Photon Detection (Position Sensitive) by Structured Converter Layers in Micro-Pattern Gaseous Detectors

Joint Particle Physics Group Seminar

29.6.2022

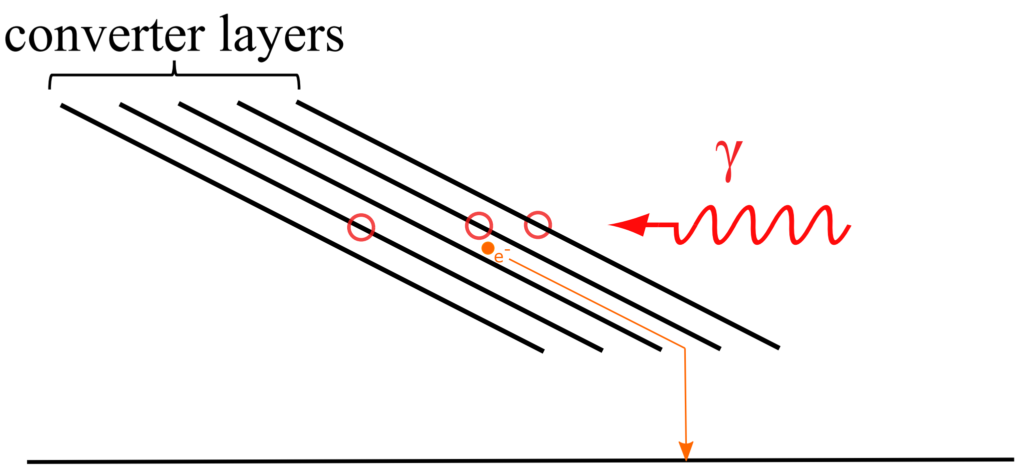
Katrin Penski

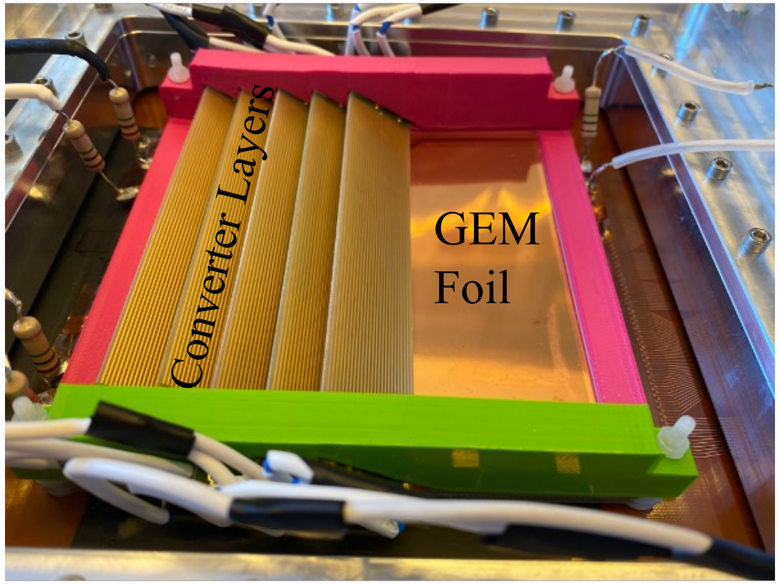
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

TUM LMU ORIGINS Excellence Cluster ESO lrz

Motivation

- Micro-Pattern Gaseous Detector: extremely good spatial resolution and high-rate capability
- but: low gas density → poor detection efficiency for photons
- idea: increase detection efficiency by using several solid converter layers



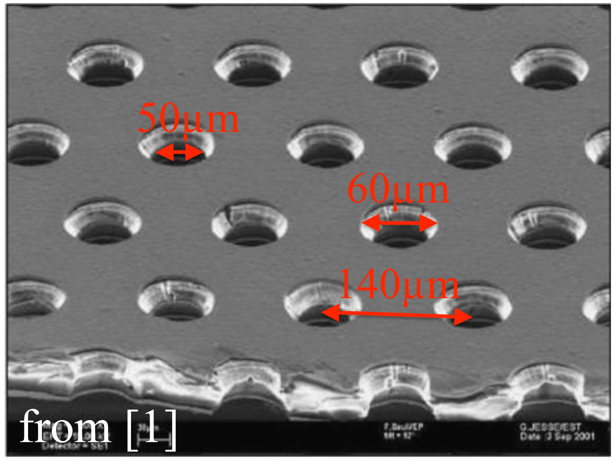


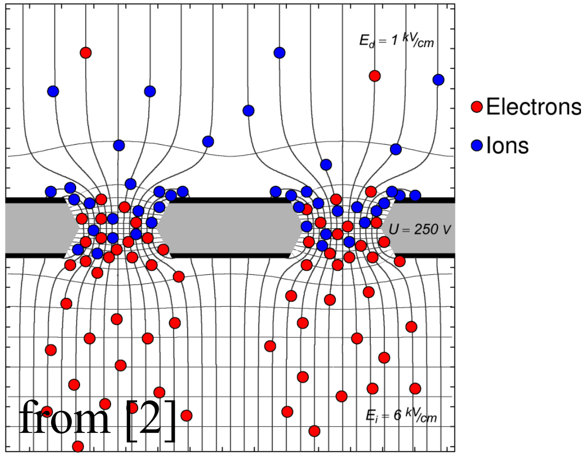
multiple converter layers

multiple converter layers in detector

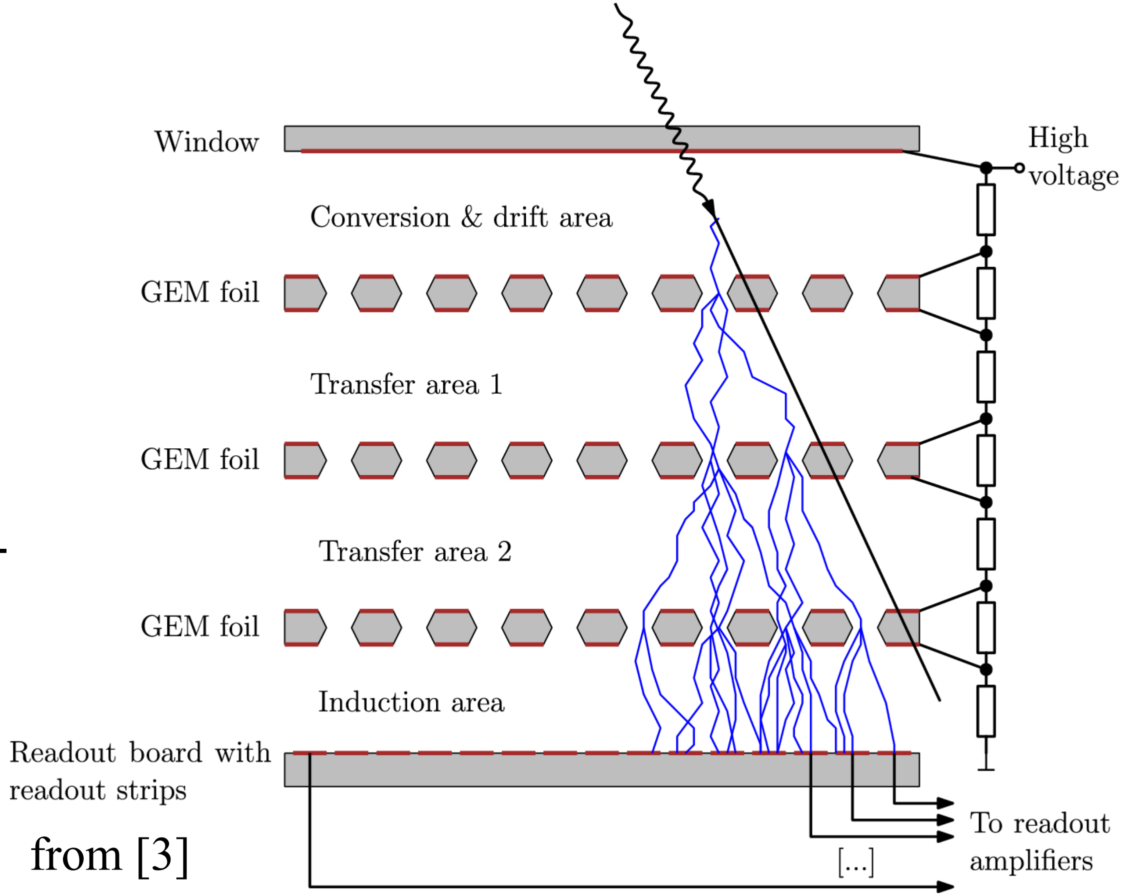
The GEM Detector Principle

- **G**aseous **E**lectron **M**ultiplier
- amplification by GEM foils:



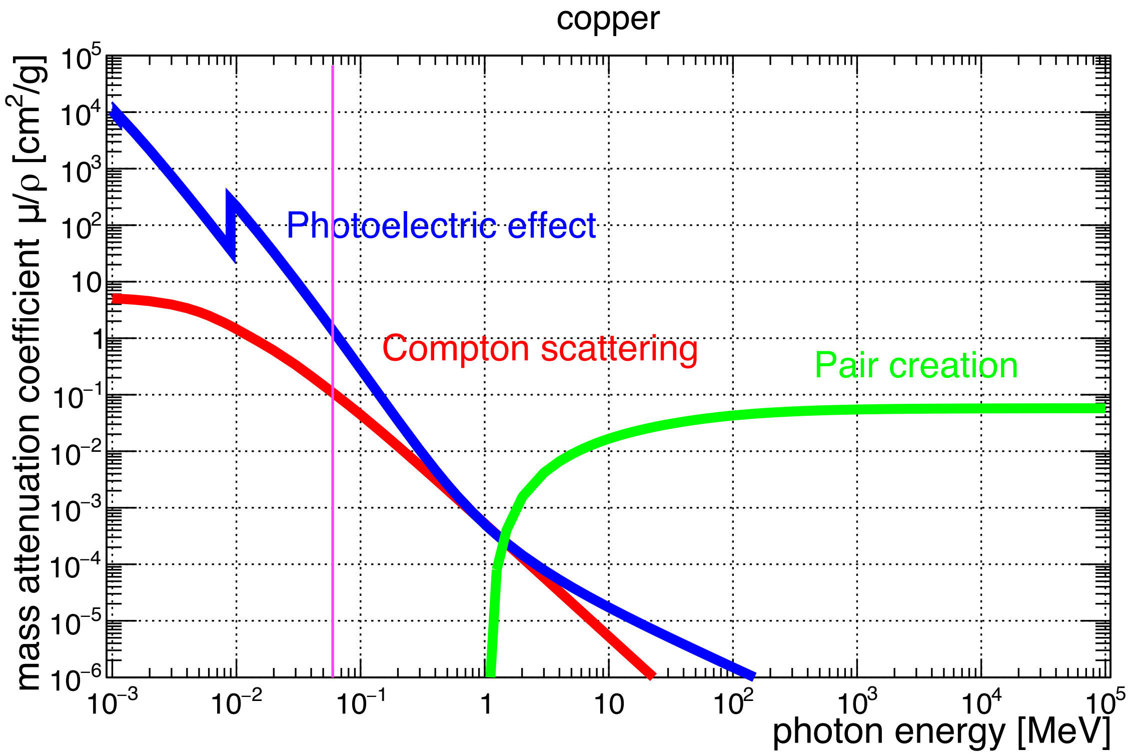


- copper plated Kapton foils
- electron amplification factor per foil: 20
  → 3 foils → $20^3 = 8000$



- advantages: → excellent spatial resolution (< 100 µm)
  → high-rate capability

Photon Detection Process



data from [4]

- first attempt: optimize detection for E_γ = 59 keV

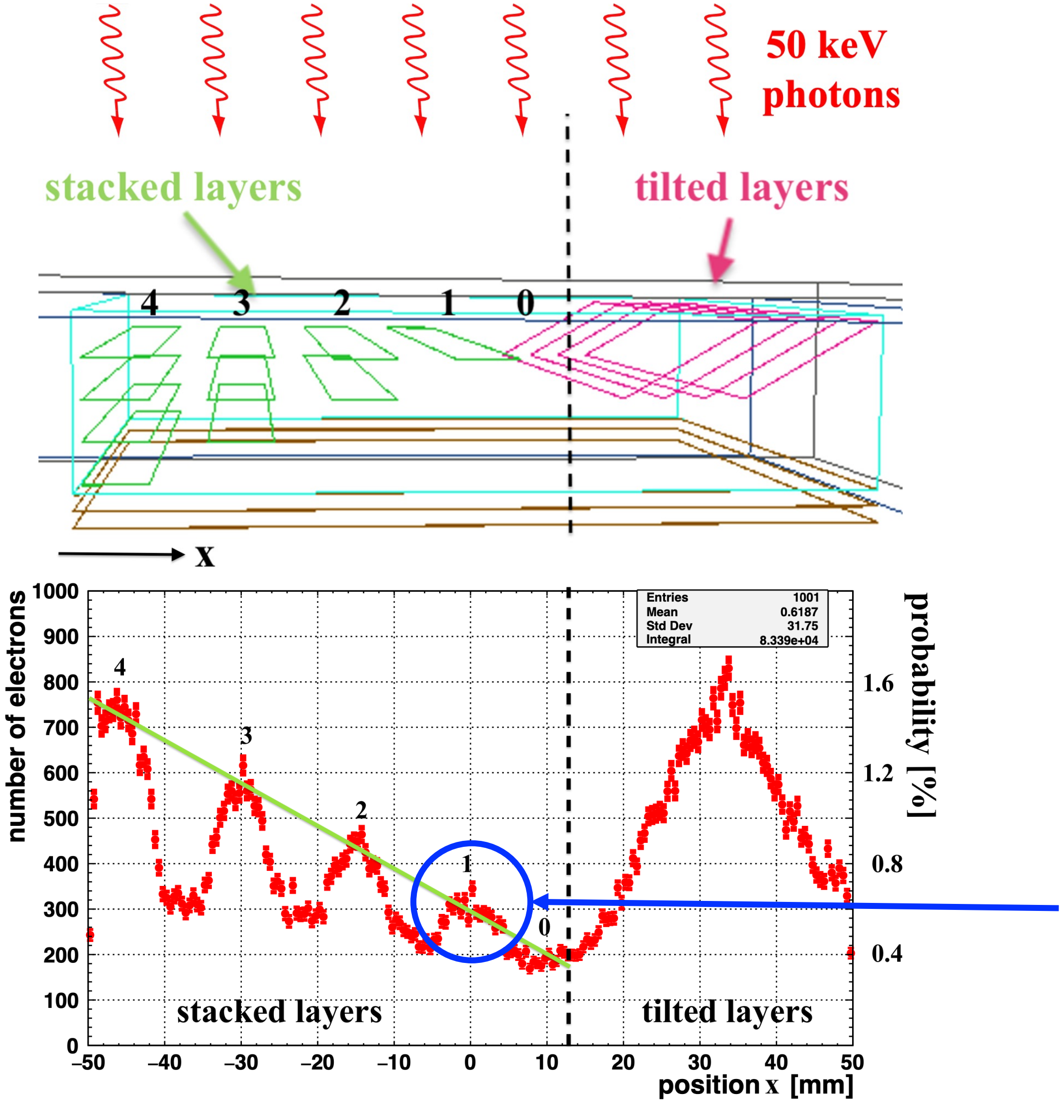
- solid copper layer enhances detection efficiency compared to pure argon due to:

  → Photoelectric effect: $\sigma_{ph} \sim Z^5$

  → higher mass attenuation coefficient
  $\mu(\mathrm{Ar}) \approx 0.001\ \mathrm{cm}^{-1}$
  $\mu(\mathrm{Cu}) \approx 20\ \mathrm{cm}^{-1}$

aim: enhance detection efficiency by **multiple** solid converter layers with high-Z coating

Simulation: Photon Conversion Efficiency

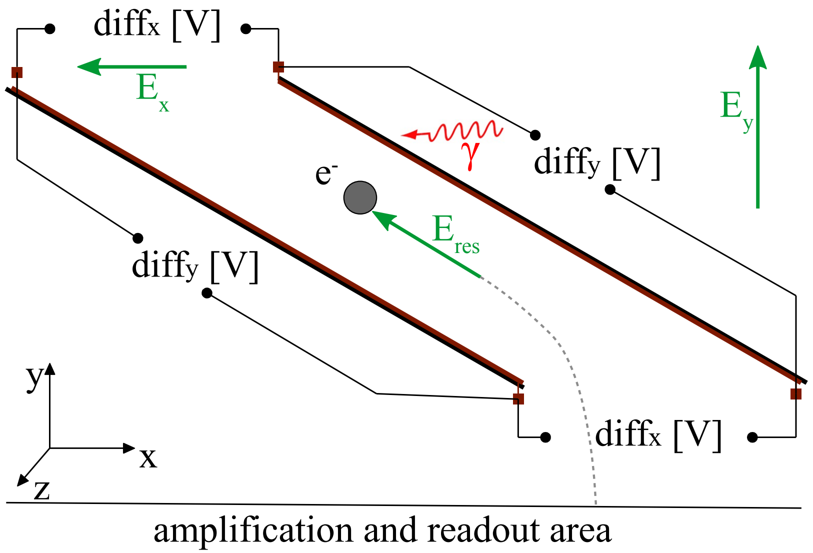


- Geant4 simulation
- on top of GEM foil: 0-4 stacked layers vs. 4 tilted layers
- 20 µm thick copper layers
- irradiation with 50 keV photons
- simulated detection of electrons exiting converter layer

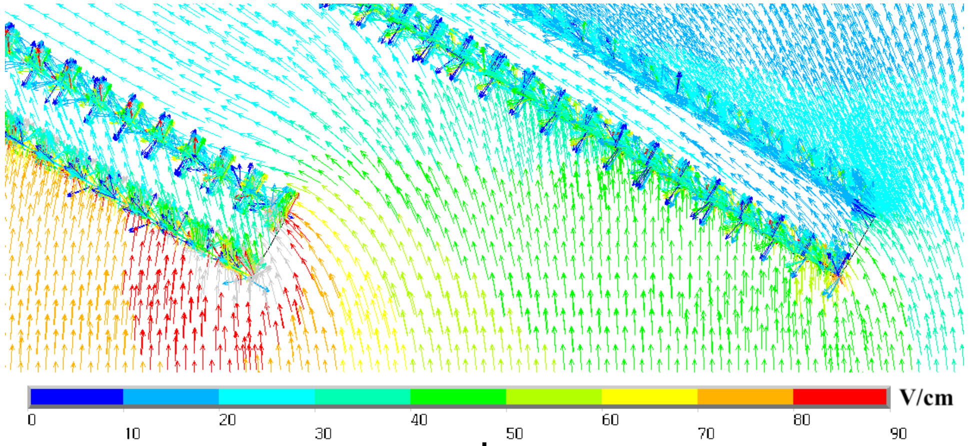
→ ε = 0.5 % per copper layer
20 layers → ε = 10 %

Simulation: Principle of Electron Guiding

Geometry: Tilted Converter Cathodes

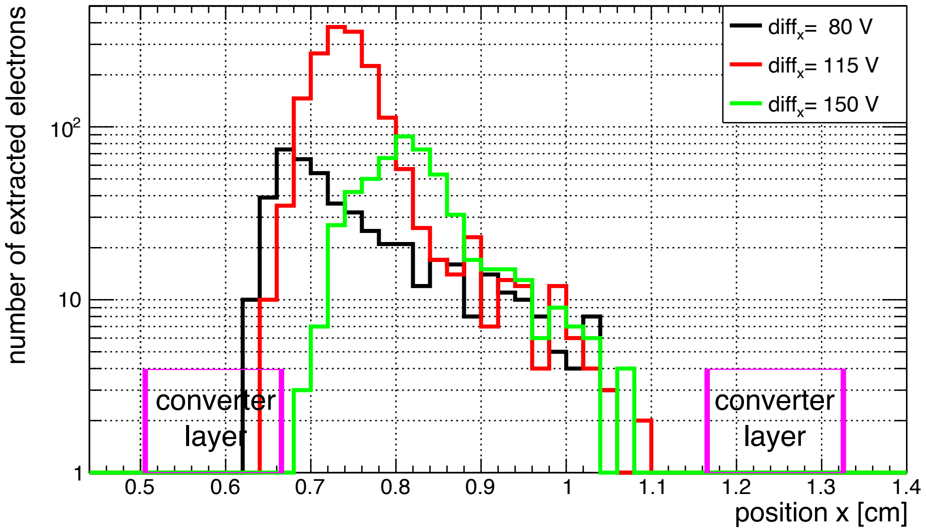


E-field →



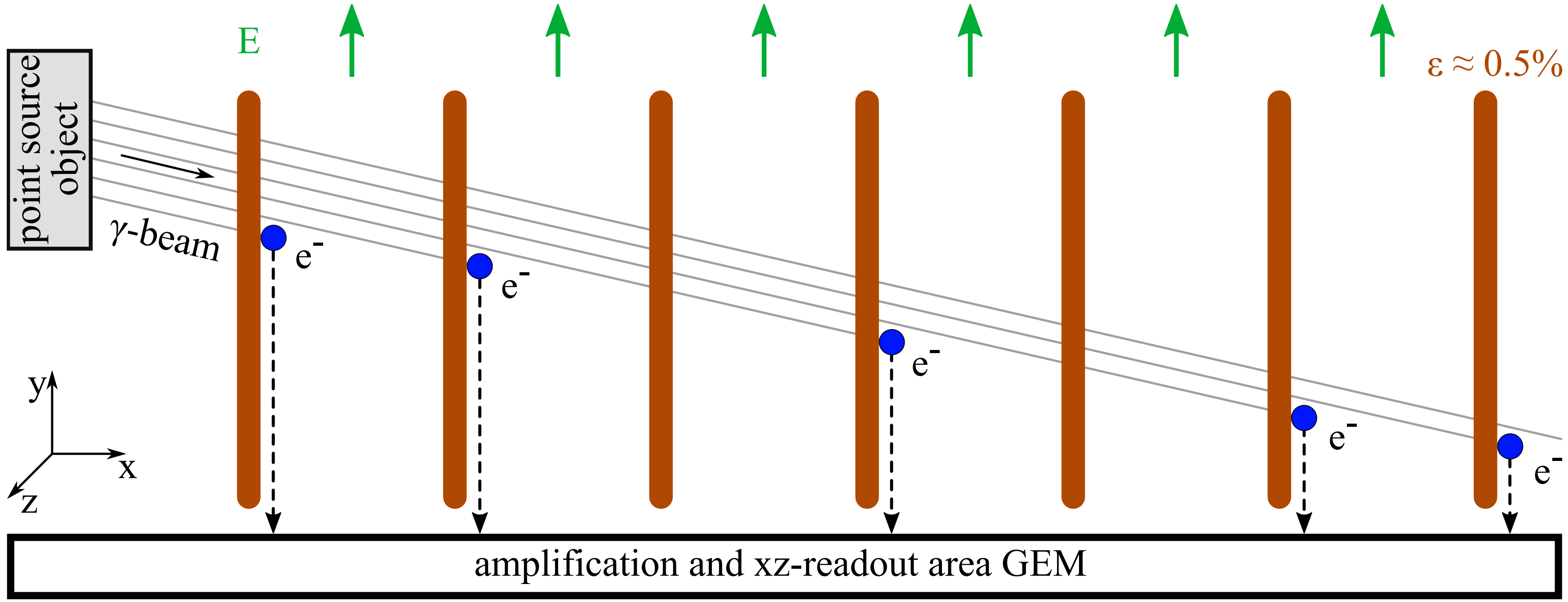
↓ result

electron endpoint distribution below converter layers



- electron guided by voltages **diff$_x$** and **diff$_y$**
- electron drift direction described by electric field vectors
- voltage dependent electron extraction (on the right for diff$_y$ = 400 V)

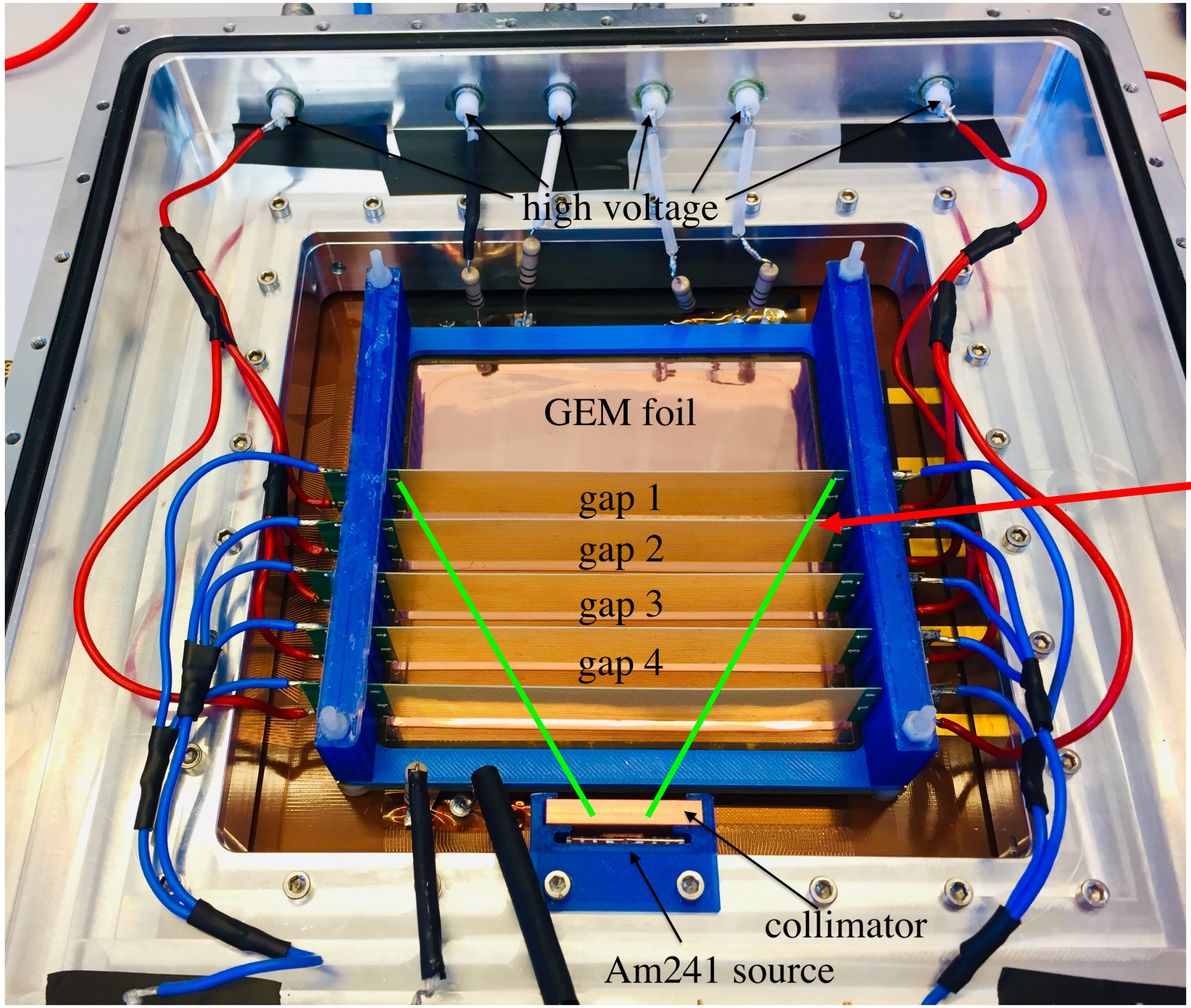
Alternative: Perpendicular Setup



Shown: 5 different X-ray events

1. **high guidance efficiency** (optimized electric field)
2. **high detection efficiency** when using many layers, ε = 0.5 % per layer
3. **3D tracking** for potential reconstruction of point sources
   x, y, z resolution necessary
   y: trigger on conversion electrons and drift time (complex) or by different geometry (slide 23)

Measurement Setup



Electron Guiding

→ structured copper-plated layers with vertical guiding E-field:

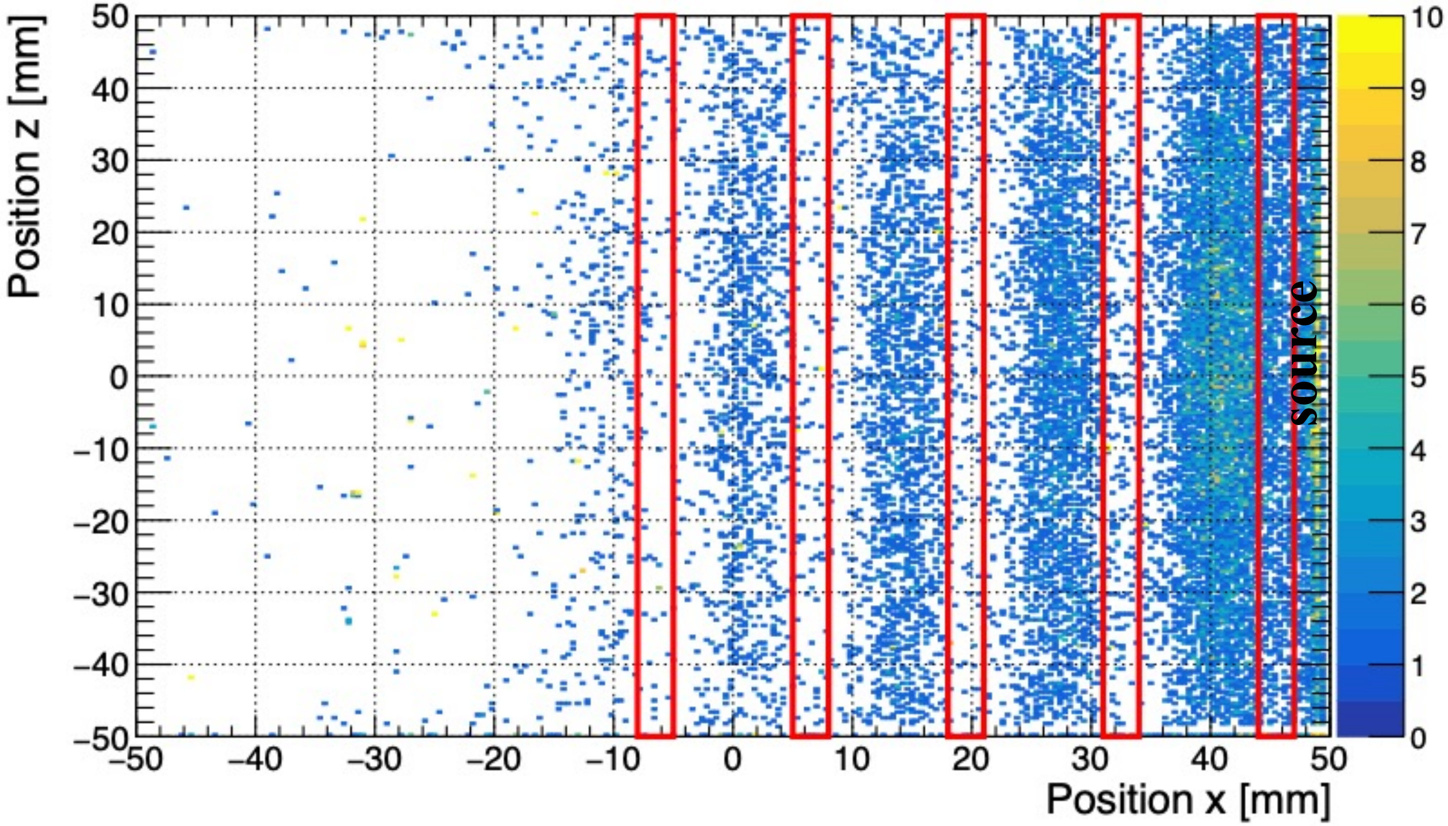
- copper strips on PCB
- connected with resistors

→ positioning in detector

- 5 layers with a certain distance
- perpendicular arrangement to anode

Measurement Results (without collimator)

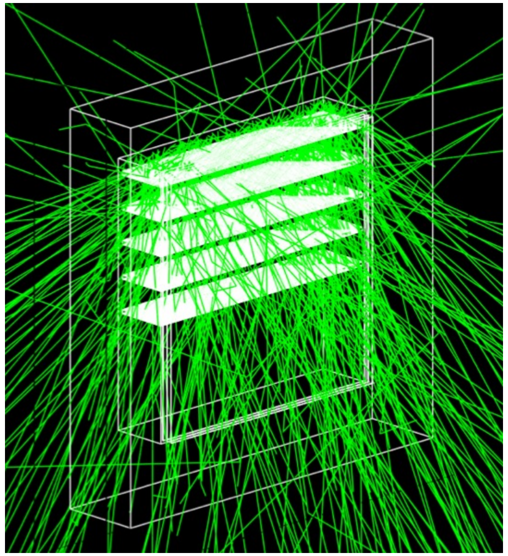
x, z - anode plane

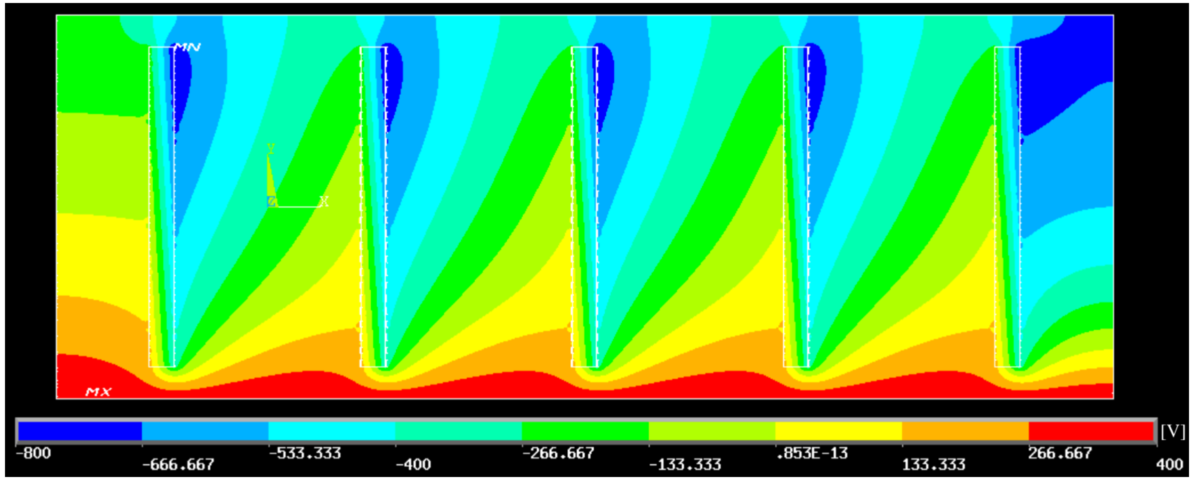


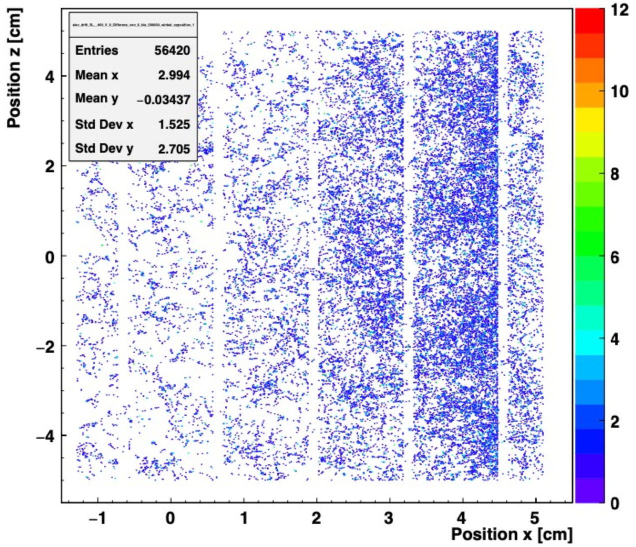
- irradiation with Am-241 (59.5 keV photons)
- $diff_y = 400$ V and $diff_x = 0$ V
- red boxes: assumed converter layer position
- significantly more hits between two converter layers
- FR4 thickness: 1.5 mm

→ comparison with simulation

1. Electric Guidance Field Simulation







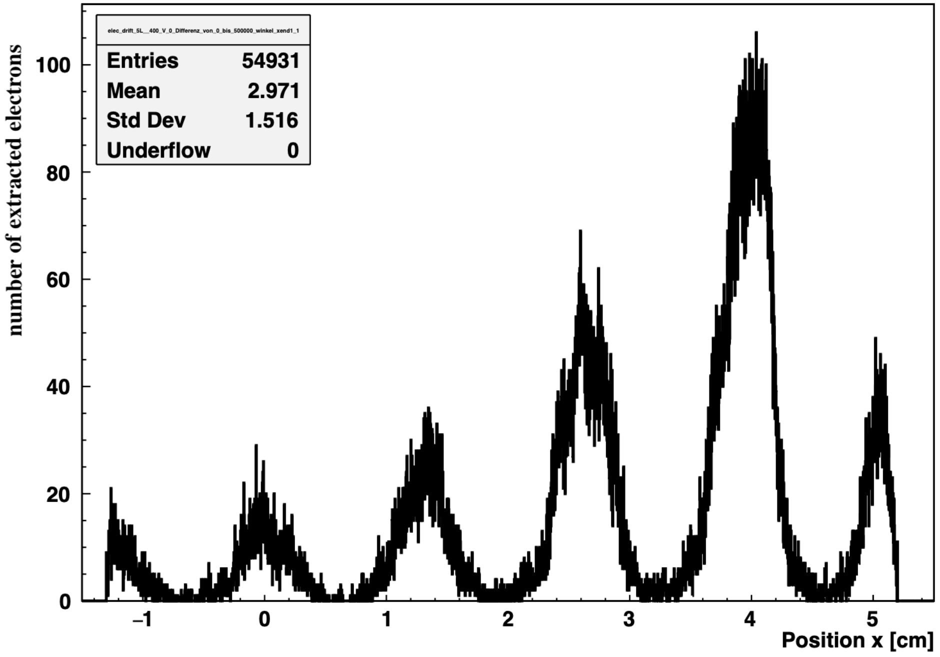
Geant4:
- photon-matter interaction
- creation of electrons
- get electron position

ANSYS:
- creation of potential distribution
- electrons drift perpendicular to equipotential lines
- here shown for: $diff_y$ = 400 V, $diff_x$ = 600 V

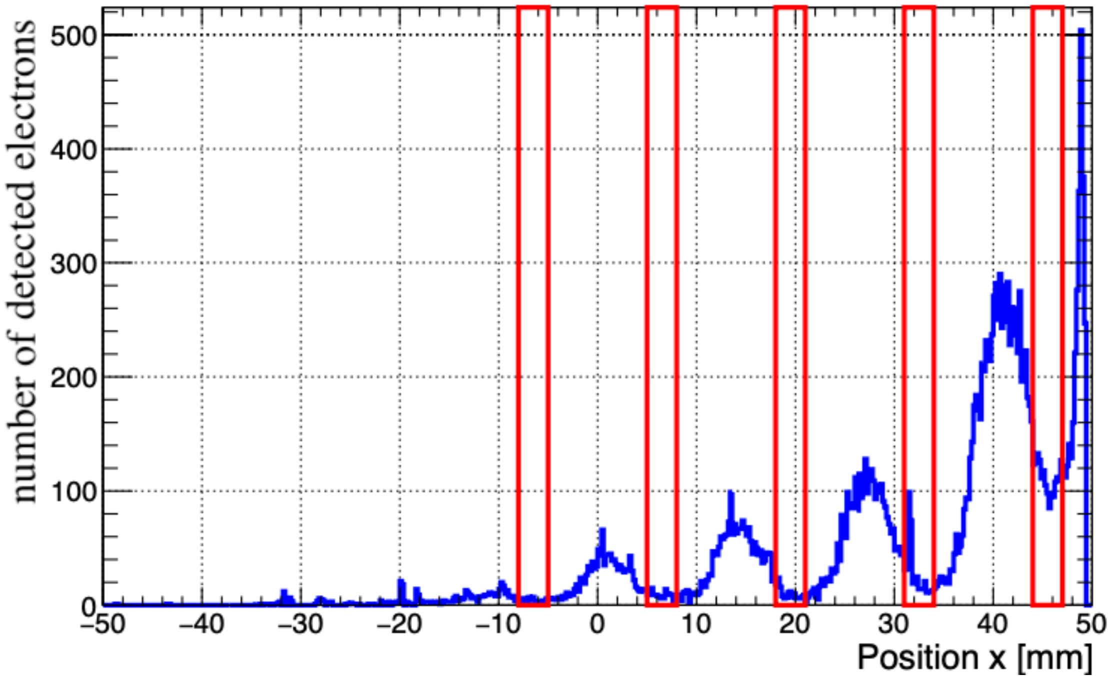
Garfield++:
- imports electron position and electric field
- simulates electron drift

1. Comparison of Results: Profile

simulation



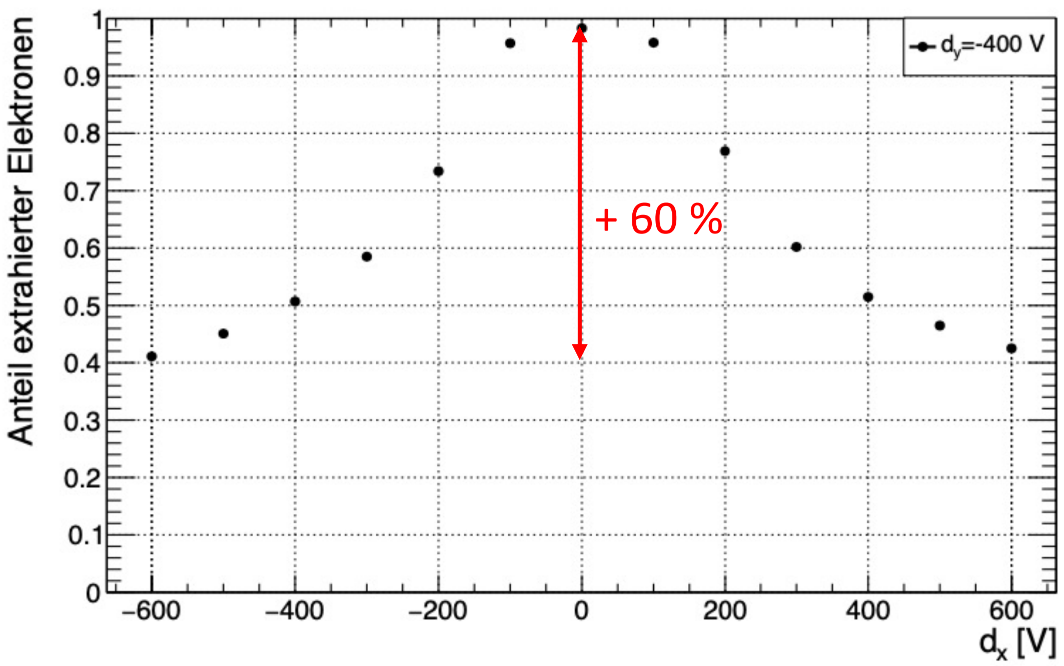
measurement



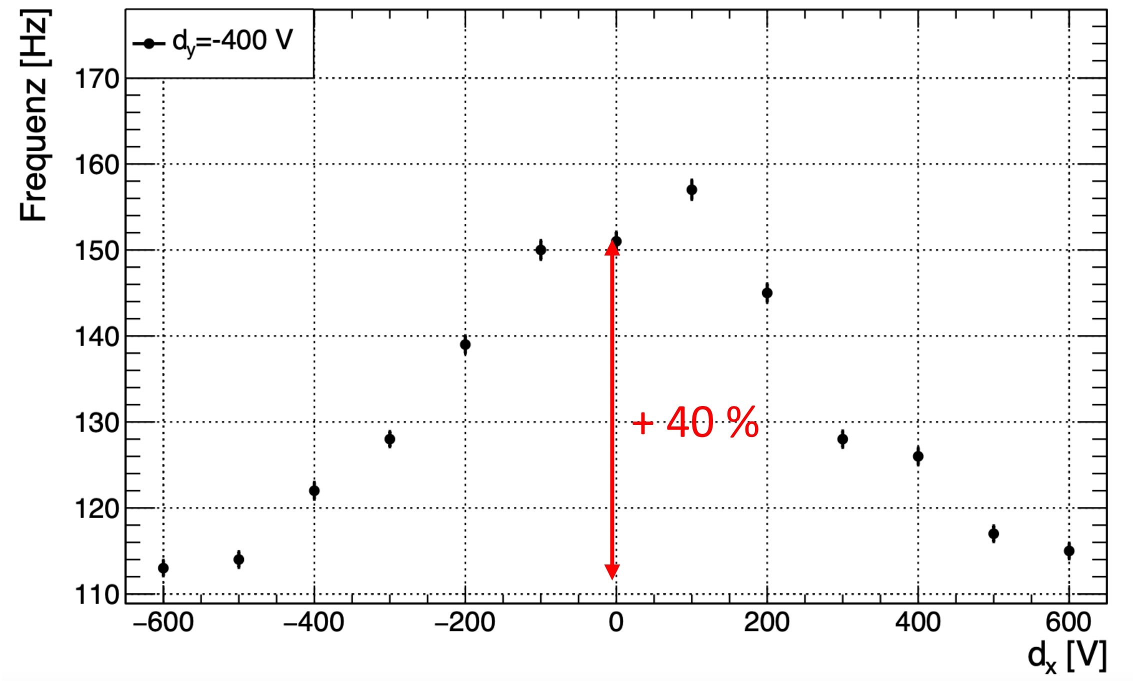
- both for $diff_y = 400$ V and $diff_x = 0$ V
- in both cases exponential peak height decrease
- agreement between simulation and measurement

1. Comparison of Results: $diff_x$ influence

simulation



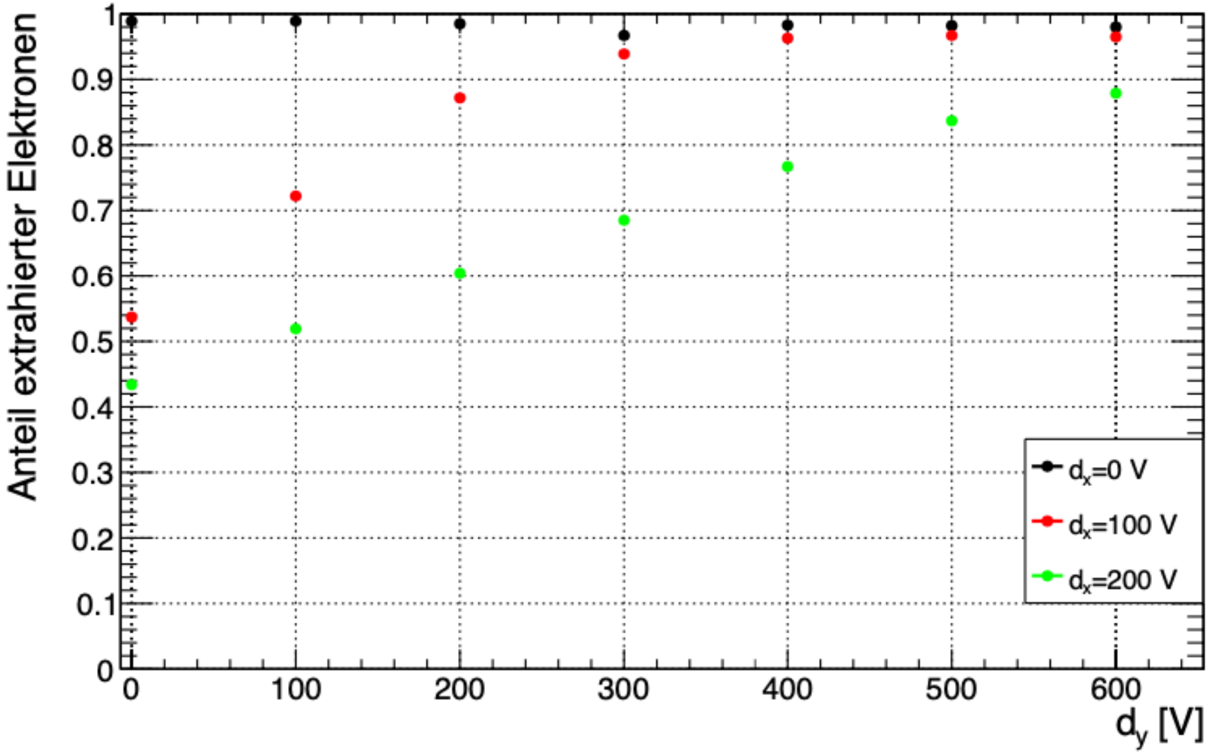
measurement



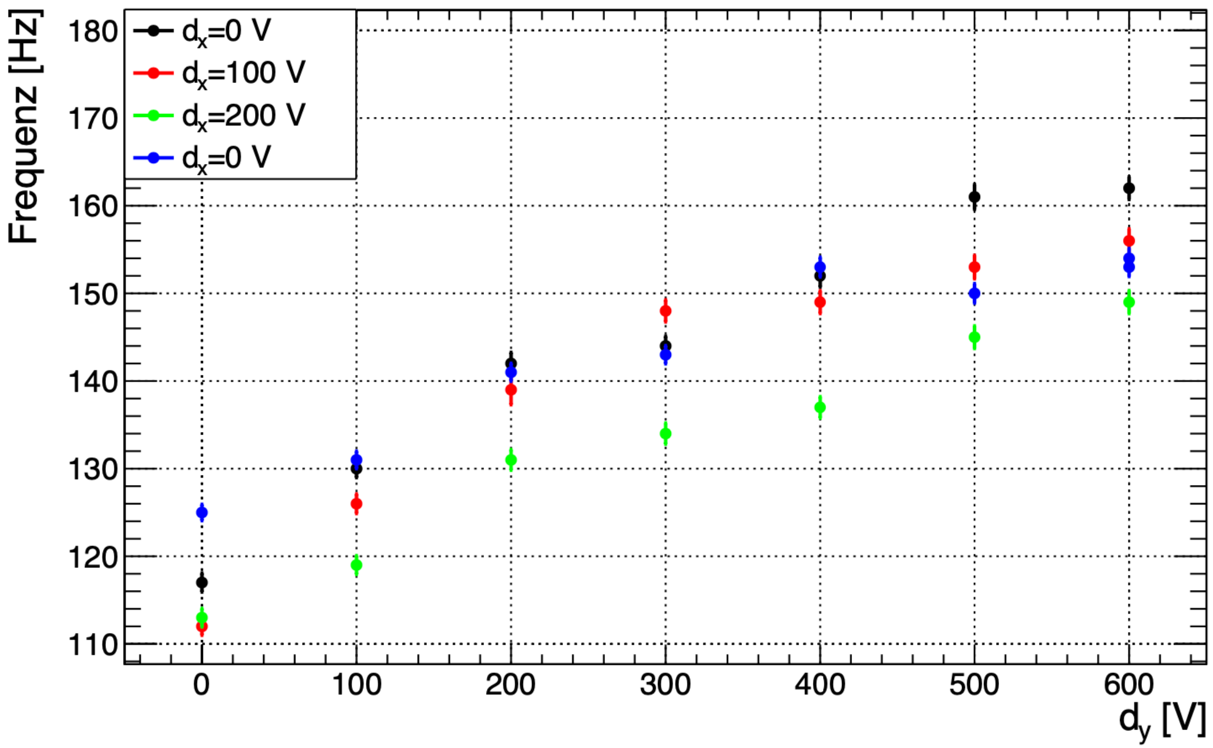
- both show maximum around $diff_x$ = 0 V as expected
- shift in measurement due to misalignment of layers
- in simulation extraction of nearly 100 % achievable due to simplifications (long drift time of electrons with no collisions) but not in measurement → discrepancies

1. Comparison of Results: $diff_y$ Influence

simulation



measurement



- allowance of large drift time also lead here to differences in $diff_x = 0$ V behavior
- same behavior for simulation and measurement:

→ highest guidance efficiency for $diff_x = 0$ V and high $diff_y$

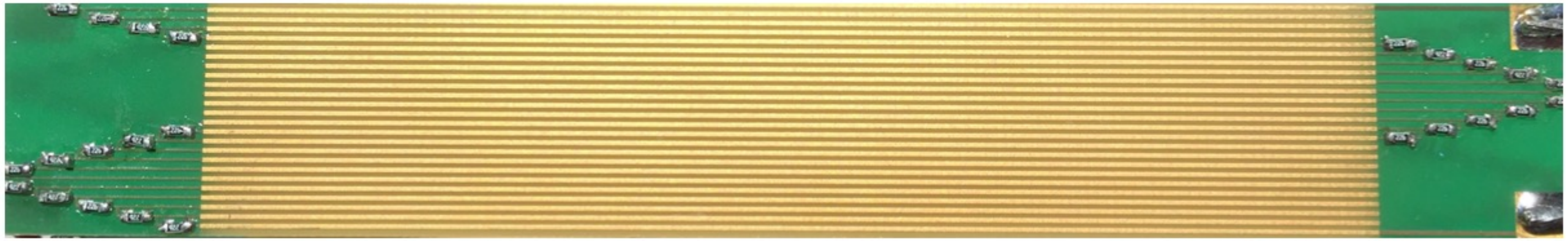
2. Photon Conversion Efficiency

Investigation of 3 different layer types

- **copper layer** made of 125 µm FR4 and 35 µm Cu on one side

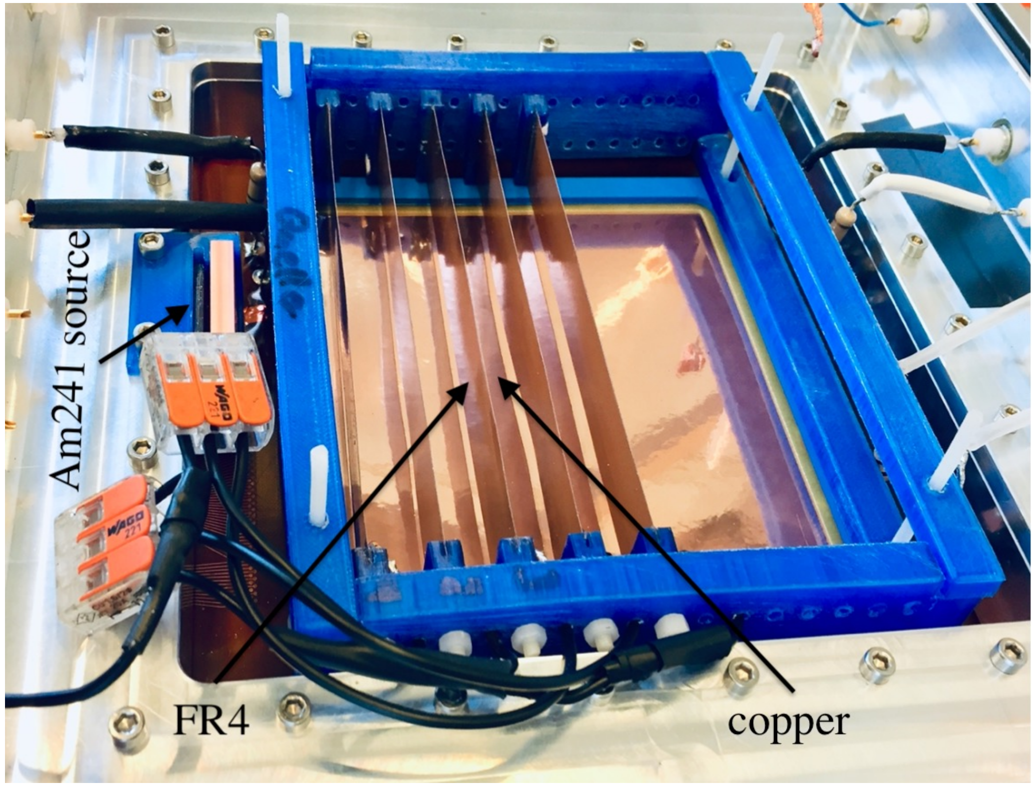
→ simpler design, useful for pre-studies

- **structed copper layers** made of FR4 (**1.5 mm and 0.3 mm**) and 35 µm Cu strips on both sides



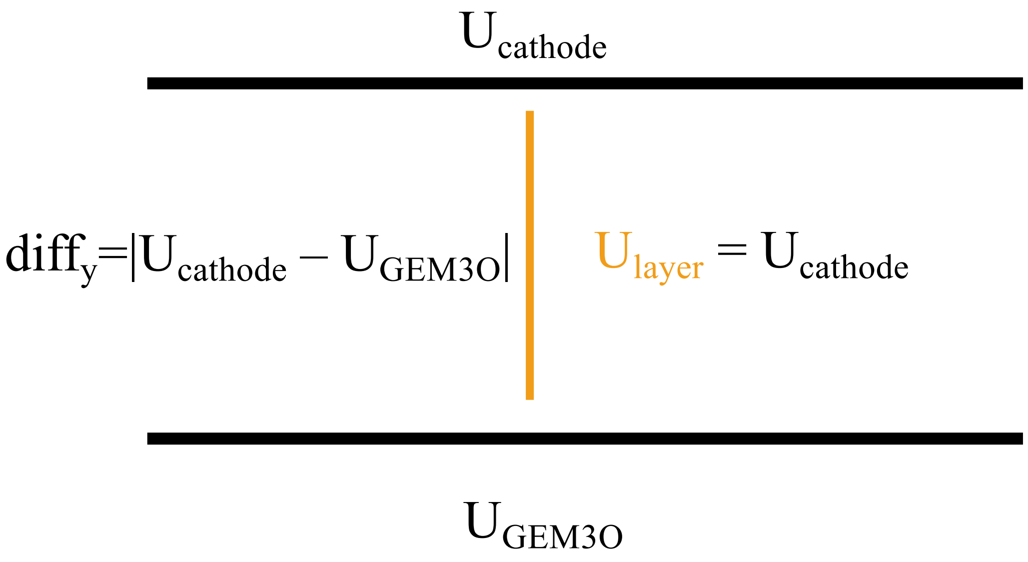
→ homogeneous electric guidance field

2.1 Copper Layers: Setup



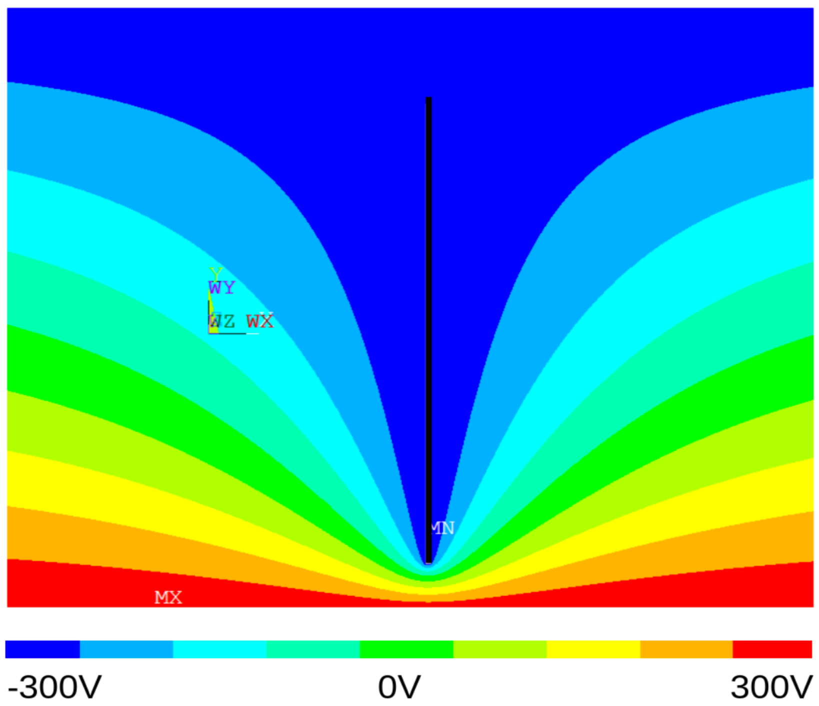
Measurement setup: 5 Layers with FR4 facing source, copper facing away ($\sigma_{ph} \sim Z^5$); additional cathode on top (not shown)

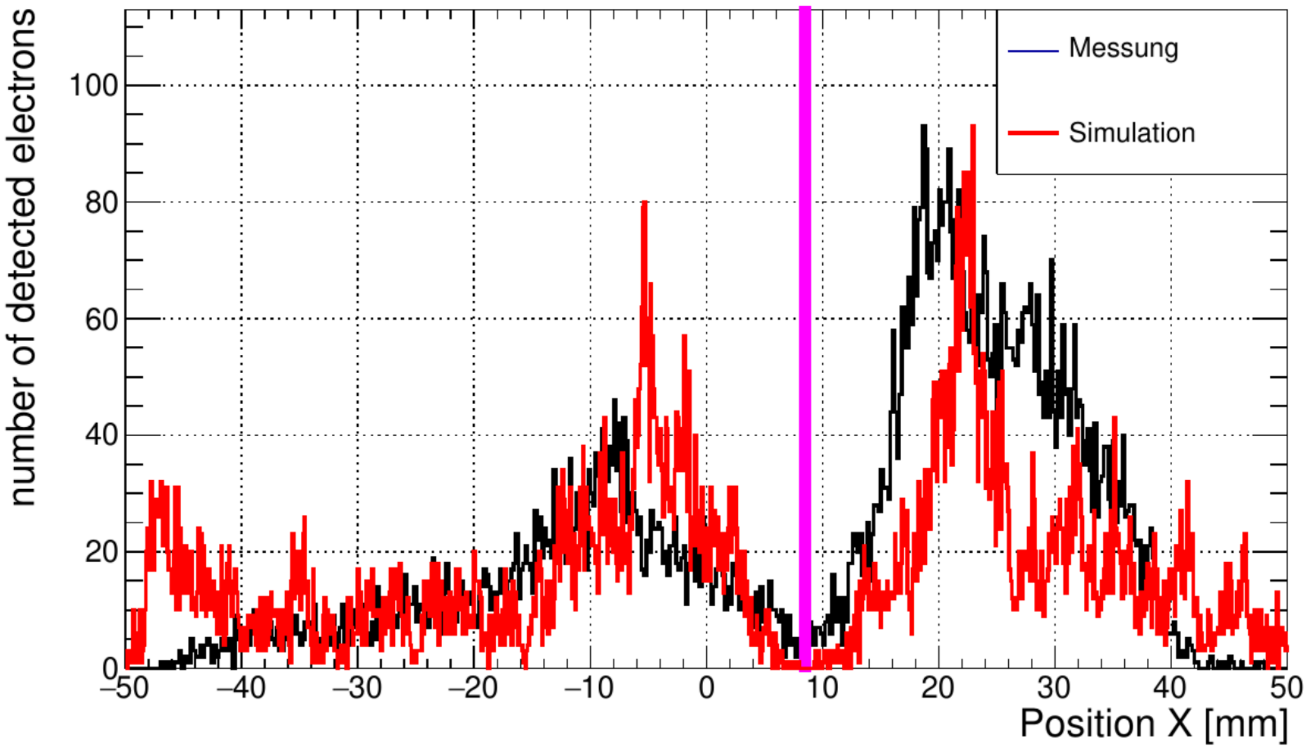
Applied voltages:



- converter plate at same potential as cathode
- $diff_y$ guides down electrons

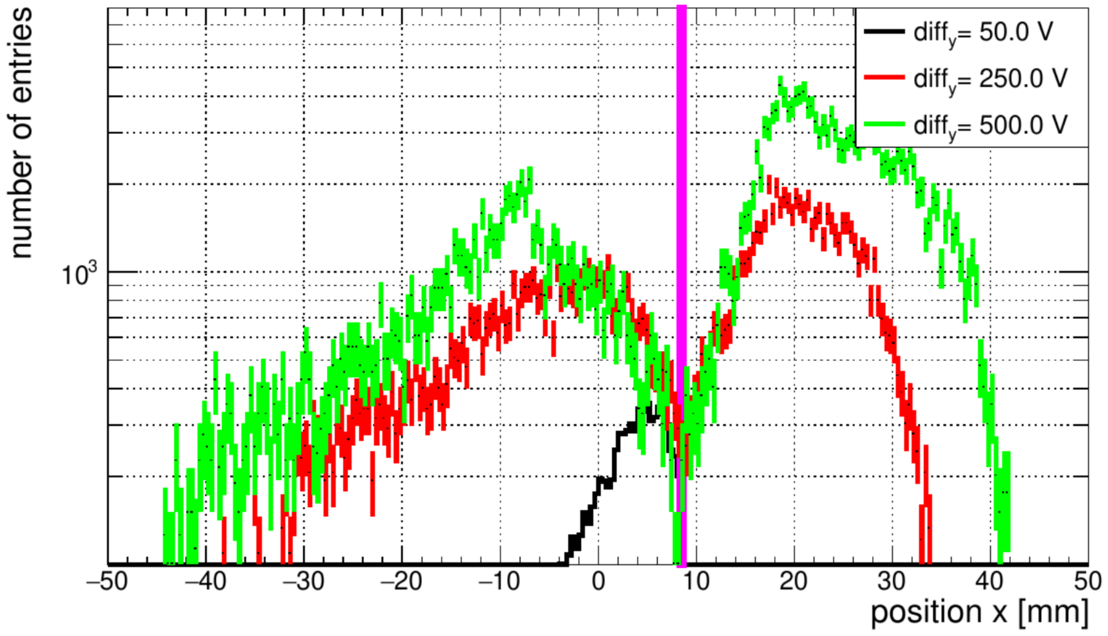
2.1 One Layer: Comparison

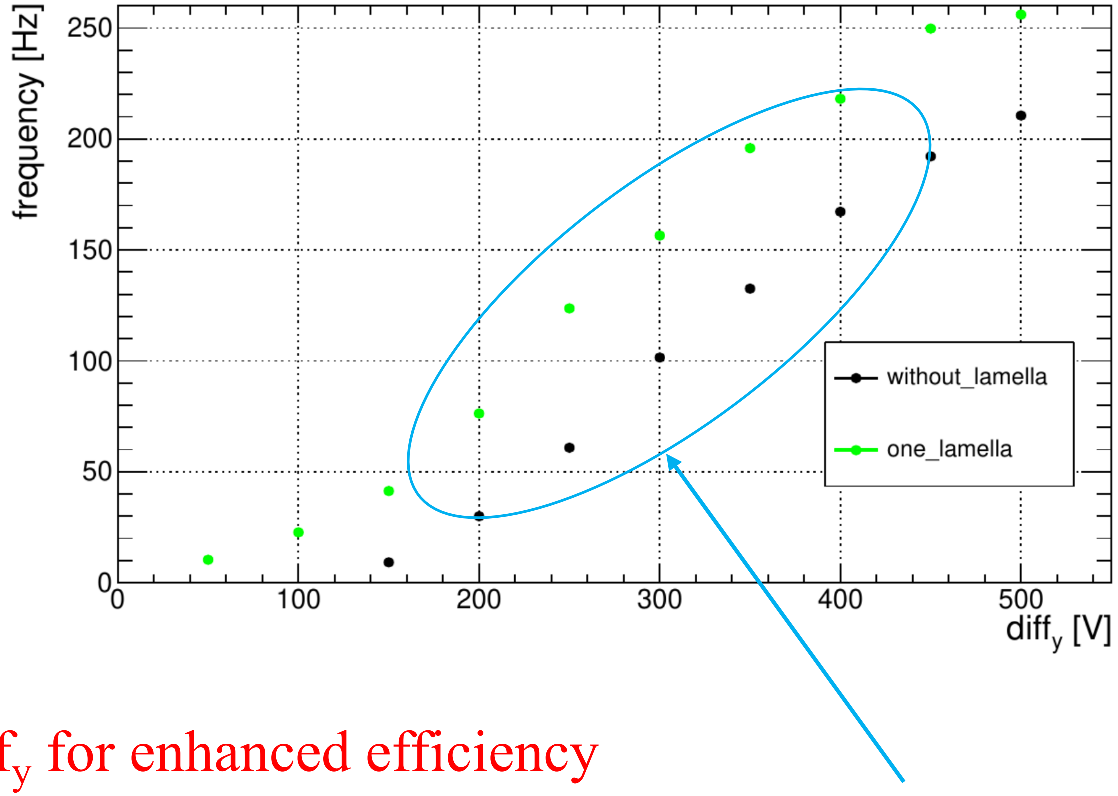




- electric potential distribution guides electrons away from layer
- measurement and simulation show agreement for $\text{diff}_y = 500$ V
- differences between simulation and measurement due to discrepancies in geometry, source characterization (collimator), simplification of simulation (no momentum)

2.1 One Layer: Efficiency

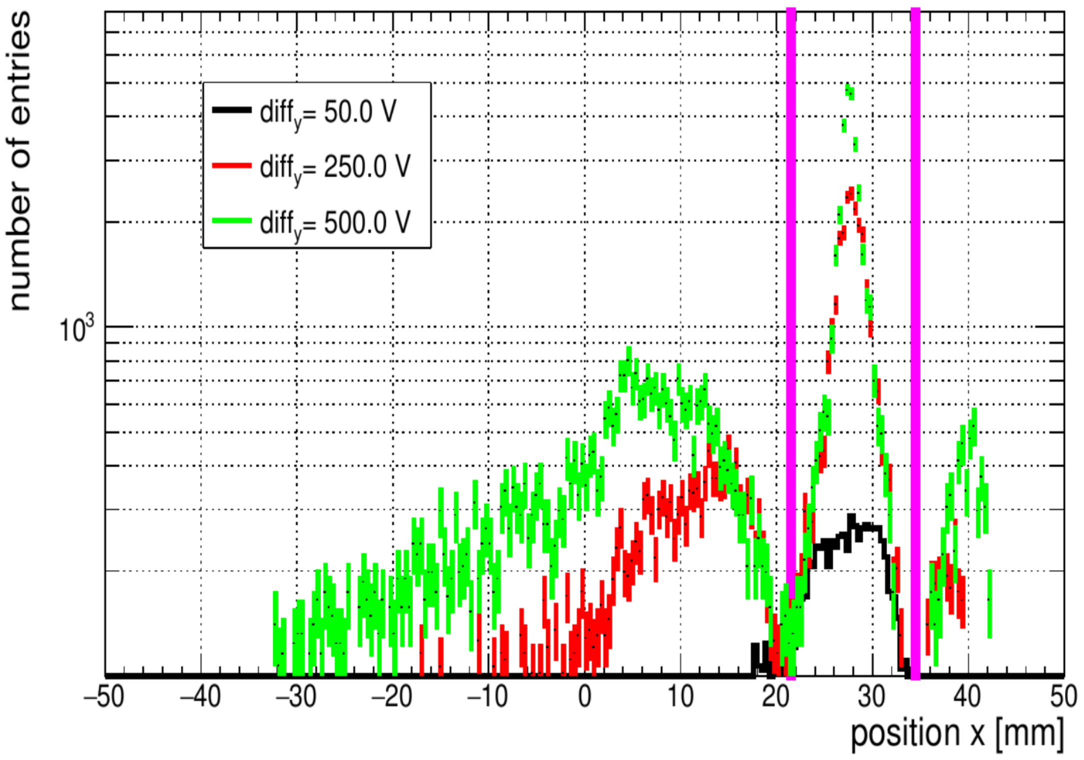


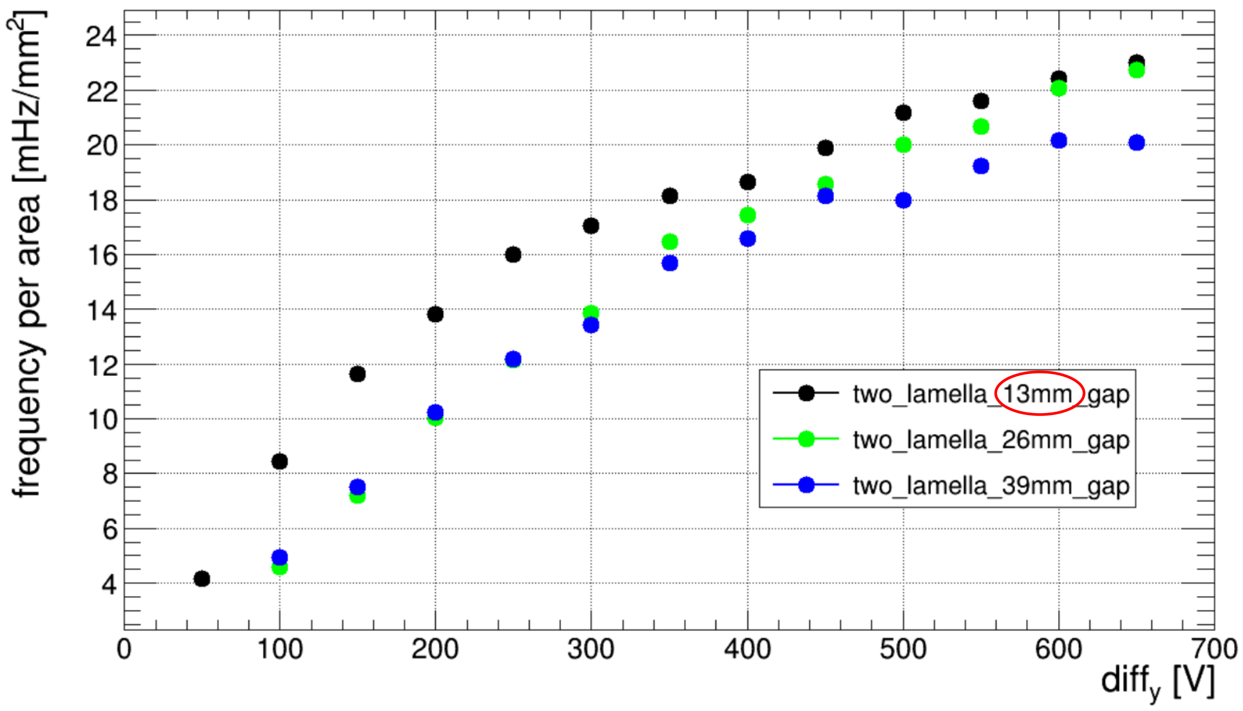


- measurement for same number of events: high diff$_y$ for enhanced efficiency
- comparison of no layer and one layer in conversion area: frequency increases by a factor of up to 2

→ layers increase conversion efficiency

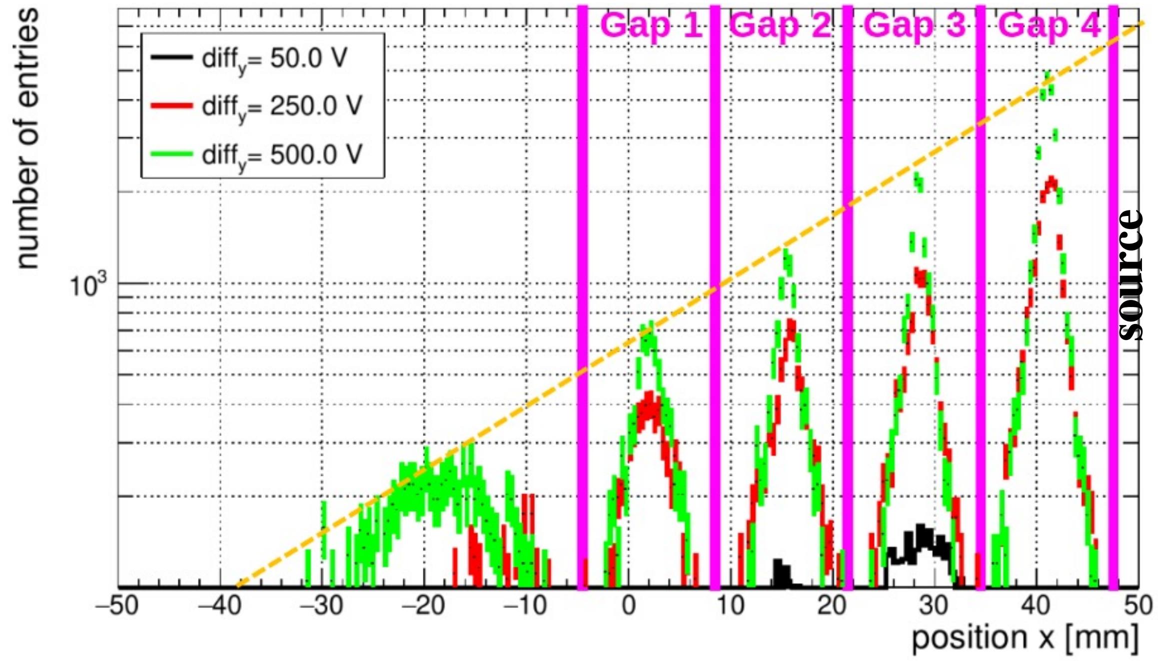
2.1 Two Layers: Distance

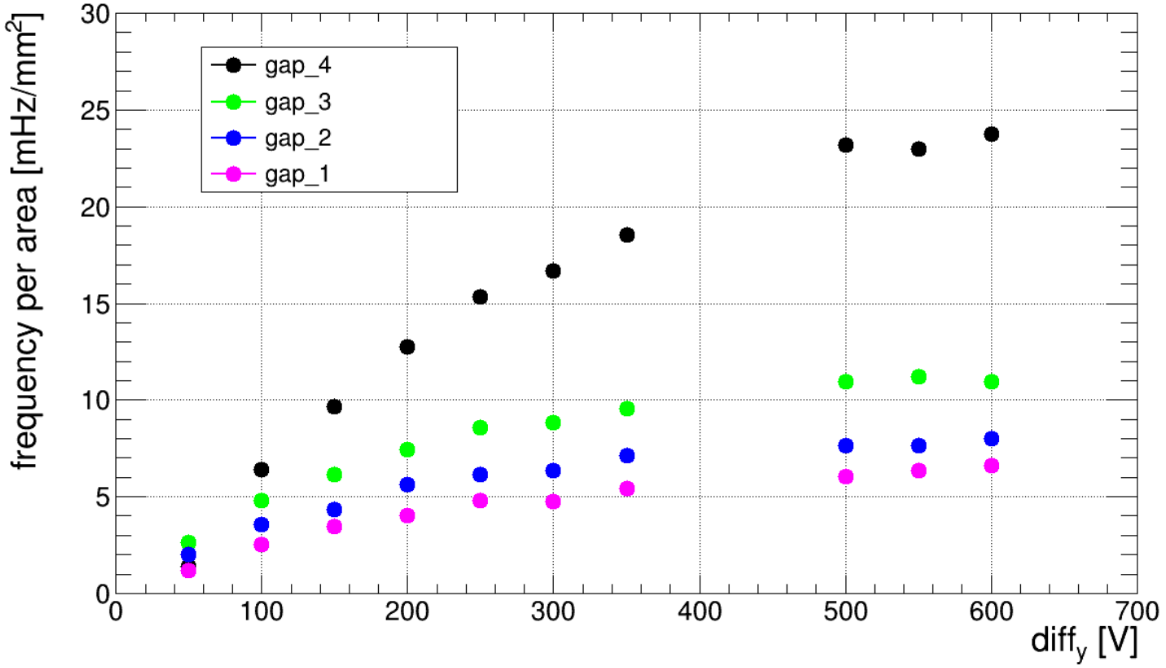




- variation of distance for two copper layers
- for comparison take frequency per area between layers
- smaller distance has tendency of higher frequency

2.1 Five Copper Layers



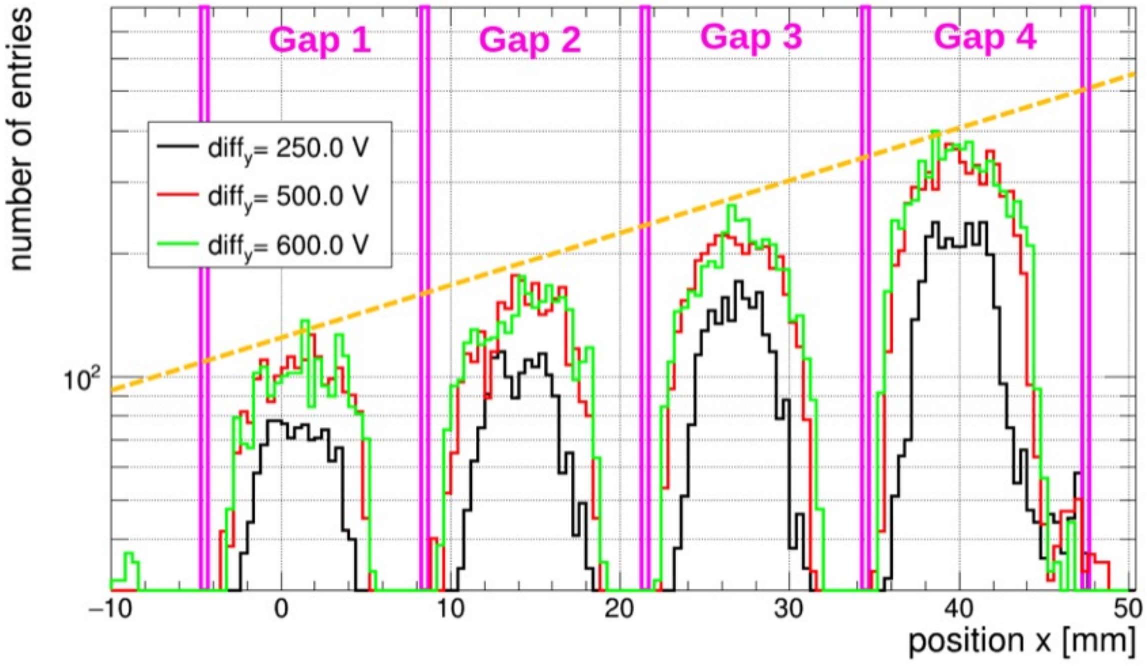


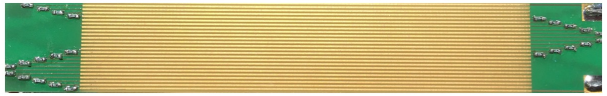
- for five layers there is an exponential peak height decrease
- take measured frequency per area in each gap for different voltages → later used for comparison

→ these layers allow for increased photon detection
→ but the electric guidance field is improvable

2.2 Structured Copper Layers: Measurement

measurement



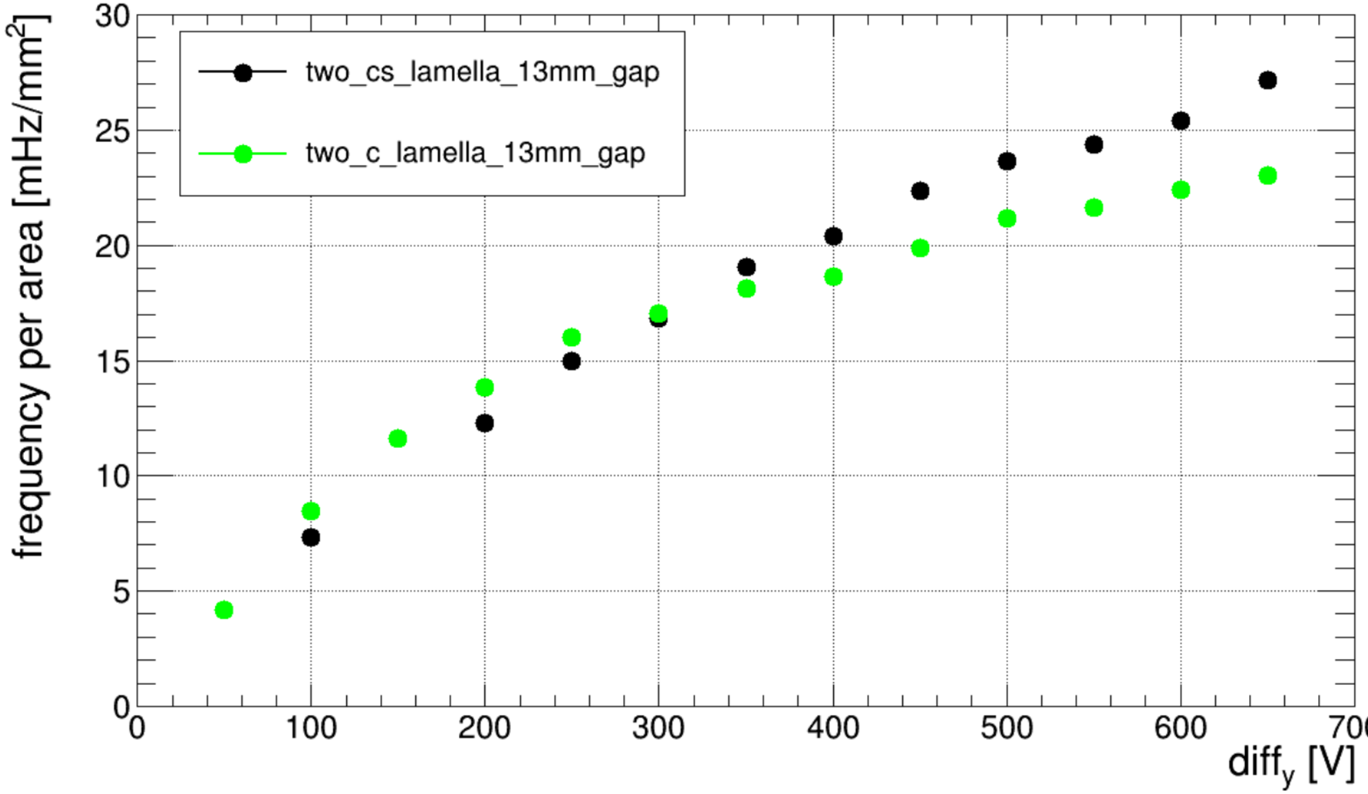


structured layer

- $diff_y = 500$ V and $diff_x = 0$ V
- structured copper layers with **0.3 mm FR4** carrier material and no additional cathode
- same experimental result as for copper layers:
  - exponential peak height decrease
  - highest frequency for large $diff_y$

→ comparison of both layer-types

2.2 Comparison of Layer-Types



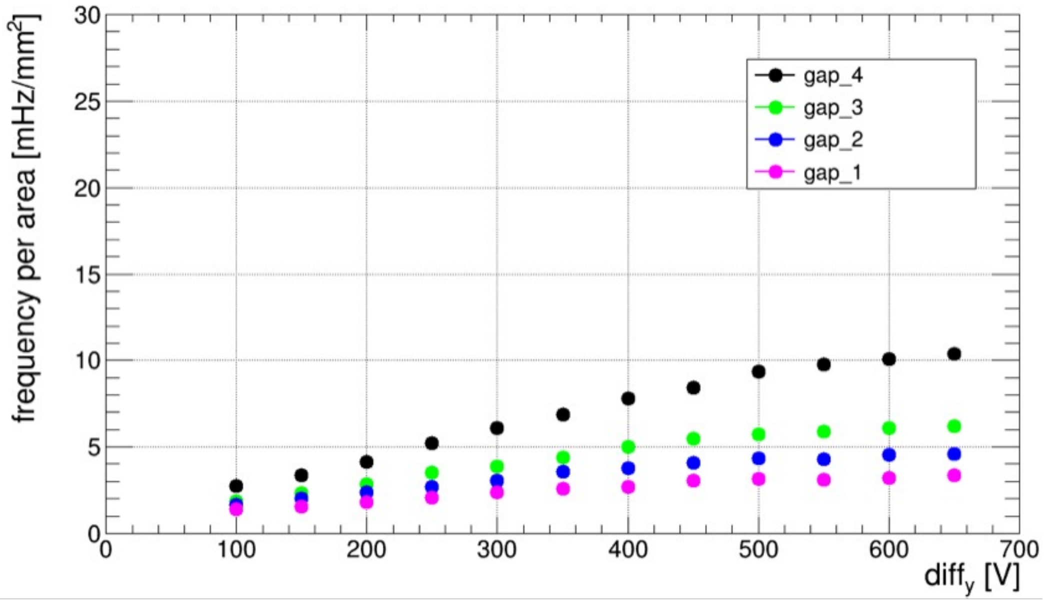
2 layer-types with distance of 13 mm: copper (c) layers and structured copper (cs) layers

- nearly same frequency per area
- for larger $diff_y$ structed layers provide higher frequency

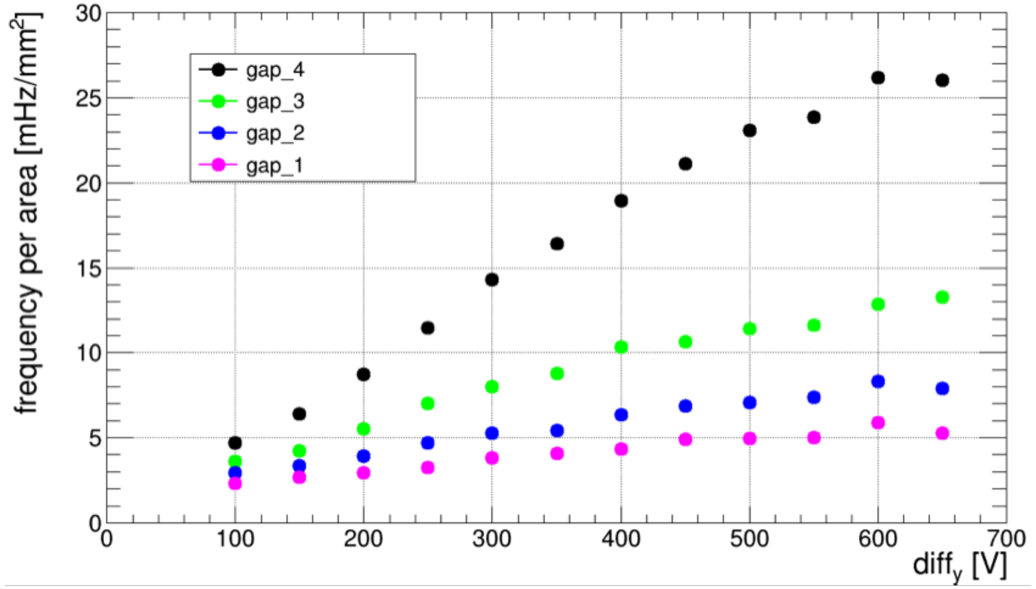
→ although structured copper layers have preferable electric field the measured frequency is nearly the same for the copper layer due to thinner FR4 layer (300 µm vs. 125 µm)

2.3 Structured Layers: FR4 Thickness

1.5 mm FR4



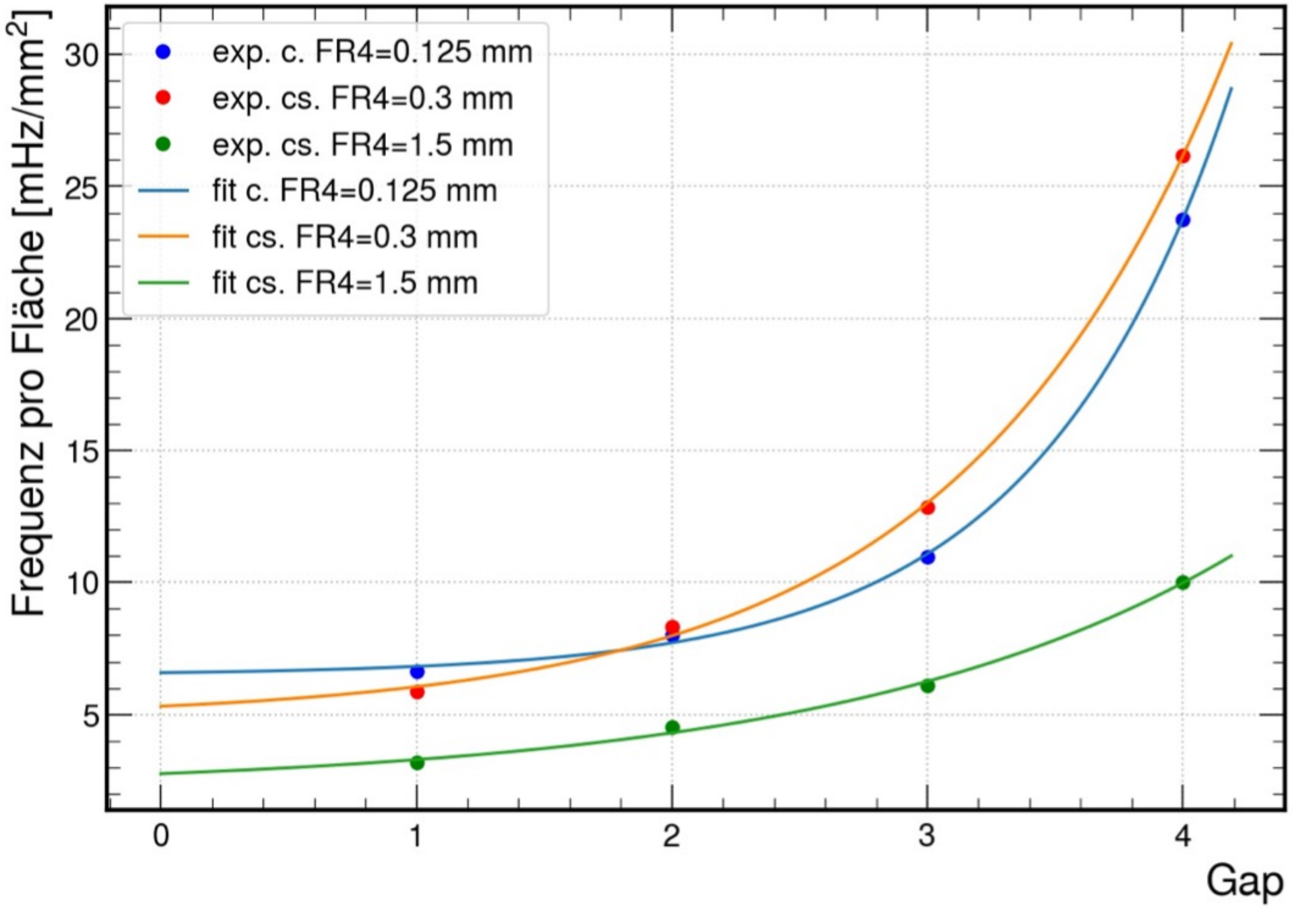
0.3 mm FR4



- measured frequency per area in each gap for both thicknesses for structured copper layers
- frequency decreases with each layer

→ measured frequency per area about a factor of 2.5 higher for 0.3 mm FR4

2.4 Comparison of All Layers

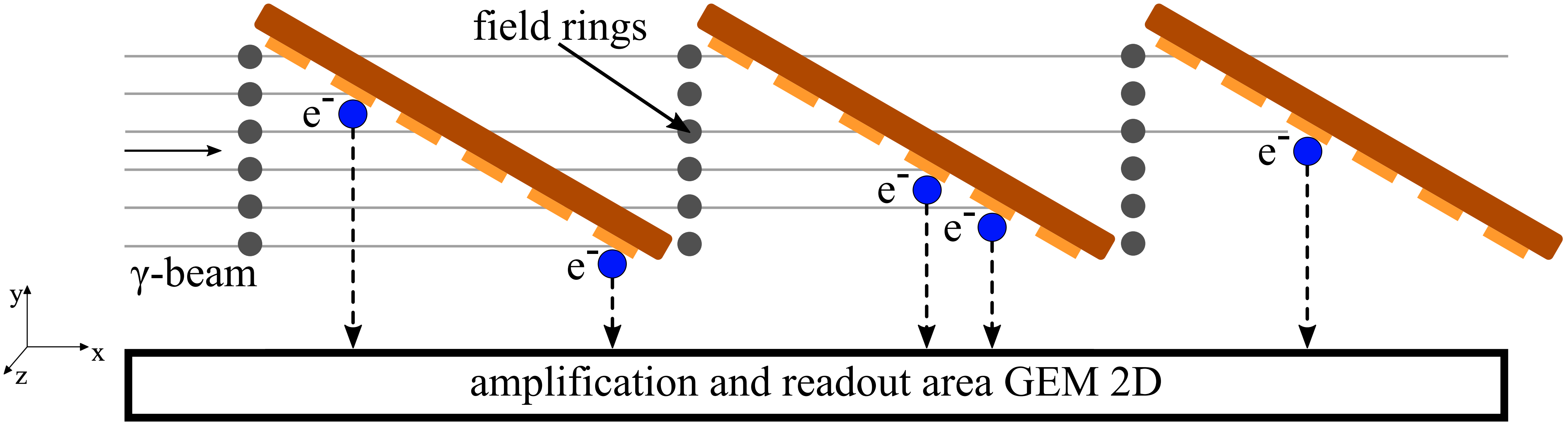


y

- comparison of all layer types for diff_y = 600 V

→ thin FR4 material provides high efficiency

3. Theoretical 3D Position Reconstruction



Basic idea:

- use tilted layers → defines y-position by x-measurement
- can be reconstructed by the 2D GEM readout

→ under investigation

Achieved:

- optimized fields
- higher efficiency

Summary and Outlook

→ successful pre-studies → cathode works as intended
→ good agreement of simulation and measurement
→ $diff_x = 0$ V and high $diff_y$ lead to high efficiency
→ use small distance between layers
→ thinner FR4 layer increases detection efficiency

Outlook

- improvement of structured cathode regarding thickness of carrier material and copper, layer distance and design for further increasement of conversion efficiency
- 3D position reconstruction by tilted conversion layers

Thank you for your attention!

Literature

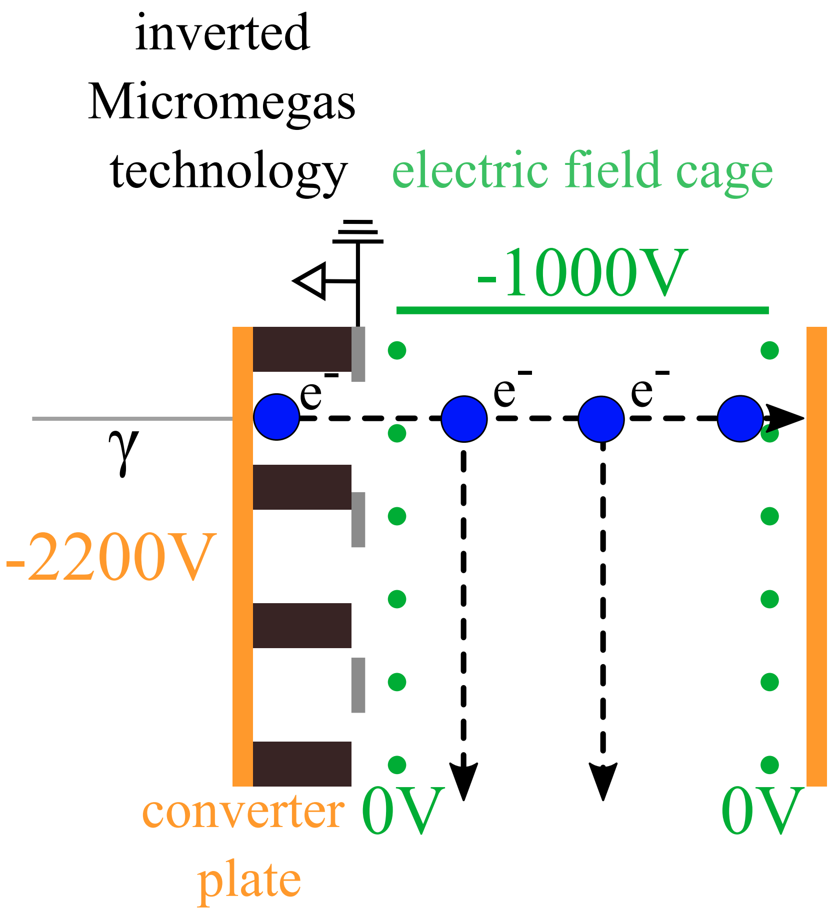
[1]: Fabio Sauli. The gas electron multiplier (gem): Operating principles and appli- cations. Nuclear Instruments and Methods in Physics Research Section A: Ac- celerators, Spectrometers, Detectors and Associated Equipment, 805:2–24, 2016. https://doi.org/10.1016/j.nima.2015.07.060, [Online; Accessed: 5.10.2021]

[2]: Deutsches Elektronen-Synchrotron DESY. FLC - Forschung mit Lepton Collidern – GEM Gas Electron Multipliers (GEMs), https://flc.desy.de/tpc/basics/gem/index_eng.html, [Online; Accessed: 5.10.2021]

[3]: Zabołotny, W.M., Kasprowicz, G., Poźniak, K. et al. FPGA and Embedded Systems Based Fast Data Acquisition and Processing for GEM Detectors. J Fusion Energ 38, 480–489 (2019) doi:10.1007/s10894-018-0181-2, https://doi.org/10.1007/s10894-018-0181-2, [Online; Accessed: 5.10.2021]

[4]: National Institute of Standards and Technology: XCOM: Photon Cross Sections Database. https://www.nist.gov/pml/xcom-photon-cross-sections-database, [Online, Accessed: 5.10.2021]

Appendix



→ photon conversion: $1e^-$ → inverted Micromegas amplification: $\approx 10^5\ e^-$ → transparency: $\approx 10^2\ e^-$ → further ionization: $\approx 10^3$ drift e^-

→ voltages and geometries have to be optimized

Appendix

Optimization of structured converter foils

- coating, thickness, design
- minimization of dead material
- direction memory of photoelectric effect:

$$J(\theta,\beta) = A\cdot\beta^2\sin^2\theta\left(\frac{\sqrt{1-\beta^2}}{(1-\beta\cos\theta)^4} - \frac{1-\sqrt{1-\beta^2}}{2\sqrt{1-\beta^2}(1-\beta\cos\theta)^2} + \frac{2(1-\sqrt{1-\beta^2})}{4(1-\beta\cos\theta)(1-\beta\cos\theta)^3}\right)$$