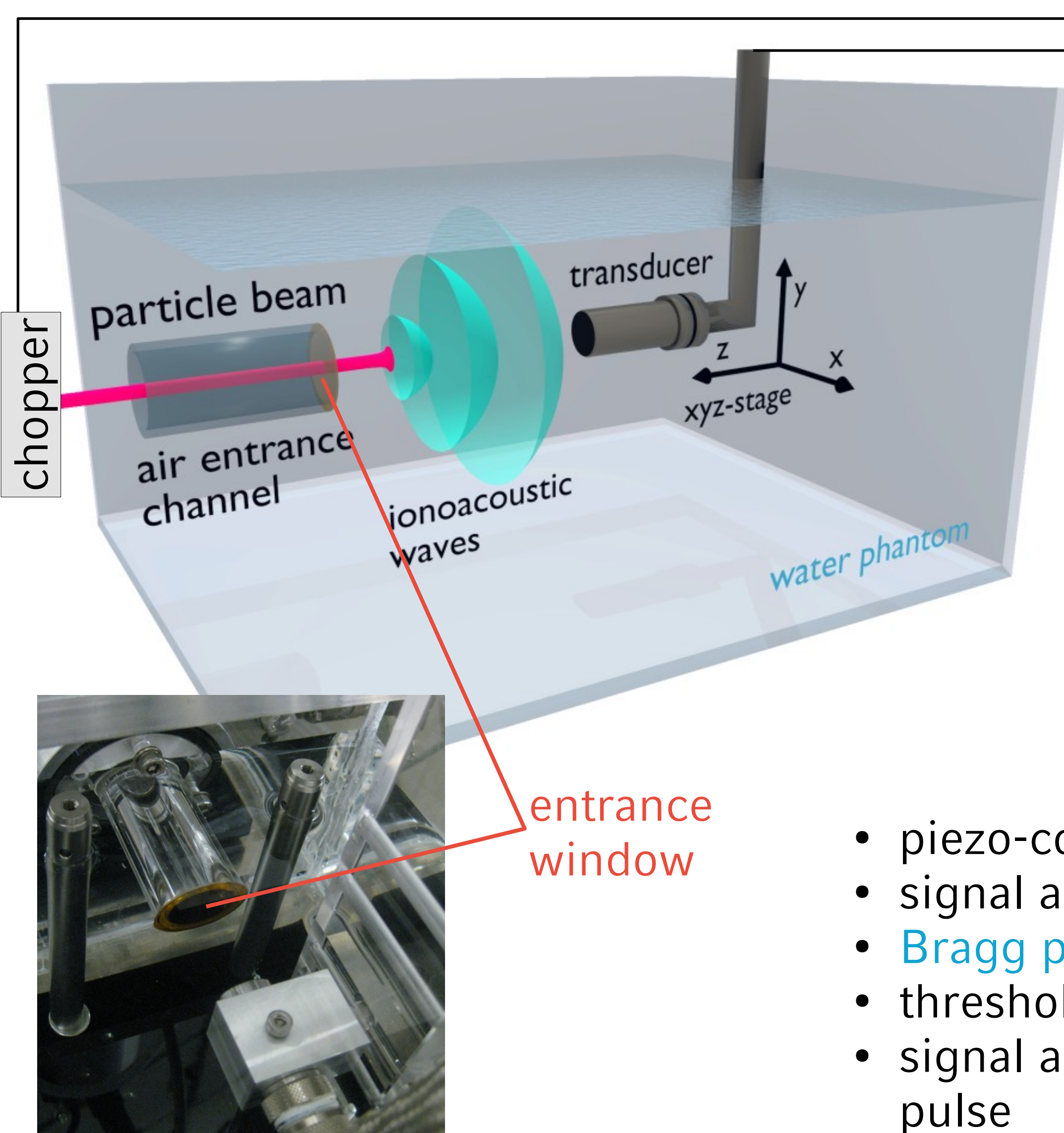
Y. Hayakawa et al, Rad. Onc. Invest. 3 (1995) 42-45

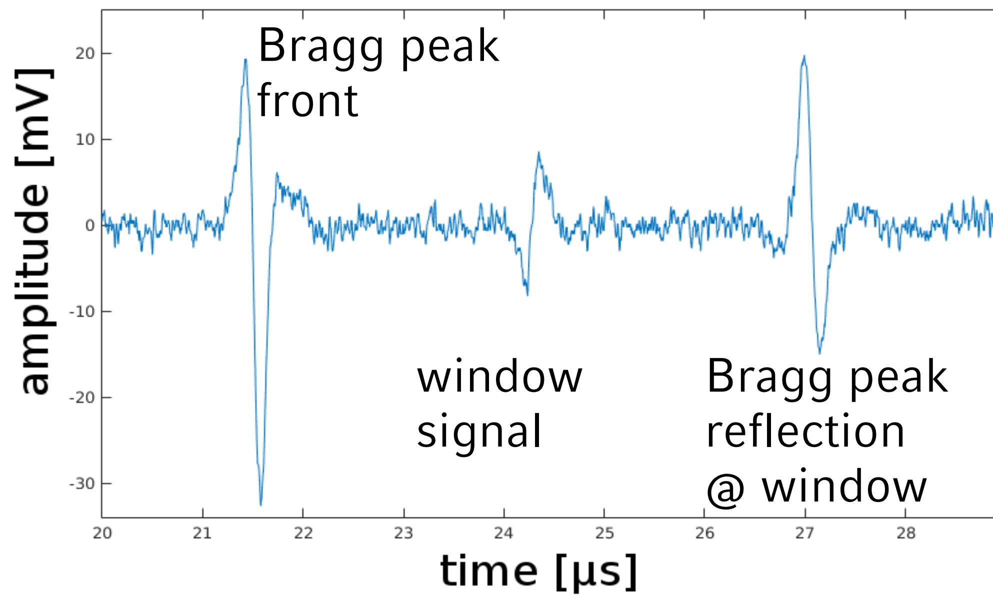


Hepatic cancer treatment

(weak) acoustic signal observed for passive delivery of 50ns pulsed *p*

Proof of Principle: 20MeV p @ Tandem Garching

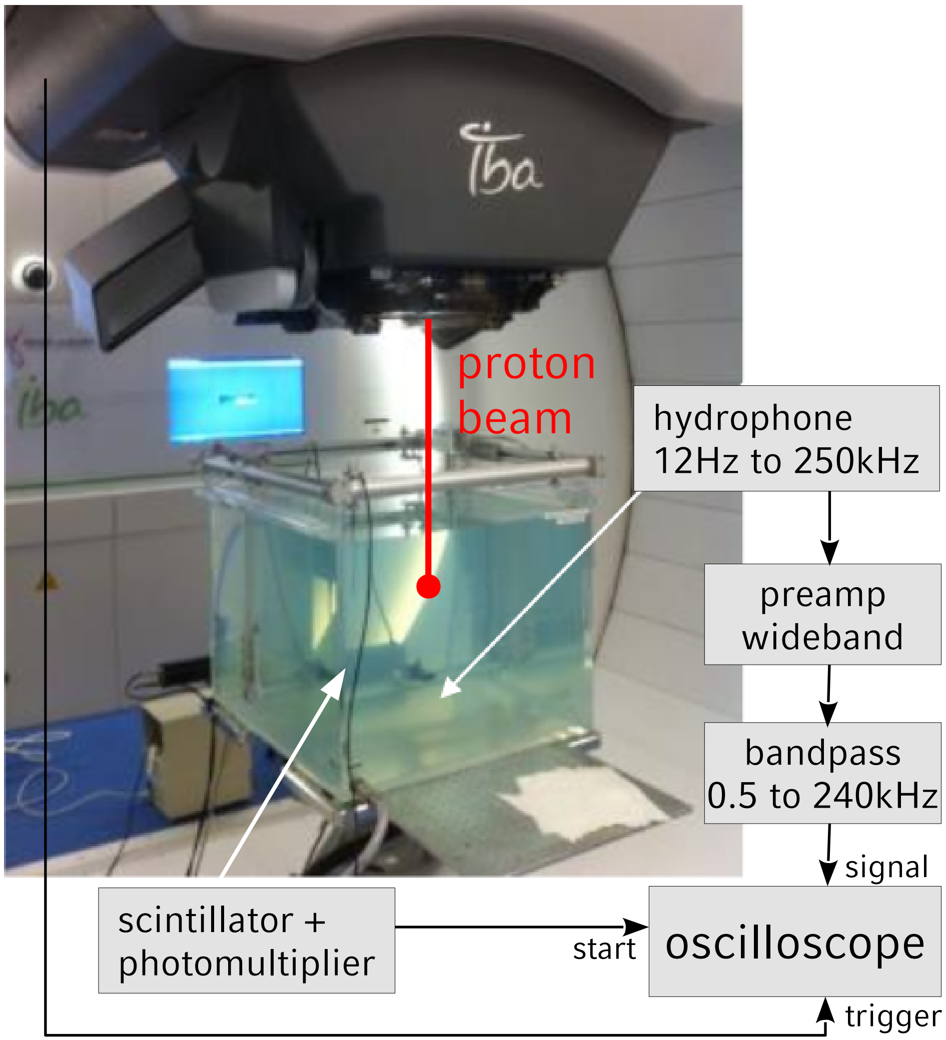




Assmann et al. Med. Phys. 42 (2), Feb 2015

- piezo-composite US transducers 3.5MHz & 10MHz
- signal averaging ~ 16
- Bragg peak localization accuracy: < 100µm
- threshold dose ~ 1.6Gy
- signal amplitude ↔ rise time & amplitude of charge pulse
- optimum conditions: Bragg peak narrow, sharp energy

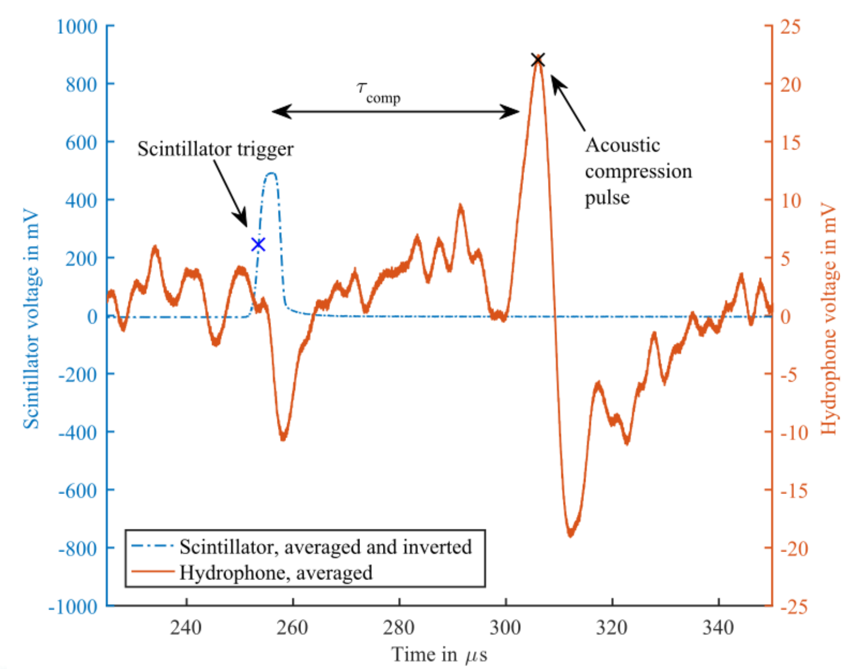
Tests at Clinical Energies: Synchro-Cyclotron @ CAL Nice



IBA 230 MeV S2C2

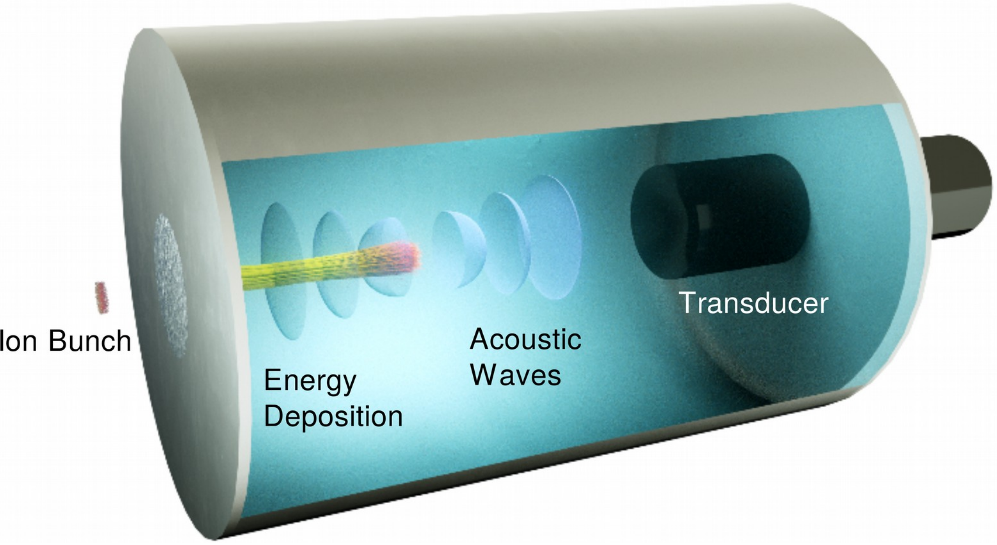
- high pulse intensity: 2pC
- short pulse duration: 4μs FWHM

- scintillator: prompt-gamma signal → start time
- signal averaging x 1000
- threshold dose ~ 4Gy
- Bragg peak localization accuracy: < 1mm
- development of new readout electronics ongoing



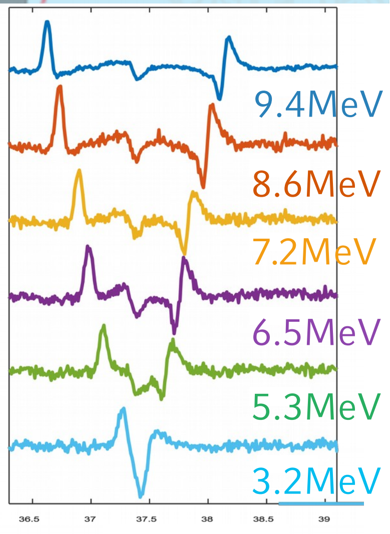
Lehrack et al. Phys. Med. Biol. 62 (2017) L20

Characterization of Laser-Accelerated Proton Beams



I-BEAT: Ion Beam Energy Acoustic Tracing

- US transducer in water tank
- acquire complete US signal with oscilloscope
- transmission function: mono-energetic p beams at Tandem/Garching
  → time (= p energy)
  → amplitude (= # of p)



Haffa et al., I-BEAT – Energy measurement of short intense ion bunches, 2018

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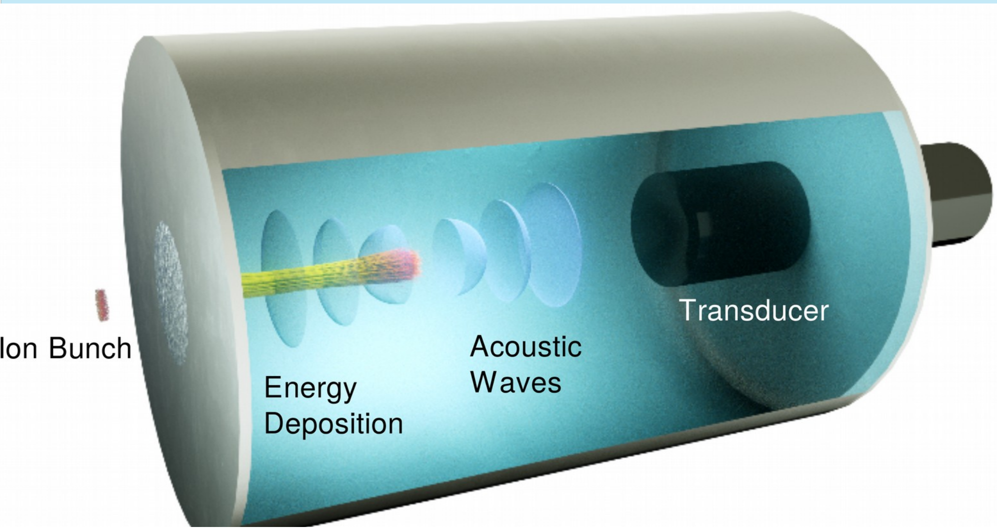

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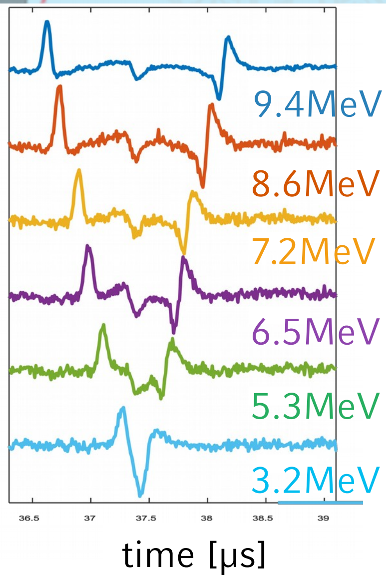
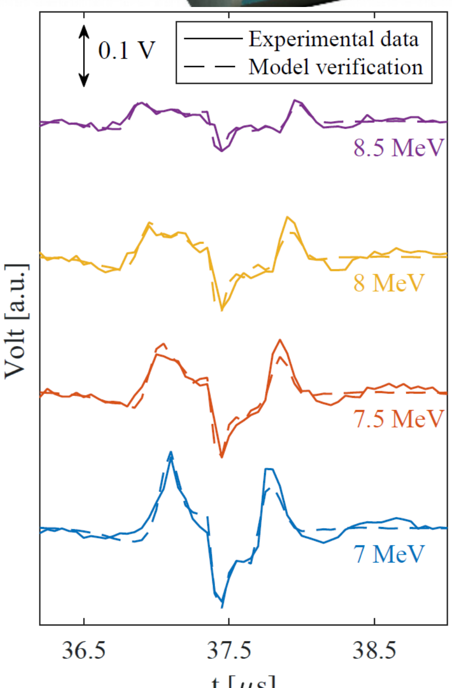
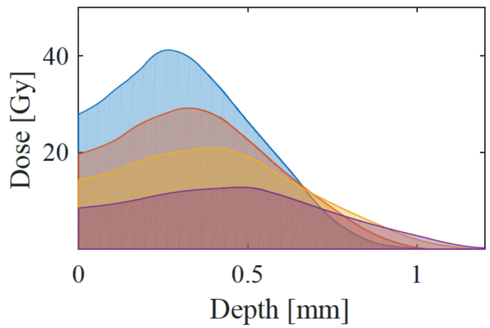
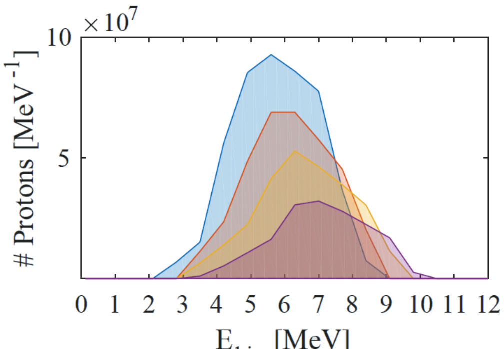


measurement @ LEX (CALA predecessor)

- poly-energetic proton bunches, energy spectrum varied via quadrupole magnets (filter)
- iterative reconstruction: randomly modify assumed spectrum → calculate signal → difference w.r.t. measured signal →..→ **energy spectrum reconstruction**
- comparison with radiochromatic stack at 16MeV @ Draco/Dresden confirms absolute calibration

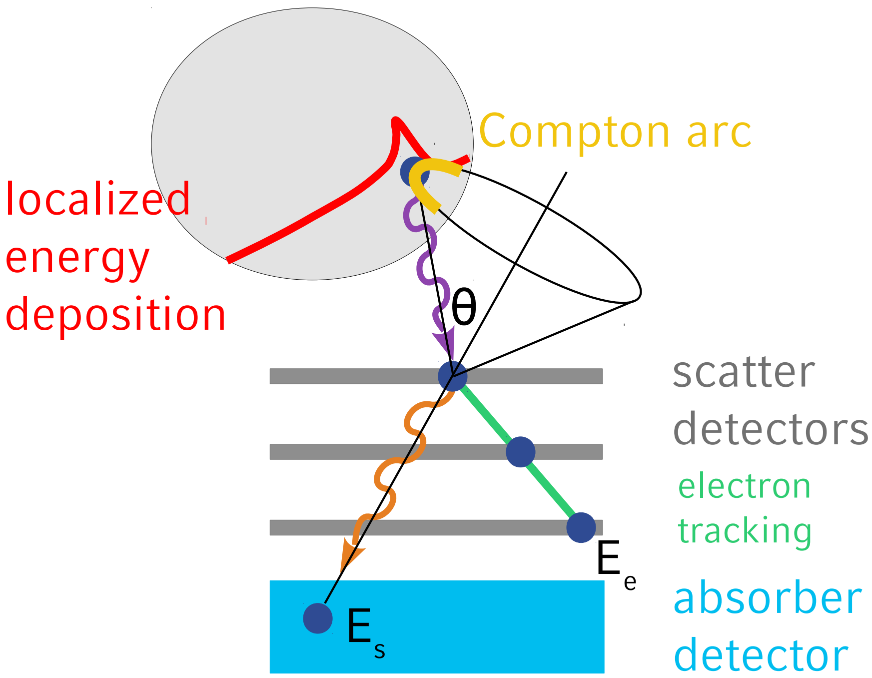






Haffa et al., I-BEAT – Energy measurement of short intense ion bunches, 2018

Prompt gamma Beam Detection: Compton Camera



in vivo range verification: prompt gamma detection

incident photon scatters in silicon detector

→ Compton electron: creation point & energy measured in scatter detectors

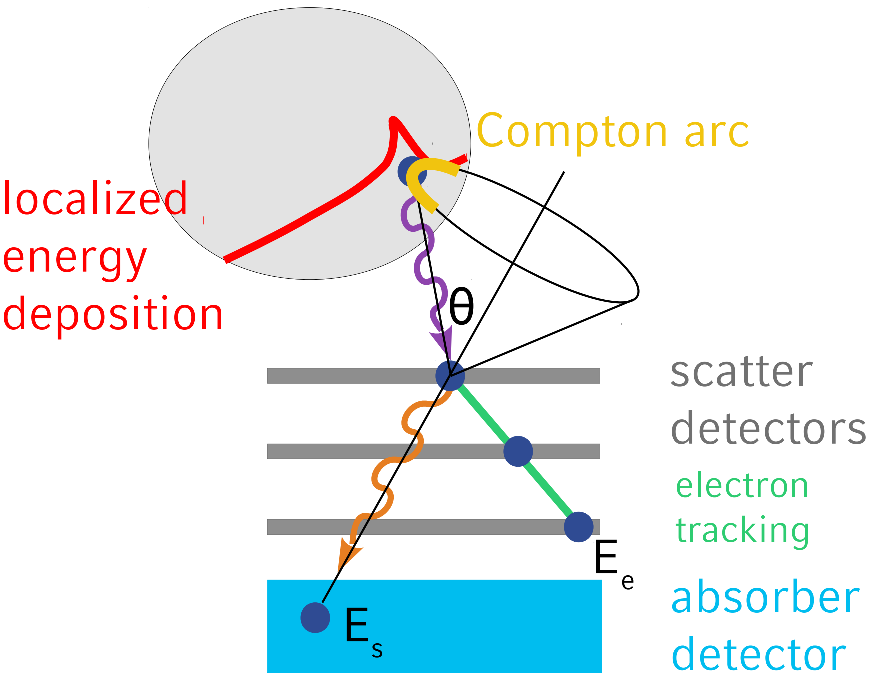
→ Compton photon: absorption point & energy measured in absorber

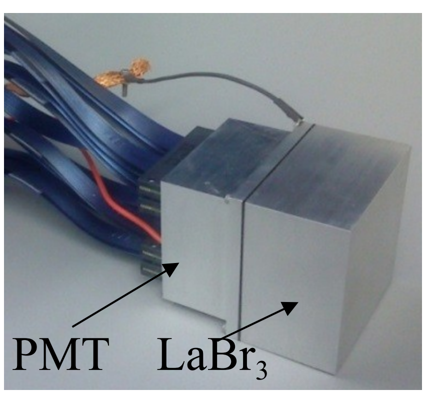
$$\cos(\theta) = 1 - m_e c^2 \left(\frac{1}{E_s} - \frac{1}{E_e + E_s} \right)$$

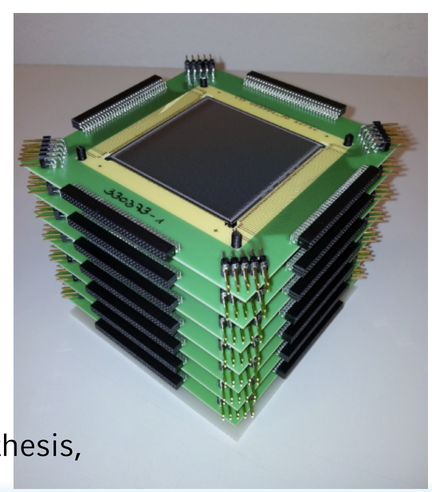
→ Compton cone

→ additional electron tracking: confine cone to arc

Prompt gamma Beam Detection: Compton Camera







S. Aldawood, PhD thesis, LMU 2016

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→ Compton cone

→ additional electron tracking: confine cone to arc

6 scatter detectors

double sided silicon strip dets, $50\text{x}50\text{mm}^2$, 0.5mm thick

128 strips per side, 0.39mm pitch

probably issue with implantation: low signal on n-strips

absorber detector

monolithic $LaBr_3$:Ce scintillator + multi-anode PMT (16x16)

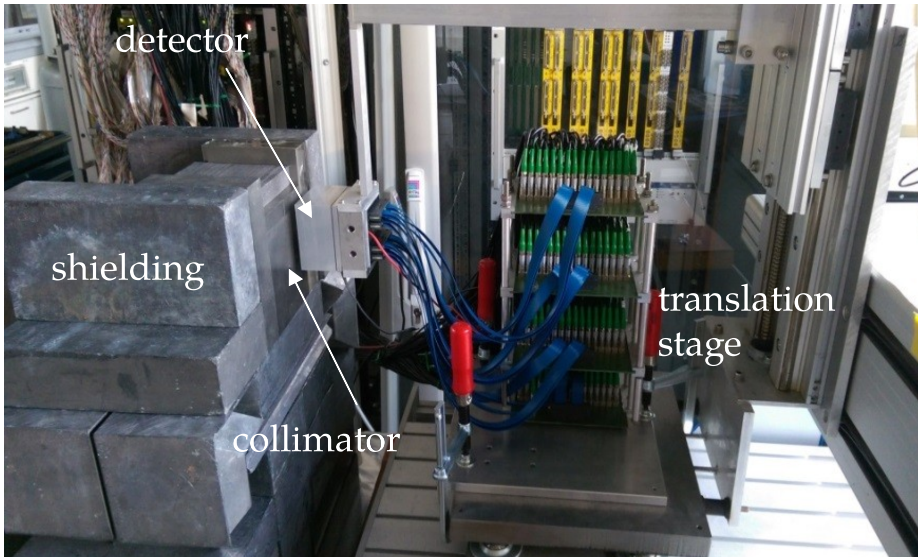
$50\text{x}50\text{x}30\text{mm}^3$ → $3\text{x}3\text{mm}^2$ pixel

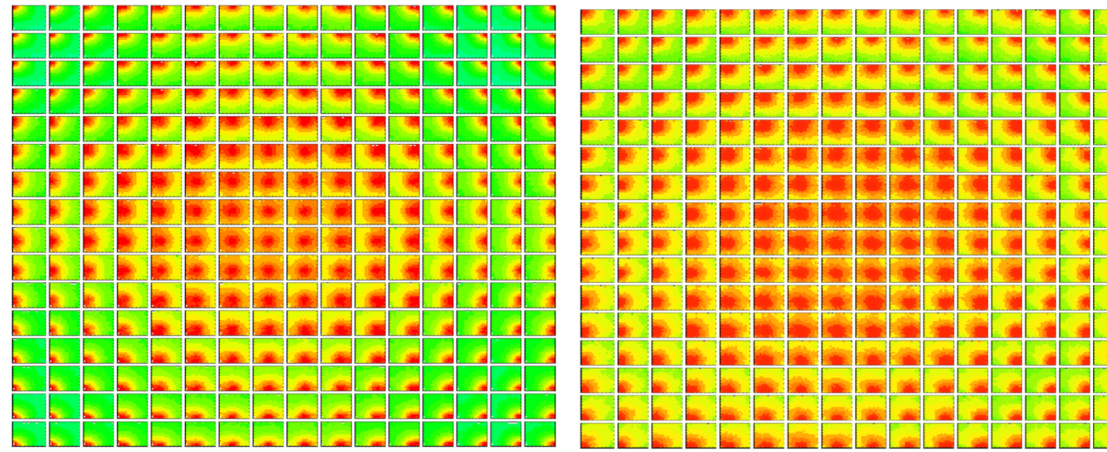
readout electronics evolution

Gassiplex ASIC + Mesytec CFD & QDC

→ custom Mesytec frontend boards, self-triggering: amps & discriminators & ADC & common time & FPGA

Scintillator Spatial Resolution Calibration: Collimated Sources





incident (Compton) photon: signal on many pixels

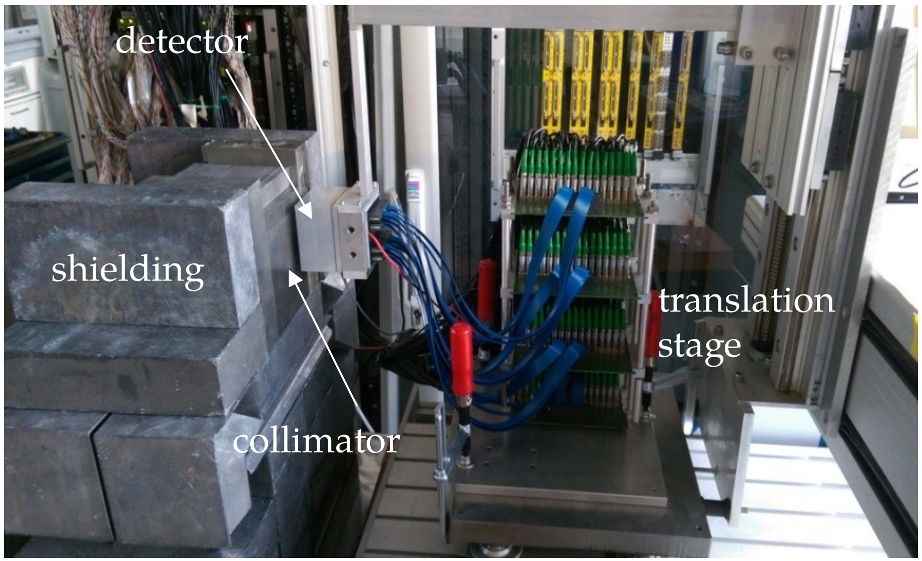
→ irradiate defined positions, collimation ~ 1mm

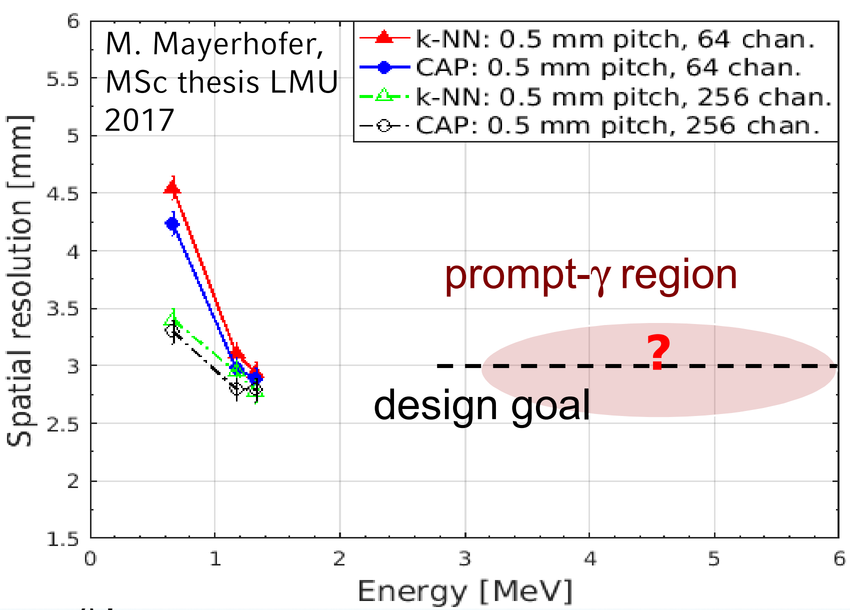
→ record amplitude on all pixels & correct:
amp gains, QDC offsets, PMT pixel gains, light collection inhomogeneities (use internal activity)

→ select only fully contained events (amplitude cut)

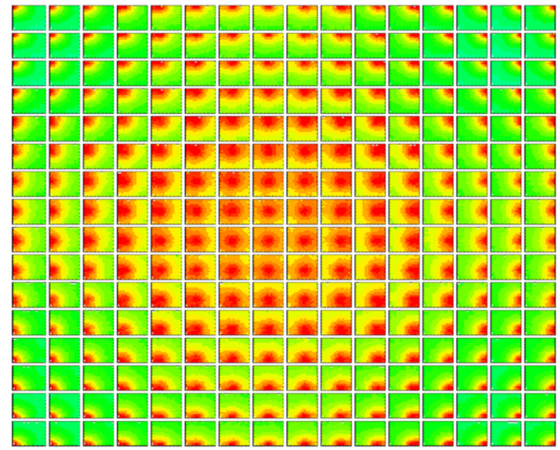
→ library of light pattern ↔ photon position

Scintillator Spatial Resolution Calibration: Collimated Sources

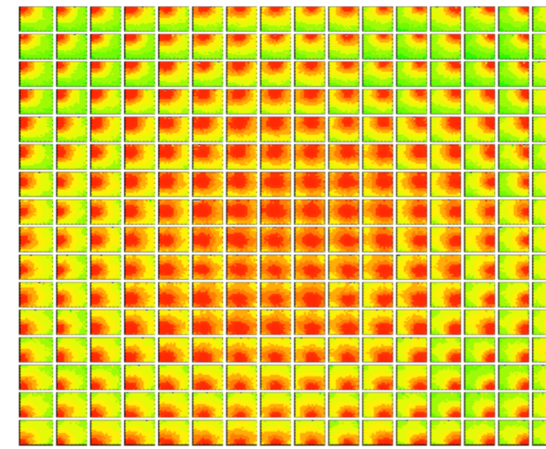




^{137}Cs: 0.662 MeV



^{60}Co:1.3MeV



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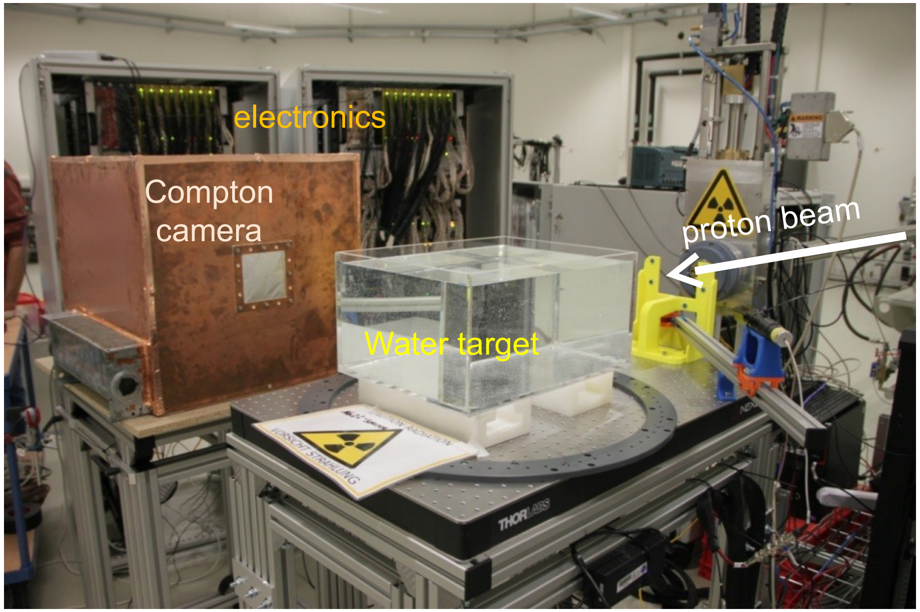
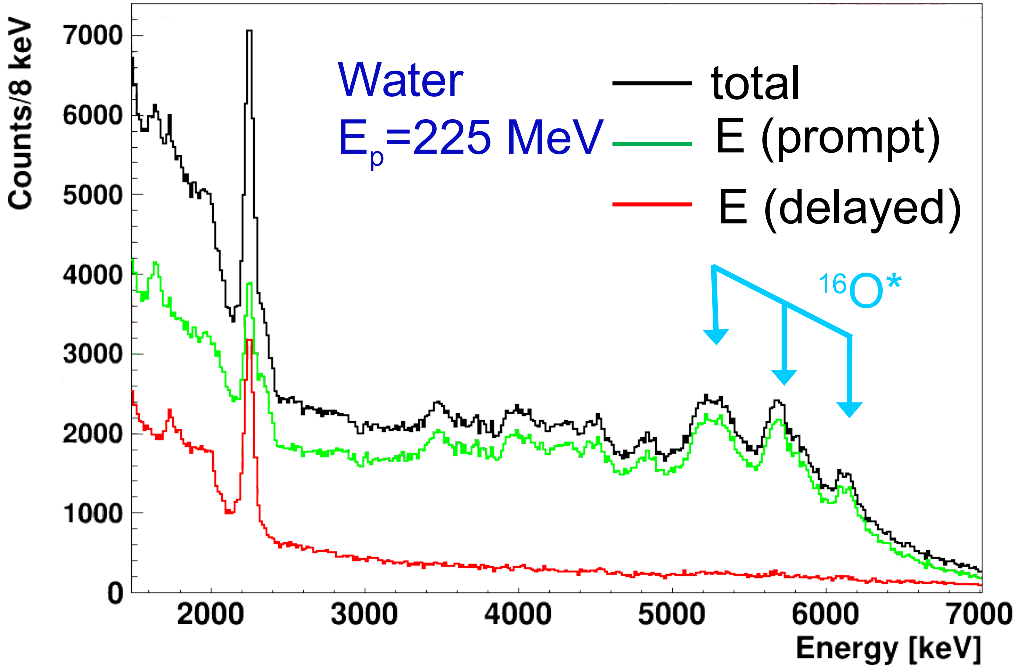
k-nearest-neighbor algorithm

- find k library patterns with minimum deviation from measured signal
- average over corresponding (x,y) positions

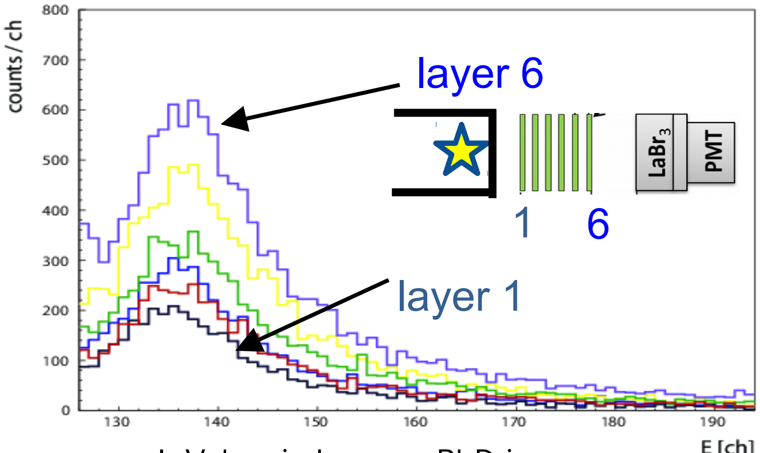
→ measured signal position

Tests at Clinical Energies: OncoRay @ Dresden





DSSSD p-strips: Compton electrons

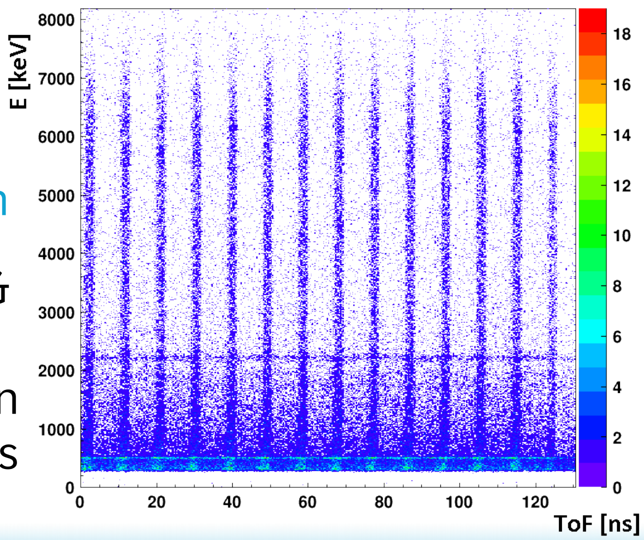


I. Valencia Lozano, PhD in prep.

$LaBr_3$ timing

$\Delta t = 9.4$ns

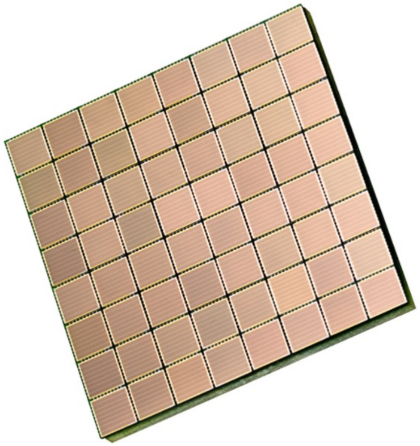
→ gamma/n discrimination

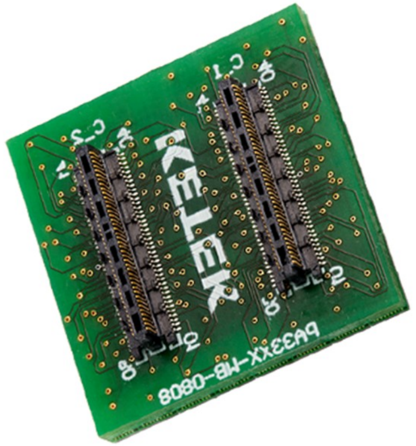


- coincident Compton photon & electron detection works
- source position reconstruction without perpendicular n-strips difficult

Compton Camera: Foreseen Improvements and Outlook

- commission and characterize new Mesytec electronics: homogeneous readout of scatterer & absorber (ongoing testbeam at Tandem/Garching)
- new scintillator: $LaBr_3$:Ce → $CeBr_3$
  - cheaper, more flexibility
  - but no internal activity (light yield homogenization)
- multi-anode PMT → SiPM arrays + possibly generic readout electronics (PETSys, FPGA)
- if electron tracking not advantageous: alternative scatterer
  - pixelized GAGG, 1x1mm^2, 6 to 10mm thick
  - SiPM array with Anger logic (reduces readout channels)
- new double sided silicon strip detectors
  - n-strip doping issue
  - thickness 0.5mm → 1mm (efficiency!)



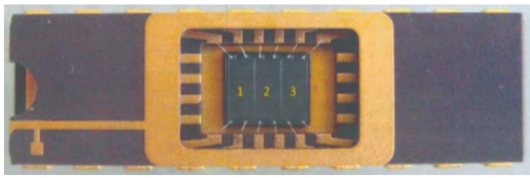


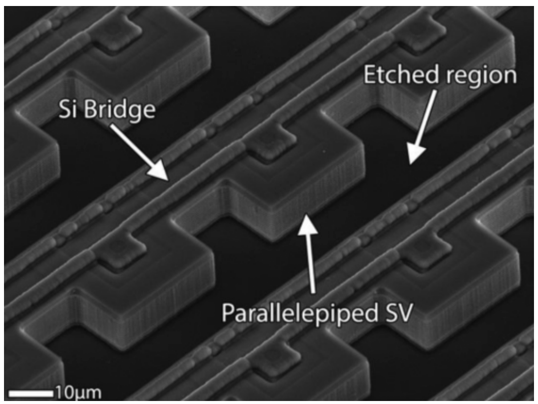
Time-of-Flight Characterization of Poly-Energetic Beams

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

"Bridge" microdosimeter

University of Wollongong/AUS



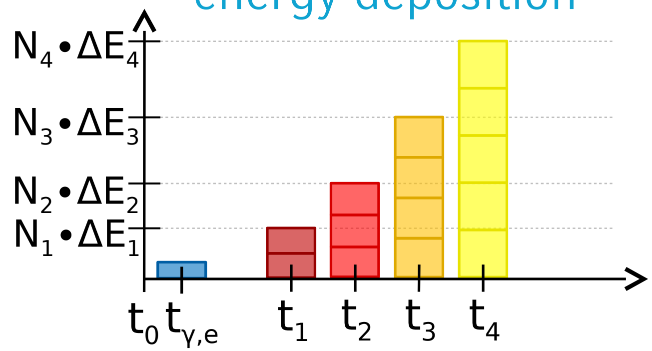


- 4.1x3.6mm^2
- 30x30x10μm^3 pixels
- 3 segments, 2 arrays of pixels in parallel per segment
- read out with oscilloscope
- fast rise time < 0.5 ns

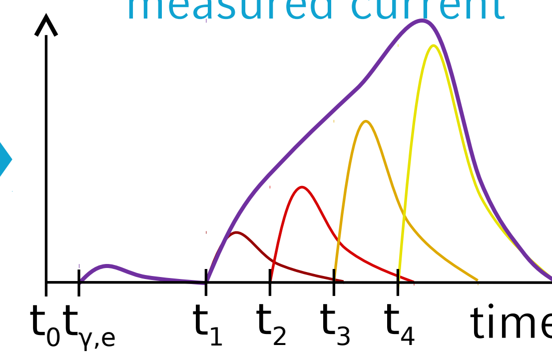
Würl, Englbrecht et al, 2017

measurement principle

energy deposition

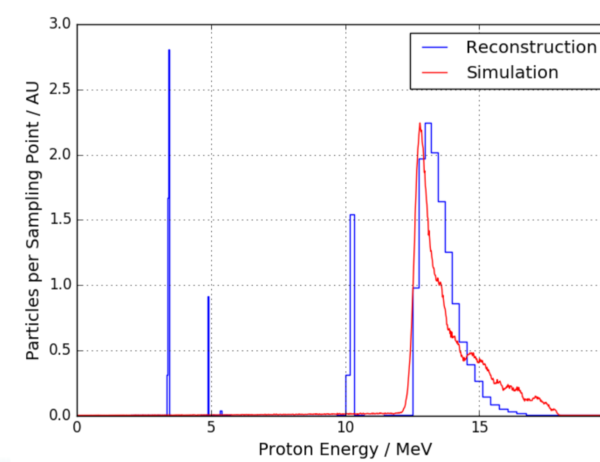


measured current



test @ Tandem/Garching

- 20MeV p beam degraded → poly-energetic
- reconstruction works, few artifacts
- suitable for very high fluxes



Summary

- diverse R&D program on detectors for
  - medical imaging
    - integrating residual energy/range detectors (IC or CMOS based)
    - single particle range imaging systems (SSD + Light, MPGD + Light, MPGD + TPC)
  - range verification
    - ionoacoustic
    - Compton camera
  - characterization of laser accelerated beams
    - ionoacoustic
    - time of flight with microdosimeter
- considerable collaborative efforts
- in-house developments of scintillator-based and micro-pattern gaseous detectors
- very interested in future collaborations for detector R&D

Thank you!