HSE

Occupational Health & Safety
and Environmental Protection unit

Microdosimetry with GEMTEQ, a novel gas microdosimeter with a highly pixelated readout

Johannes Leidner[1], F. Murtas[1,2], M. Silari[1], A.J. Waker[3]

[1)] CERN HSE-RP-SP, [2)] INFN, [3)] University of Ontario Institute of Technology

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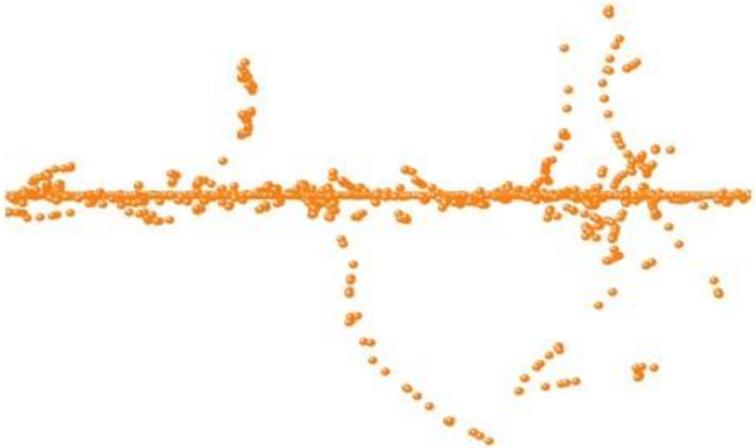
Outline

- Introduction to microdosimetry
- The GEMTEQ detector
- Measurements with the GEMTEQ
- FLUKA simulation of the GEMTEQ
- Planned/on-going work
- Conclusions and outlook

Motivation: Cell Damage by Radiation

Microscopic world of interest for radiation damages is highly structured!



Ionisation events occur stochastically around a carbon ion track.

The DNA is highly structured.

Concept of absorbed dose loses its validity in the microscopic world: neither the radiation nor the target can be described well by an average number. Which type of radiation is best for cancer therapy?

Slide from: P.Colautti, Introductory lecture on microdosimetry, 2nd ARDENT workshop. Milano 14-18 October 2013

From Dosimetry to Microdosimetry

Dose: How much energy is absorbed in a volume of a certain mass (human body)?

$$D = \frac{\Delta E}{M}; \ [D] = \text{Gray}$$

Dose equivalent: Dose weighted by a quality factor that depends e.g. on the particle type.

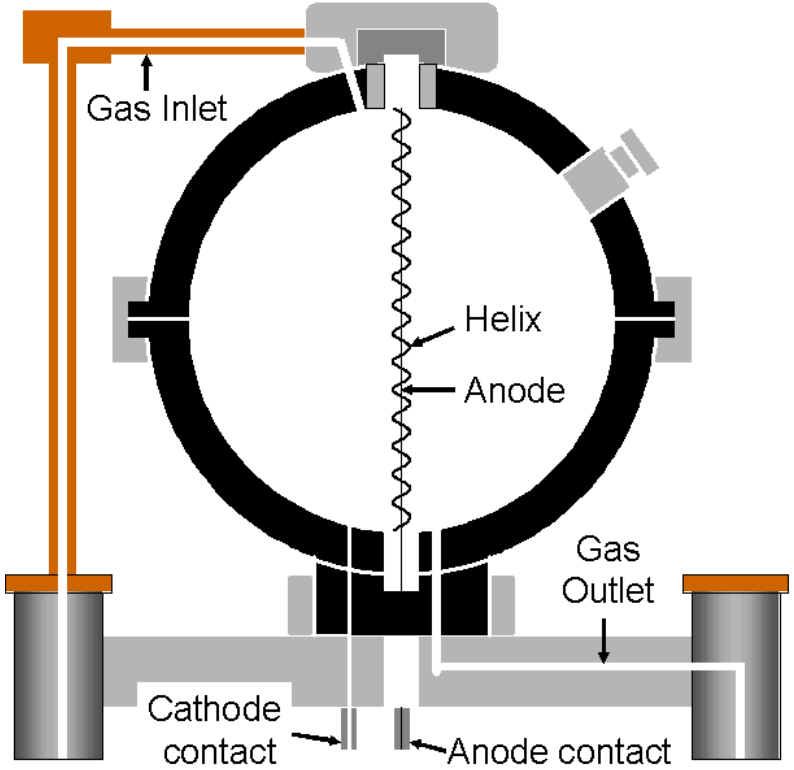
$$H = QD; \ [H] = \text{Sievert}$$

What is this quality factor? What does it depend on?

'Microdosimetry is the systematic study and quantification of the spatial and temporal distribution of absorbed energy in matter.' Rossi, Zaider: Microdosimetry and Its Applications

Experimental Microdosimetry I

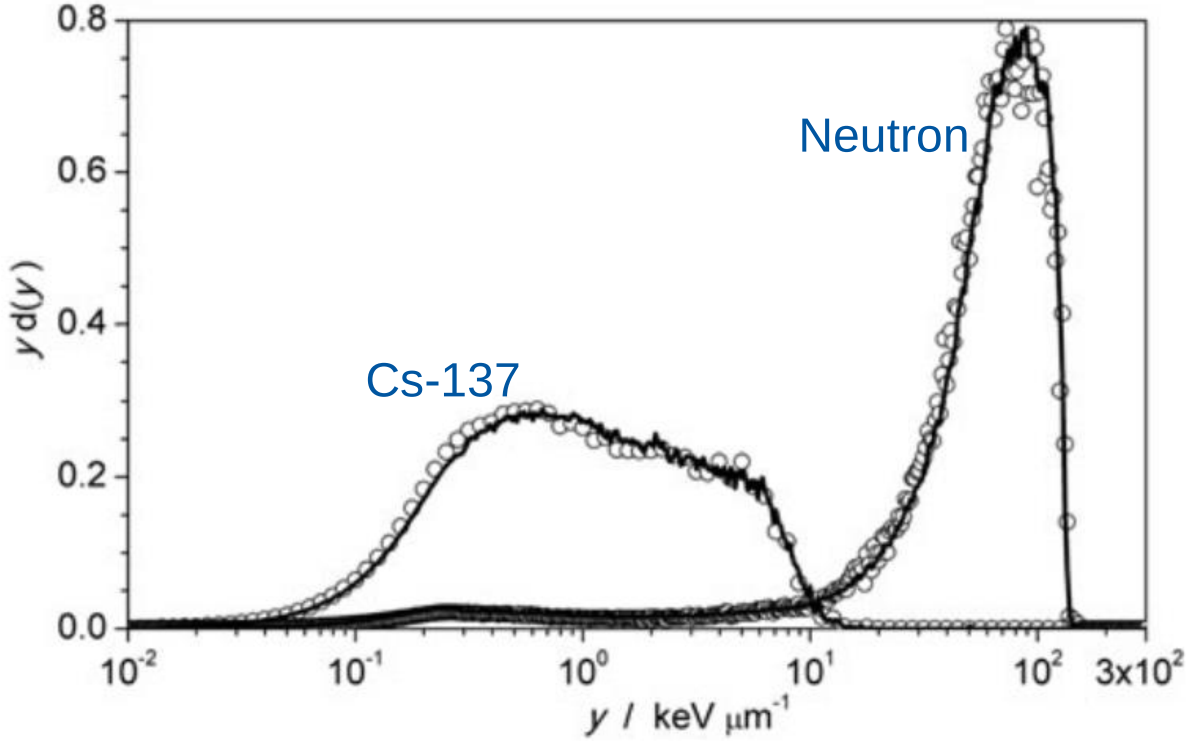
- Idea: small equivalent length scale in tissue by using tissue-equivalent gas at low pressure
- Tissue equivalent gas: propane or methane based plus CO_2 plus N_2
- TEPC (Tissue equivalent proportional counter) is the gold-standard in microdosimetry



Rossi counter, https://www.orau.org/ptp/collection/proportional\%20counters/rossi.htm

Experimental Microdosimetry II

Measure energy depositions in low-pressure tissue-equivalent gas
→ measure pulse height spectrum (frequency distribution f(y)) in micrometer scale equivalent tissue



Chiriotti et al: Equivalence of pure propane and propane TE gases for microdosimetric measurements, Rad Prot Dos, 2015

- Lineal energy: $y = \varepsilon/\bar{l}$
  - ε: imparted energy
  - $\bar{l}$: mean chord length; $\bar{l} = 4\frac{Volume}{Surface}$
- Usually dose distribution is of interest:

$$D \propto \bar{y} = \int_0^\infty yf(y)dy \;\rightarrow d(y) \propto yf(y)$$

- Logarithmic distribution (on x-axis) needed

$$\int_{y1}^{y2} d(y)dy = \int_{y1}^{y2} [yd(y)]\, dlog(y)$$

Why Developing GEMTEQ, a Novel Detector for Microdosimetry?

TEPCs only have a single channel information.

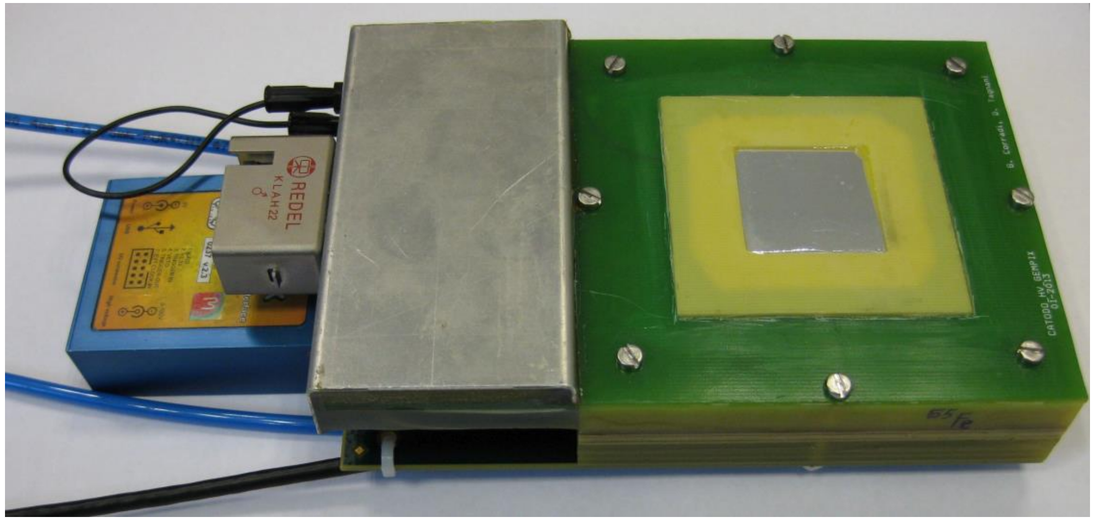
The GEMTEQ
- offers high granularity of readout: 1 pixel = 100 nm in tissue
- potentially allows to perform sub-microdosimetry (at low pressure)
- allows to study multiple microdosimetric volumes simultaneously
- potentially allows 3D particle track studies

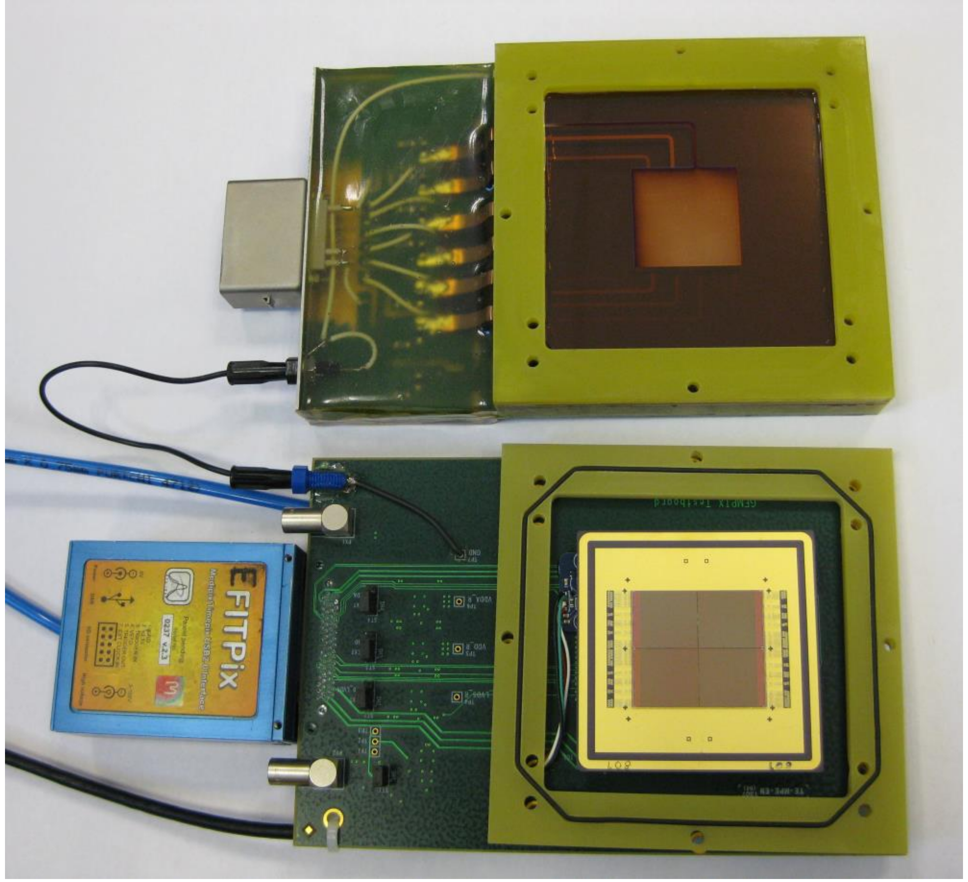
→ The GEMTEQ introduces a new detector concept to microdosimetry.

The GEMTEQ Detector

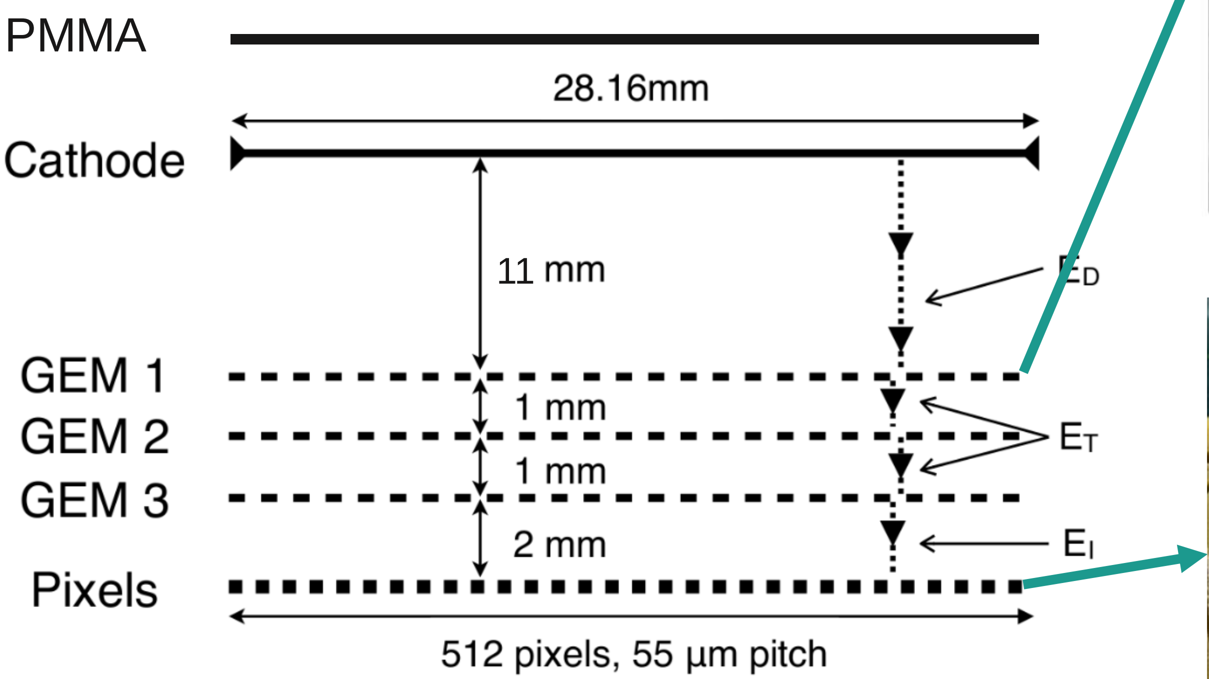
GEMTEQ based on GEMPix:
Gas Electron Multipliers (GEMs) + Timepix

- 9 cm^3 gas detection volume (TE gas at atmospheric pressure)
- 3 GEMs for electron multiplication
- 4 naked Timepix ASICs as readout (55 µm pixel pitch, 512x512 pixels)





GEMs and Timepix



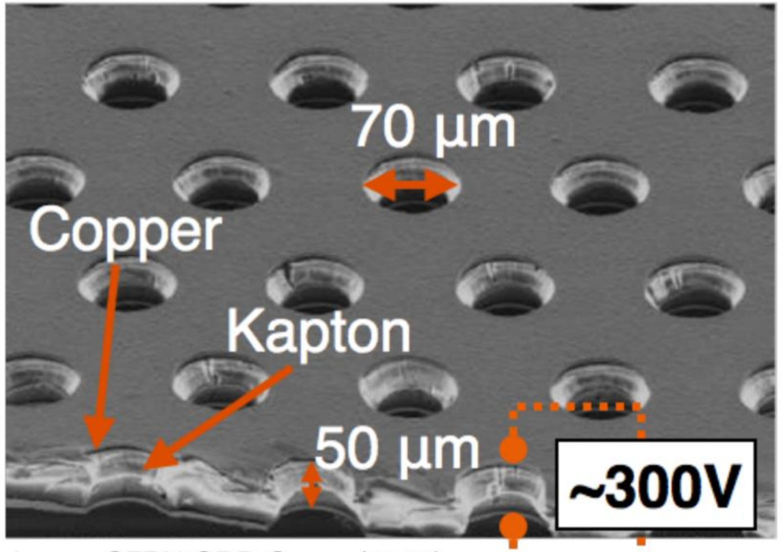
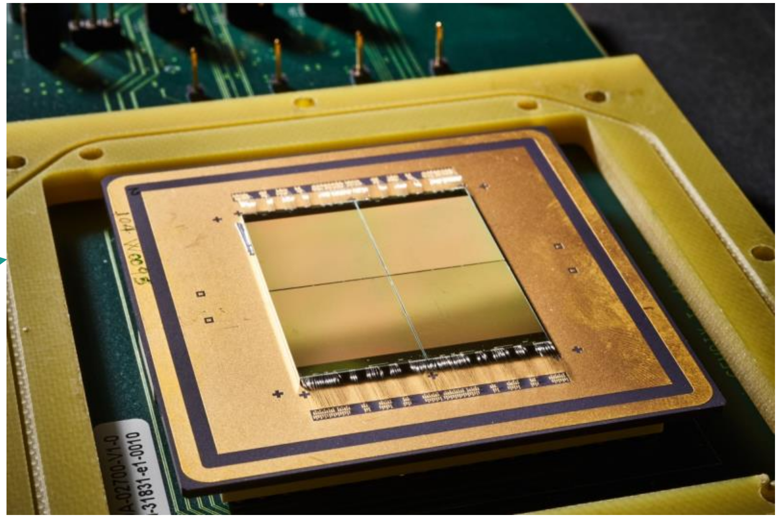


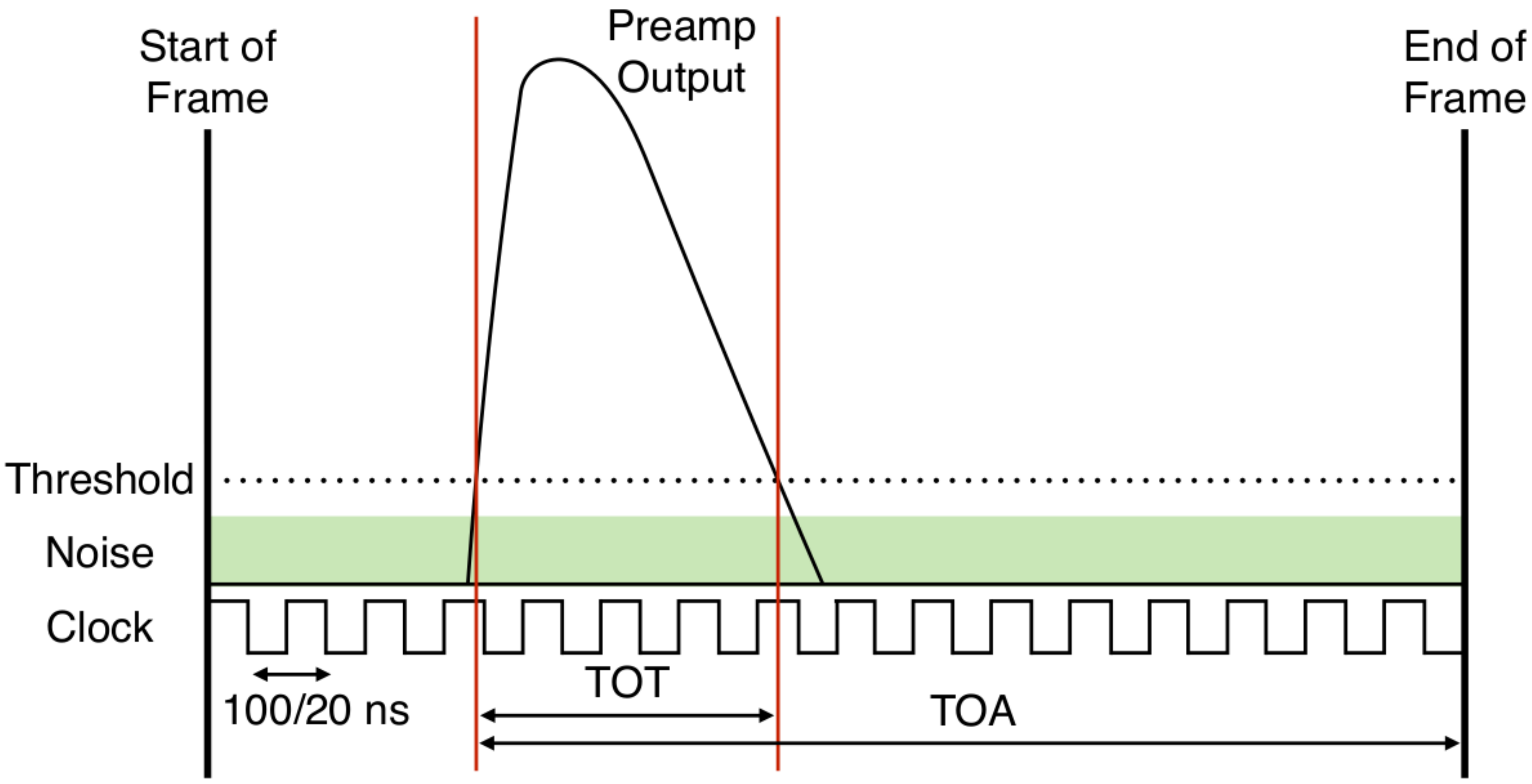
Image CERN GDD Group (2001)

3 GEMs:
- Kapton + thin copper layers
- Large fields in holes
- Electron multiplication



4 naked Timepix ASICs:
- 512 x 512 pixels
- 55 µm pixel pitch

Timepix: frame based signal digitization

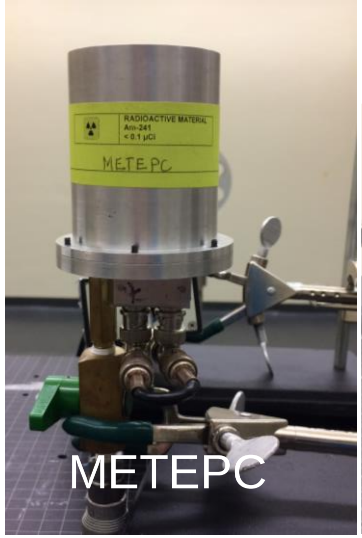


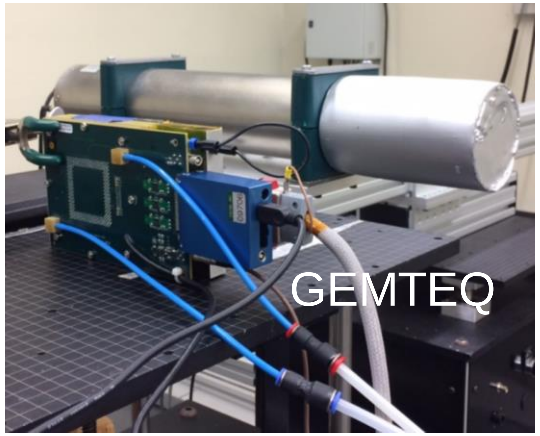
Different readout modes possible:

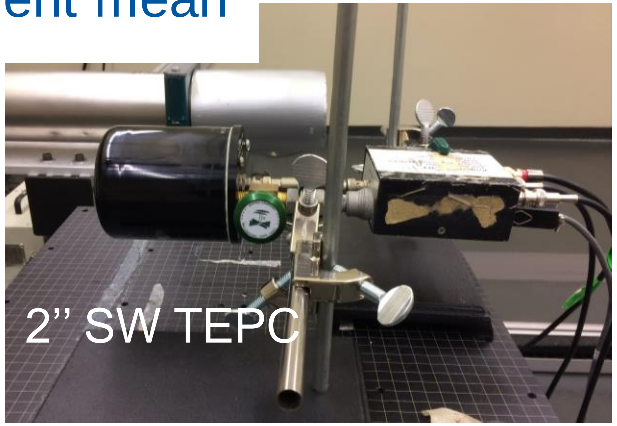
- Pulse counting
- Time of Arrival (ToA)
- Time over Threshold (ToT) -> deposited energy

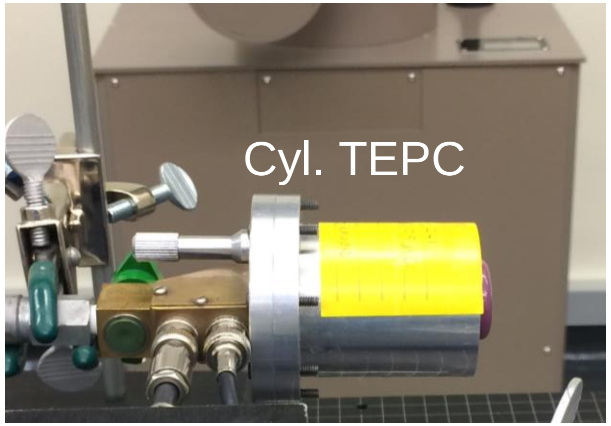
Measurements

- 2.5 MeV **neutrons** (D-D generator), ^{137}**Cs**, 65 keV **X-rays**
- Detectors:
  - **GEMTEQ**
  - **METEPC** [(1)]: 61 cylindrical volumes (l=50 mm, d=5 mm) in an A150 block with 1 mm wall thickness, 1 summed signal
  - **Cylindrical TEPC** [(2)]: cylindrical detection volume (d=h=1.5 cm)
  - **2'' Single-Wire Spherical TEPC** (Far West Technology)
- Adjust pressure in all detectors to have same equivalent mean chord length of 1 µm



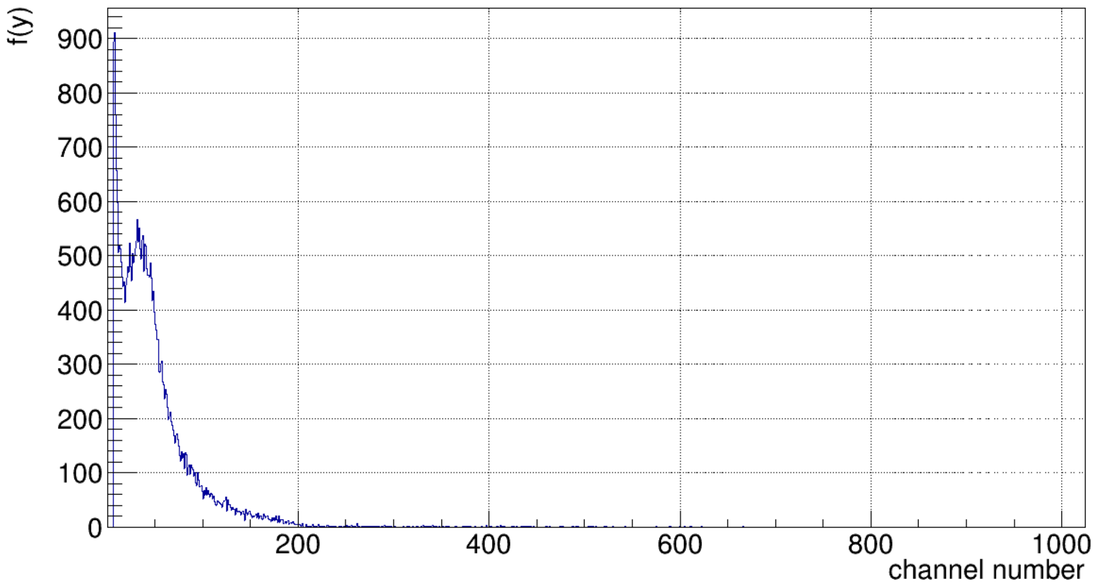




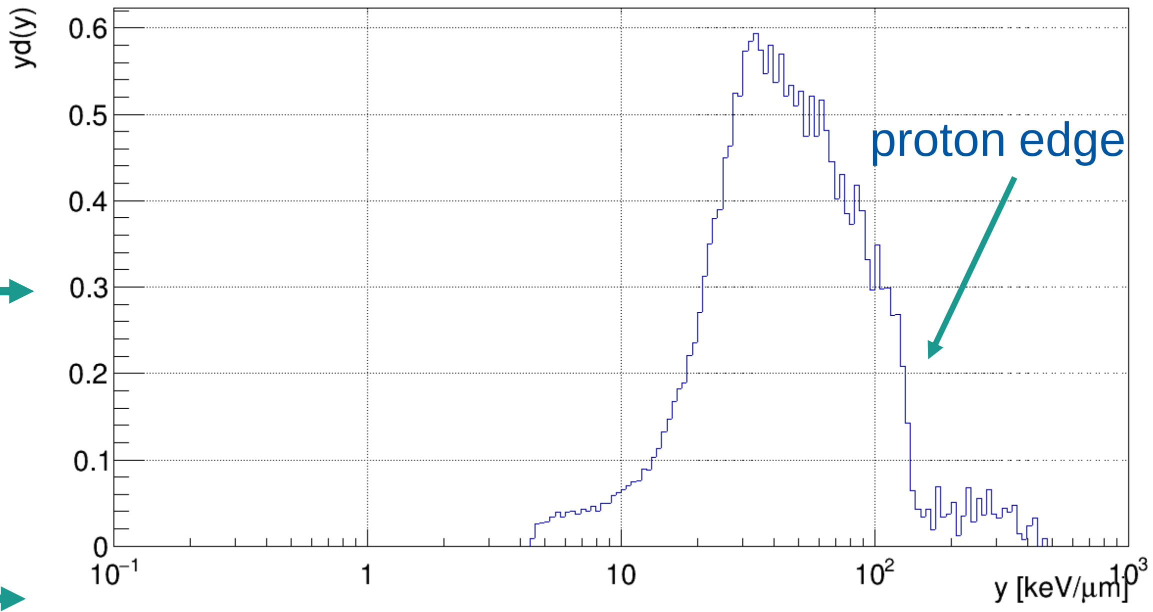


(1) Waker et al. Design of a multi-element TEPC for neutron monitoring. *Rad. Prot. Dos.* 2011.
(2) Forouzan et al. Development of heterogeneous proportional counters for neutron dosimetry. *Rad. Prot. Dos.* 2018.

TEPC Analysis: Neutrons, E_N=2.5 MeV



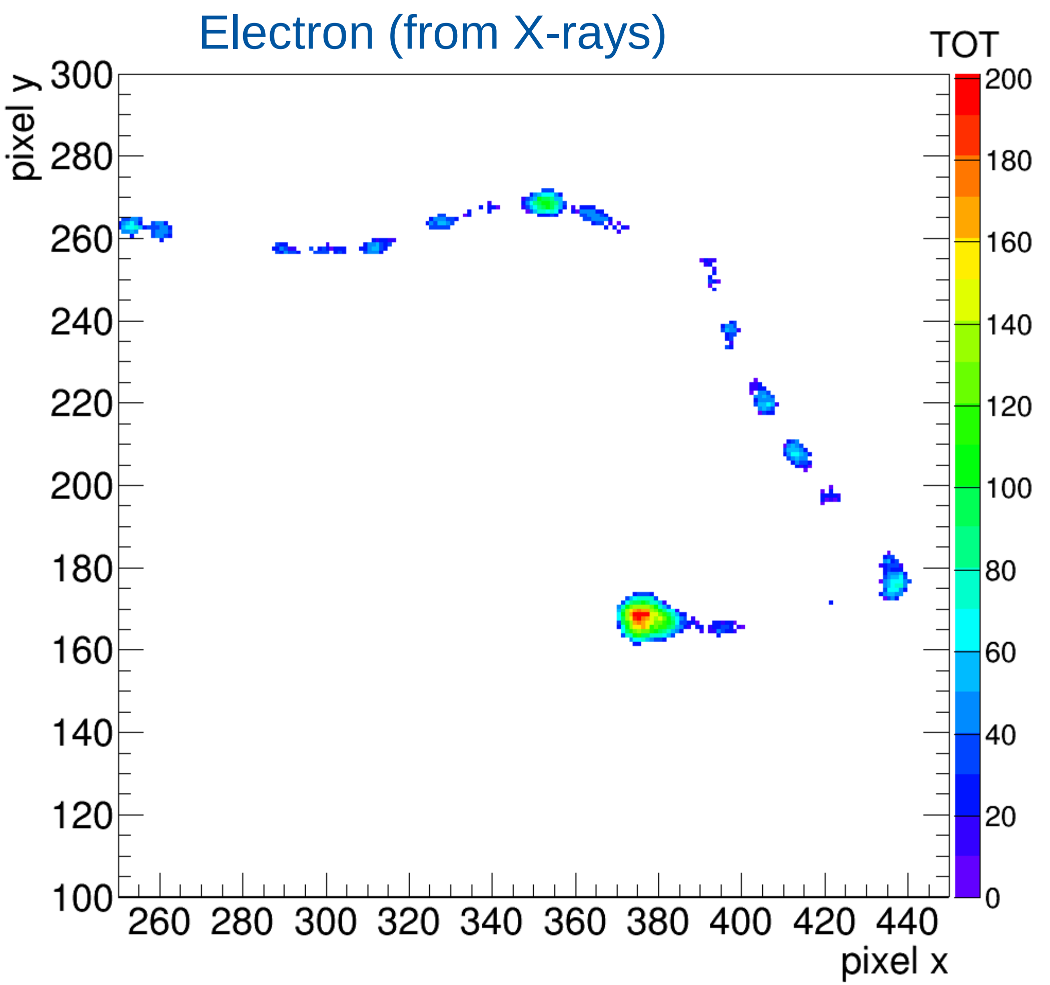
Raw data

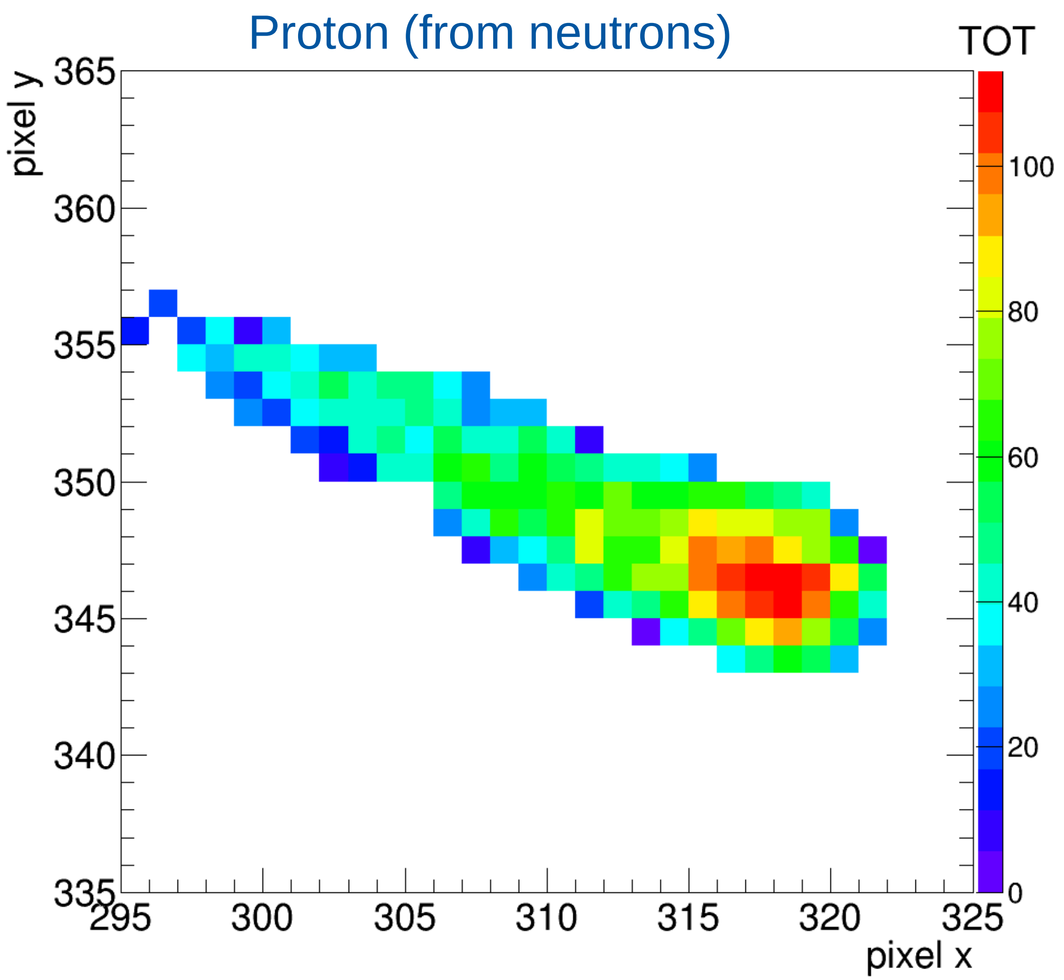


Energy calibration
Dose spectrum
Equal logarithmic binning
Area normalization

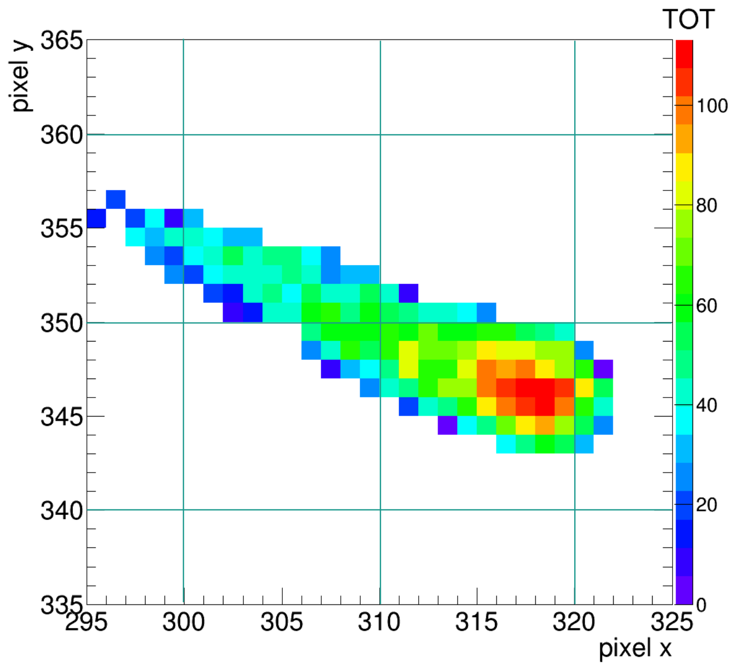
yd(y) spectrum

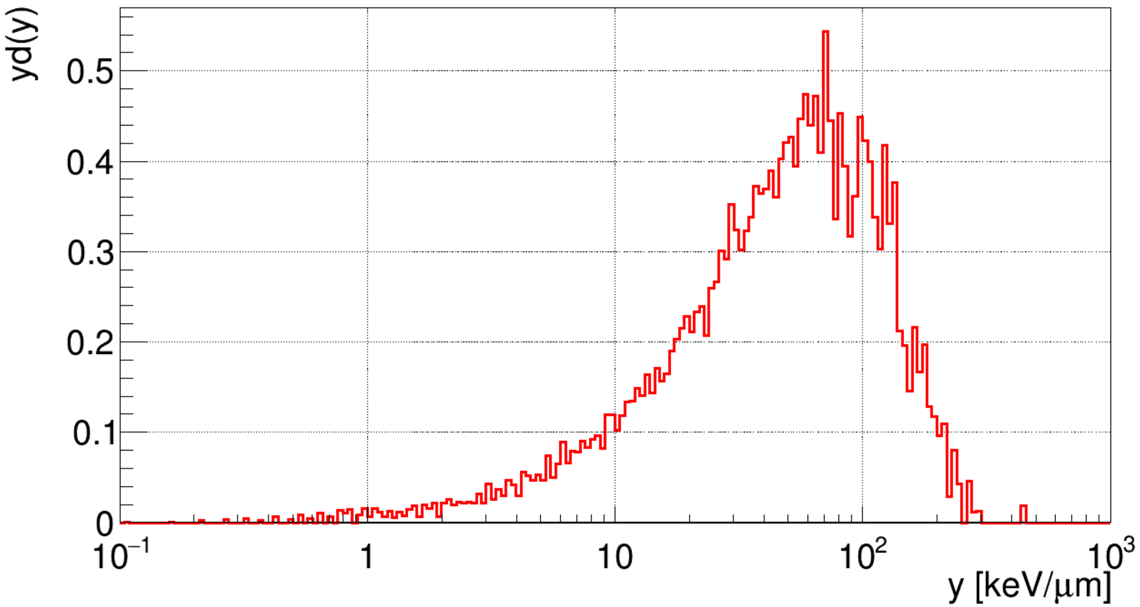
GEMTEQ Images: Particle Tracks





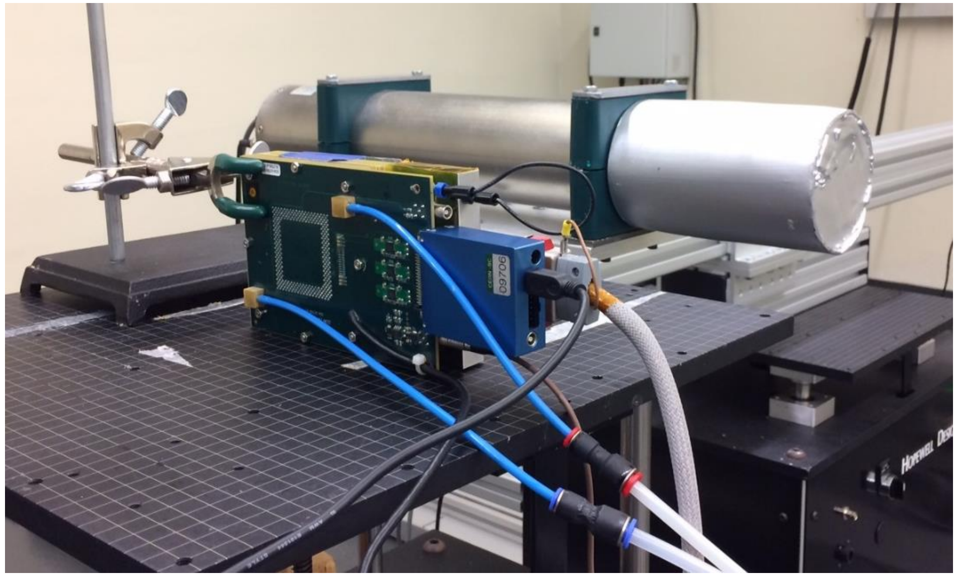
GEMTEQ analysis

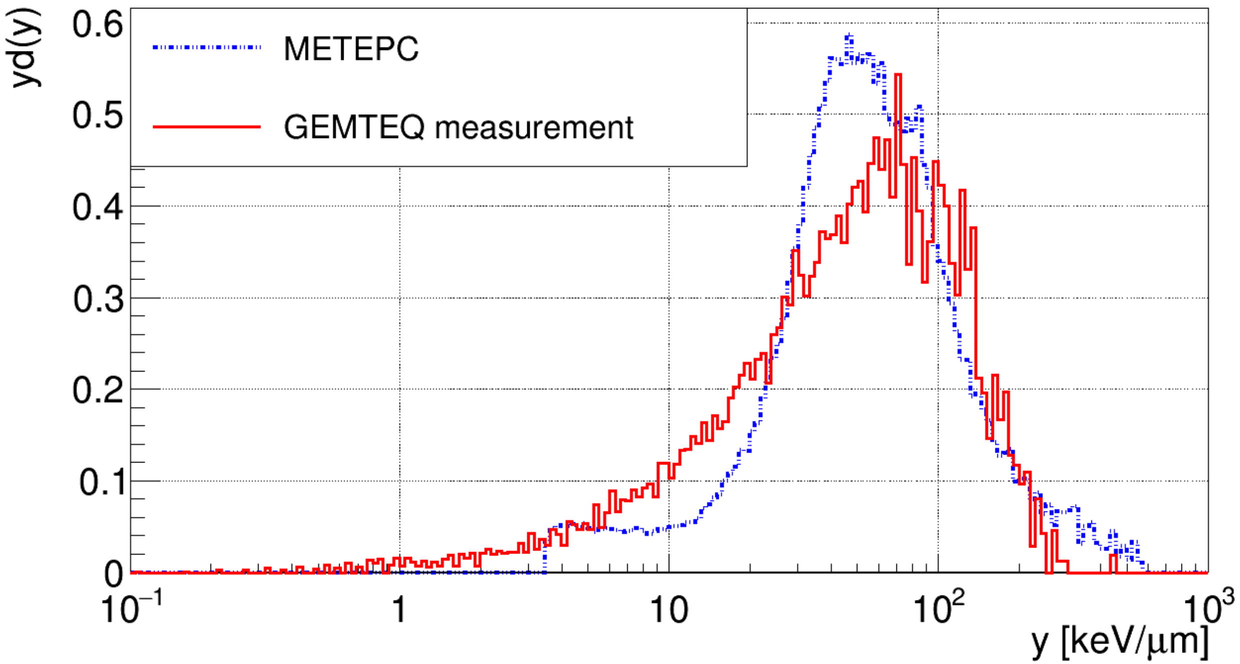




- 1 pixel length in gas (55 µm) → 100 nm in tissue
- Volume: superpixel (10x10 pixels) x drift gap →1 µm x 1 µm x 20 µm, mean chord length: 1 µm
- TOT counts / superpixel in “channels” histogram → same analysis as for TEPCs
- TOT counts → energy calibration via electron / proton edge

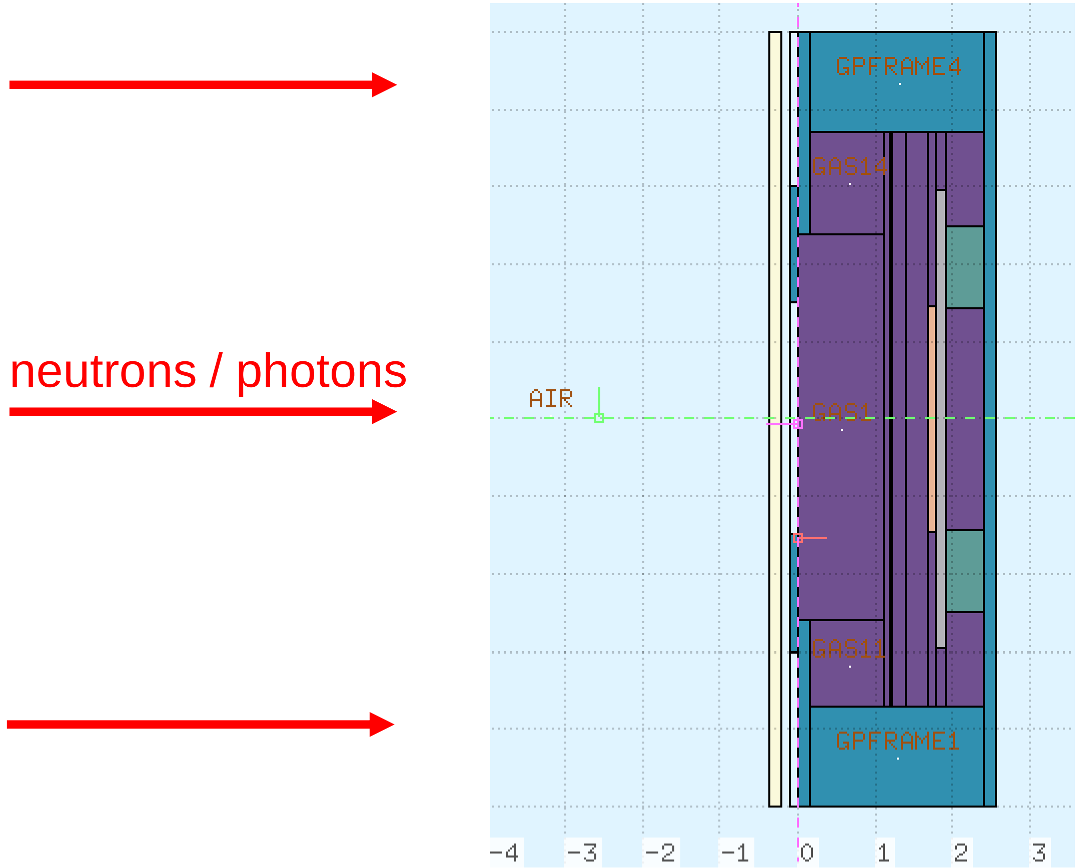
Neutron Measurements, E_N=2.5 MeV





Why is there a difference between METEPC and GEMTEQ?
→ FLUKA Monte Carlo simulation of GEMTEQ

FLUKA Simulation of the GEMTEQ



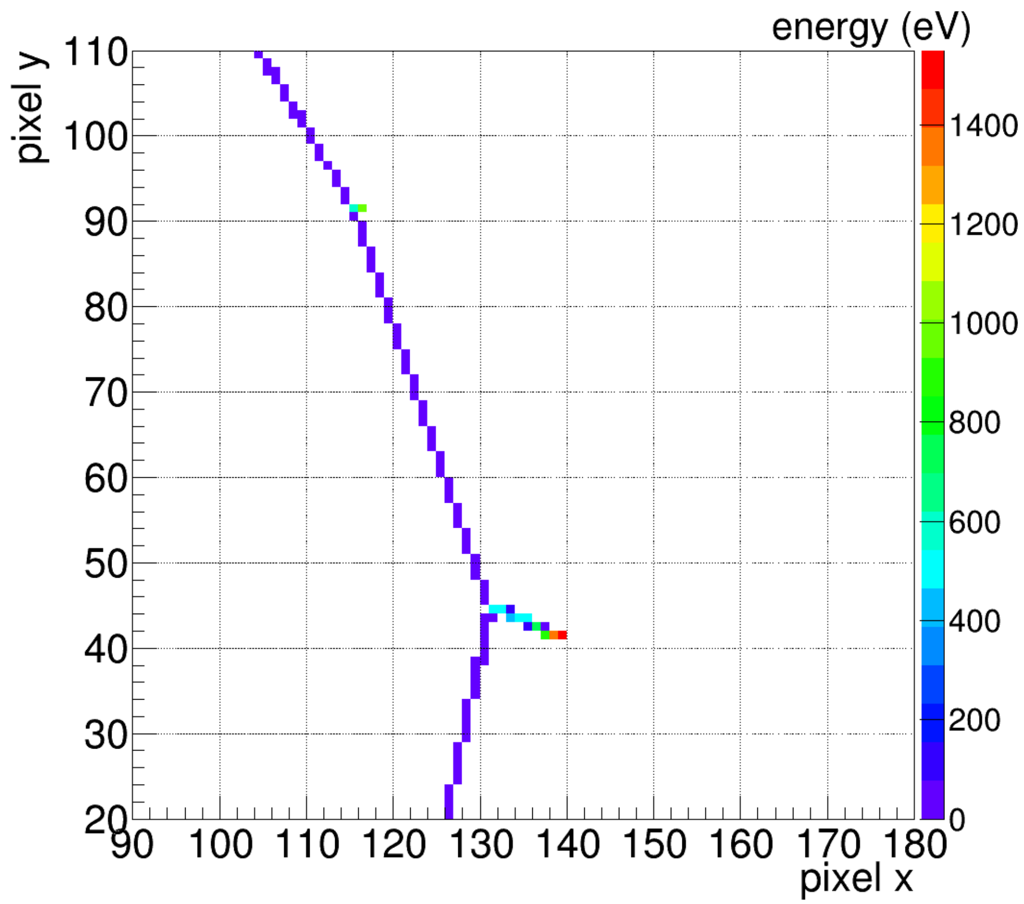
- Idea: simulate GEMTEQ results with FLUKA Monte Carlo simulation (2D images, yd(y) spectra)
- GEMTEQ: simplified geometry
- Beam: neutrons/photons, mono-energetic, flat

- FLUKA output: energy deposition in drift gap above each pixel
- Same analysis as for GEMTEQ measurements (superpixels → yd(y) spectrum)

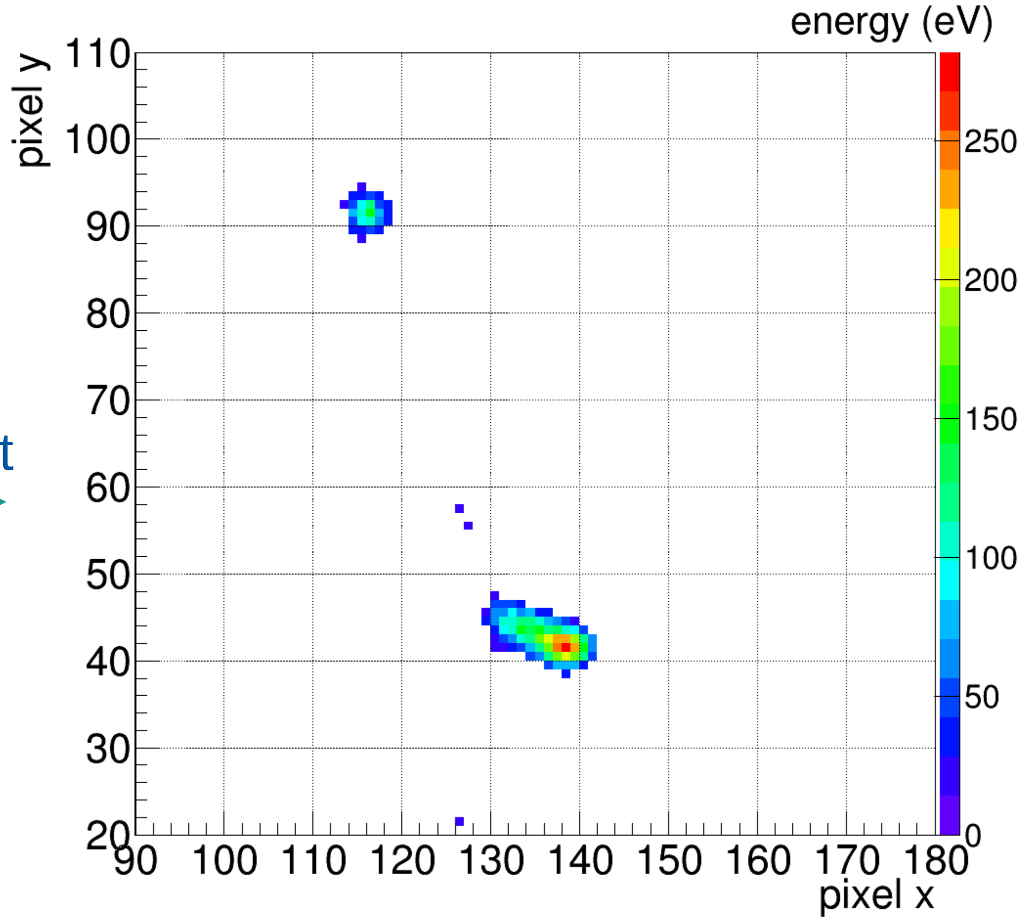
Diffusion, Threshold Cut, Energy Smearing

- FLUKA: no detector effects included
- Diffusion:
  - Reality: electron cloud spread out due to diffusion
  - Simulation: average sigma for GEMTEQ with TE gas estimated, 2D Gaussian to re-distribute energy deposition over pixels
- Timepix threshold cut:
  - Reality: Timepix readout only registers events above a certain threshold per pixel
  - Simulation: Minimum energy per pixel required (1 keV per pixel for neutrons)
- Energy resolution:
  - Reality: 20% FWHM/mean at 5.9 keV
  - Simulation: Gaussian re-distribution of energy / pixel
- Check: input values for these effects varied around estimated value → only small impact on dose spectra

Diffusion and Threshold: Impact on 2D Images from FLUKA

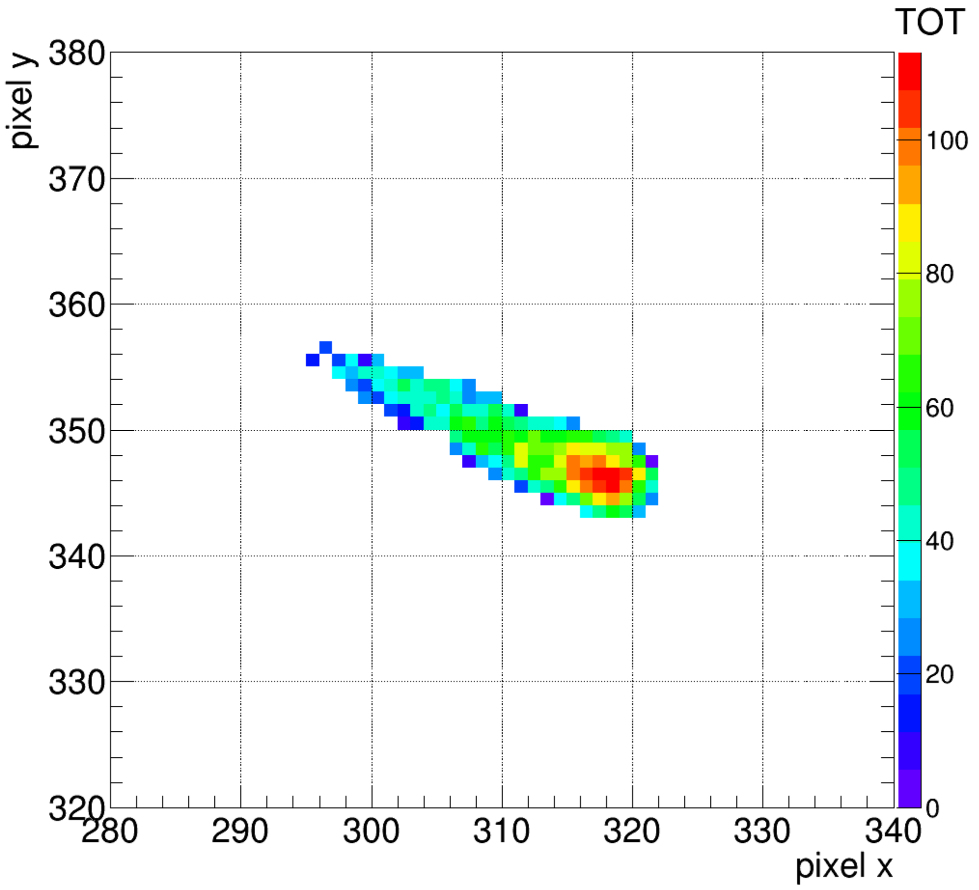


Diffusion
Threshold cut

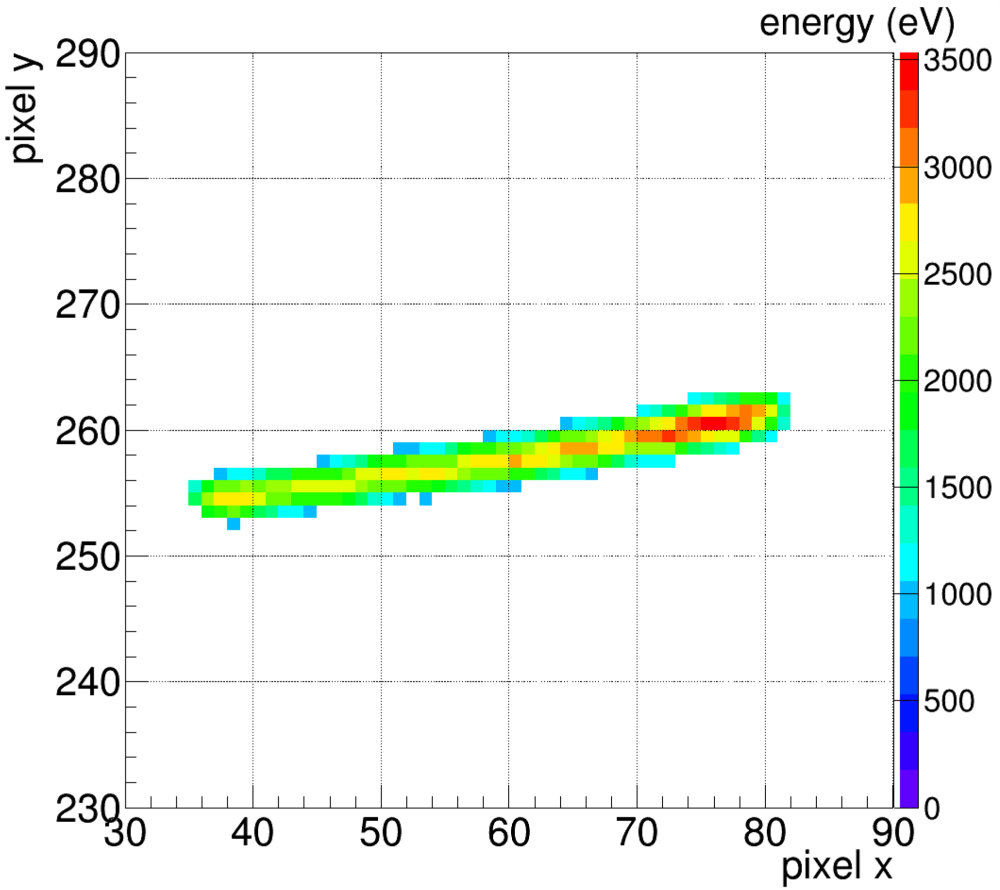


^{137}Cs

2D Images Neutrons

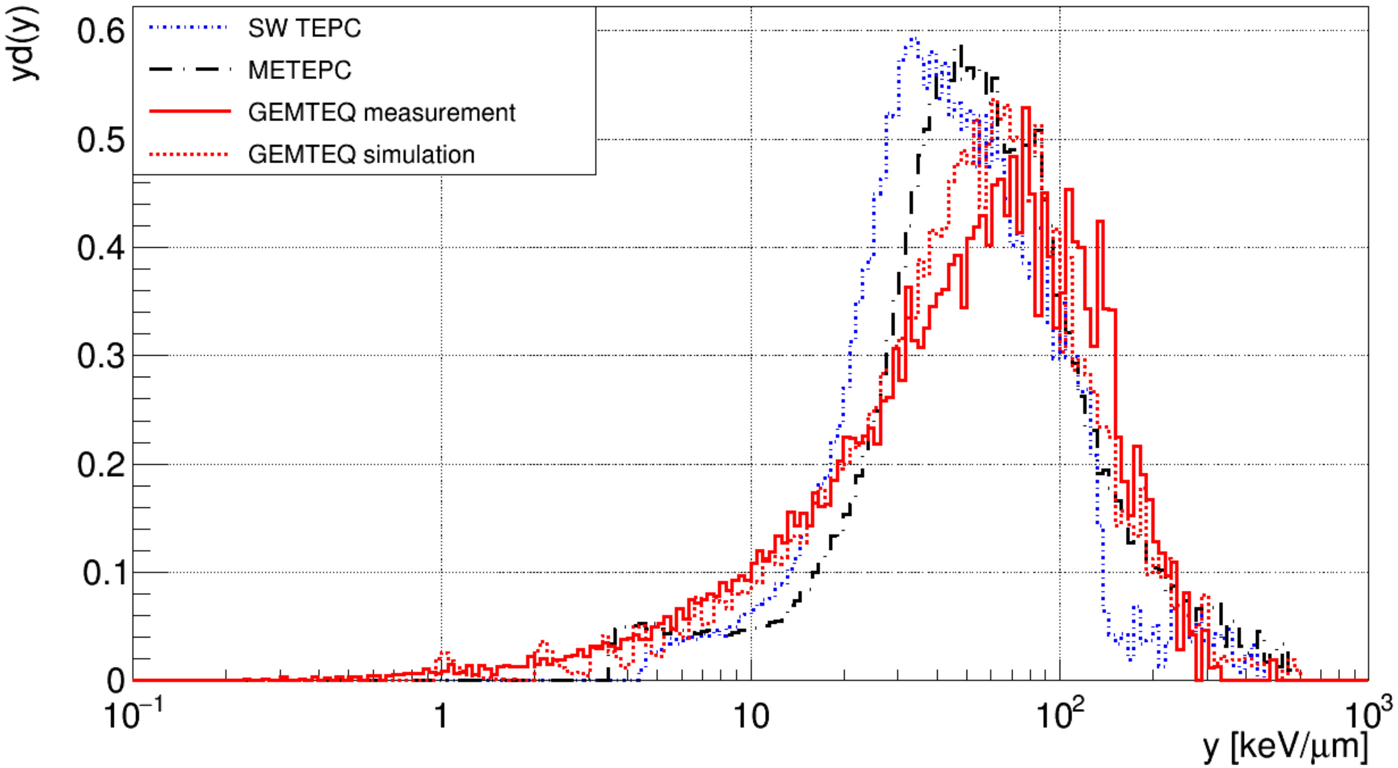


Measurement



FLUKA Simulation

Neutrons (E_N=2.5 MeV)

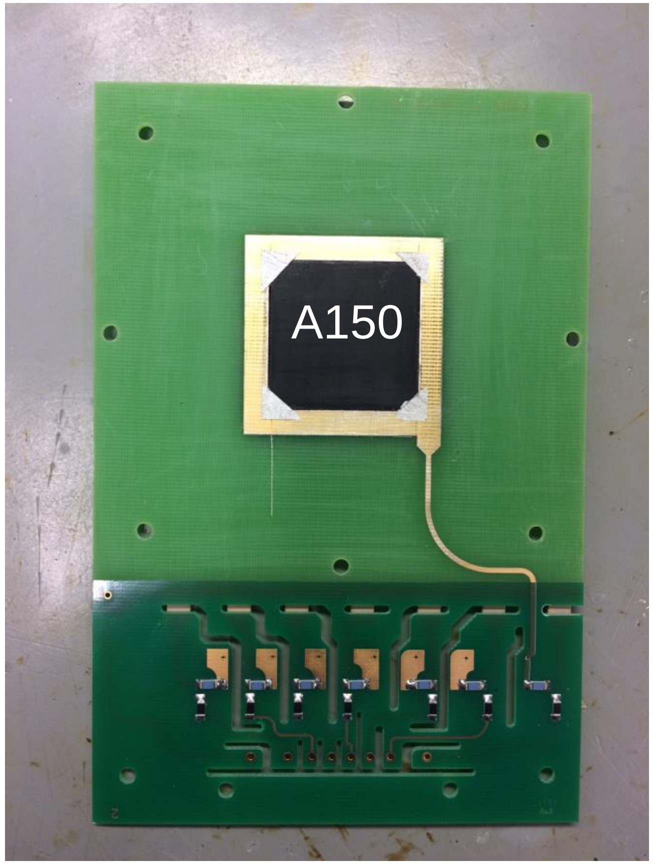


Detector	$\overline{y_F}$	$\overline{y_D}$
GEMTEQ, measurement	40.9	71.5
GEMTEQ, simulation	42.3	74.2
METEPC	46.1	77.5
SW TEPC	38.1	60.5

y_{min} = 10 keV/µm

GEMTEQ experimental results and FLUKA simulation match well.
Similar result with the METEPC and the SW TEPC.

GEMTEQ with A150 TE Window



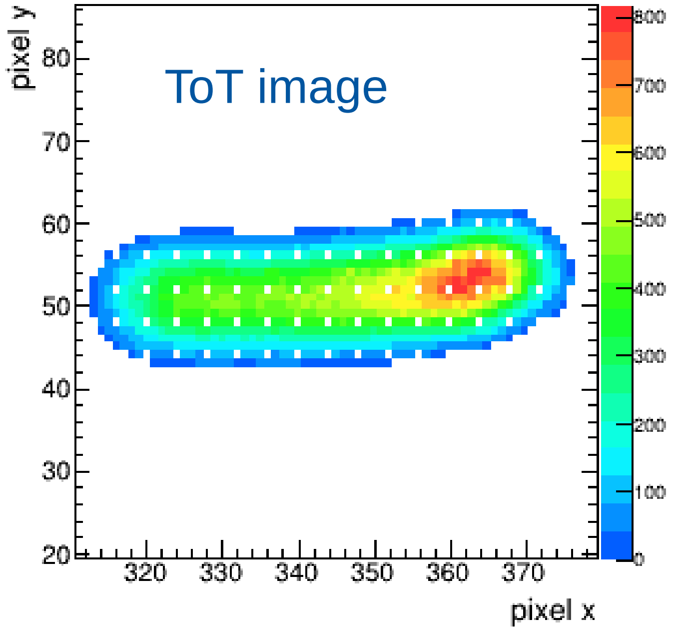
Bottom view

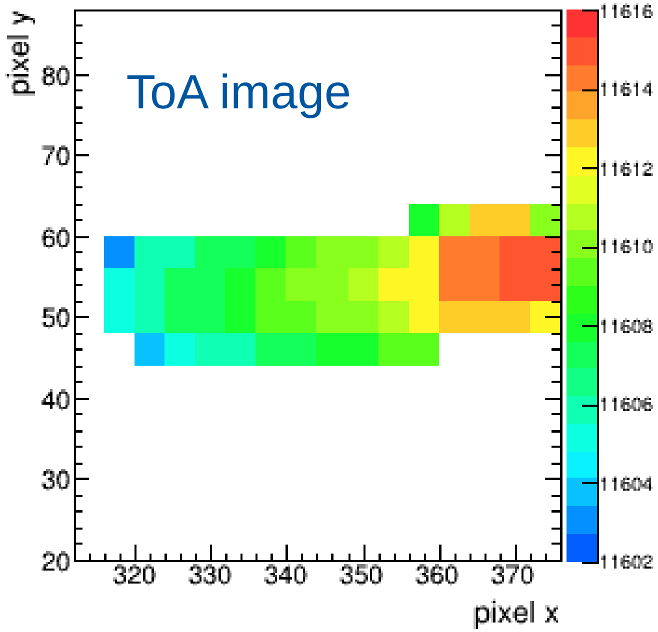
Top view

- New GEMTEQ: A150 TE plastic window / cathode
- The detector is working and ready for measurements!

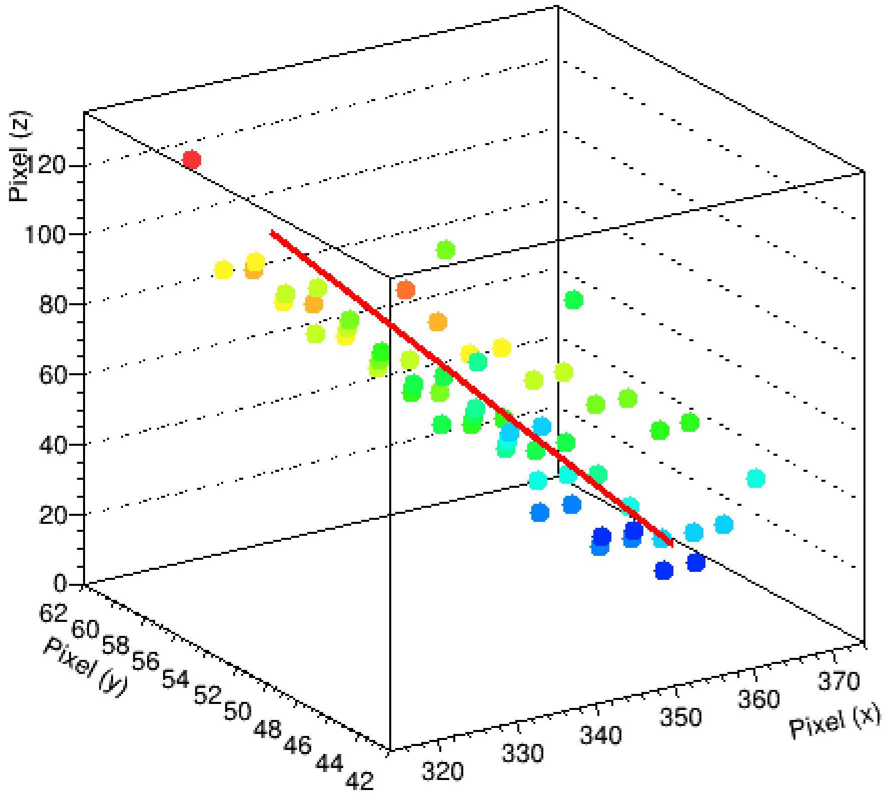
Work in progress:
3D Particle Track Reconstruction I

- Measurements performed with Ar:CO_2:CF_4
- Mixed mode: 1/16 pixels in ToA mode, all others in ToT mode

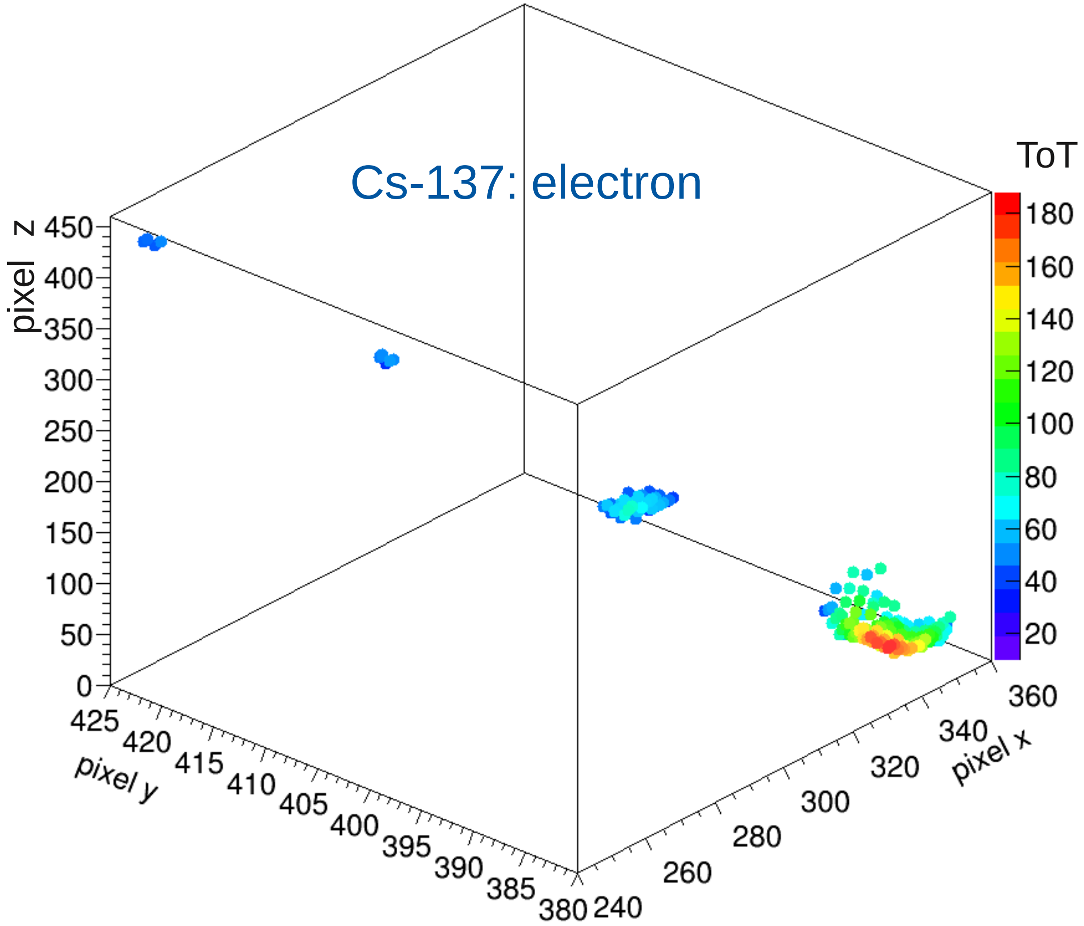


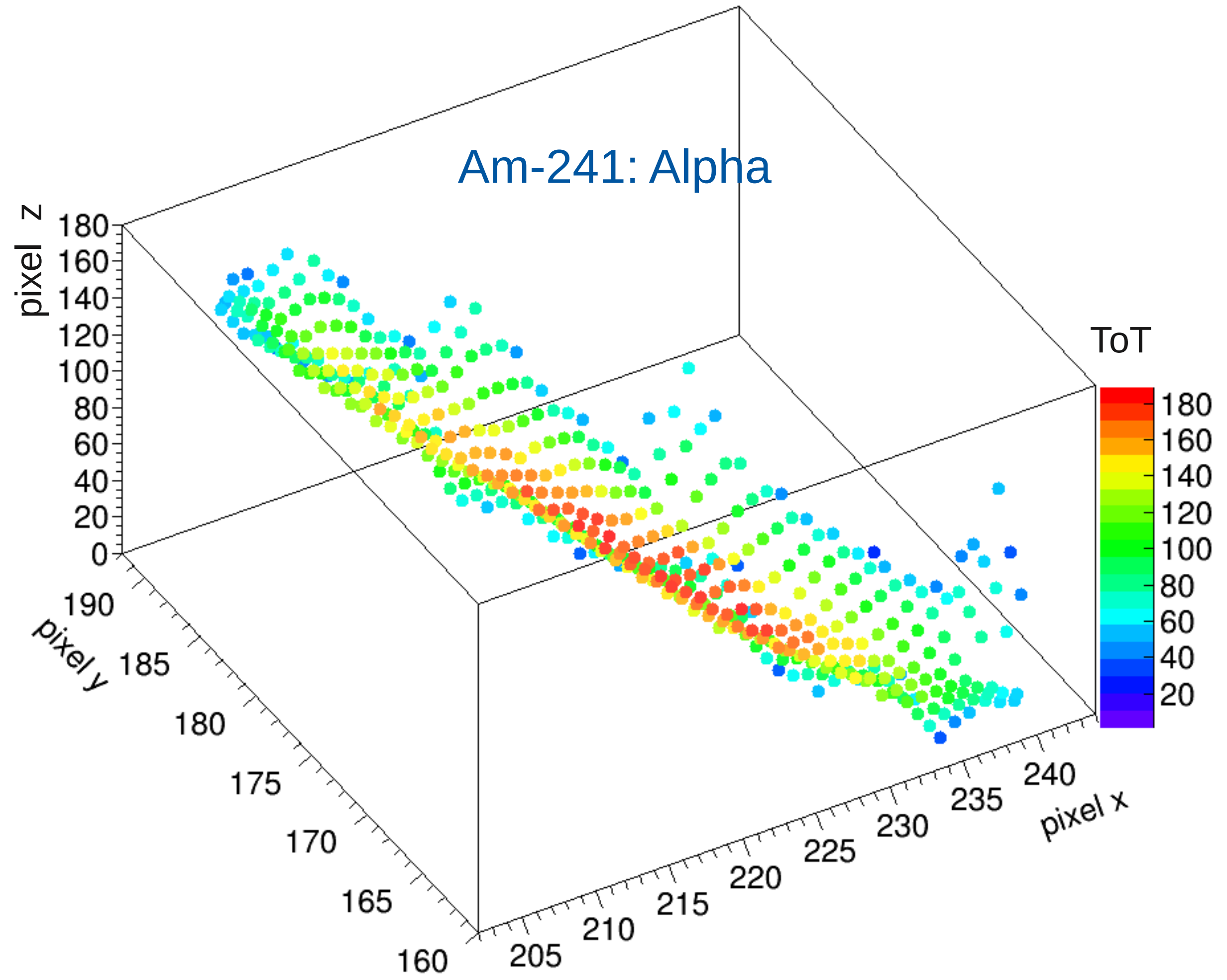


3D reconstruction



Work in progress:
3D Particle Track Reconstruction II





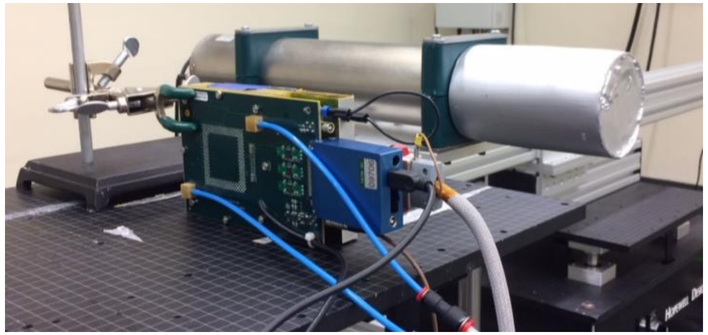
On-going Development: Sealed / Low-pressure GEMTEQ

- Goals:
  - Sealed GEMTEQ: obtain a sealed detector that can be operated for a couple of days without refill
  - Low-pressure GEMTEQ: increase the equivalent spatial resolution by lowering the pressure
- Challenges:
  - Sealed/low-pressure detector: stable detector response
  - Low-pressure detector: GEMTEQ behavior at low pressure

→ How much do we gain in equivalent spatial resolution?

Conclusions & Outlook

Conclusions:
- GEMTEQ used for microdosimetry: 2D images, yd(y) spectra
- Results are similar compared to standard TEPCs
- FLUKA simulation of GEMTEQ: experimental results well understood



Outlook:
- Energy calibration, lower lineal energy (^{137}Cs)
- Low pressure detector → sub-microdosimetry
- Improve detector simulation (Garfield++)
- Using track information → 3D particle track reconstruction, electron drift velocity needed
- Timepix upgrade: TOT and TOA information → improved 3D tracks

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