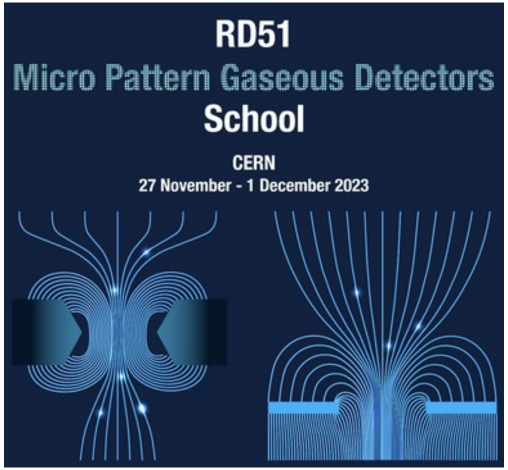
Applications beyond fundamental research



Jona Bortfeldt
LMU Munich

December 1st 2023

Overview

detector developers are widely interested people → many applications beyond fundamental research exist

separation between fundamental research and other research/application/use not always clear

→ subjective & incomplete selection of different applications from

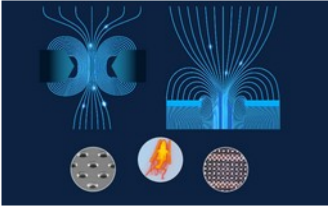
muography

neutron detection

medical applications

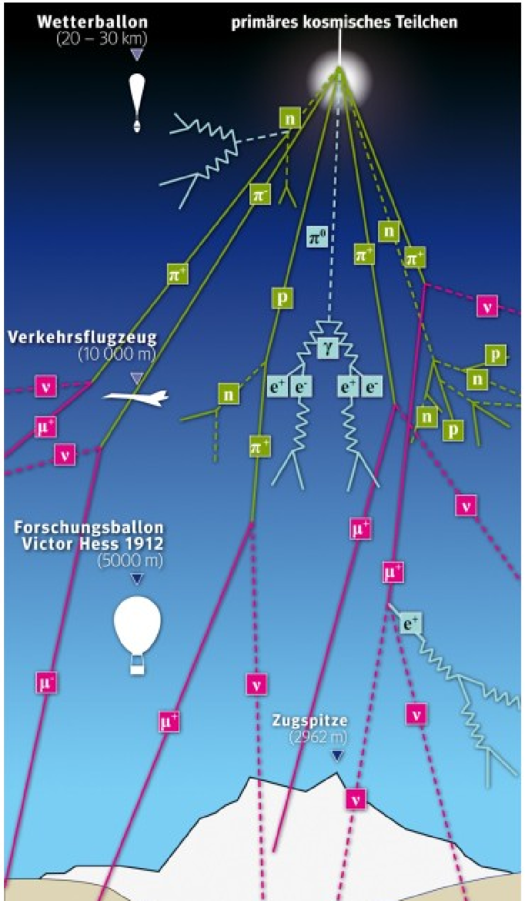
Muography

imaging with cosmic muons

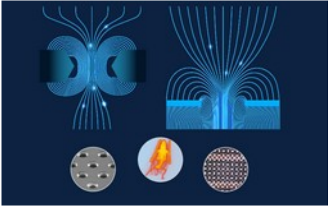


Muography: The Basics

- cosmic muons: primary cosmic radiation (mainly protons) hit atmosphere → hadronic interactions → pions & kaons → decay into muons
- lifetime 2.2μs but $p_{\mu} \sim 4GeV$ → decay length O(20km)
- rate ~ 1/s dm²
- angular distribution ~ cos² ϑ: # vertical = 8 # horizontal



DESY
Zenith angle dependence of Cosmic muons



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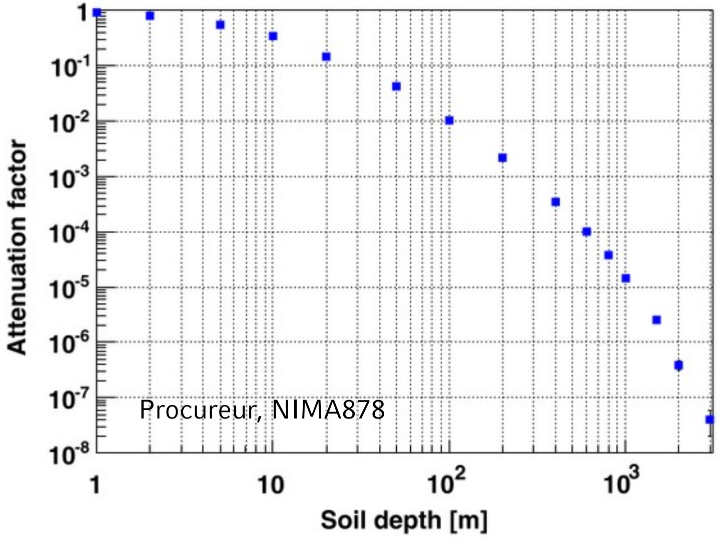
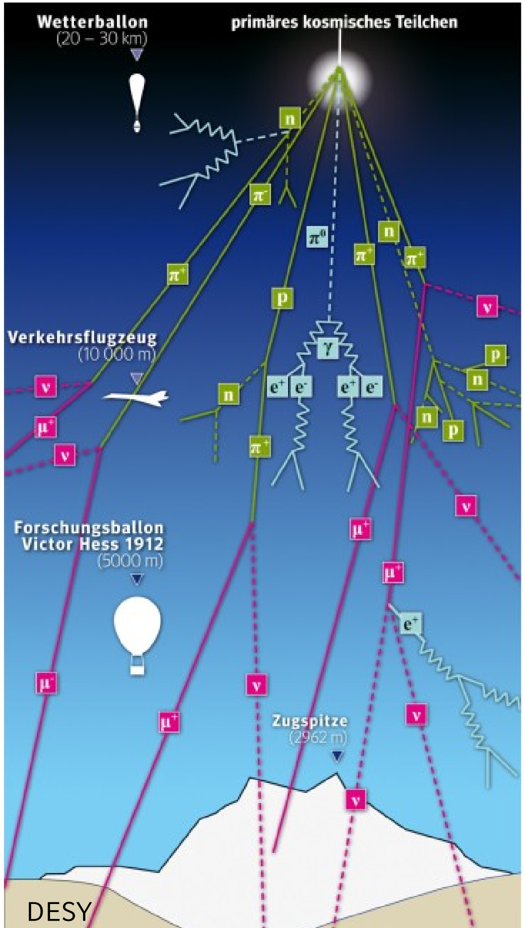
- lifetime 2.2μs but $p_\mu \sim$ 4GeV → decay length O(20km)
- rate ~ 1/s dm²
- angular distribution ~ $\cos^2 \vartheta$: # vertical = 8 # horizontal
- no hadronic interactions, no bremsstrahlung → can traverse large scale or shielded structures



Procureur, NIMA878



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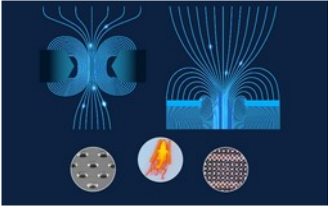


Muography: Concepts

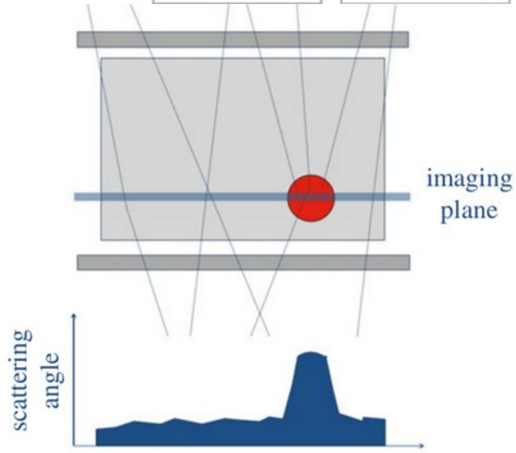
scattering-based muography

$$\sigma_\theta = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{x}{L_{rad}}} \left[1 + \frac{1}{9} lg \left(\frac{x}{L_{rad}} \right) \right]$$

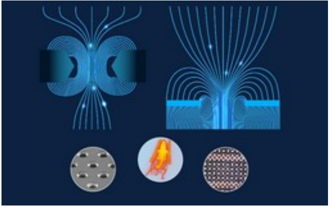
- tracklet upstream & downstream of object → point of closest approach
- object thin enough: only one major scattering event

muon metrology

- no object, compare tracklets in two trackers → determine relative position



Kaiser, 10.1098/rsta.2018.0049



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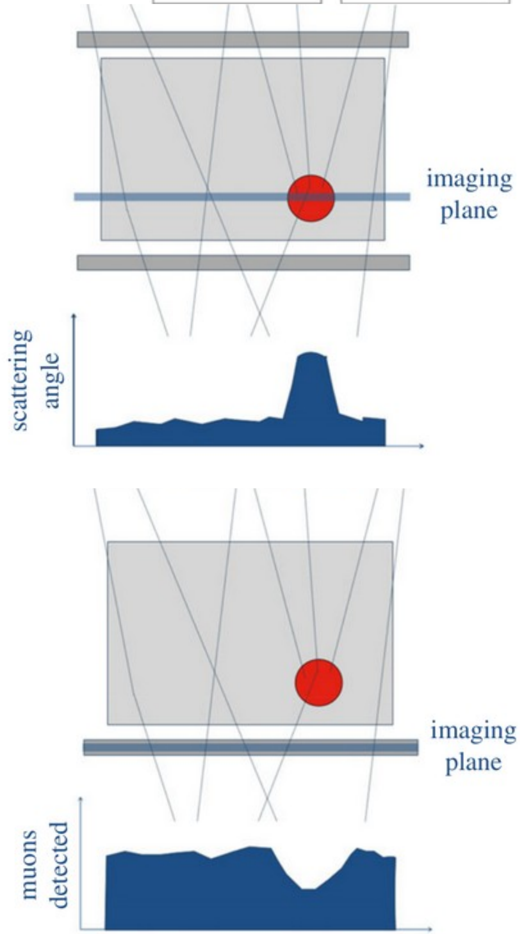
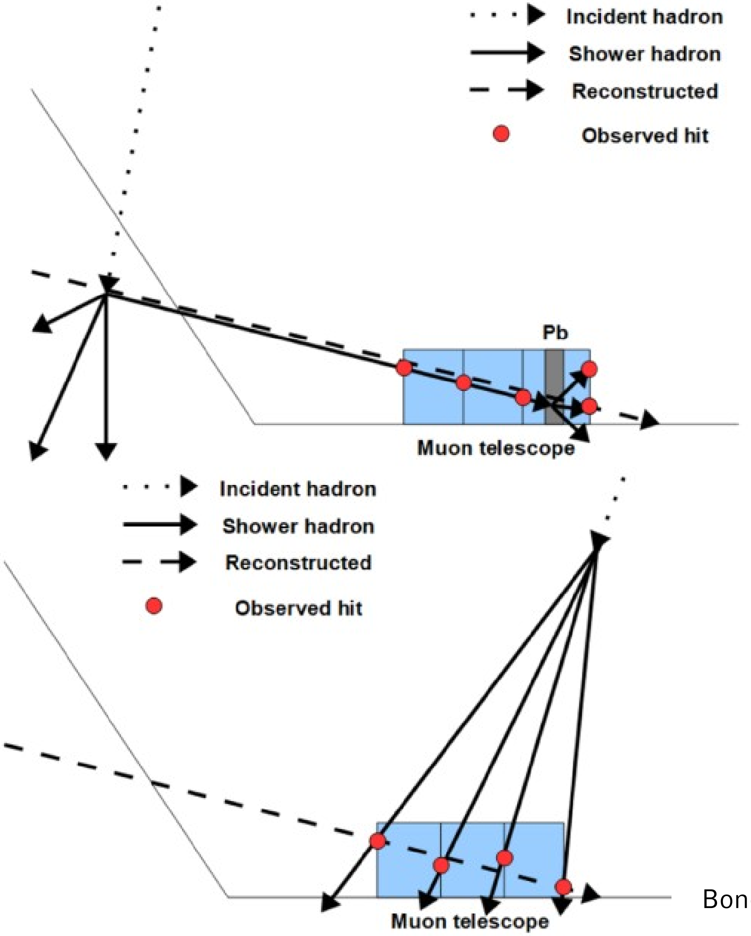
absorption-based (transmission) muography

- muons have finite range in matter + polyenergetic spectrum → more muons absorbed by more opaque material
- determine change in muon flux w.r.t. free sky measurement → opacity along line of sight
- objects of several 100m thickness



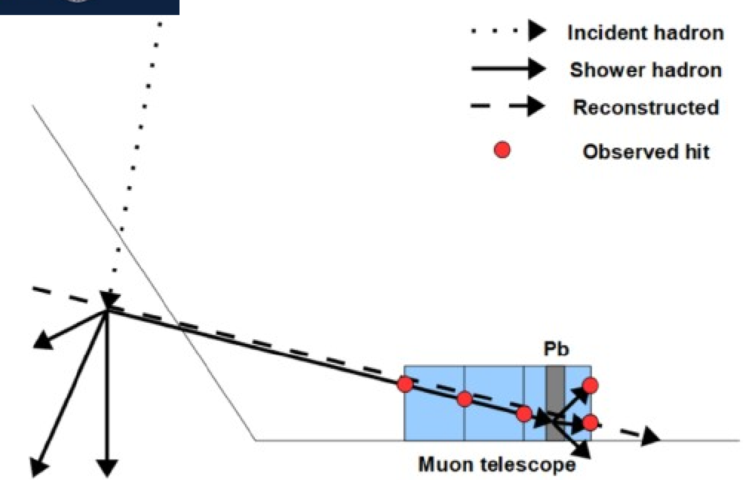
Kaiser, 10.1098/rsta.2018.0049

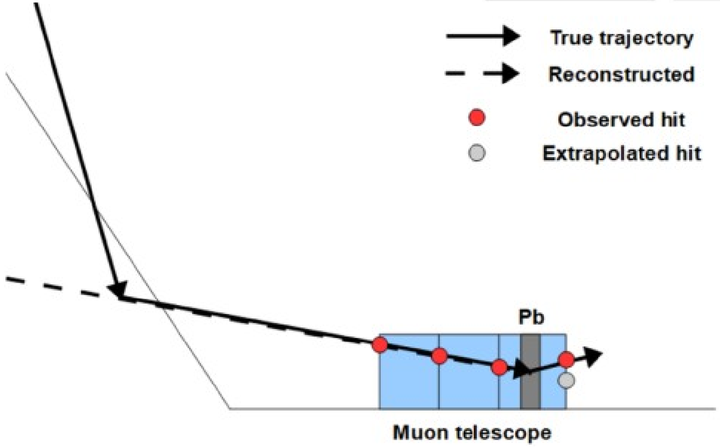
Muography Background Events

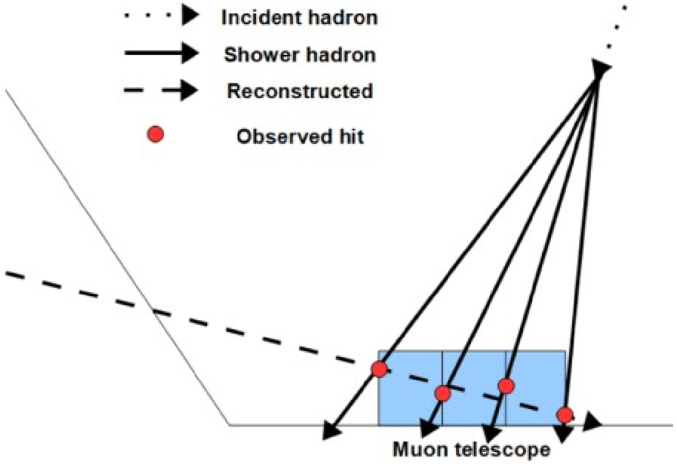


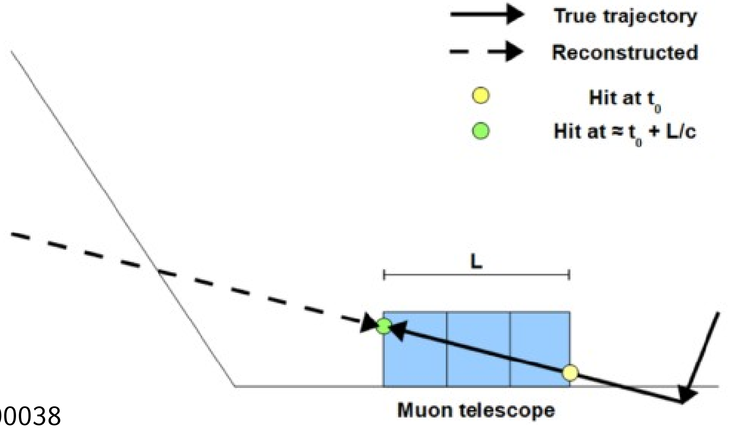
Bonechi 10.1016/j.revip.2020.100038

Muography Background Events









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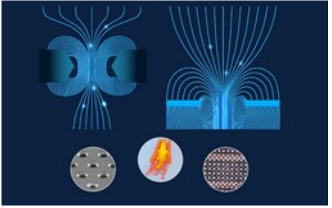
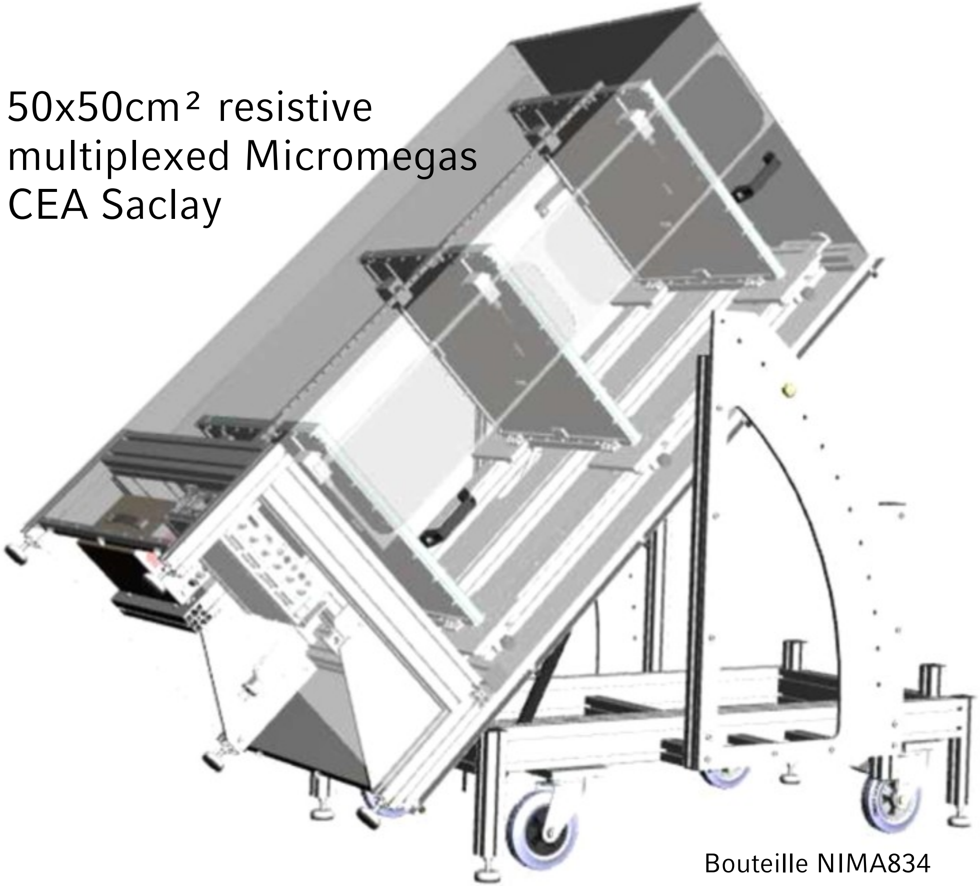


Suitable Instruments

nuclear emulsions
- no power during acquisition
- very good spatial resolution
- lengthy off-line readout (scanning)

plastic scintillators
- online events
- coarse spatial resolution

gaseous detectors
- good spatial resolution
- online events
- power & gas supplies needed
- temperature & pressure dependence



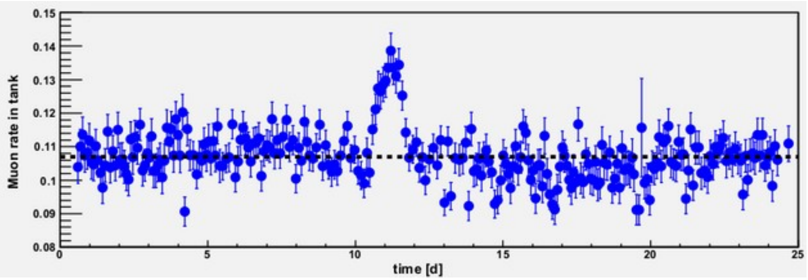
Bouteille NIMA834

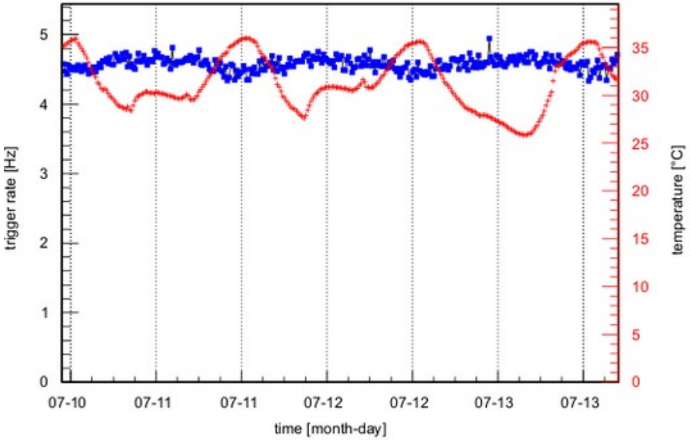
Water Tower Muography

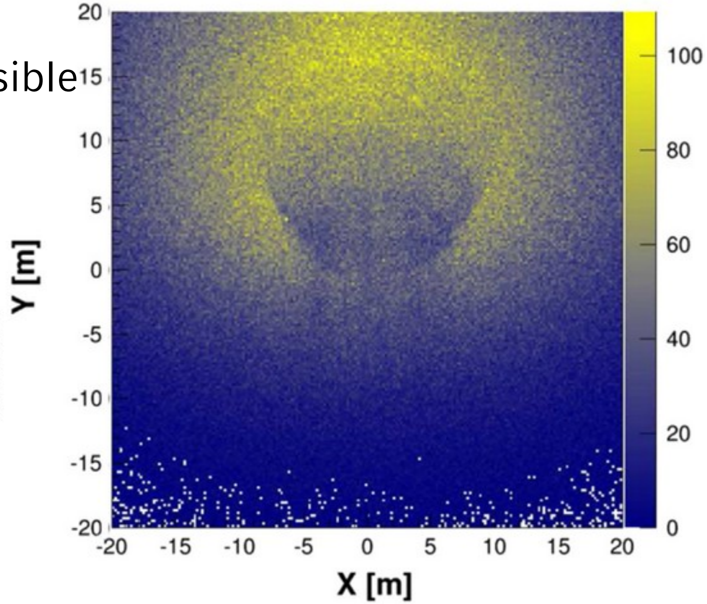
four 50x50cm² Micromegas

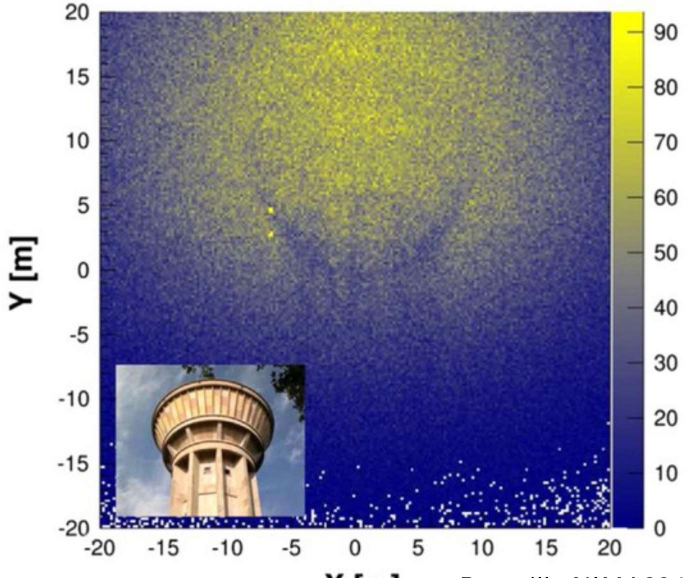
- test autonomous operation
- implement correction for pressure & temperature variations
- image water tower at Saclay, also during yearly emptying

→ dynamic imaging outdoors possible







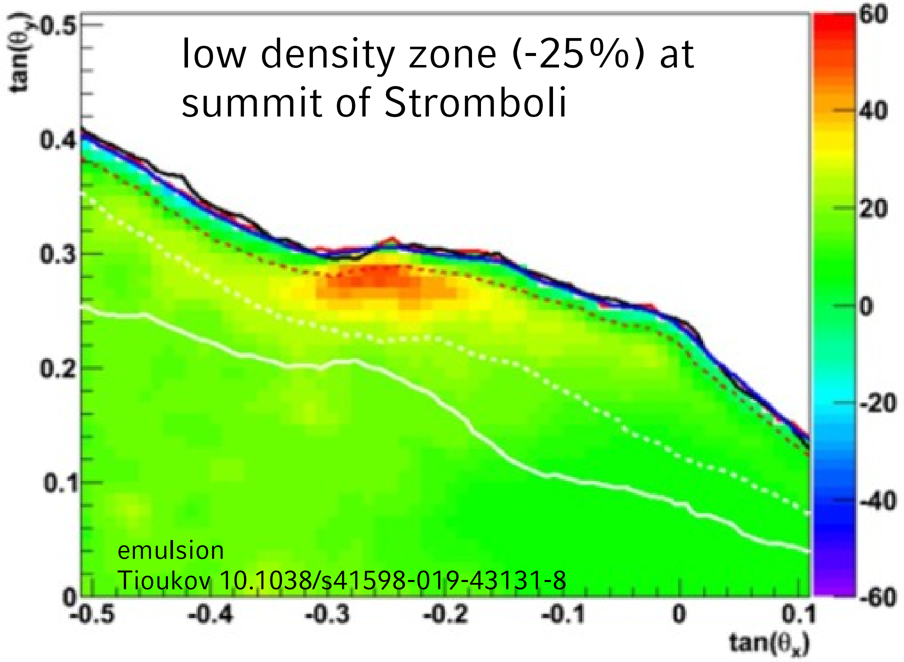


Bouteille NIMA834

Volcano Muography

static Muography

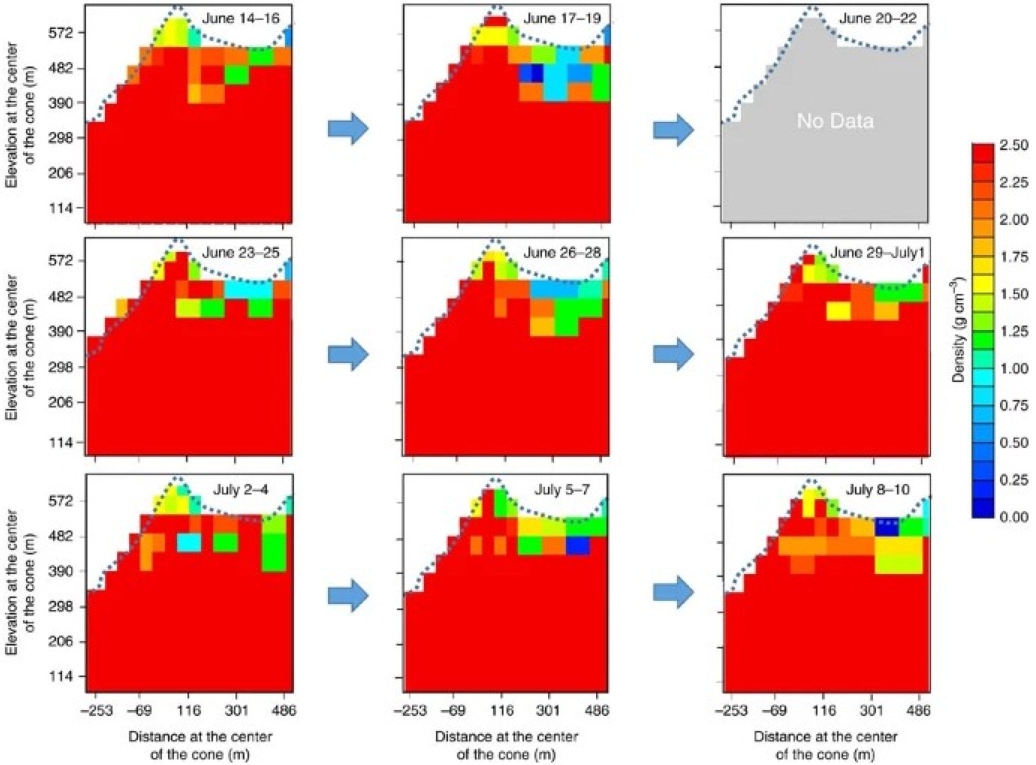
- investigate internal structures → understand stability, internal mechanisms, ...



emulsion
Tioukov 10.1038/s41598-019-43131-8

dynamic Muography

- risk assessment & eruption monitoring

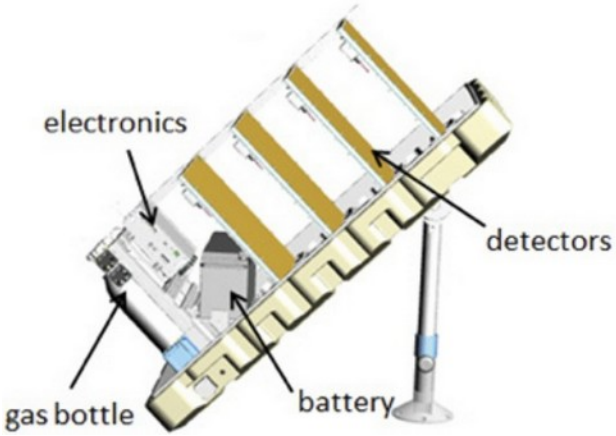


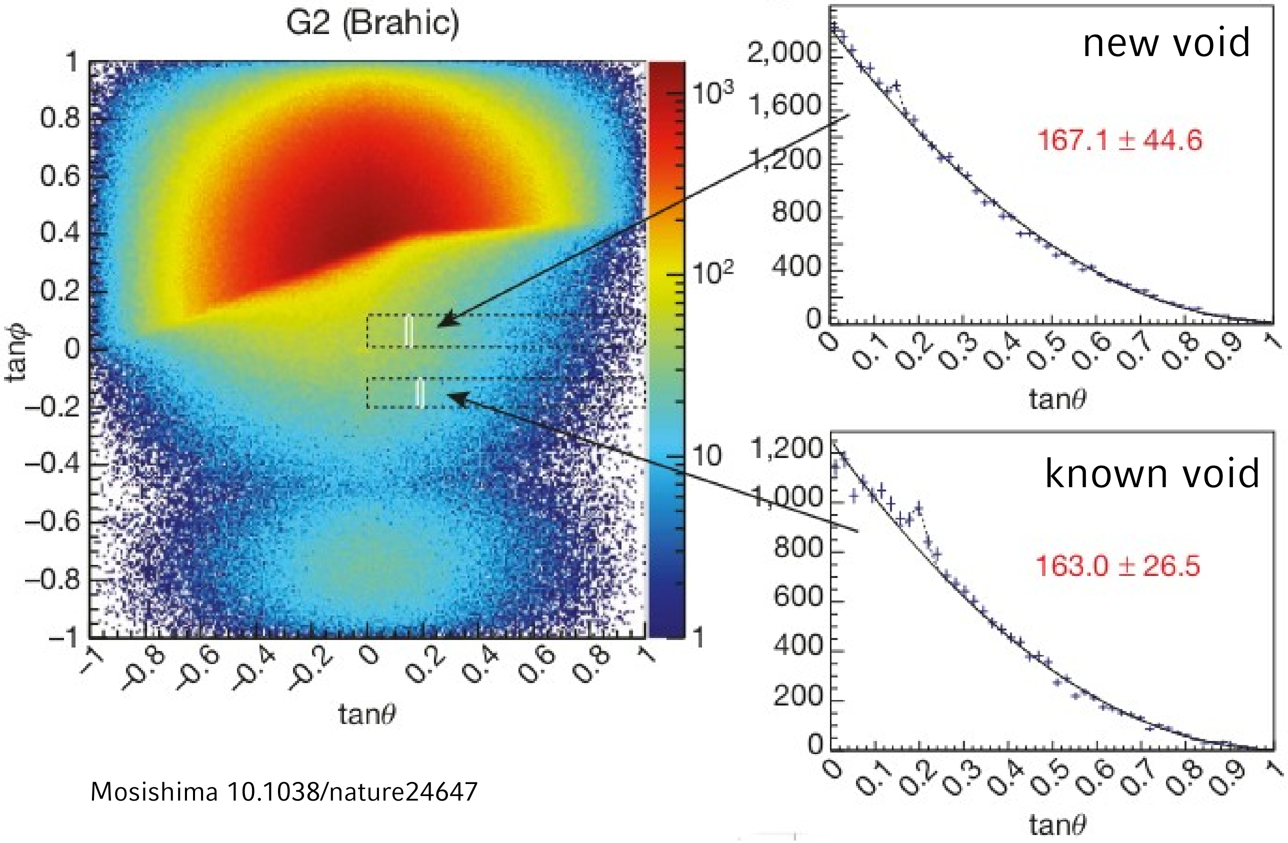
plastic scintillators, Tanaka 10.1038/ncomms4381

Muography: Archeology Khufu's Pyramid

ScanPyramids project
- combined measurements with emulsion, scintillators, Micromegas
- unknown void (length>30m) discovered

two Micromegas telescopes
- four 50x50cm² resistive multiplexed Micromegas each
- 10^7 track candidates in 2 months
- 35W power consumption

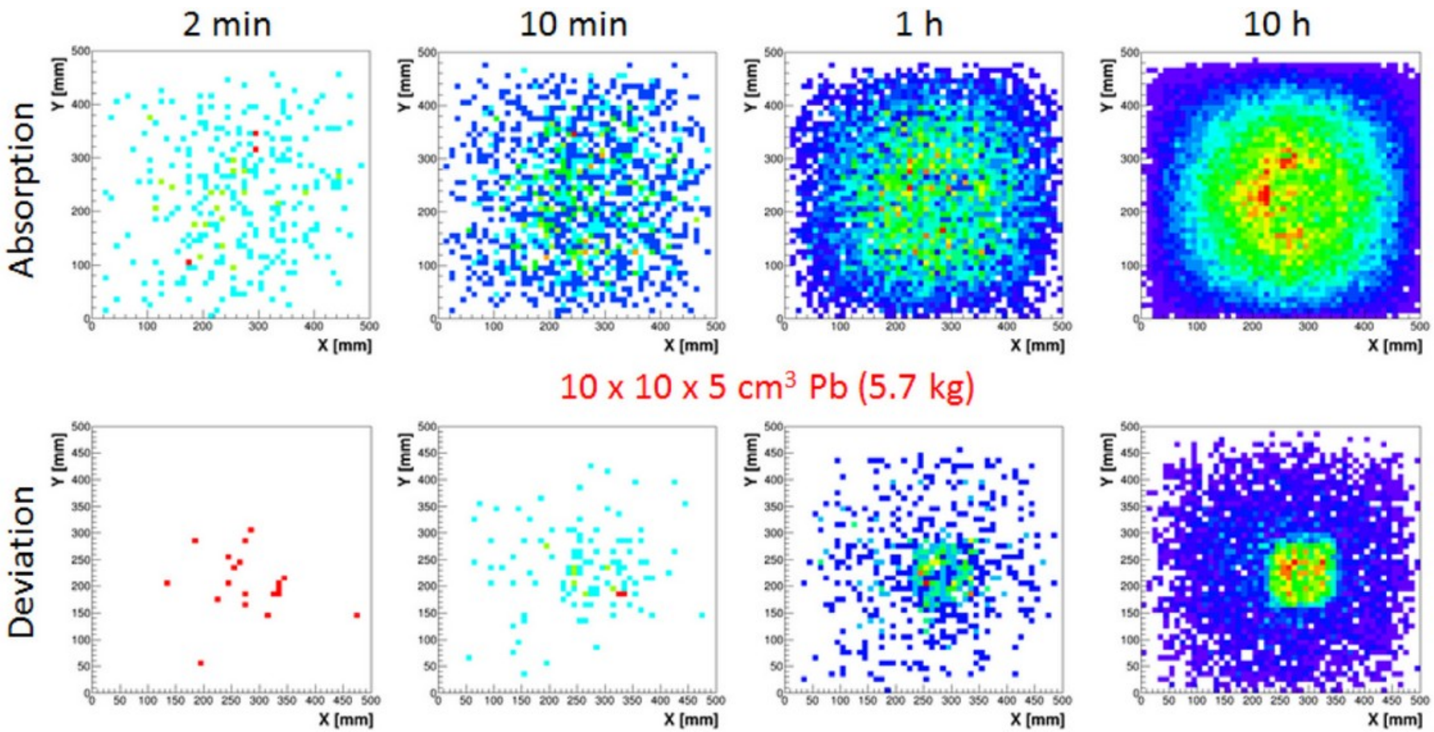




Mosishima 10.1038/nature24647

Scattering vs Absorption Muography

- scattering muography only possible for smaller objects
- lead brick imaged in Saclay telescope
- sensitivity in scattering mode considerably faster
- in principle: detection of high-density or high-Z material within lower density material possible (container, casks, trucks, …)
- hot topic for „special nuclear material" detection



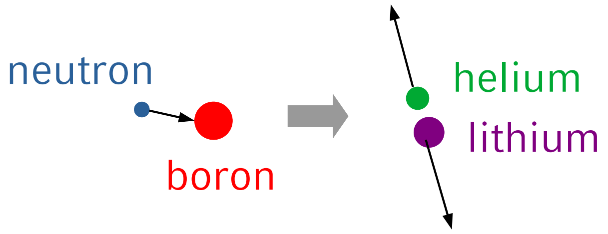
Procureur NIMA878

Neutron Detection

Neutron Detection in MPGDs

neutron interaction in typical gas mixtures quite unlikely
→ „convert" into charged particle
→ use MPGD features (spatial resolution, timing, …) to register charged products

solid converters ^{6}Li(n,α)^{3}H, ^{10}B(n,α)^{7}Li, U(n,f), …
→ strongly ionizing charged particles



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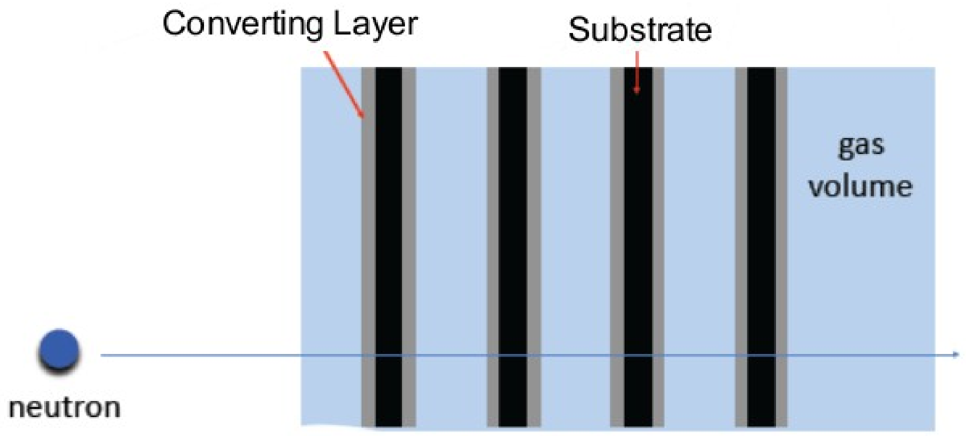
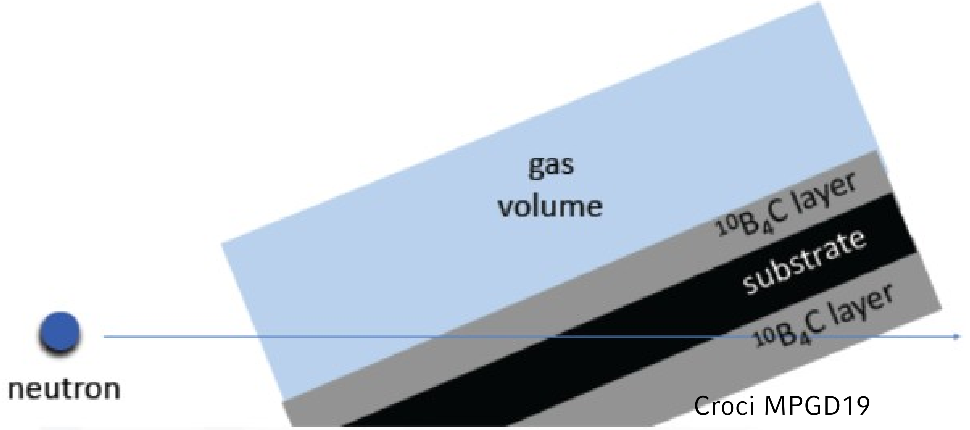
- charged particles only useful inside gas
  → limited thickness → single layer efficiency ~ 5%
- multi-layer
- grazed incidence





Croci MPGD19

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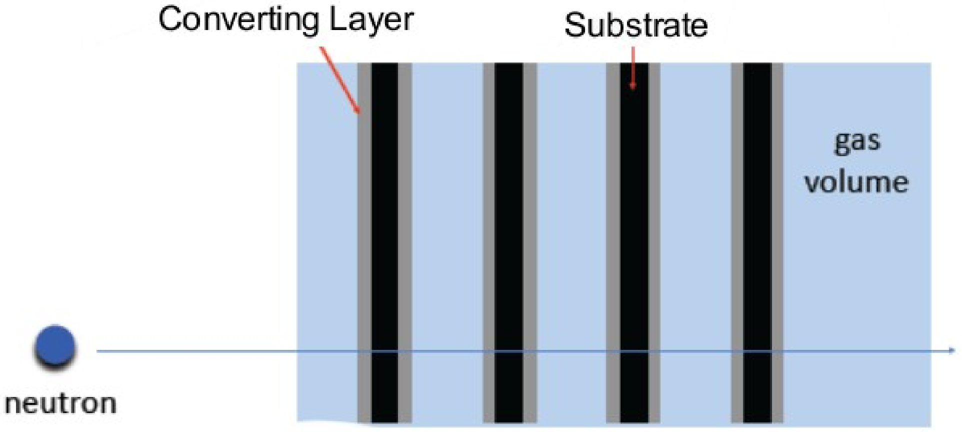
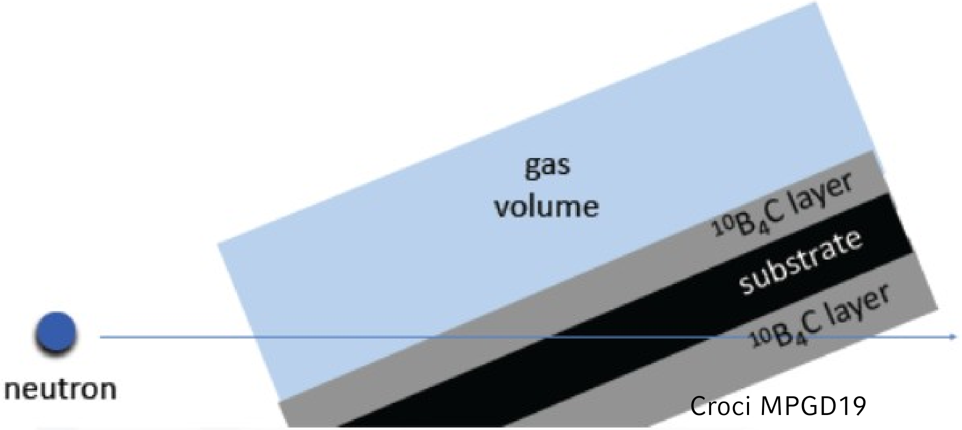
solid converter Gd: (n,gamma) → electrons, photon

high energy n: elastic interaction

- similar-mass interaction partners
- add He or protons (CH_4, C_4H_{10}) to gas mixture
- (thick) plastic + (thin) aluminum window

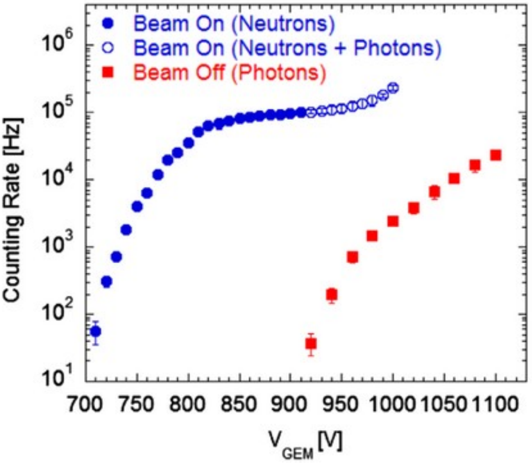


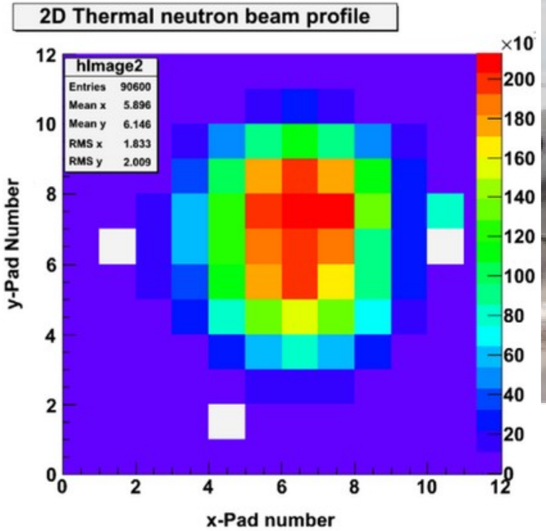


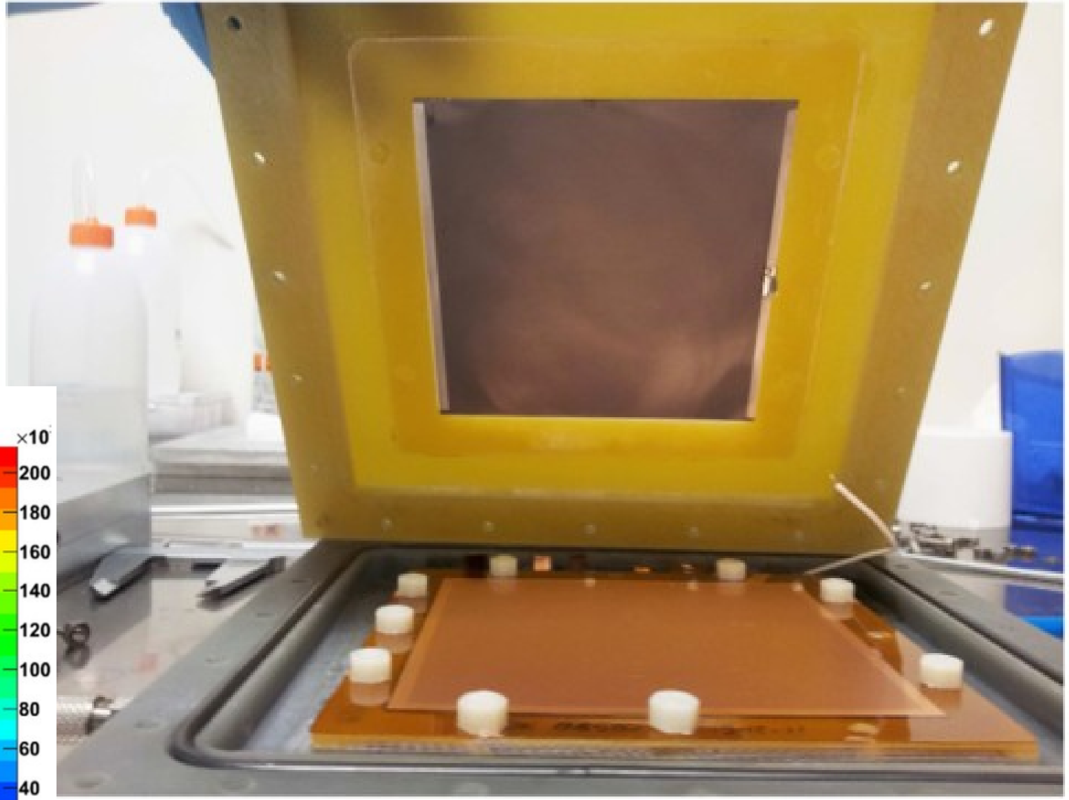
Croci MPGD19

Boron triple-GEM detector

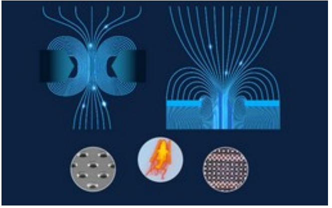
- 400µm aluminum cathode + 1µm $^{10}B_4C$
- 12x12 readout pads with 8x8mm²
  → rate capability
- thermal neutrons interact with boron
- Li or alpha (back-to-back) can escape cathode,
  E ~ O(1MeV)
- $\Delta E_{neutron} >> \Delta E_{photon}$ (activation)
- efficiency O(1%)





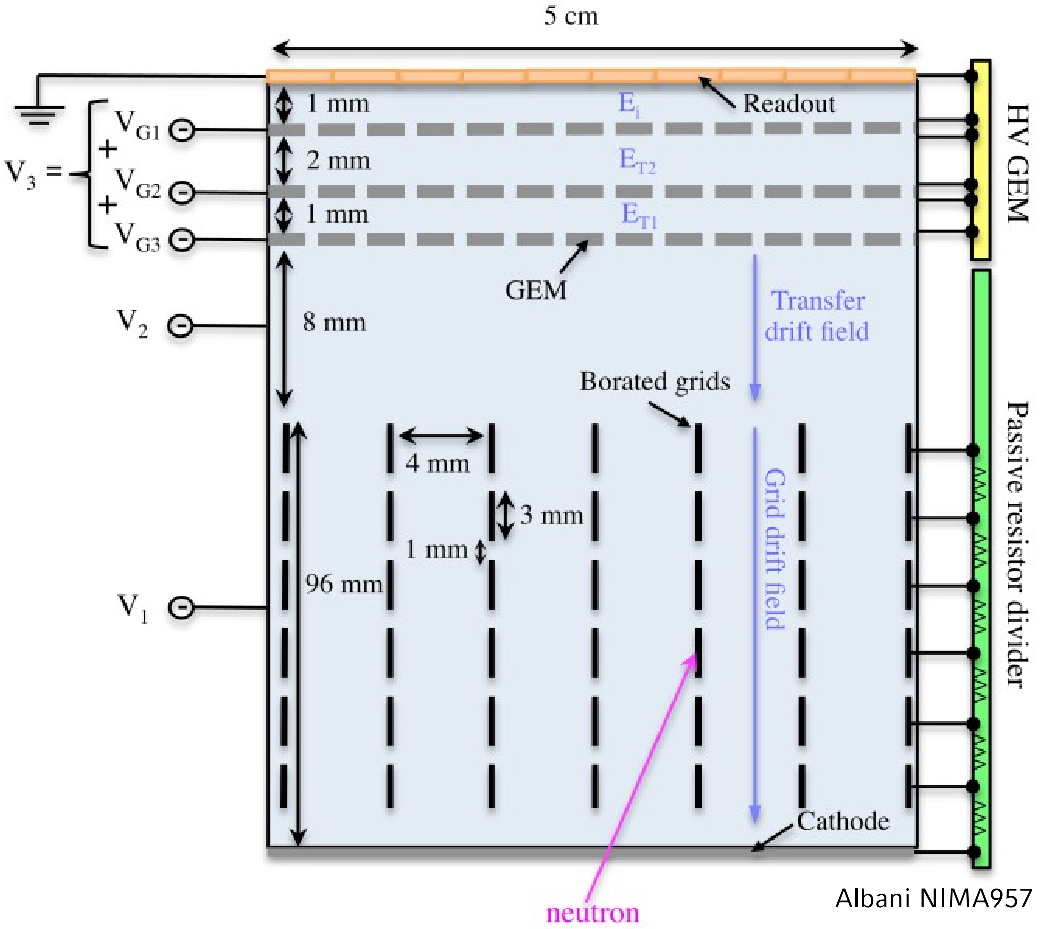


Croci NIMA732

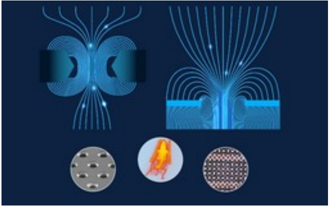


*B*oron *A*rray *N*eutron *D*etector GEM

- converter: 24 aluminum grids + 1µm $^{10}B_4C$
  → 10kV extraction voltage
- detector tiled by 5° → increase efficiency



Albani NIMA957



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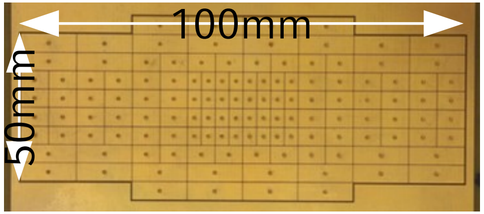
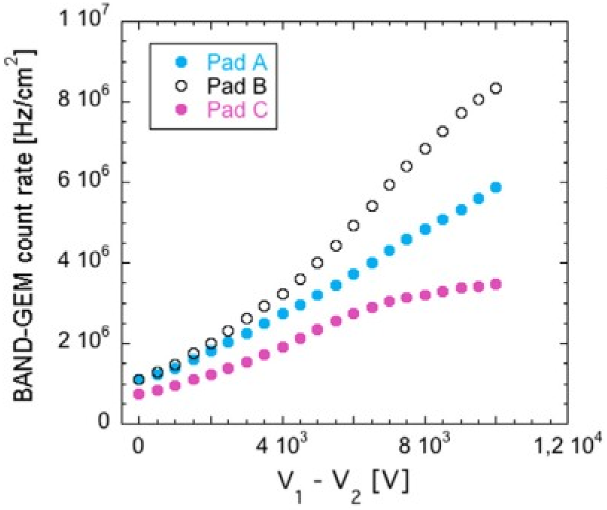
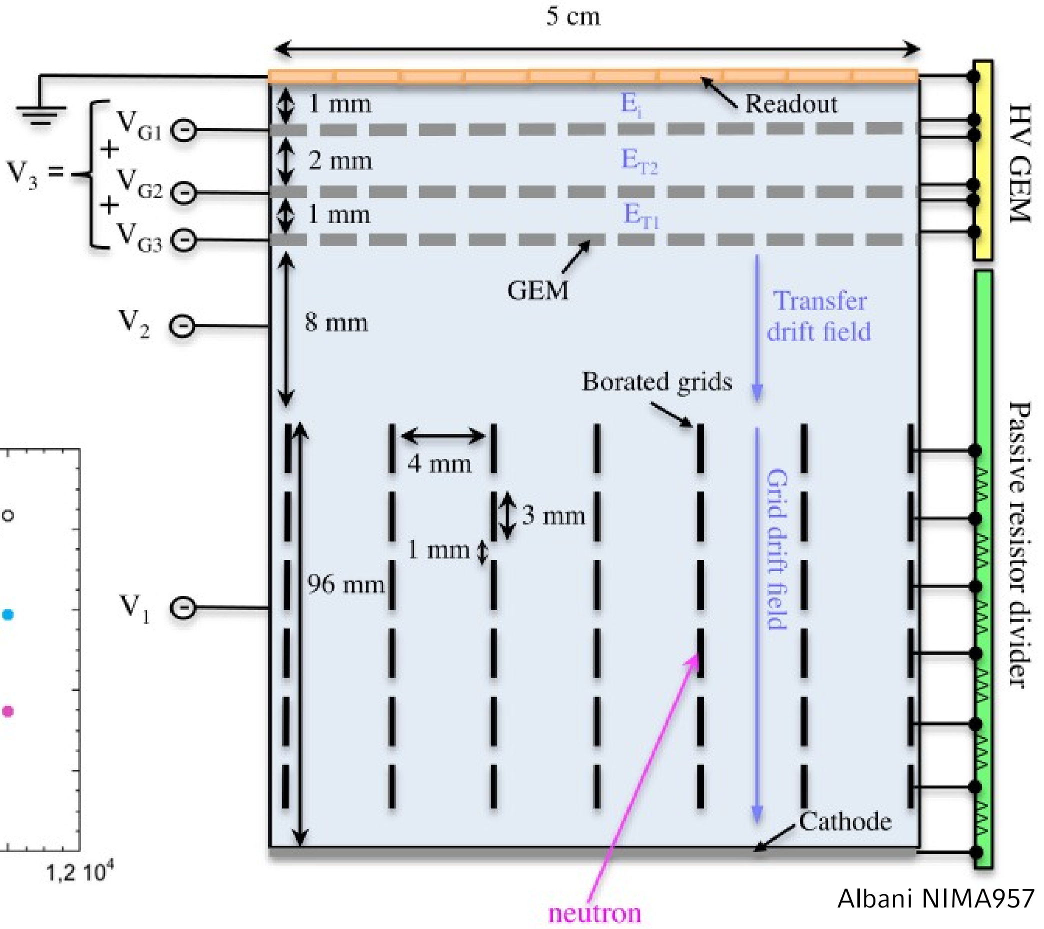
- converter: 24 aluminum grids + 1µm $^{10}B_4C$
  → 10kV extraction voltage
- detector tiled by 5° → increase efficiency
- high count-rate reachable
- efficiency not limited by neutron conversion but electron extraction from grid
- full module: 50% efficiency reachable
- long conversion region → bad timing accuracy



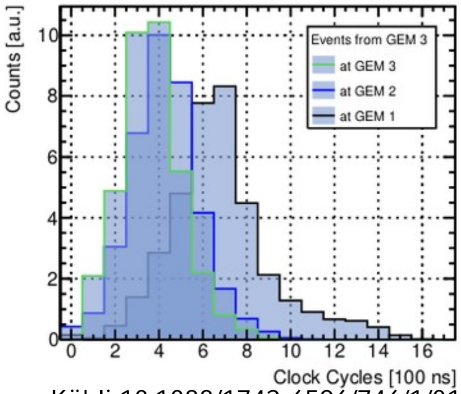


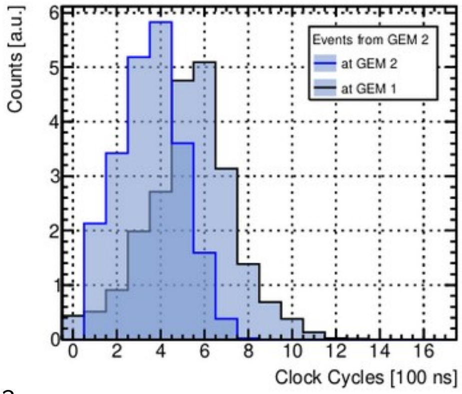


Albani NIMA957

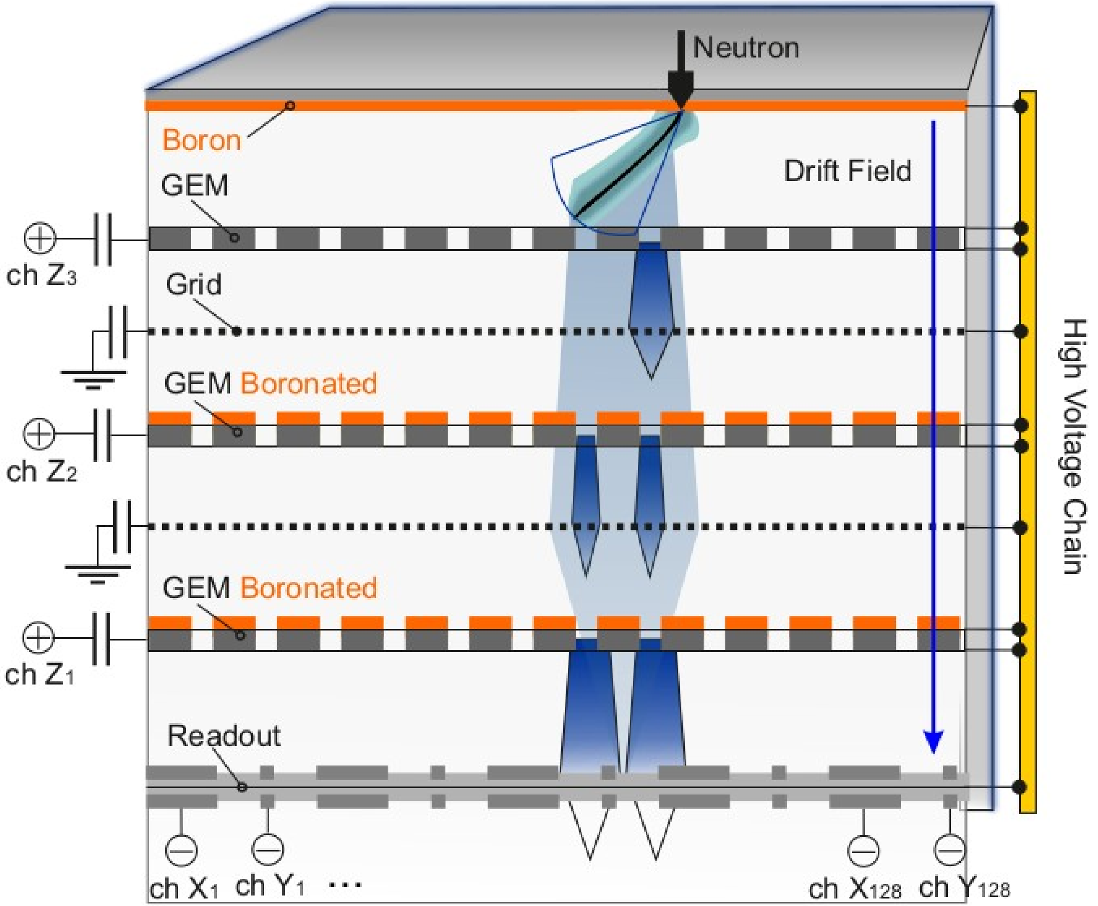
Cascade GEM Detector

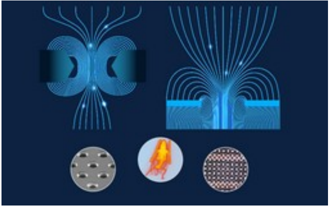
- 20x20cm² triple GEM doublet detector back-to-back
- 6 ^{10}B layers on cathodes + GEMs
- GEMs read out → identify interacting ^{10}B layer → time resolution 100ns
- meshes: shield GEMs electrically
- crossed readout strips (128)
- O(50%) efficiency





Köhli 10.1088/1742-6596/746/1/012003





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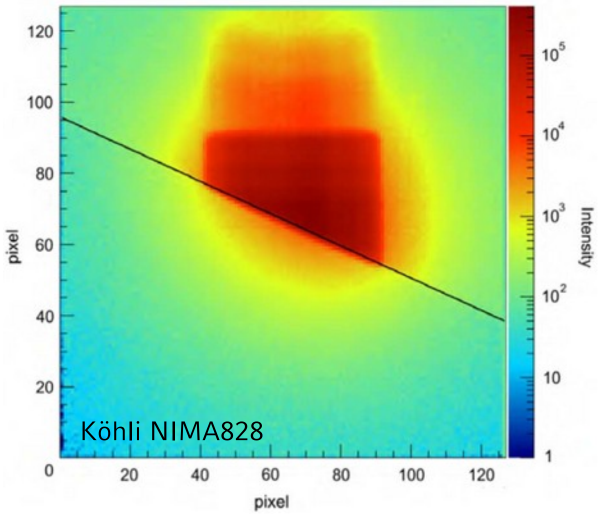
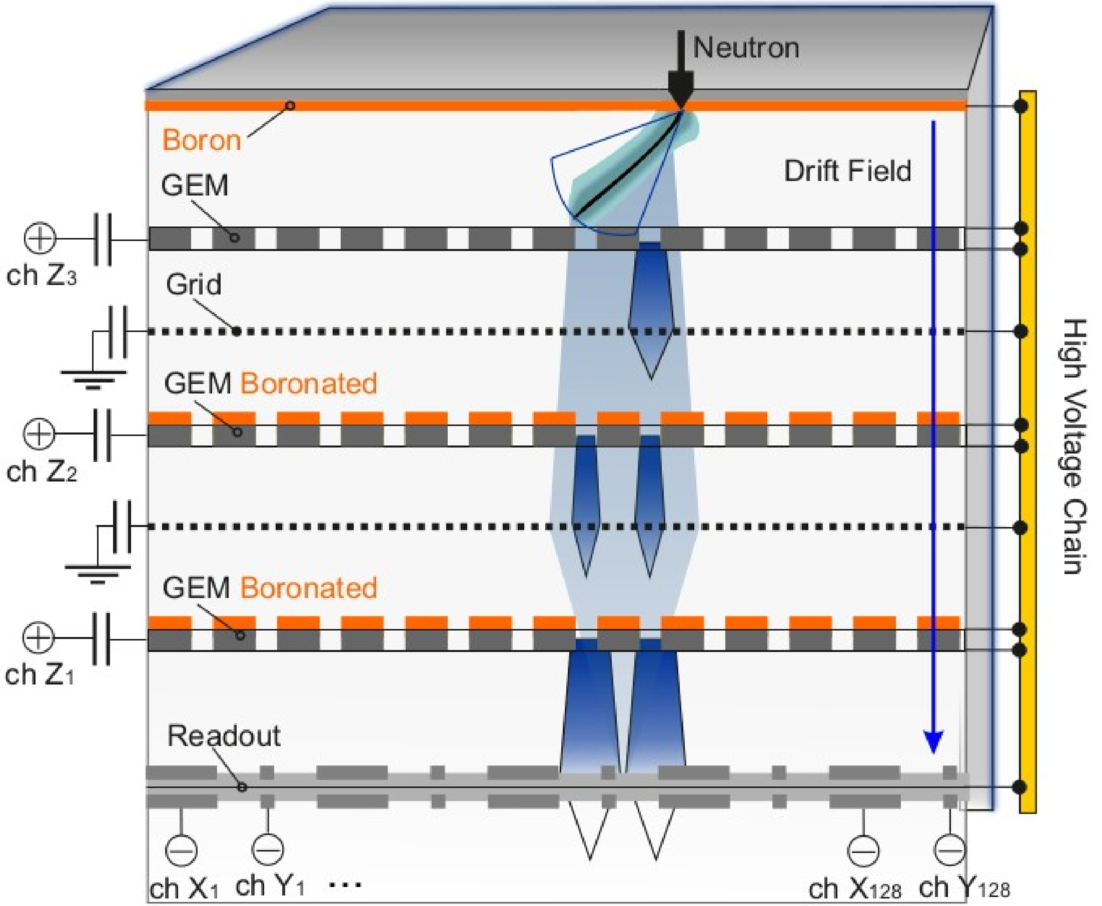
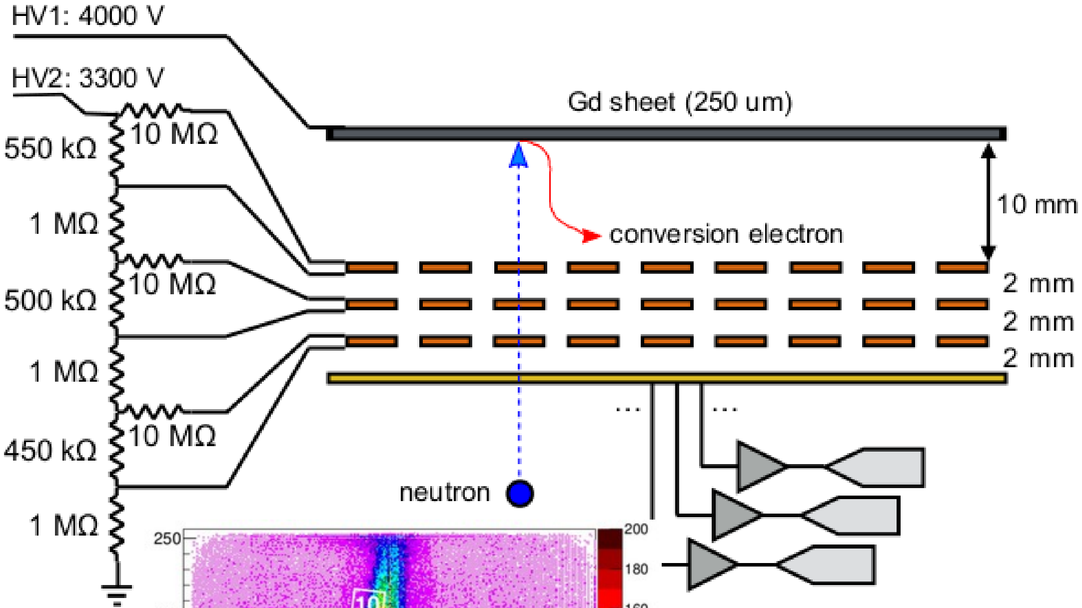


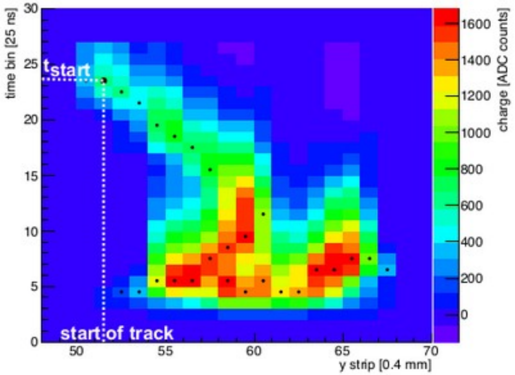


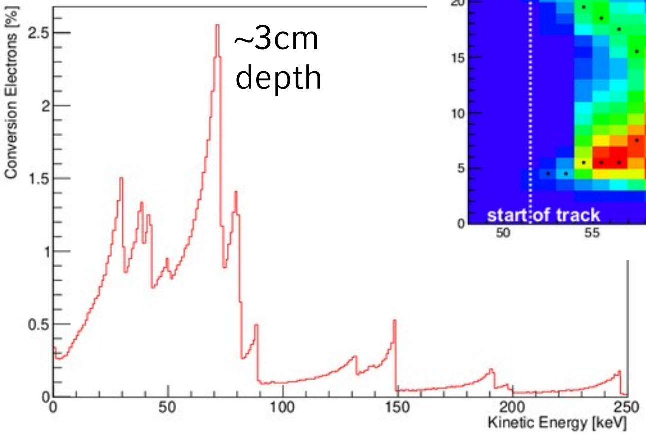
Gadolinium GEM

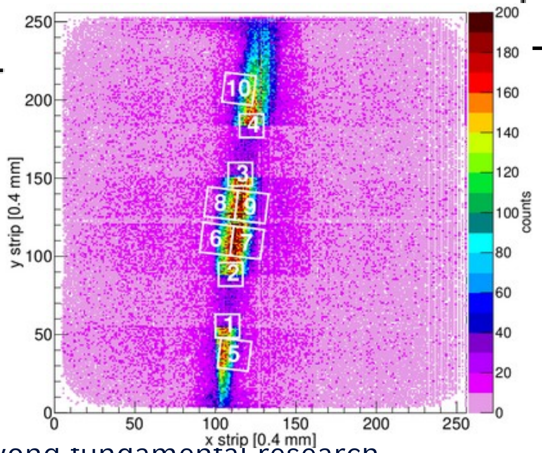
250µm Gd: high n-capture cross section
→ prompt gamma emission + conversion electrons

- triple-GEM with 2x 256 strips (400µm pitch)
- µTPC mode → reconstruct conversion point







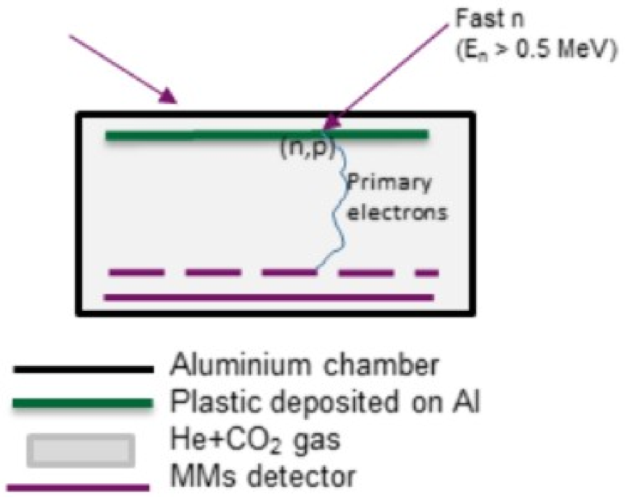


Pfeiffer
10.1088/1748-0221/11/05/P05011

neutron Beam Loss Monitor @ ESS

ESS linac: proton beam up to 2GeV, 62.5mA
→ detect starting beam losses essential

Micromegas based neutron BLM in low energy region
- fast losses monitor: 128µm Mylar as n → p converter



Segui 10.18429/JACoW-IBIC2019-MOBO04

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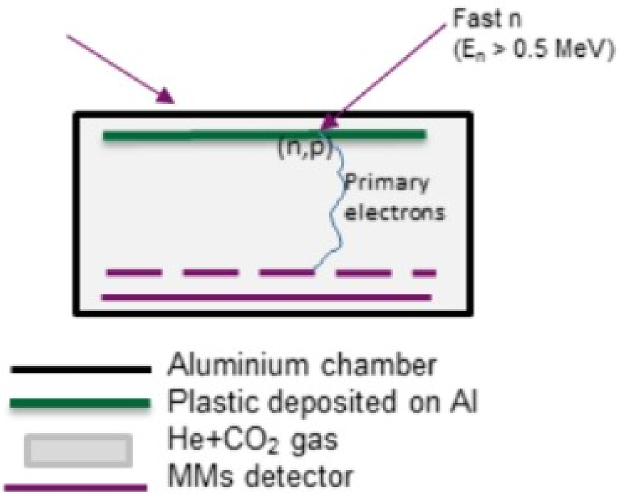
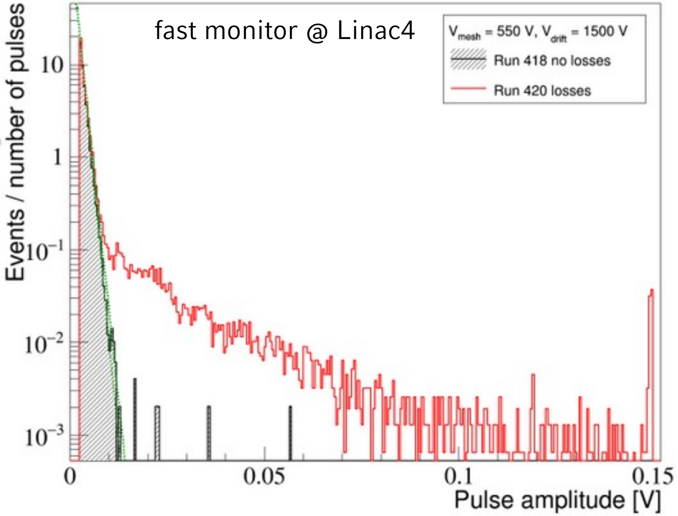
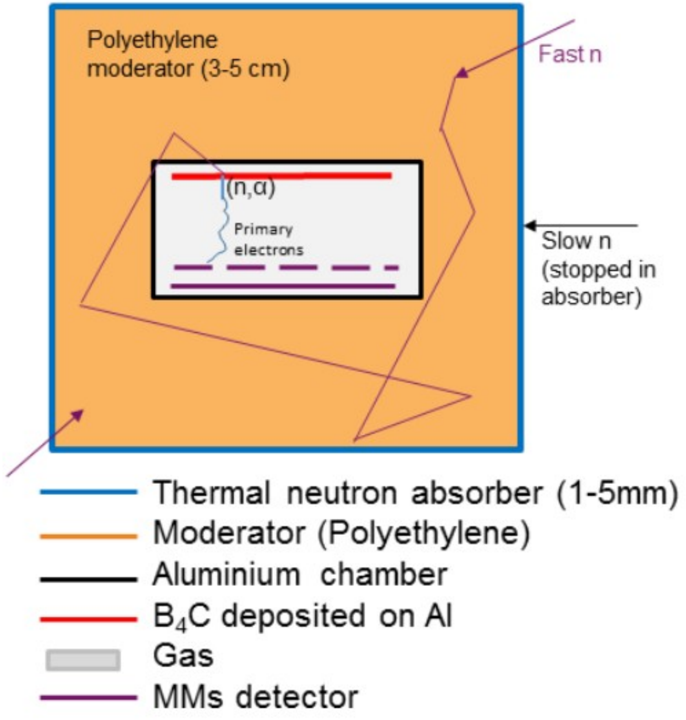
Micromegas based neutron BLM in low energy region
- fast losses monitor: 128μm Mylar as n → p converter
- slow losses monitor: $^{10}B_4C$ cathode







Segui 10.18429/JACoW-IBIC2019-MOBO04

Medical Applications

Medical Applications

diagnostics and treatment monitoring heavily based on particle and photon detectors

- different level of reliability, accuracy and fail safety needed, if radiation used on living beings
- non-laboratory environment: supplies, operation by non-experts, construction, certification
- medicine is conservative environment
  - experimental operation ethically difficult
  - new technologies only accepted, if considerably better than previous

Medical Applications

diagnostics and treatment monitoring heavily based on particle and photon detectors
- different level of reliability, accuracy and fail safety needed, if radiation used on living beings
- non-laboratory environment: supplies, operation by non-experts, construction, certification
- medicine is conservative environment
  - experimental operation ethically difficult
  - new technologies only accepted, if considerably better than previous

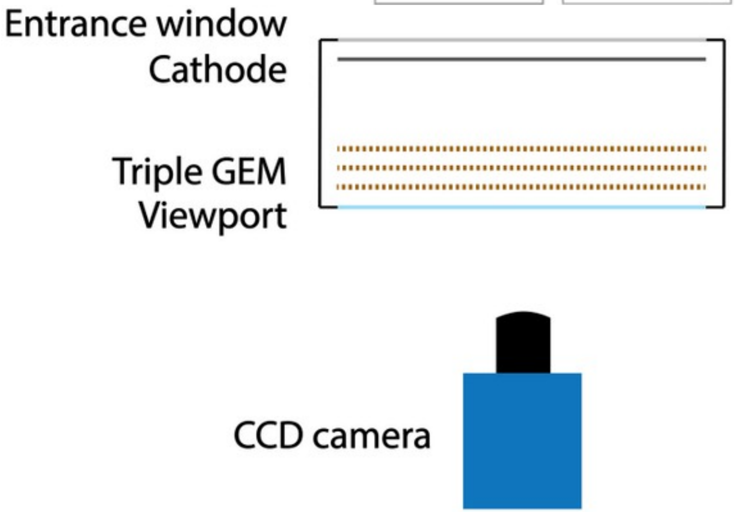
imaging
- pre-clinical photon imaging
- (non-clinical) positron emission imaging
- ion radiography and tomography

beam monitoring and control
- beam monitor chambers for pre-clinical and clinical radiation

dosimetry and beam characterization
- characterization of (pre-)clinical treatment beams

Soft X-Ray Imaging with Optically Readout GEM Detector

- soft X-rays interact via photo effect in $Ar:CF_4$
- gas amplification in triple GEM stack → charge + de-excitation light (270 & 620nm) → observe with cooled camera



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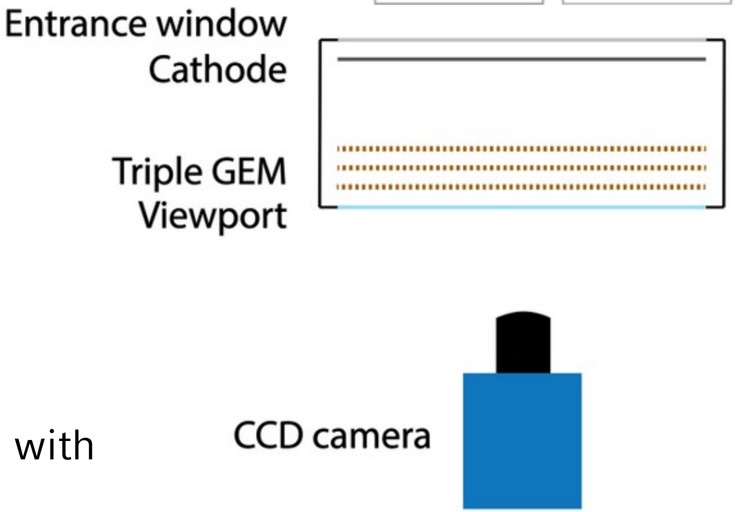
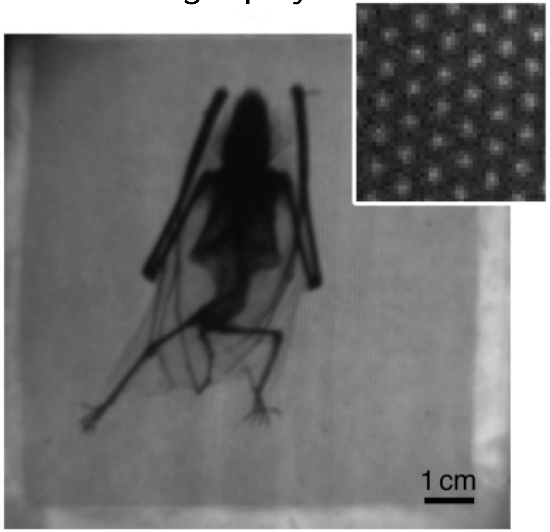
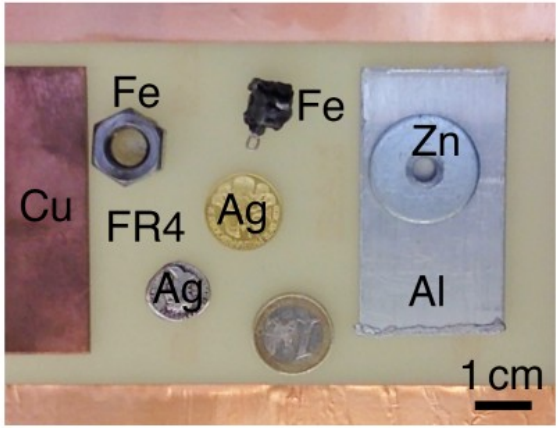
- gas amplification in triple GEM stack → charge + de-excitation light (270 & 620nm) → observe with cooled camera
- radiographic, tomographic & fluoroscopic imaging possible
- light amplitude <=> energy deposition <=> photon energy

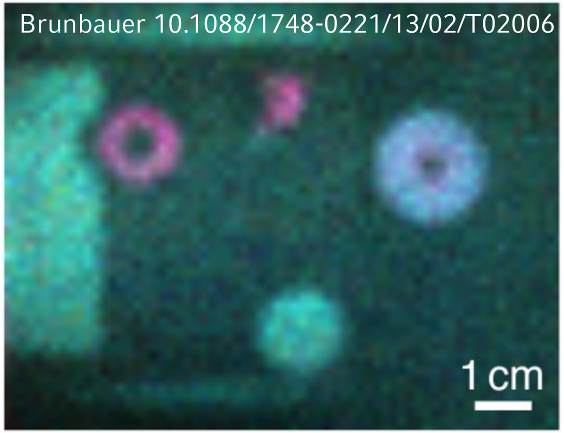


bat radiography 8keV



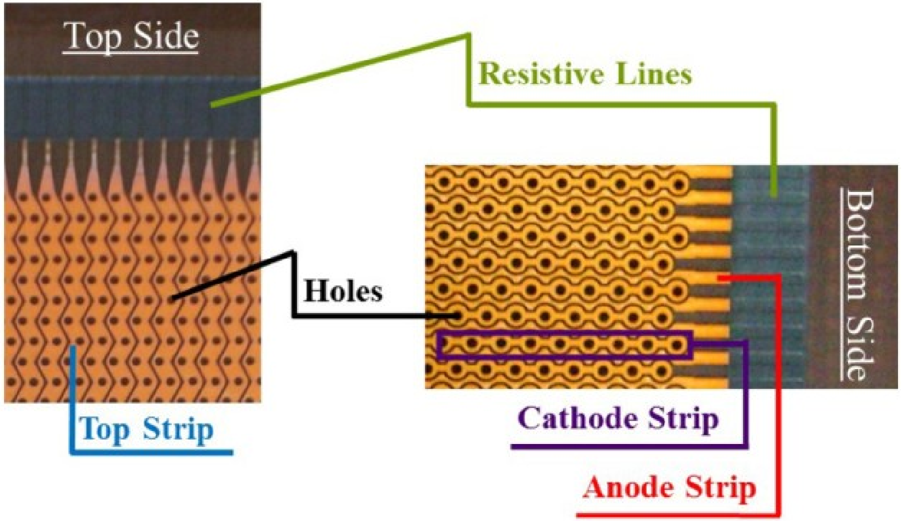
fluorescence imaging with 20keV illumination

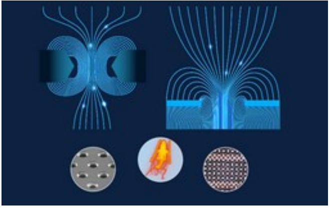




Soft X-Ray Imaging with THCOBRA Charge Readout

- soft X-rays (<50 kVp) interact in Ne:CH4 via photoeffect
- ionization charge amplified in THCOBRA structure (holes and between lower strips)
- top strips connected by resistive line → read out on both sides (2 channels)
- anode strips connected by resistive line → read out on both sides (2 channels)





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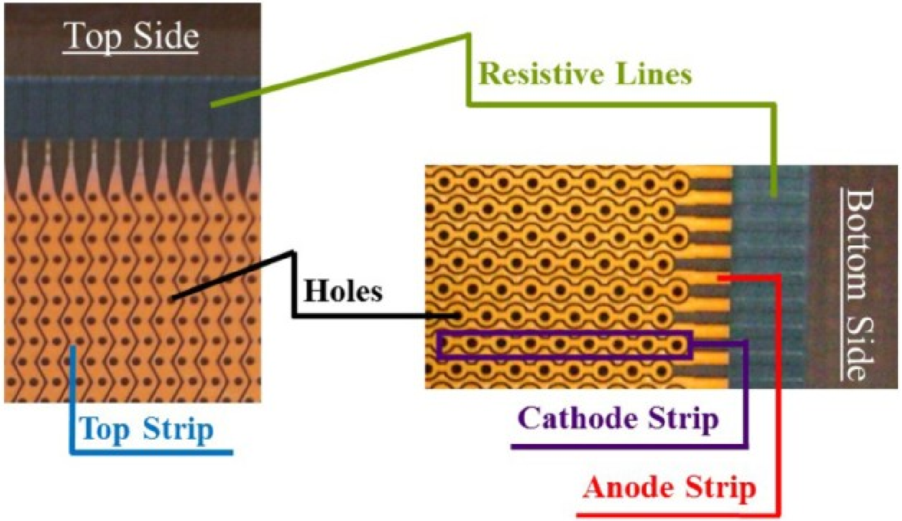
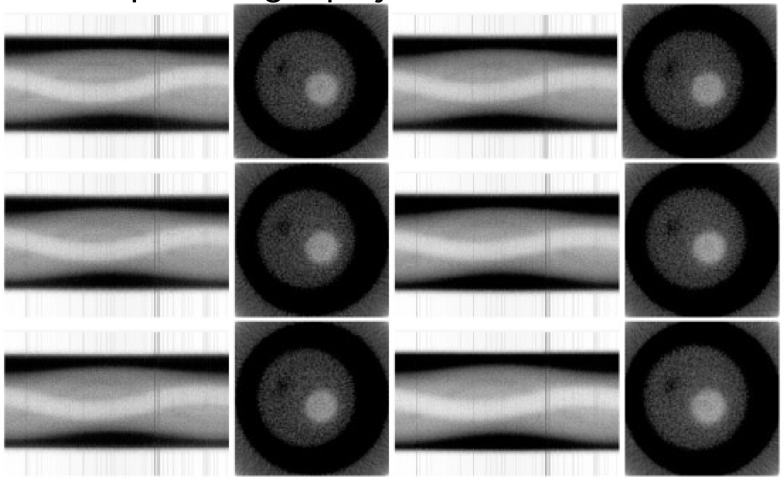
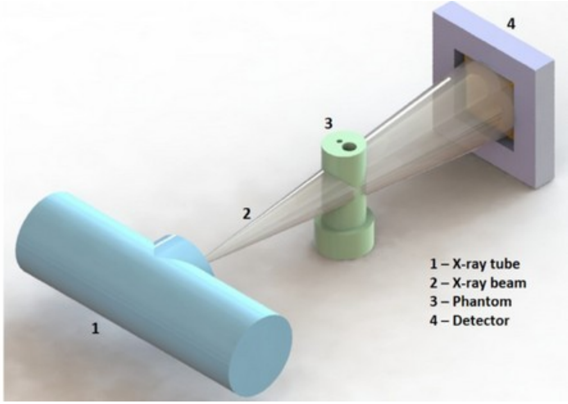


25kVp tomography: 47min, PMMA, chalk



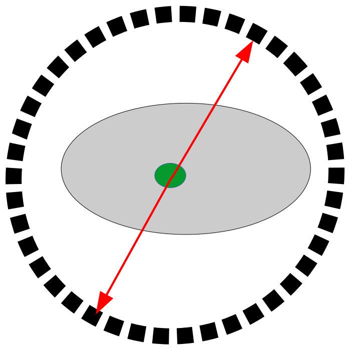


Carramate NIMA947

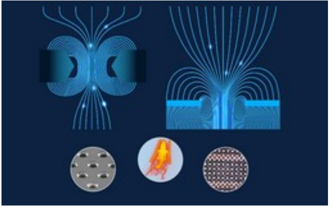
Positron Emission Imaging

Positron Emission Tomography: well established modality to image physiological activity in patients

- radioactive tracer (^{18}F, ^{15}O, ^{11}C, …) coupled to biologically active molecule (e.g. glucose mimetic)
- enrichment of tracer in „energy-consuming" tissues (e.g. tumor)
- β^+ decay → positron diffuses & annihilates with electron → two collinear 511keV photons
- tomographic image with $O(10^9)$ detected pairs



gaseous detectors?



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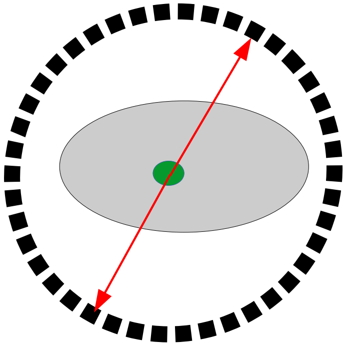

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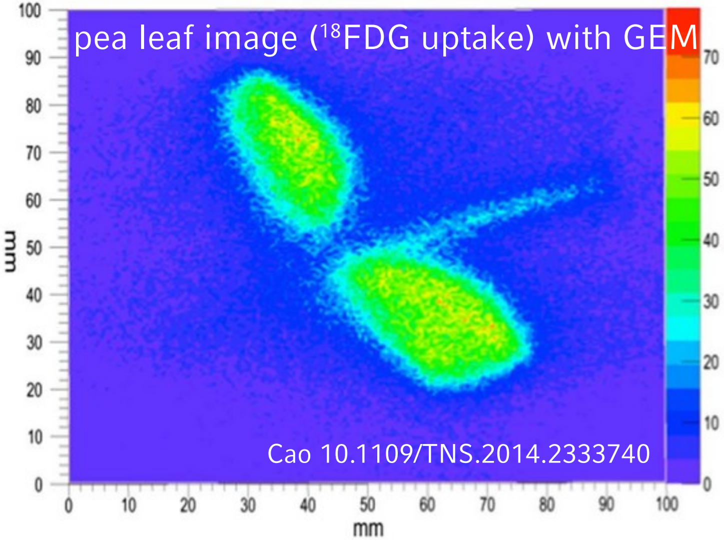
gaseous detectors?

- pro: large area coverage
- con: low efficiency to 511keV photons
- think different: directly detect positron from thin samples
- MPGD: very low material budget & good spatial resolution

→ expose living plants to $^{11}CO_2$ or ^{18}FDG → visualize physiology

- also possible in cell samples



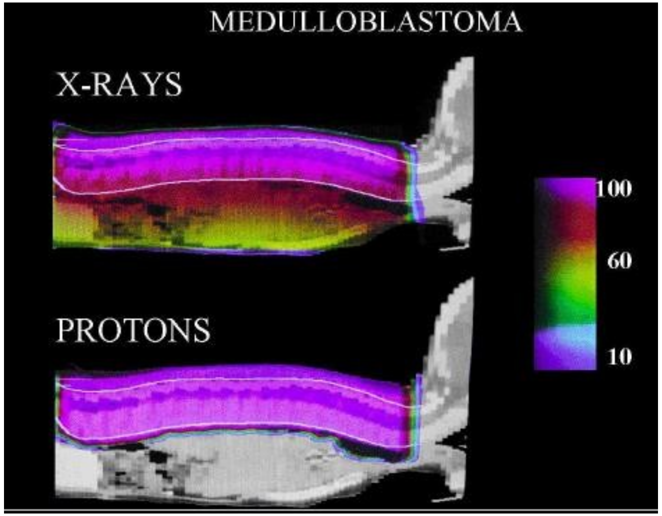
Context: Particle Therapy

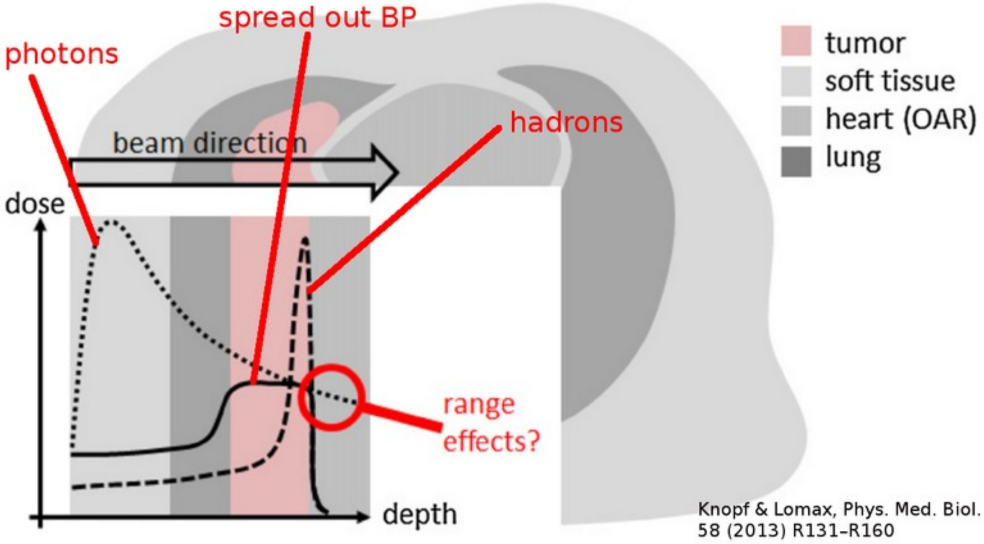
low energy ions: $dE/dx \sim 1/\beta^2$

→ favorable depth-dose:

- none behind tumor
- low in entrance

better tumor conformality → low out-of-field dose

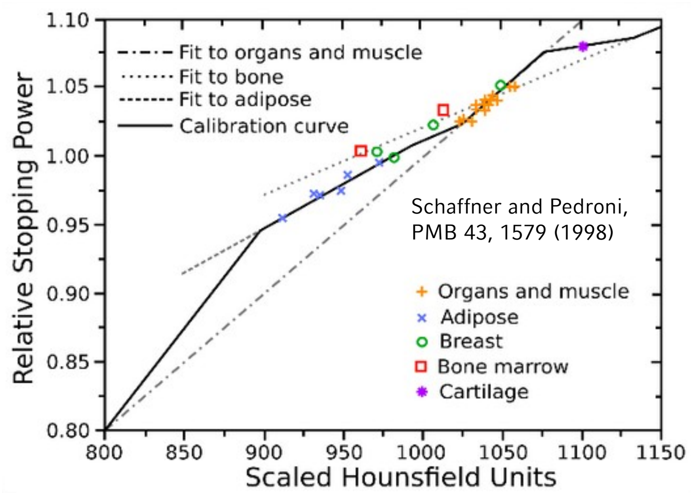


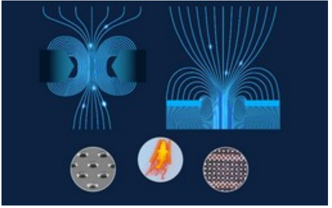


ballistic advantages obvious BUT
therapeutical advantages not fully demonstrated

Concept: Proton Radiography & Tomography

1. imaging: X-ray Computed Tomography
2. treatment planning: photon absorption <=> dE/dx
3. fractionated treatment





Concept: Proton Radiography & Tomography

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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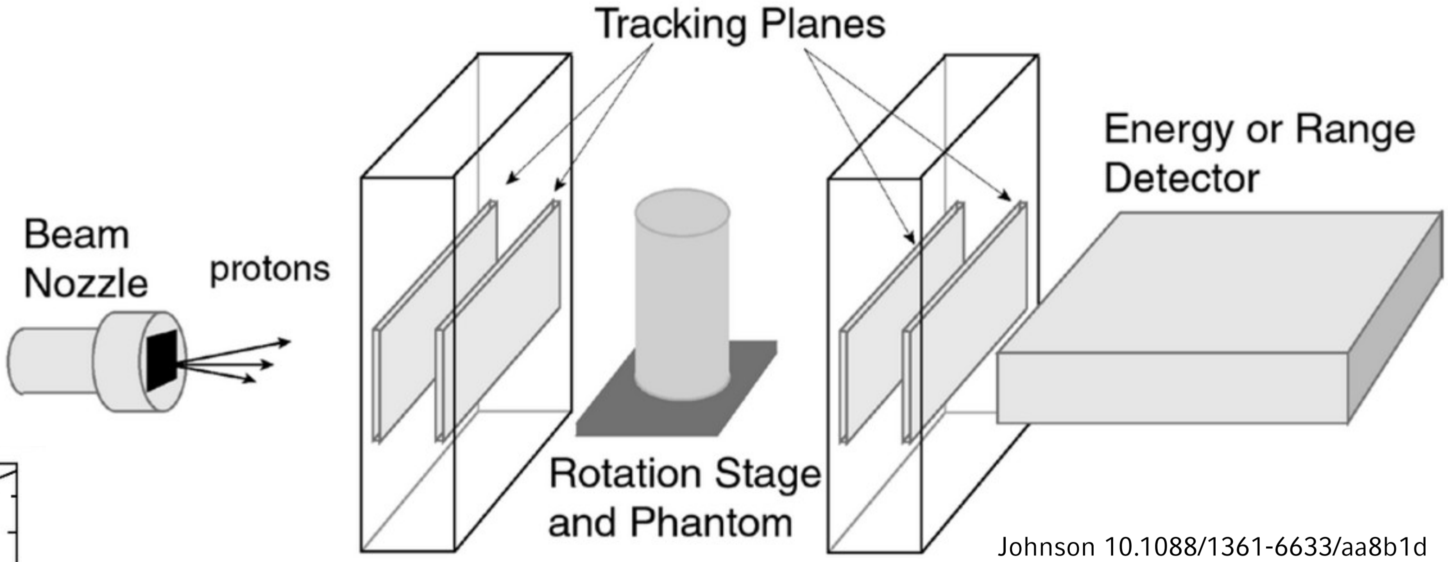
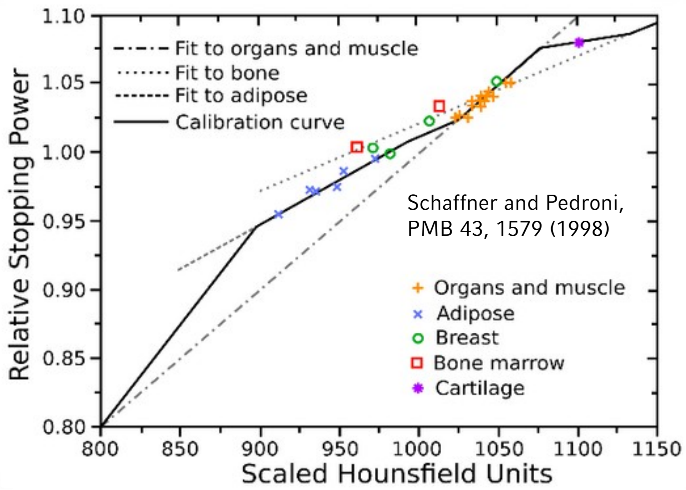


Johnson 10.1088/1361-6633/aa8b1d



ion range uncertainties: 3% + artifacts

- photon X-ray to stopping power conversion
- patient anatomy changes
- patient positioning

→ mitigate: proton CT just before treatment

AQUA Proton Radiography Detector 10x10cm²

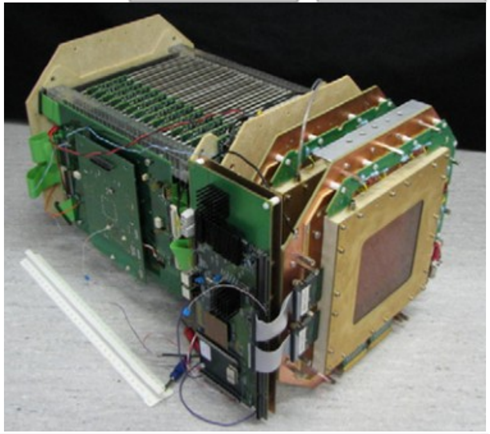
no upstream tracker

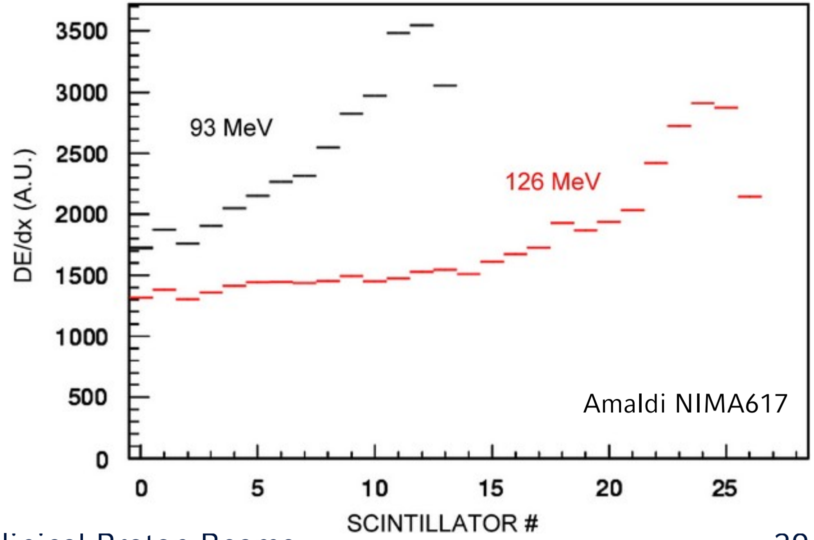
downstream tracking detectors
- pair of 10x10cm² triple GEM tracking detectors with strip readout

→ position and direction of proton trajectory

range detector
- 28 3mm thick plastic scintillator tiles
- interfaced by WLS fibers + SiPMs
- single particle range resolution 1.4 mm
- suitable for 20 to 130MeV protons

integrated readout electronics
- O(100kHz) rate → radiography in 10s
- too slow for tomography





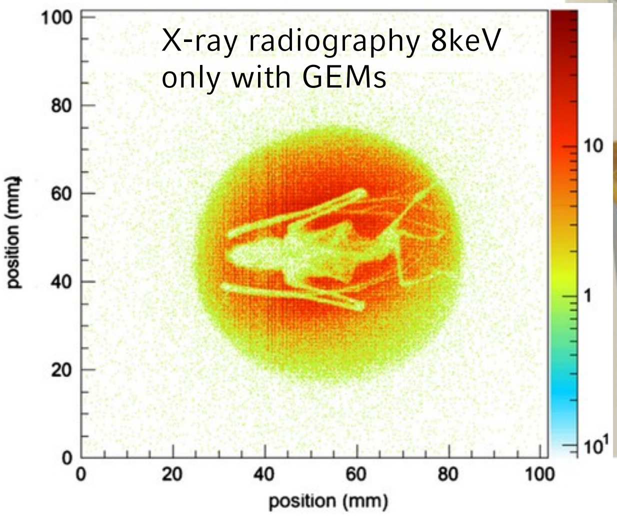
AQUA Proton Radiography System 30x30cm²

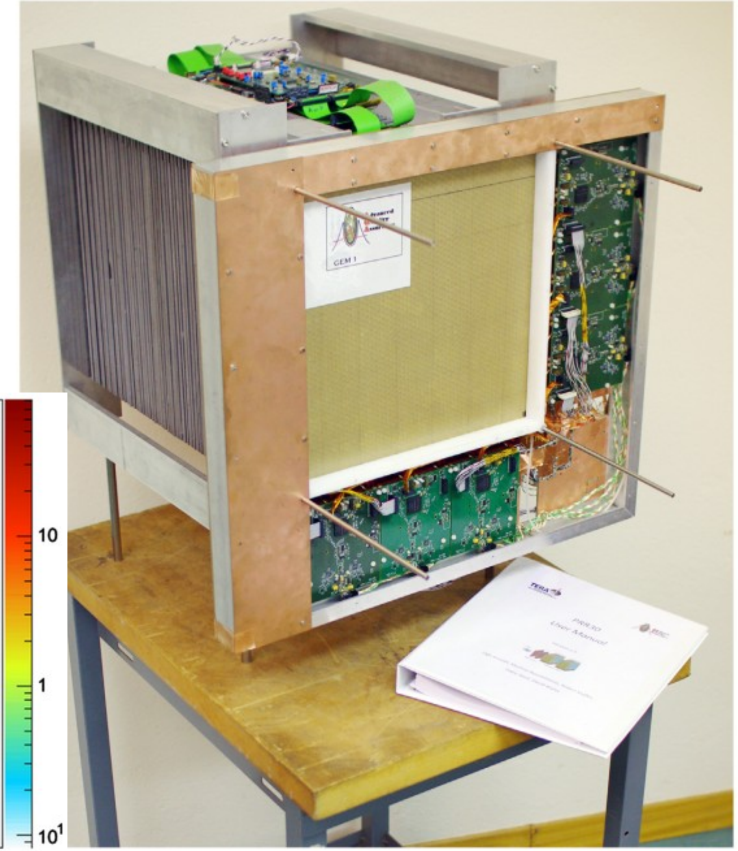
downstream tracker
- pair of 30x30cm² triple GEM detectors with strip readout
- possibility to mount third GEM detector

range detector
- 48 3.2mm thick plastic scintillator tiles
- interfaced by WLS fibers + SiPMs
- suitable for 20 to 190MeV protons

improved integrated readout electronics
- 1MHz readout rate
  → radiography in 1s

promising system, currently at HEPHY



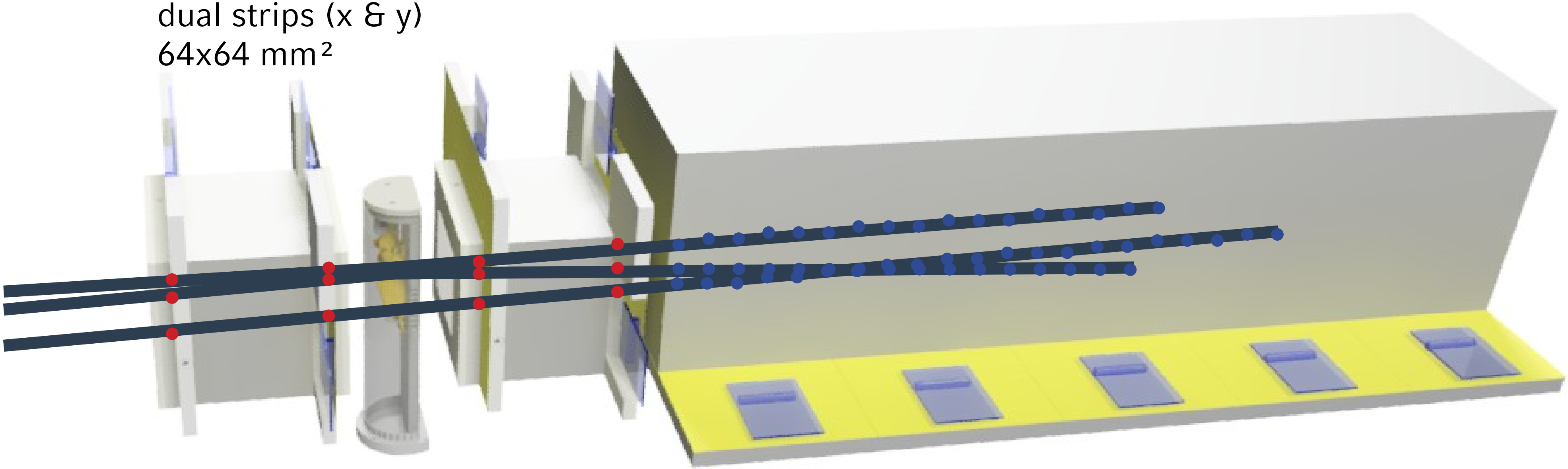


Bucciantonino NIMA732

SIRMIO Small Animal Proton Tomography System

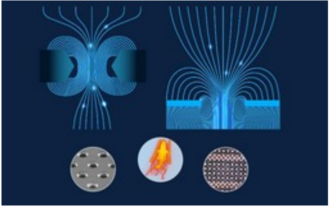
spatial information from 2d floating strip Micromegas trackers
residual range (→ energy loss) from TPC with vertical absorbers

4 aluminum floating strip Micromegas trackers
dual strips (x & y)
64x64 mm²



mouse holder
x, y, z, φ movement
sterile environment

Time Projection Chamber range detector
65 absorber foils (600μm Mylar+Kapton)
8mm gaps in between

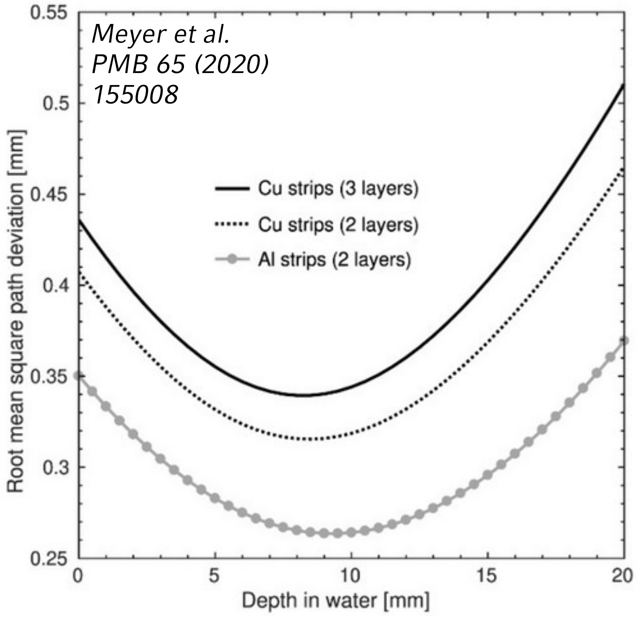


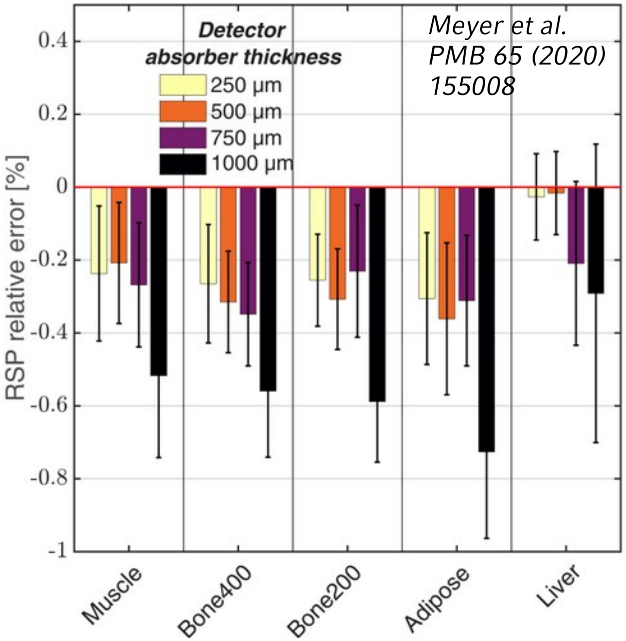
FLUKA Simulation: Geometry & Parameters

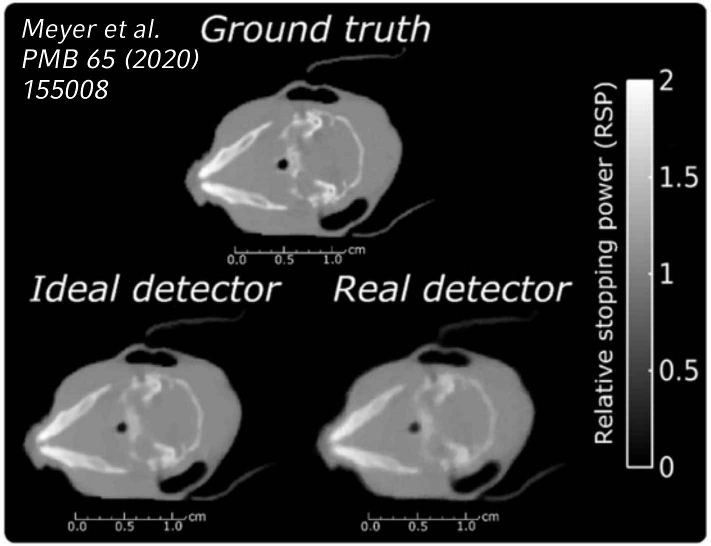
detailed simulation of trackers, object & TPC range detector

→ trackers with aluminum electrodes considerably better & spacing > 7cm: **mean path resolution 0.18mm**

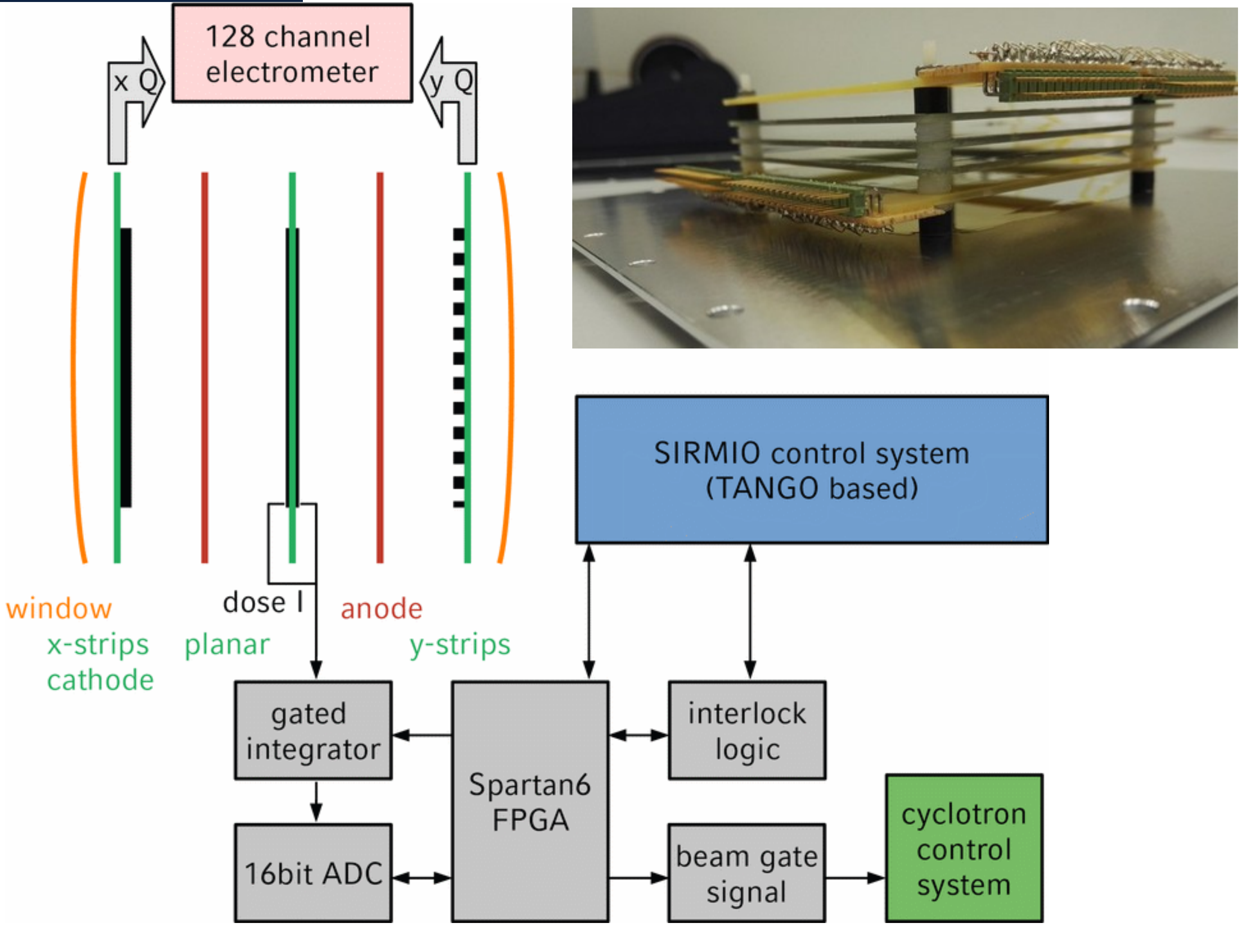
→ TPC absorber thickness 500 – 750μm: compromise between complexity & **RSP accuracy < 0.3%**







Ultra-Thin Beam Monitor Chambers

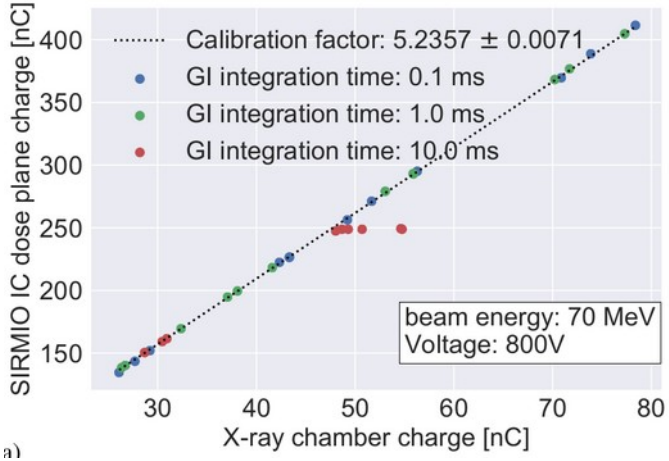


active area 64x64mm²

- 2 strip planes (64 strips, 40nm Alu on 10µm Kapton)
- 1 dose gap (unsegmented, 40nm Alu on 2µm Mylar)

stability O(0.1%) needed

- long term stable electronics
- correct p & T effects on density



6MV Photon Beam Profiling with Glass Thick-GEM

O(50%) of all cancer patients receive irradiation treatment. Vast majority treated with photons.

clincal linac
- compact 5 to 20MeV electron accelerator
- electrons steered onto tungsten target
  → bremsstrahlung
- photon field shaped by tungsten multi-leaf collimator
- field intensity and shape needs to be known with high accuracy → accurate treatment planning & delivery

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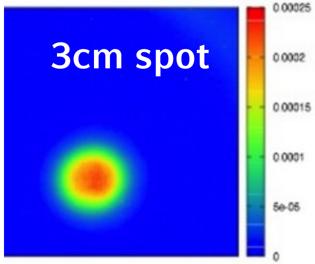
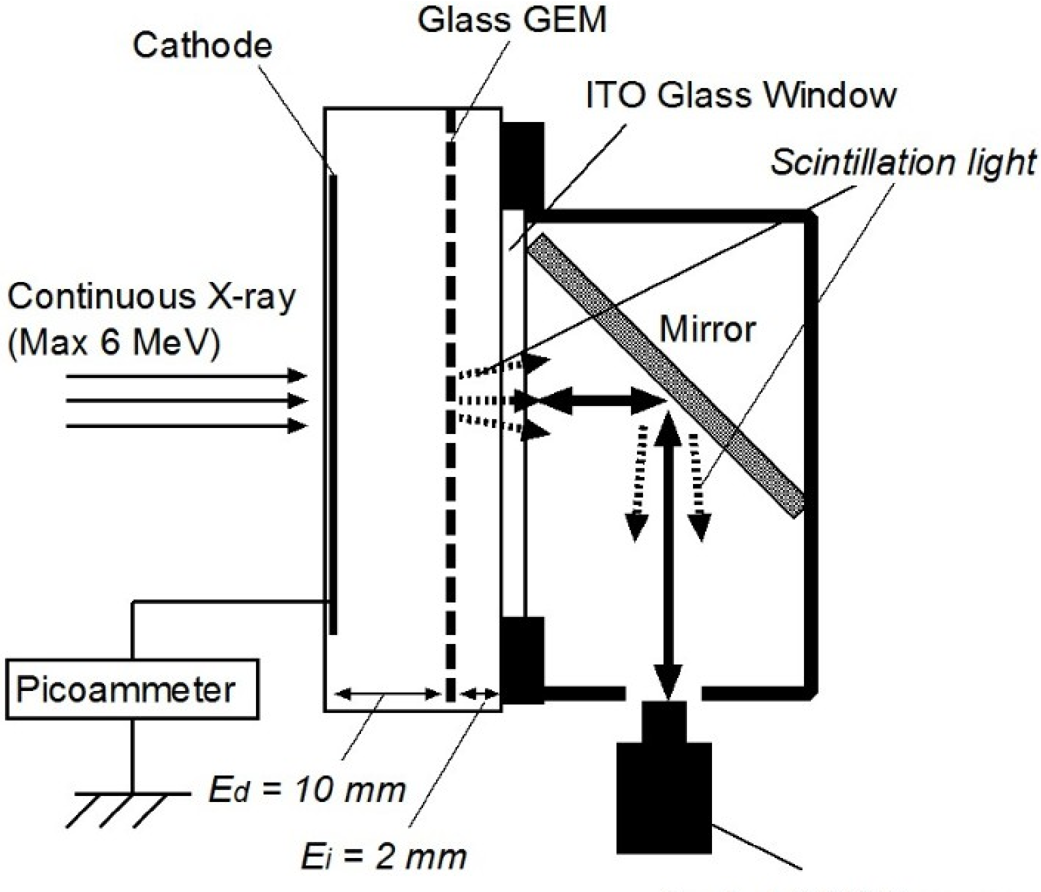
gaseous detectors well suited for routine QA: low quenching good linearity





Fujiwara 10.1088/1748-0221/8/12/C12020

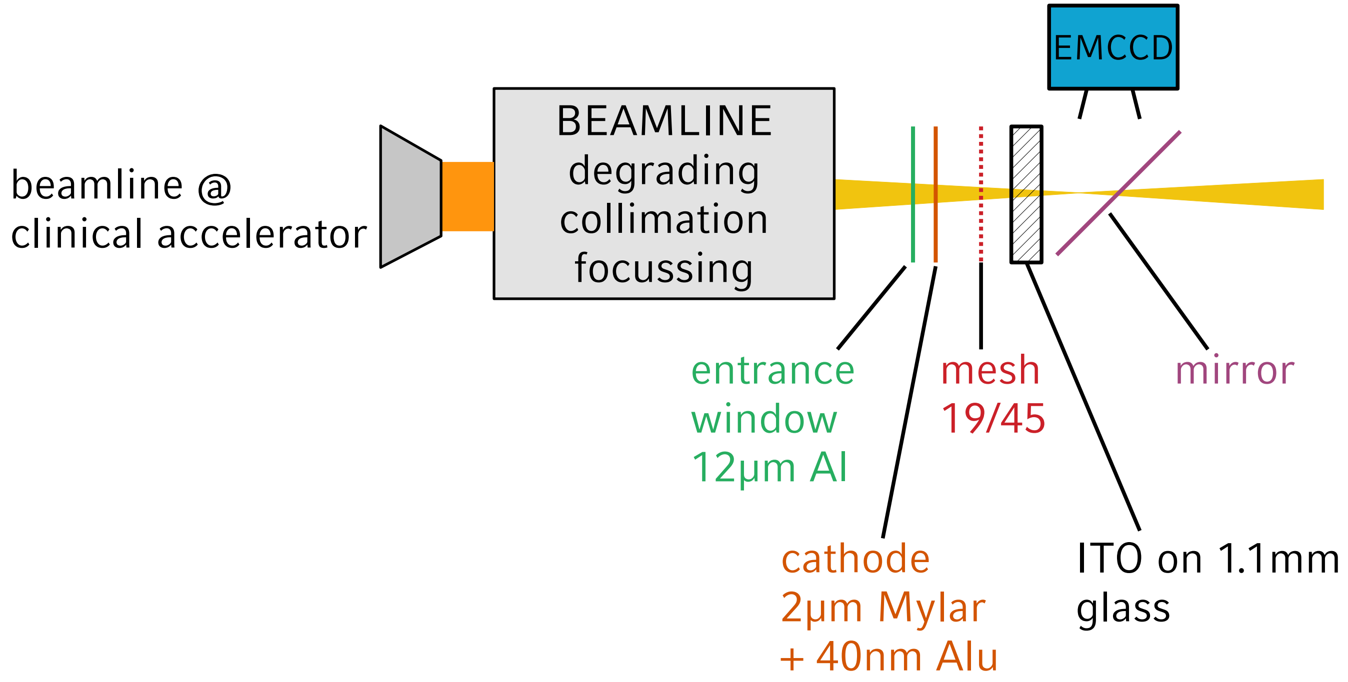
Pre-clinical Proton Beam Profiler

beamline @
clinical accelerator

requirement: scan beam profile (20mm → 0.5mm) and position longitudinally prior to irradiation

→ beam parameters for treatment planning

Pre-clinical Proton Beam Profiler



ITO: indium tin oxide
EMCCD: Electron-Multiplying CCD

requirement: scan beam profile (20mm → 0.5mm) and position longitudinally prior to irradiation

→ beam parameters for treatment planning

constraints

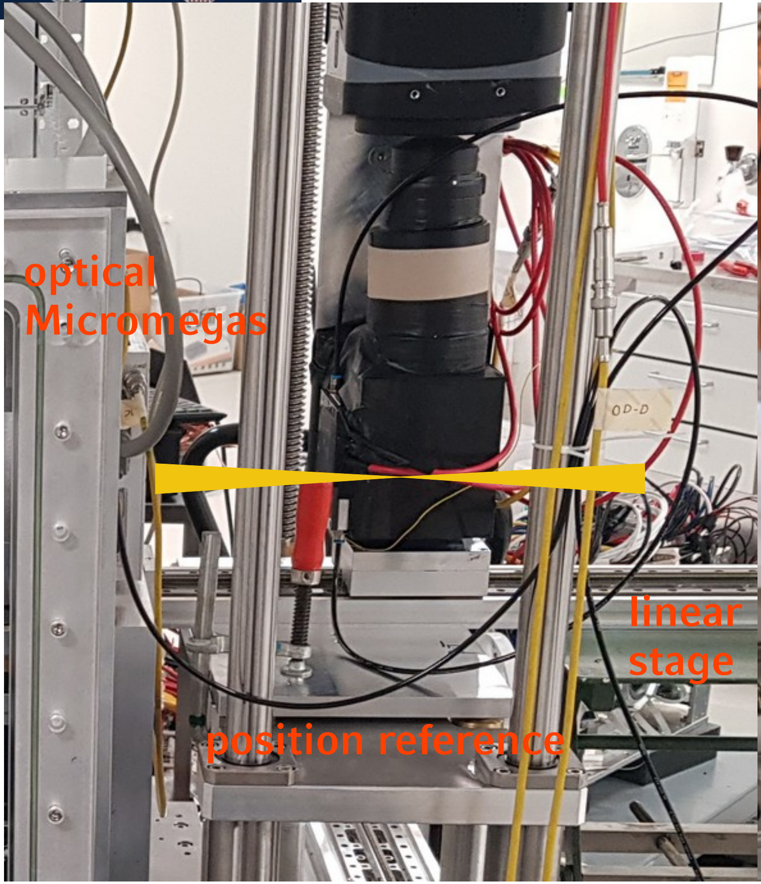
- good 2d resolution → pixels
- no beam distortion before measurement (~20-50MeV)
- large dynamic range

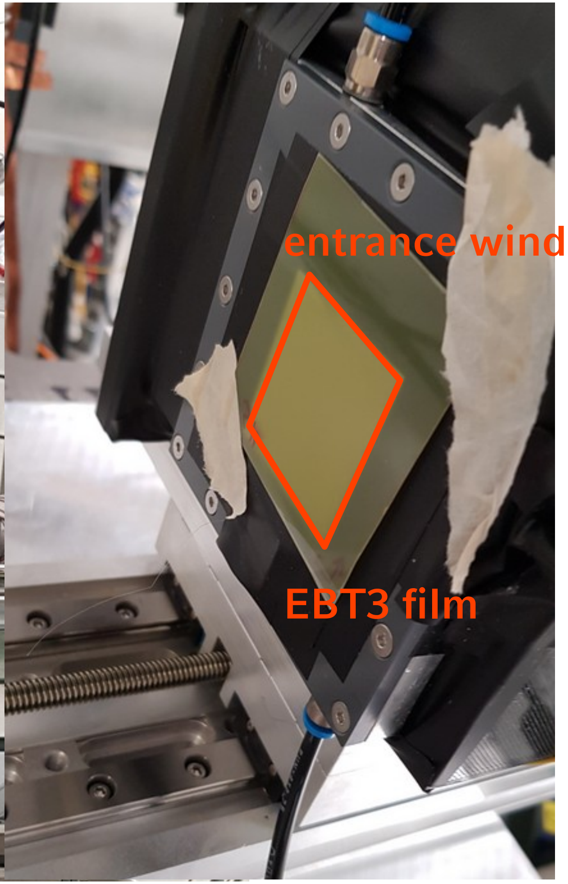
solution (inspired by Brunbauer et al. 2018 JINST 13 T02006 & Iguaz, RD51 CM 2018)

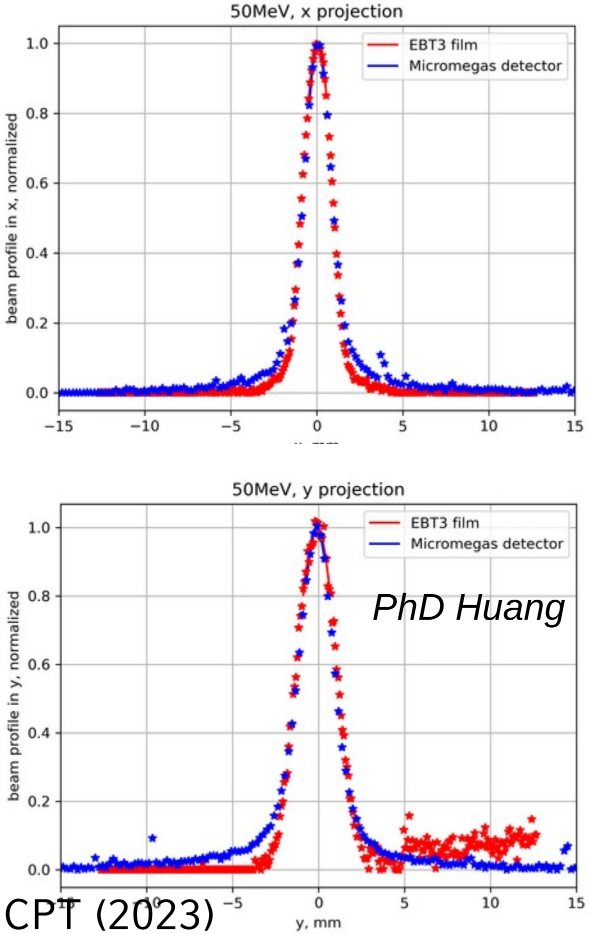
→ Glass Micromegas with optical readout

→ mounted on linear stage

Profiling Pre-clinical SIRMIO Beam @ DCPT







successfully used in beam line characterization @ PSI (2021), DCPT (2022), DCPT (2023)

Summary

numerous experimental & advanced applications of MPGDs outside fundamental research

muography

- scattering or absorption
- vulcanology, archeology, cargo scanning

neutron detection

- converters
  - B, Li, … → particles
  - H (elastic) → protons
  - Gd → electrons
- beam profiling, reaction products

medical applications

- imaging (X-ray and proton CT)
- beam monitoring
- beam characterization

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Thank you for your attention!