An Integrated System for 3D Energy Deposition Measurements in Hadron Therapy with the GEMPix Detector

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RD51 Collaboration Meeting, 2018/June/20

Physics Institute III B

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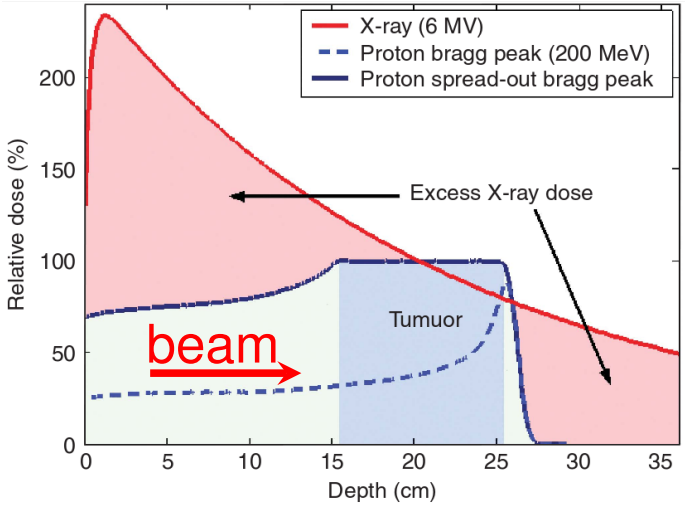
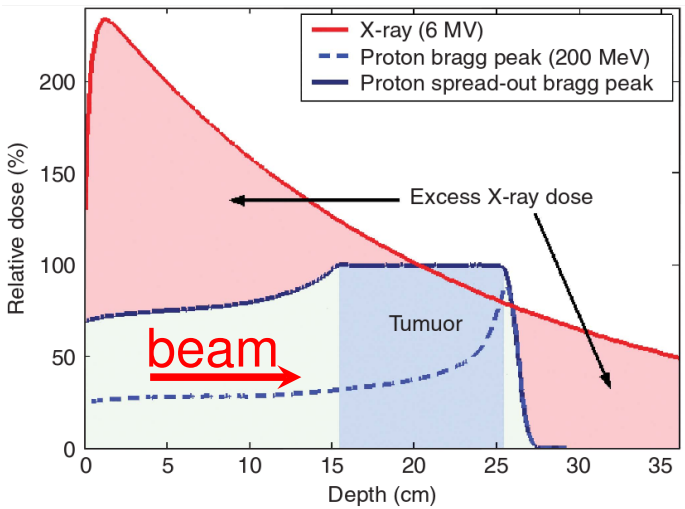
Motivation: Hadron Therapy and Quality Assurance



Efstathiou et al (2013): “Proton beam therapy and localised prostate cancer: current status and controversies”

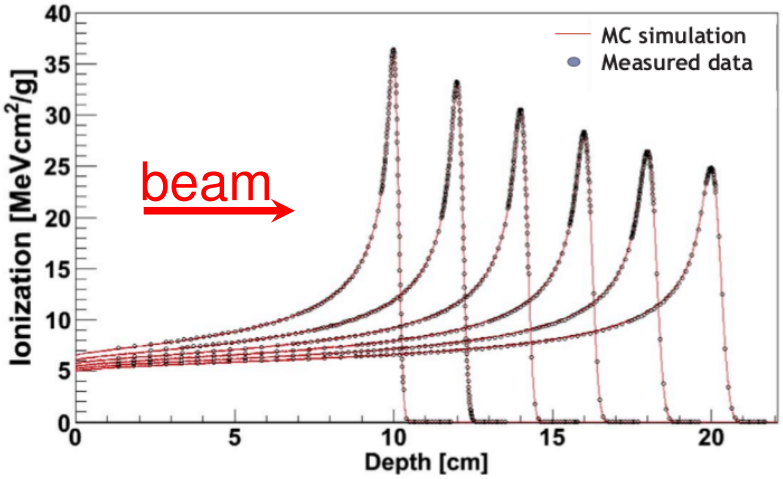
- Radiation therapy: Kill cancer cells with ionizing radiation
- Hadron therapy: Well-defined region of energy deposition (Bragg curve with Bragg peak)

Motivation: Hadron Therapy and Quality Assurance

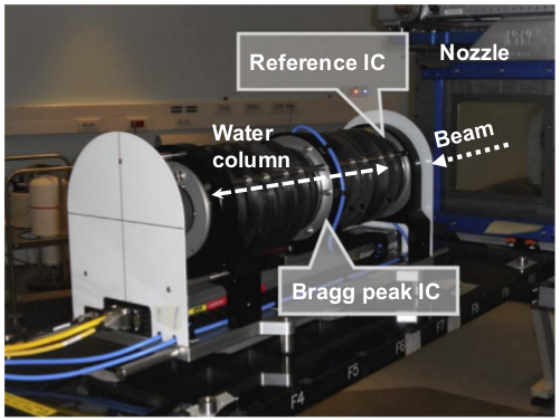


Efstathiou et al (2013): “Proton beam therapy and localised prostate cancer: current status and controversies”

- Radiation therapy: Kill cancer cells with ionizing radiation
- Hadron therapy: Well-defined region of energy deposition (Bragg curve with Bragg peak)
- QA: check range, spread of Bragg peak, treatment plan verification, ...
- QA: typical dose uncertainty $\mathcal{O}(1\%)$
- GEMPix provides better spatial resolution



a.



b.

S. Giordanengo et al. (2017): "Review of technologies and procedures of clinical dosimetry for scanned ion beam radiotherapy"

The GEMPix Detector: GEMs

- GEMPix: Gas Electron Multiplication + Pixelated Read-out
- 2.5 cm^3 gas detection volume (here: $ArCO_2CF_4$ at 5l/h)
- 3 GEMs
  - Kapton foil + thin copper layers
  - large field in the holes, electron multiplication

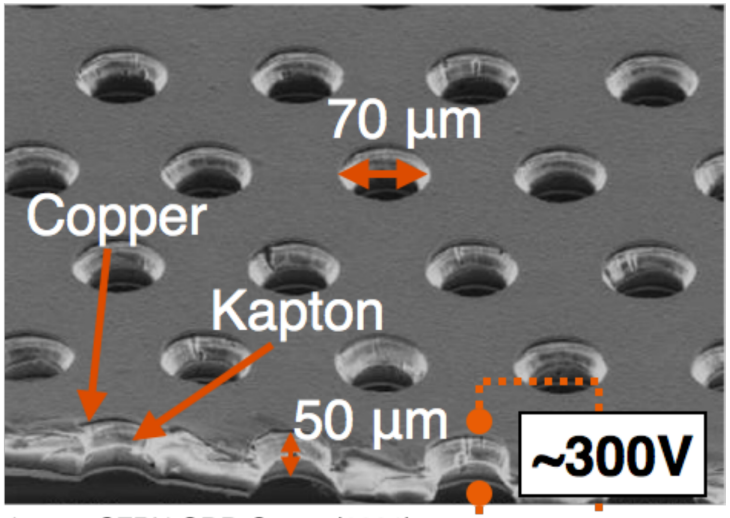
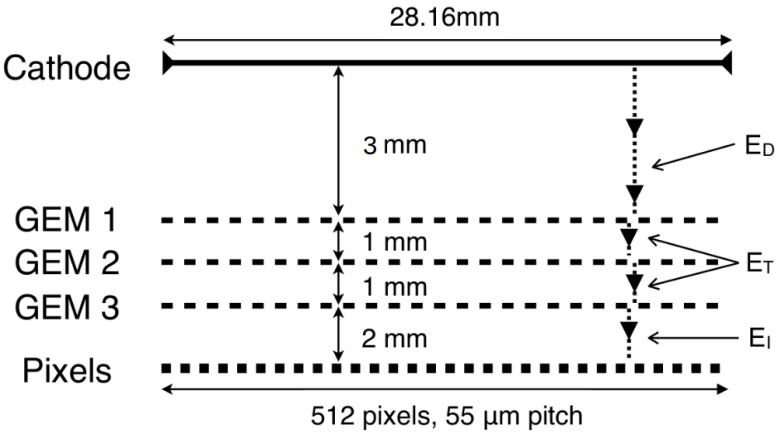
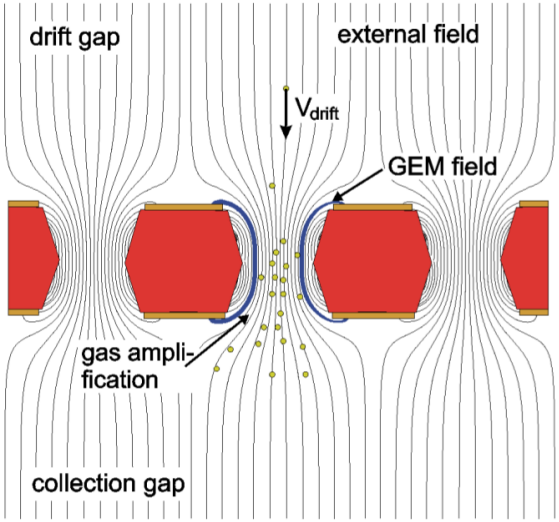


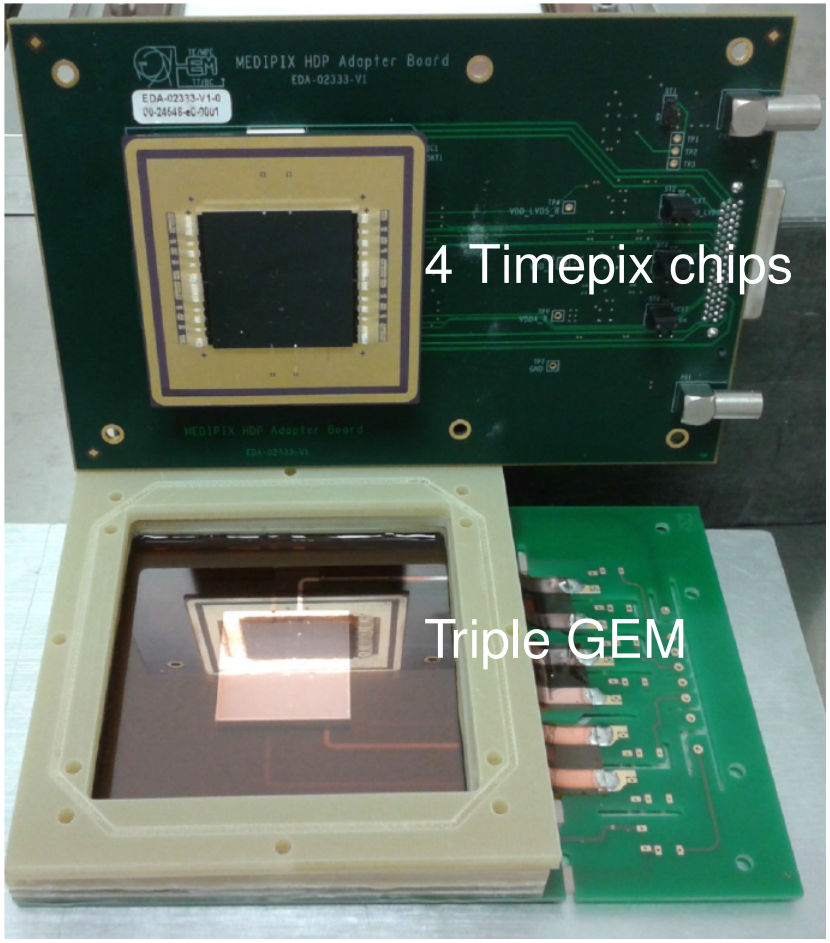
Image CERN GDD Group (2001)





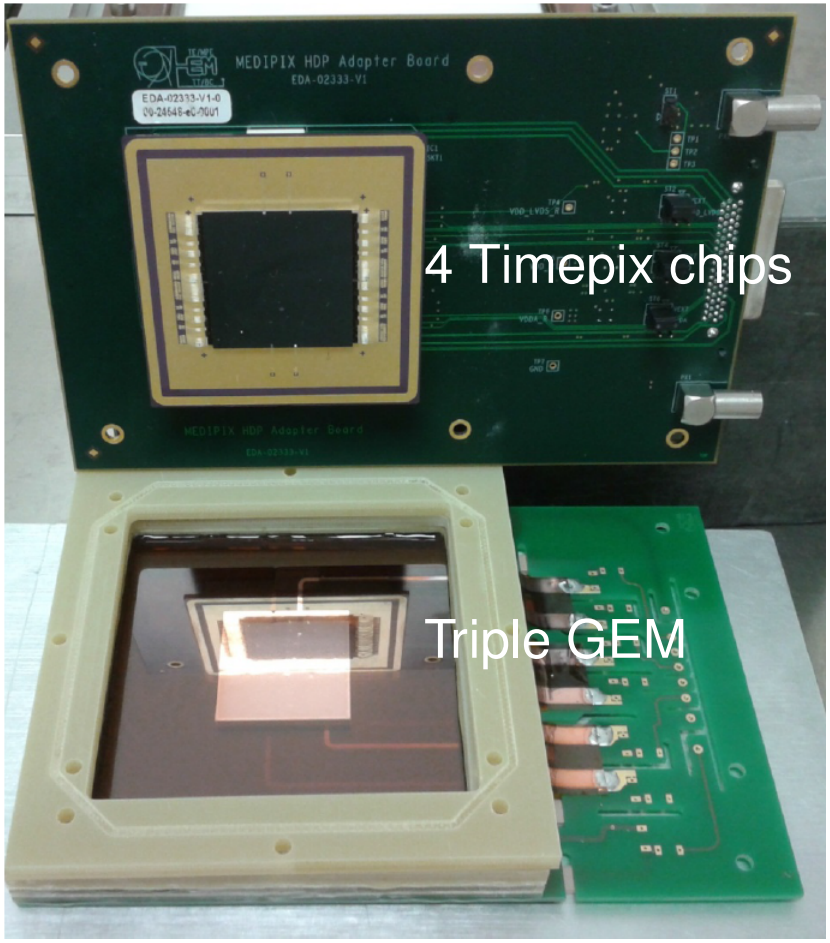
M. Ziegler (2002): "Development of a Triple GEM Detector for the LHCb Experiment"

The GEMPix Detector: Timepix Read-Out

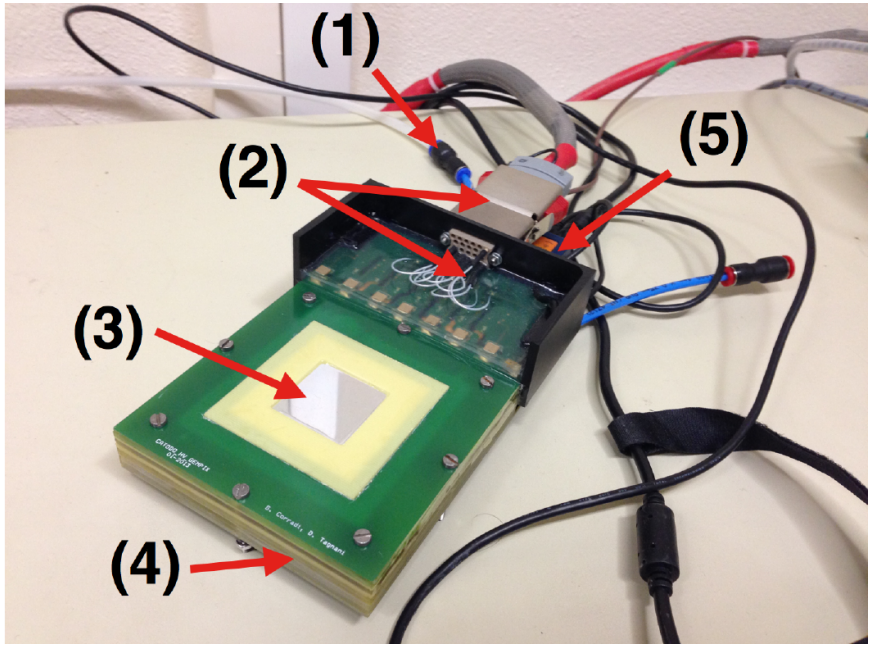


- 4 naked Timepix chips: 512x512 pixels, each 55 μm x 55 μm

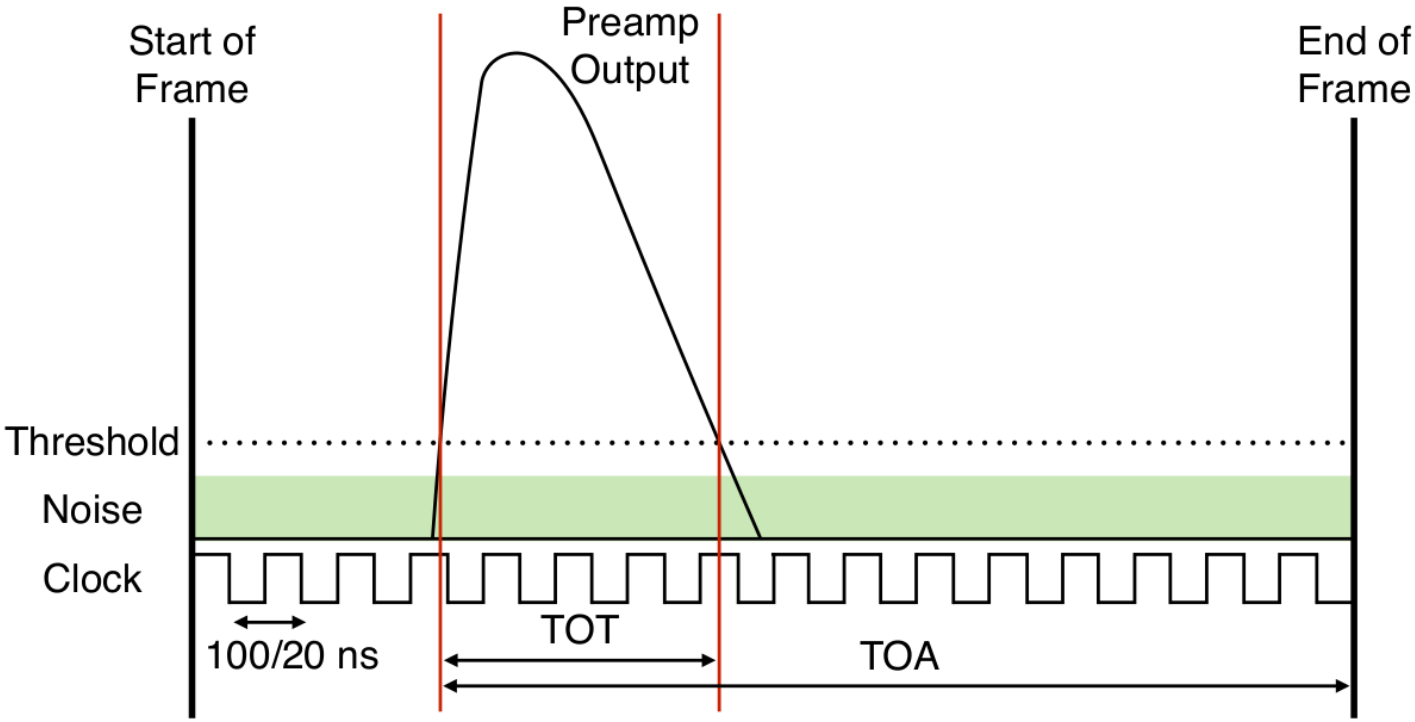
The GEMPix Detector: Timepix Read-Out



- 4 naked Timepix chips: 512x512 pixels, each 55 μm x 55 μm
- Several applications of the GEMPix: Hadron Therapy, Microdosimetry, Radiotherapy, Radioactive Waste, ...



Timepix: Time and Charge Measurements

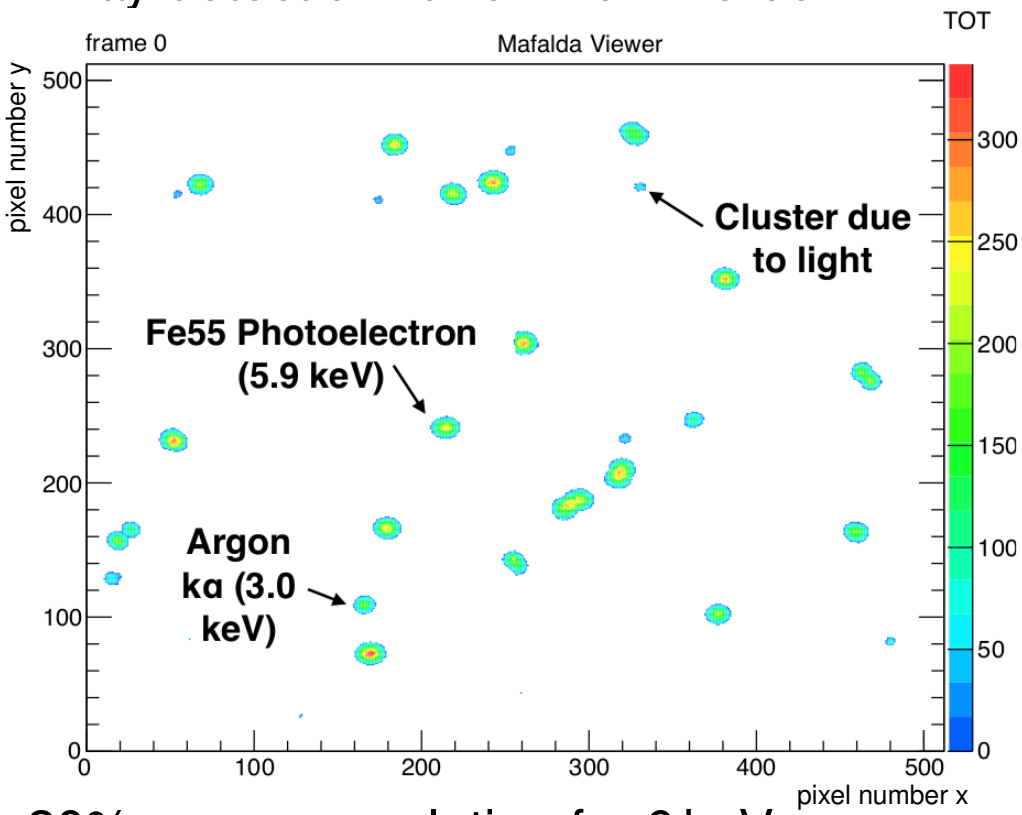


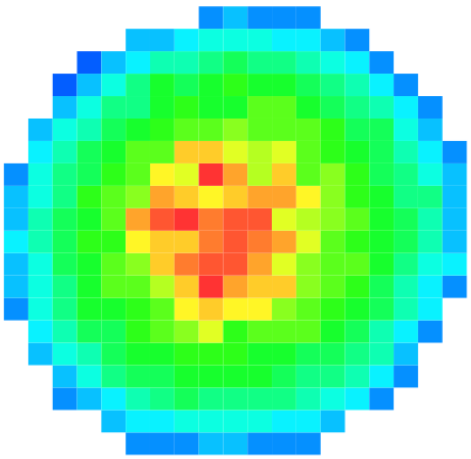
Different modes possible:

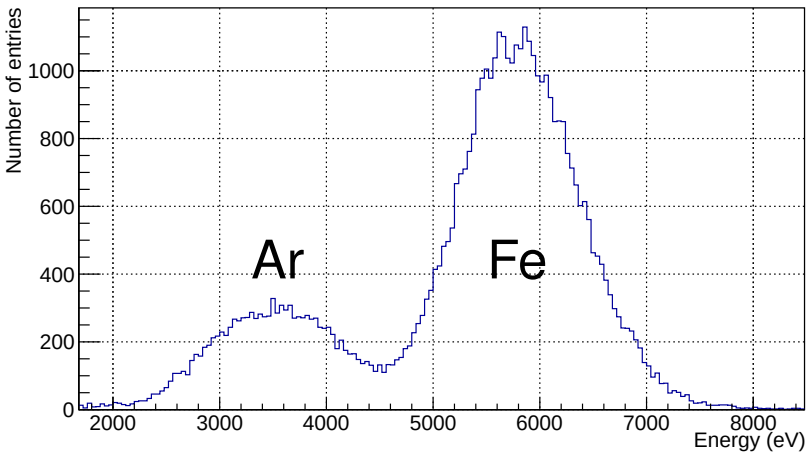
- Pulse counting
- Time of Arrival (TOA)
- Time over Threshold (TOT) → deposited energy

Typical Frame: Fe-55

X-ray detection: 6 keV from Fe-55



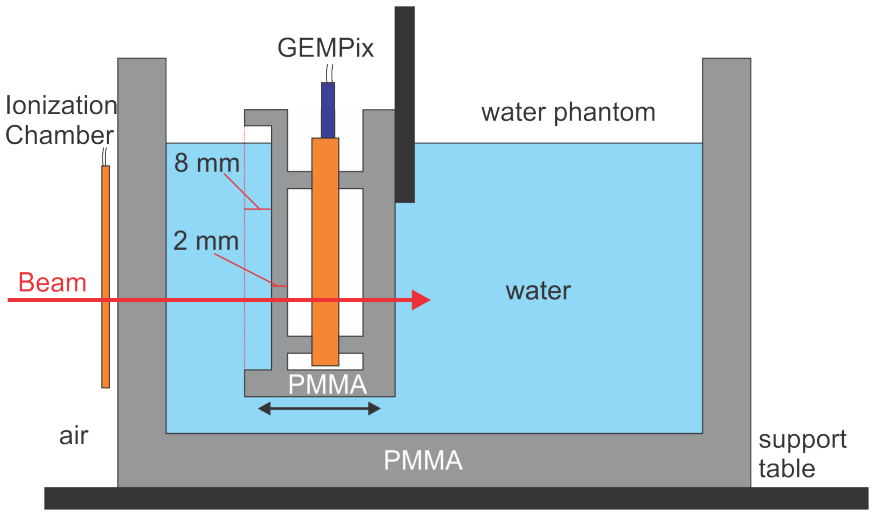


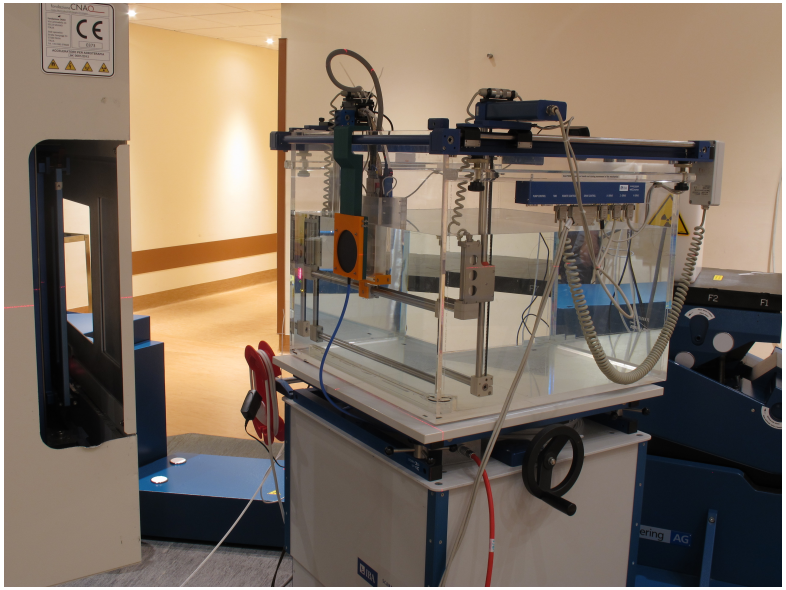


20% energy resolution for 6 keV

The Integrated System

The Integrated System



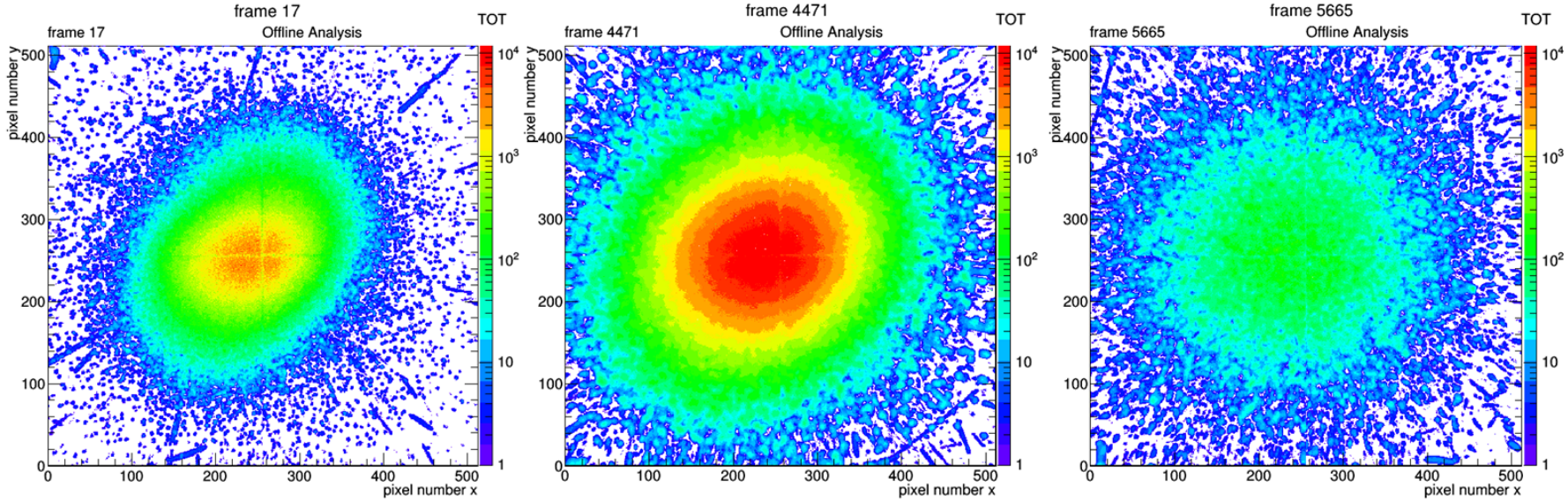


- CERN-MAPF funding, water phantom donated from Luzern hospital
- ion chamber for normalization to beam intensity
- GEMPix mounted in the phantom
- electronics on trolley for fast setup
- DAQ (trigger, IC readout, GEMPix readout, slow control) and online analysis set up
- FLUKA simulation of full setup

CNAO Measurements

- Measure 3D energy deposition in a water phantom (at CNAO)
  $\rightarrow$ Perform depth scans with the GEMPix inside the water phantom
- Beam: carbon ions, 150...250mm range (= 280...380 MeV/u), $2 \cdot 10^6$ particles/s during spill, $\sigma = 2\,\text{mm}$
- GEMPix: sum of GEM voltages: 990V $\rightarrow$ approx. gain of 100
- approx. 200 keV energy deposited per primary in gas gap at Bragg peak

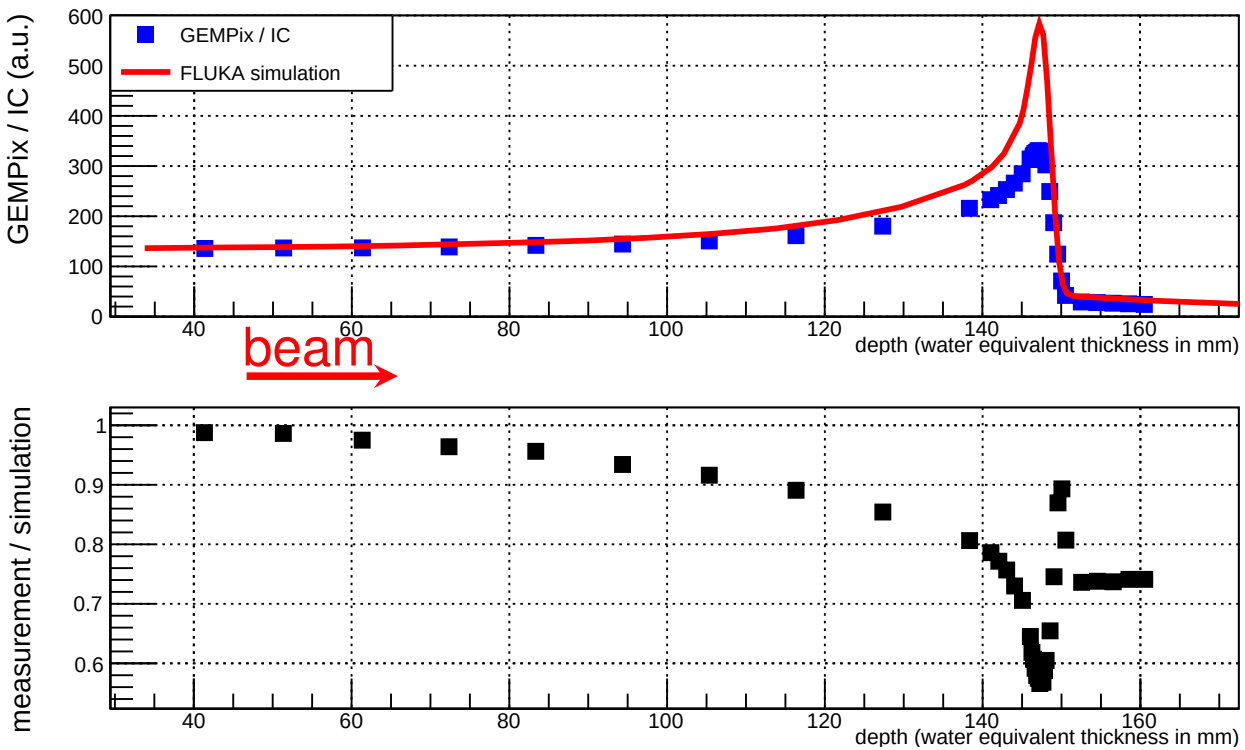
2D Images



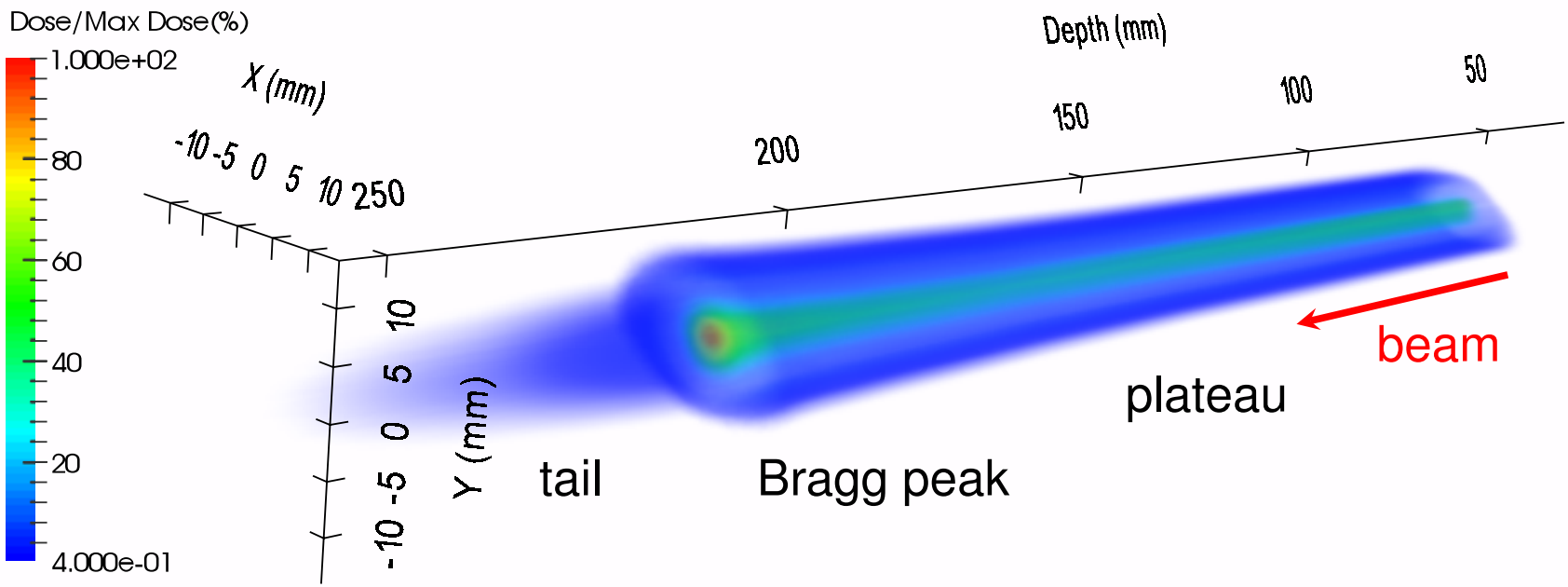
plateau Bragg peak tail

- beam halo: single particle reconstruction
- 2D images with much better spatial resolution than with ion chambers
- depth scan: take approx. 20 frames with spill per position $\rightarrow$ 20 min in total
- depth scan analysis: integrate TOT values, normalize by reference ion chamber current, take average for each depth $\rightarrow$ Bragg curve

Bragg curve: 150 mm range, carbon ions, uncorrected data



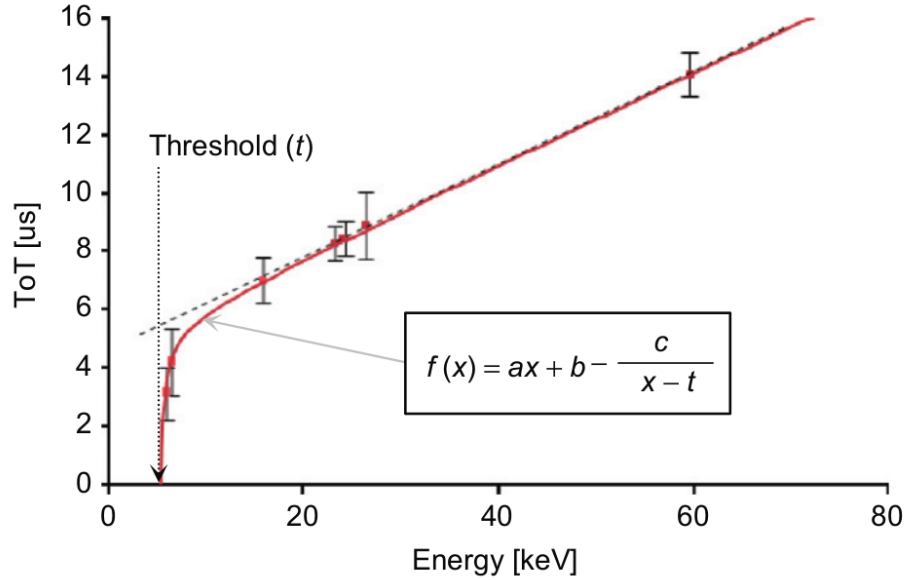
- (arbitrary) normalization to Bragg peak
- in general: smooth curves with uncertainties of approx. 2%
- systematic mismatch between measurements and reference/simulation of up to 50%



- 3D reconstruction of the energy deposition
- linear interpolation between measurement positions

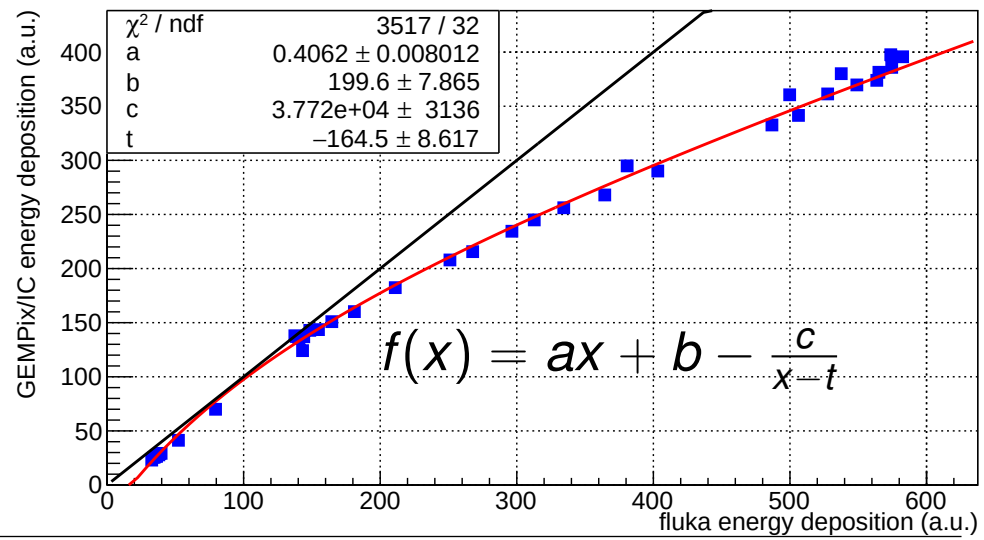
Timepix Energy Calibration

- So far: TOT $\propto$ released energy
- BUT: even in linear regime non-negligible offset
- energy calibration well established for Timepix

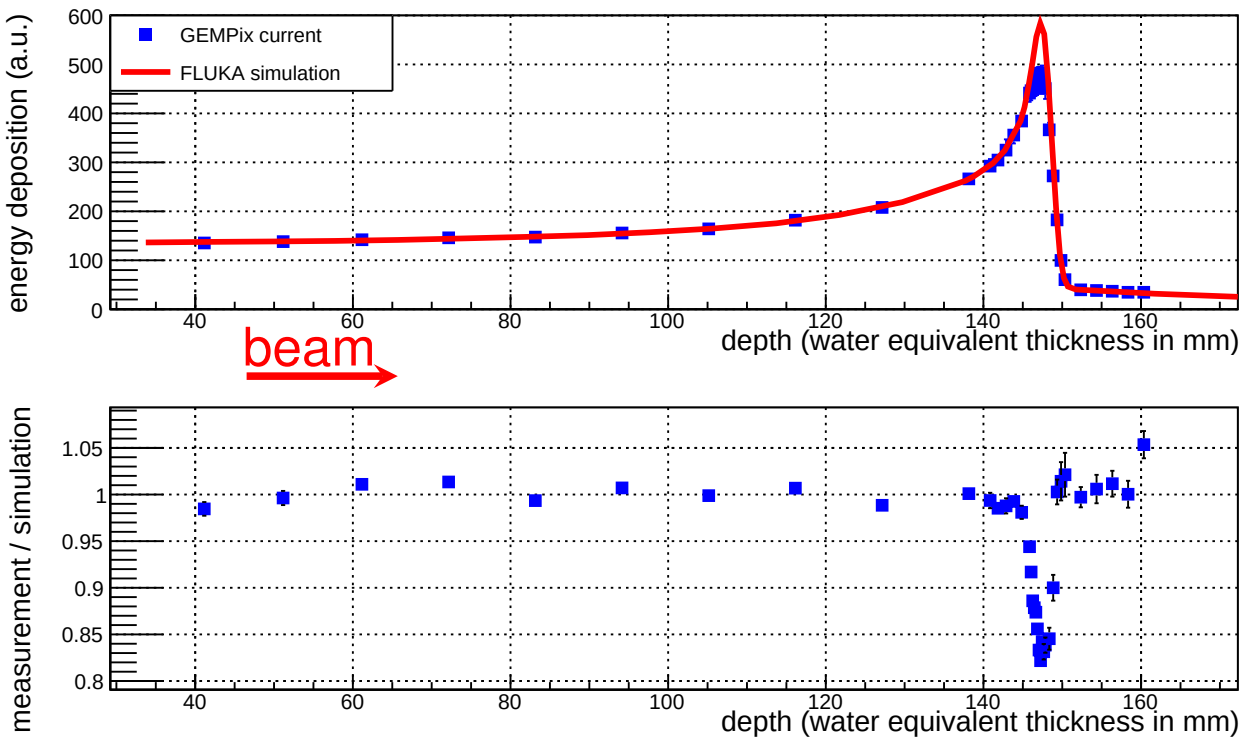


J.Jakubek et al. (2008): "Pixel detectors for imaging with heavy charged particles"

- use 150mm range scan from April beam time to develop correction
- apply correction to depth scans of May beam time

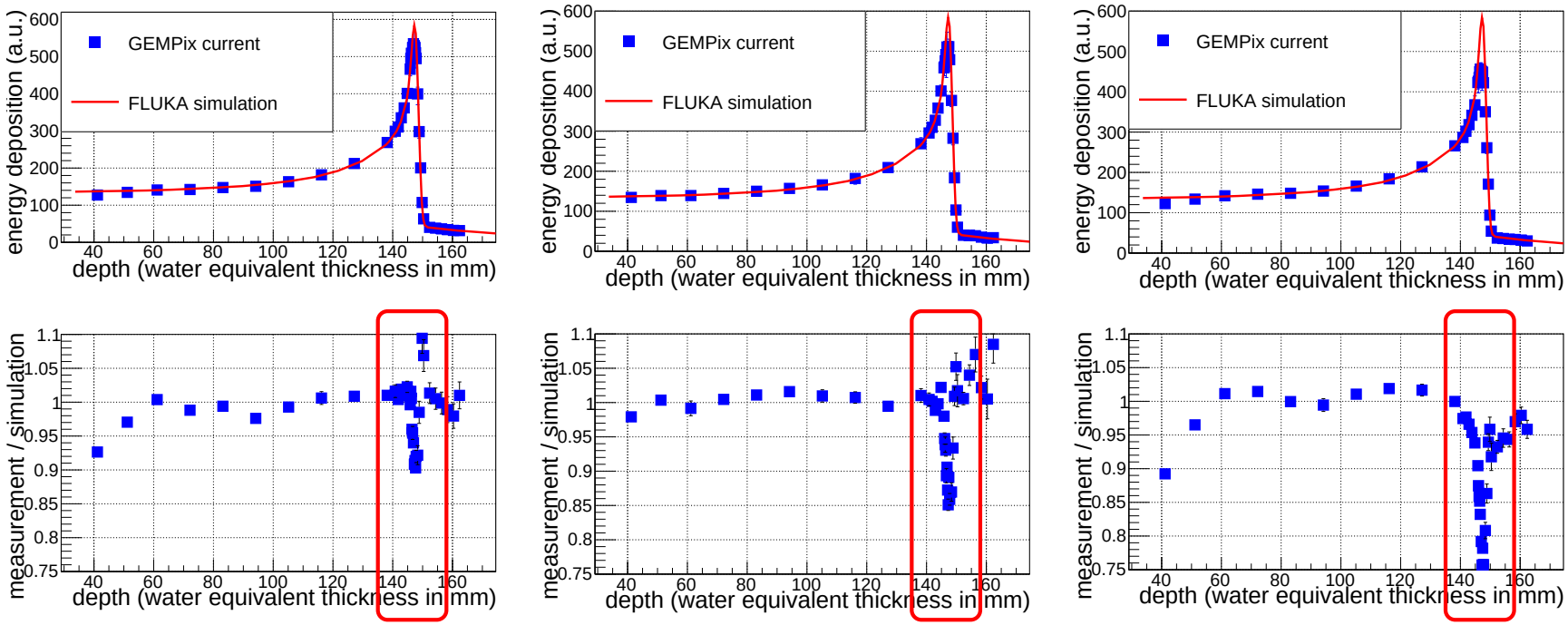


GEM Current Analysis



- Analysis of current driven for field between GEM 3 and ASIC
- Helpful to disentangle effects of readout and GEMs
- Much closer to reference curves except for Bragg peak region
  $\rightarrow$ main source of mismatch is the readout
- For now: correct data with current measurement before energy calibration

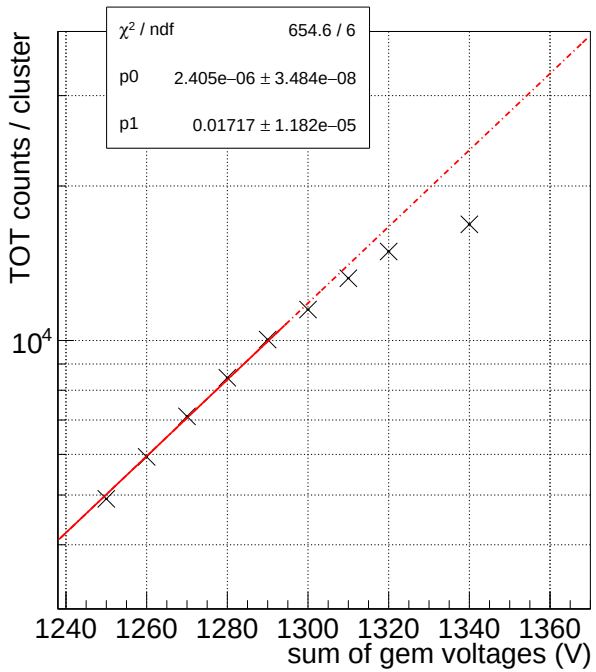
Current Analysis: GEM Saturation?



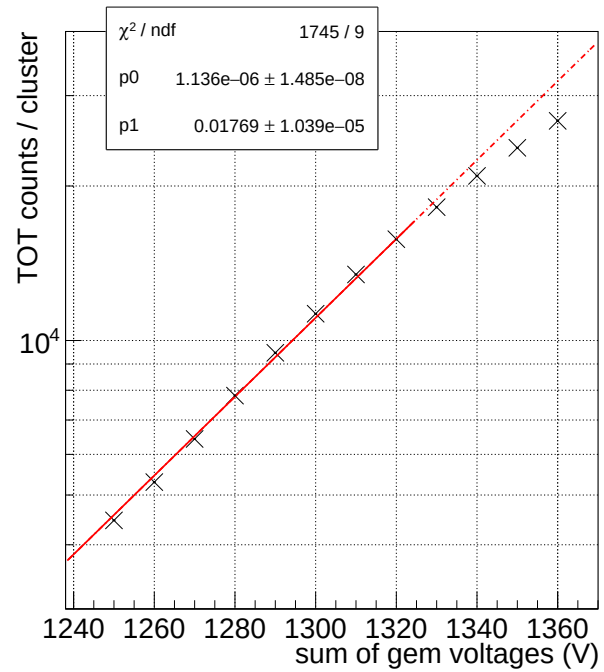
Gain: 970V → Gain: 990V → Gain: 1030V

- Underestimation in peak increases with gain
- Maybe GEM saturation?

How to overcome GEM saturation?



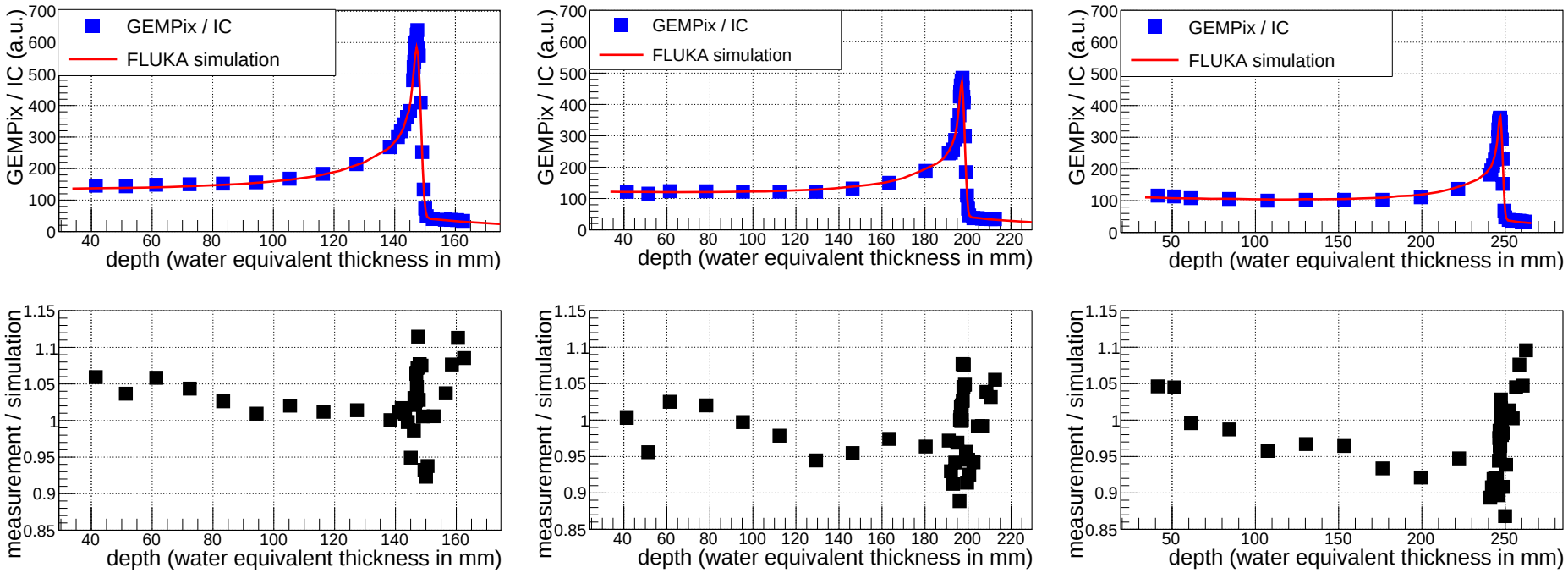
$V_1 = V_2 = V_3$



V_1=1.125 V_2; V_3=0.875 V_2

- Asymmetric GEM voltage (e.g. Bachmann et al. 2002)
  $\rightarrow$ enlarged linear response regime
- CNAO: probable improvement not sufficient to overcome saturation
- Other ideas (gas mixture, reduce gain)?
- Limitation: per pixel charge for readout must not be too low

Corrected Depth Scans



Range: 150mm → Range: 200mm → Range: 250mm

- Applying current correction and energy calibration works
- Data within ±10% compared to reference simulation
- Correction works for all three beam energies

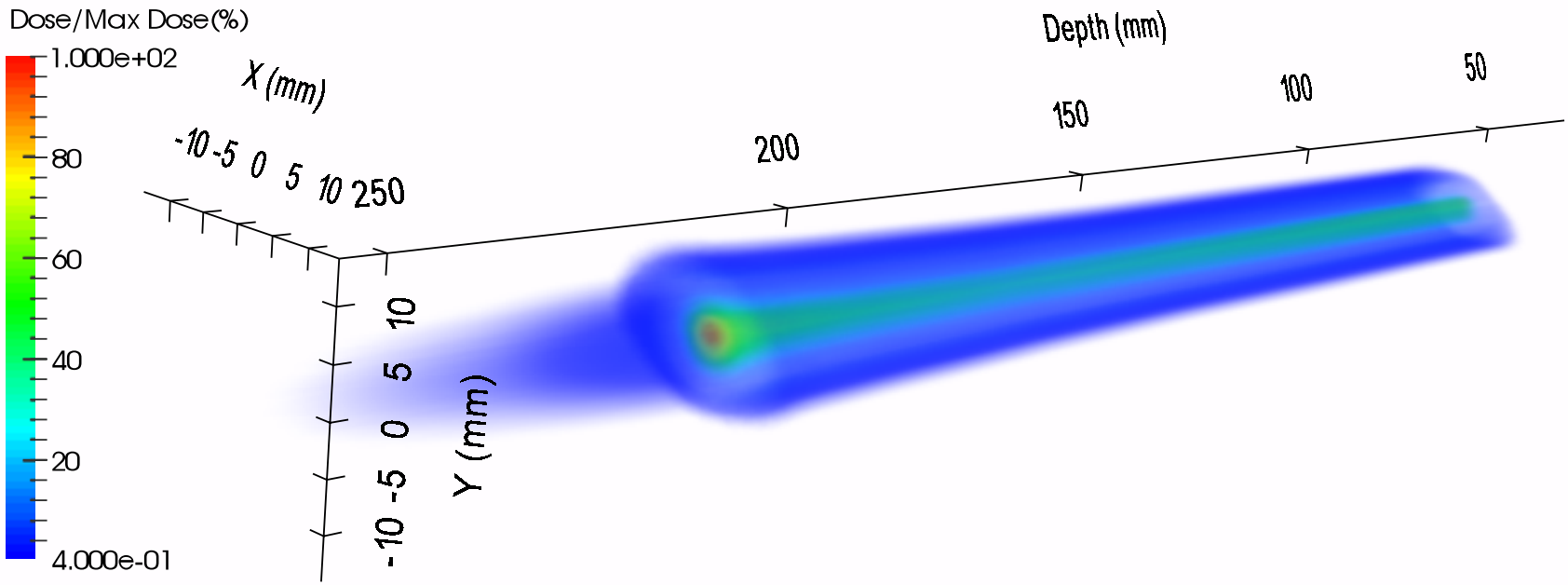
Conclusions & Outlook

Conclusions:

- GEMPix: compact gas chamber with highly pixelated read-out
- 3D energy deposition measurements in water phantom work
- Major upgrade to integrated system works well (new water phantom, new reference detector)
- Smooth, reproducible Bragg curves with small uncertainties but major systematic mismatch
- Different effects (e.g. TP correction) checked to not affect Bragg curve
- GEM current measurement: good match to reference but saturation?
- Improvement for major effect: energy calibration of Timepix readout

Outlook:

- Develop stable energy calibration
- Investigate possible GEM saturation
- For clinical application: increase detector area to minimum 15 x 15 cm^2, increase beam intensity to maximum, check 2D reliability, check long-term stability



Thank you for your attention!

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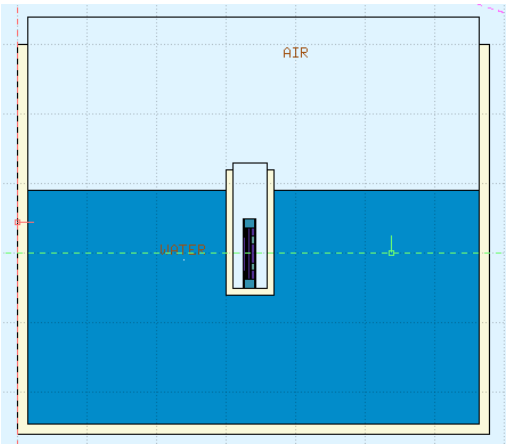
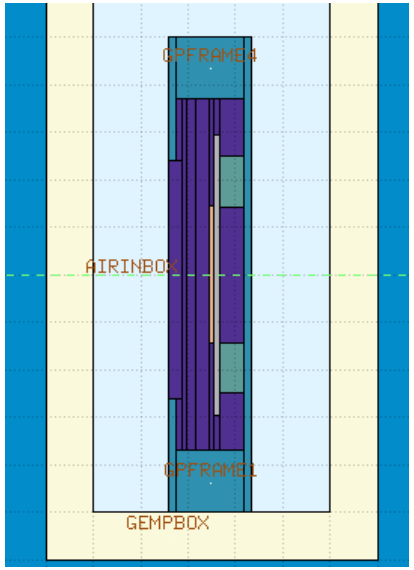
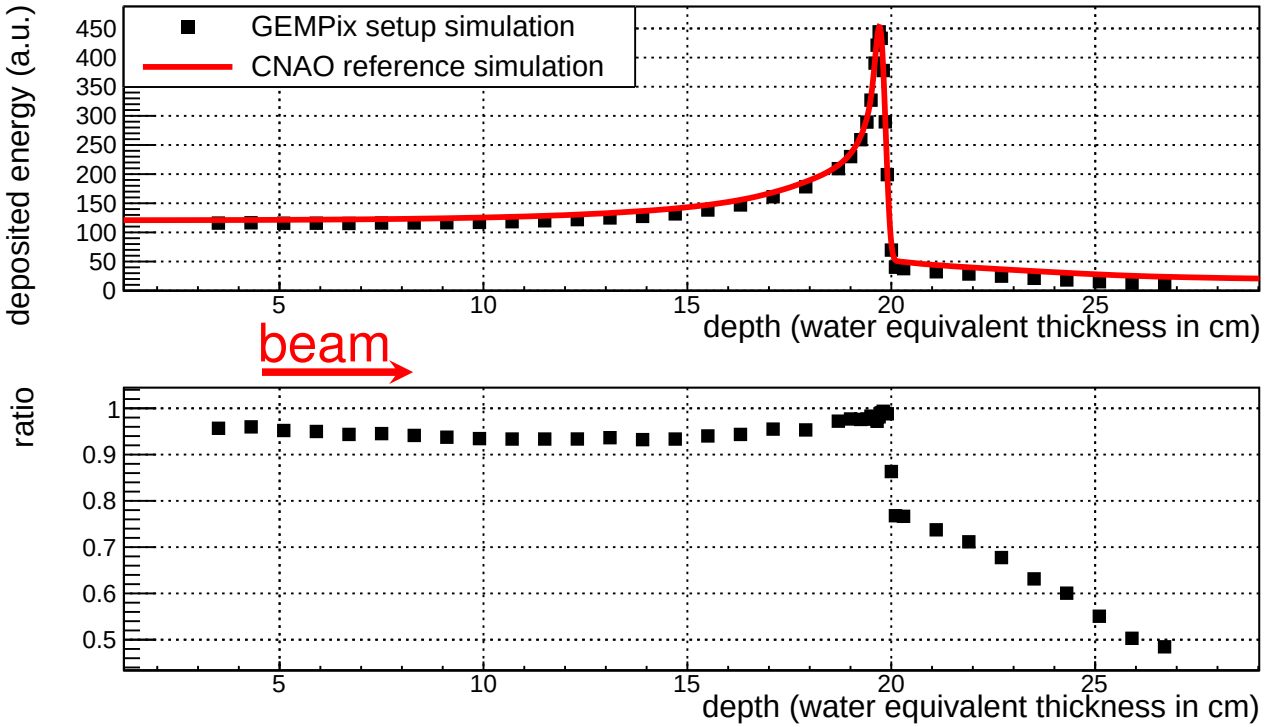
FLUKA Simulation

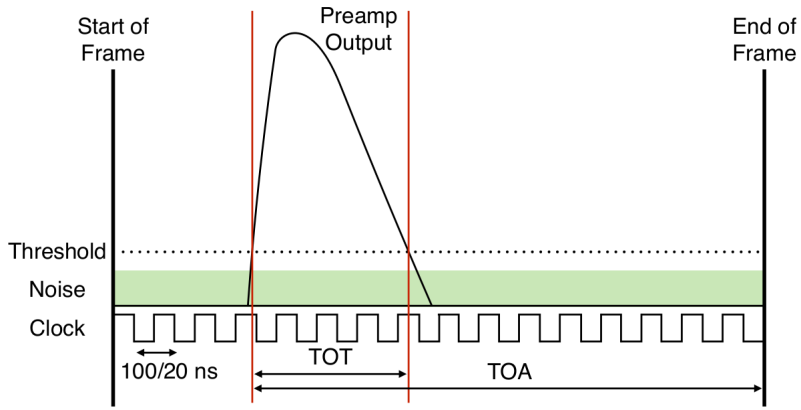




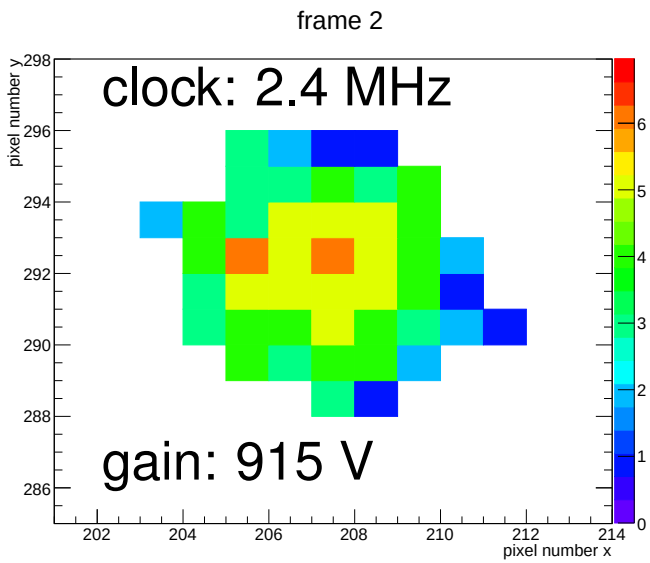


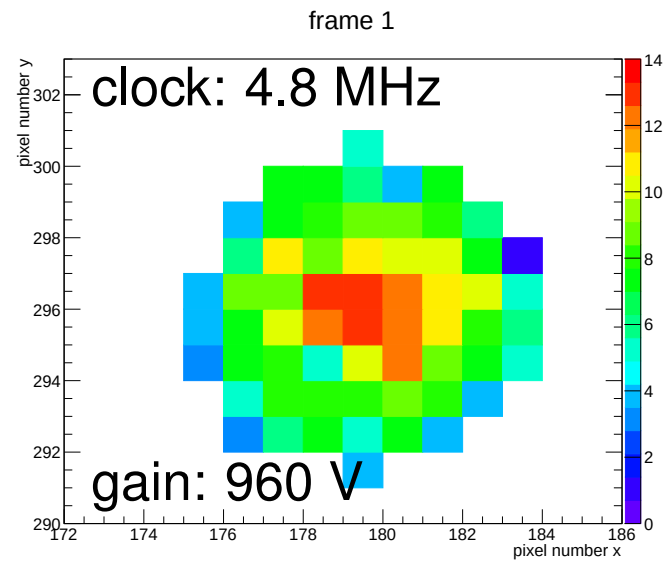
- phase space files from CNAO, start simulation at nozzle
- full geometry implemented
- loss in dose mainly due to small area of GEMPix

Increased Charge per Ionization

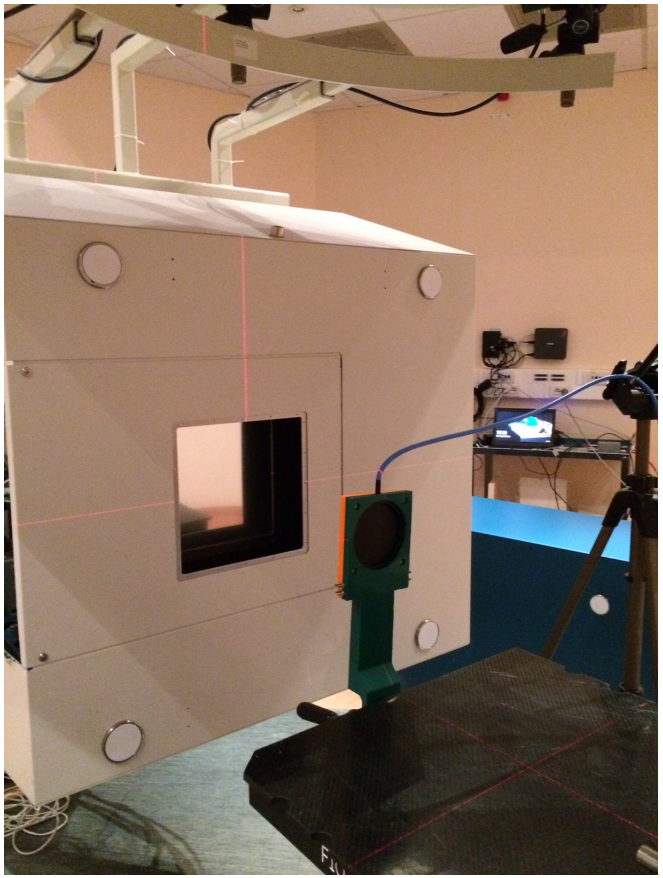


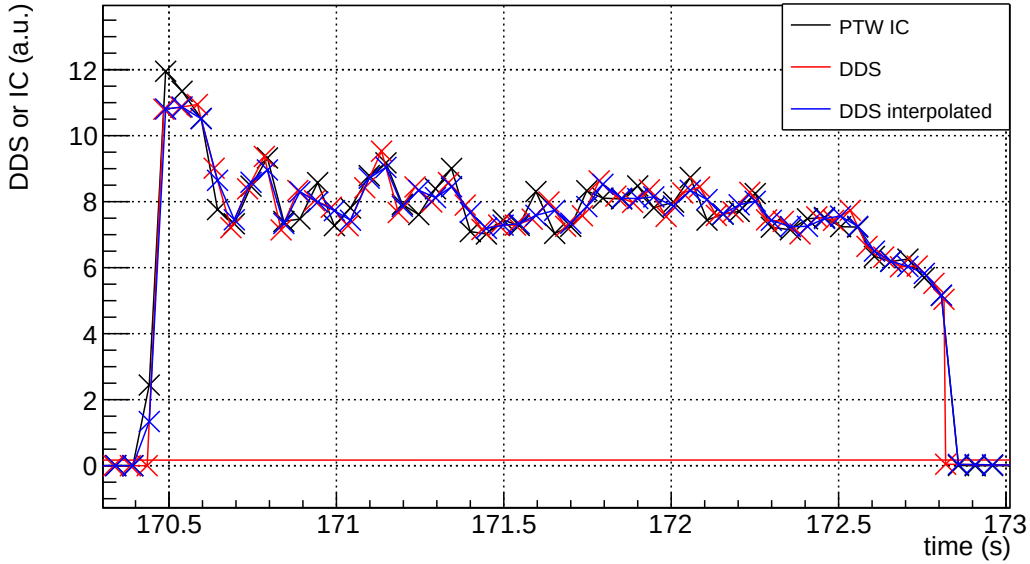
- Reminder: per-pixel digitization of signals for each single event
  $\rightarrow$ increase charge per pixel per event: increase gain
  $\rightarrow$ increase energy resolution: increase clock
- drawbacks: decrease beam intensity, shorten DAQ frame length





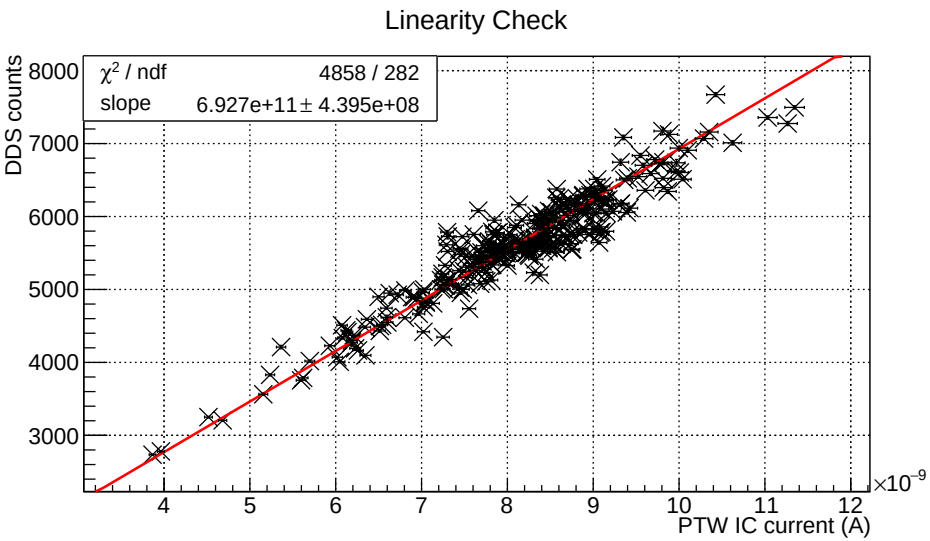
Tests with Ion Chamber at CNAO

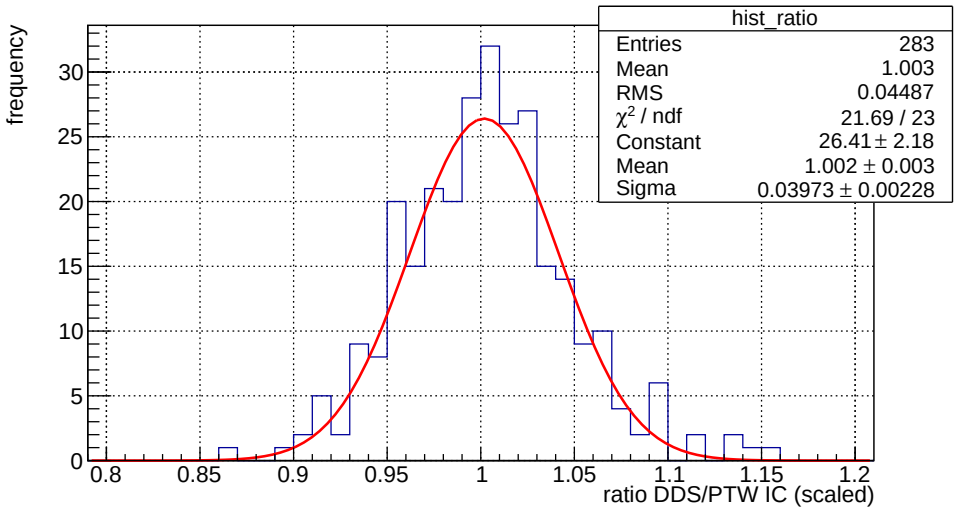




- First: tests with radioactive sources at CERN
  - 10 TBq ^{60}Co and 3 TBq ^{137}Cs to check linearity
  - Measurement: 328 $\pm$ 3 nC/Gy, PTW nominal response: 325 nC/Gy
- Then: tests in beam (p and C) at CNAO
- Main beam parameters varied to check PTW ion chamber for all future applications

Tests with Ion Chamber at CNAO

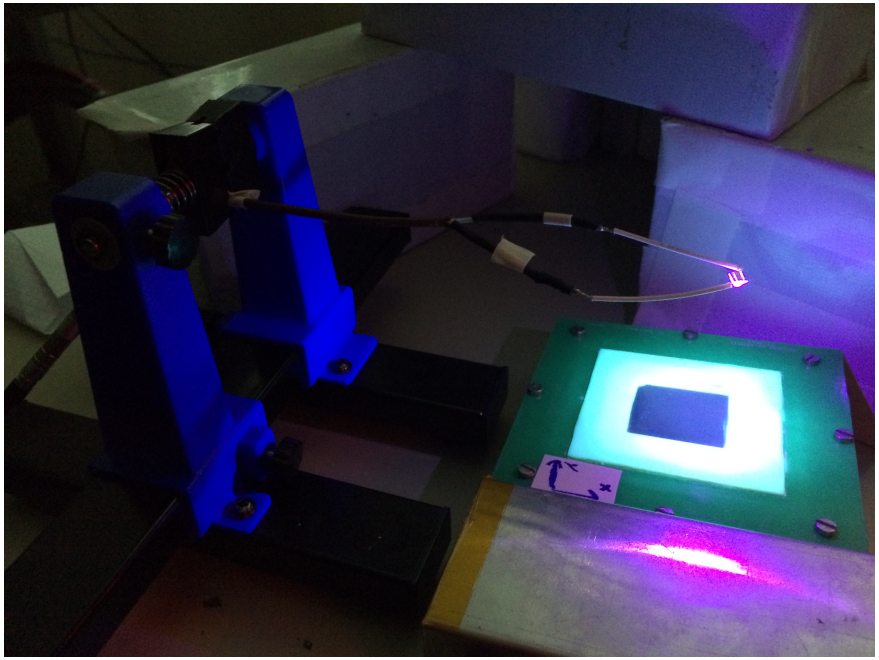


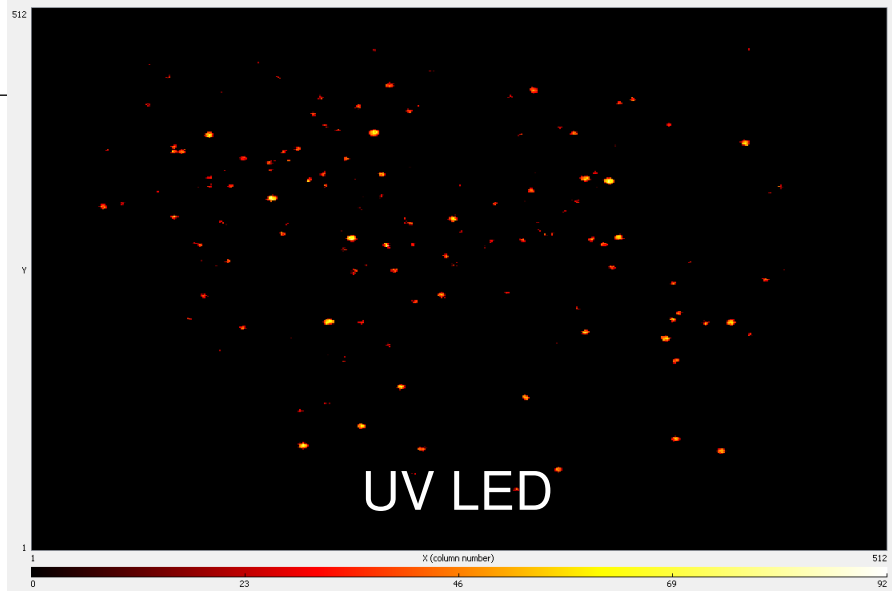


- No effect of beam energy, intensity, beam spot position
- Sigma of DDS / PTW ion chamber for single point: 4%

PTW ion chamber is suitable for use in front of the phantom as the reference detector!

Test: Trigger GEMPix with UV LED

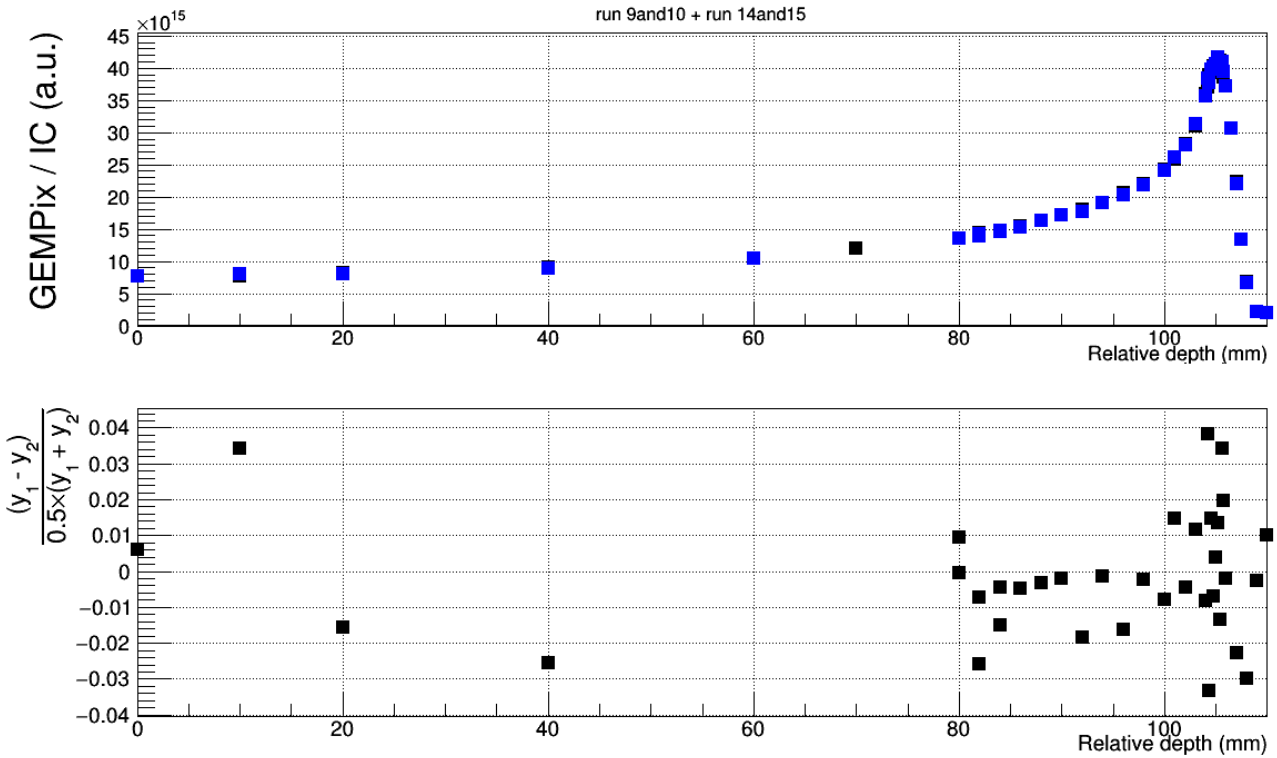




Integrated System:

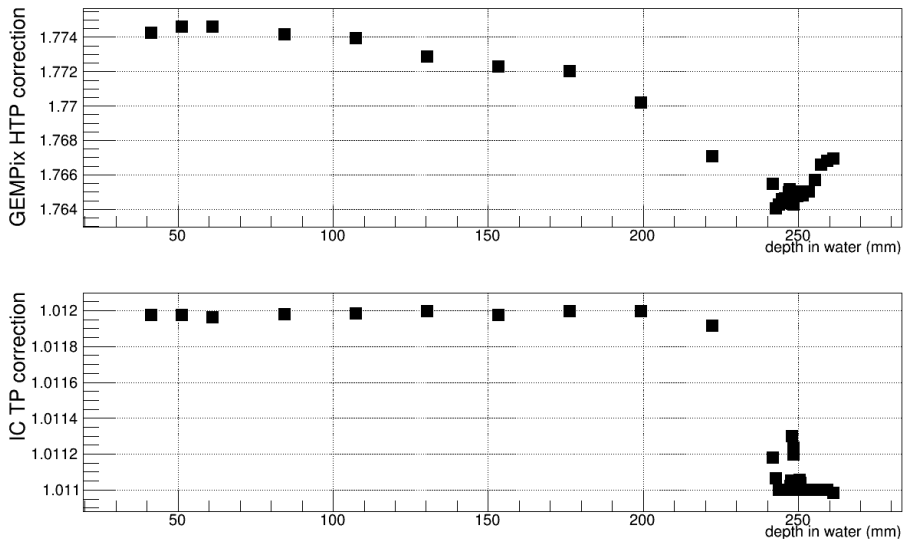
- Measures independently of beam delivery
- GEMPix: 50 ms integration, 300 ms dead time
- Reference ion chamber needs to be synchronous
- Delay of subsystems after receving trigger?
- Ion chamber and readout: no delay
- GEMPix: tested with UV LED to have no delay

Measurement Reproducibility



- runs with carbon ions repeated to study reproducibility
- relative difference within $\pm$ 4%
- compatible with uncertainties of approx 2%

Checked Possible Sources of Mismatch



Humidity, temperature, pressure:

- HTP sensor inside the gas in the GEMPix and in the ambient air
- GEMPix HTP correction developed in the lab
- ion chamber TP correction from PTW

Other checked effects:

- GEMPix background subtracted
- different response of the 4 chips
- small gap between the 4 chips
- alingment of the water phantom
- alignment of the detector
- no direct signal production in ASIC
- overflow of pixel TOT counter