Material Optimization for Photon Detection by Structured Converter Layers using Micro-Pattern Gaseous GEM Detectors

DPG Frühjahrstagung Karlsruhe 2024

07.03.2023

Nick Schneider

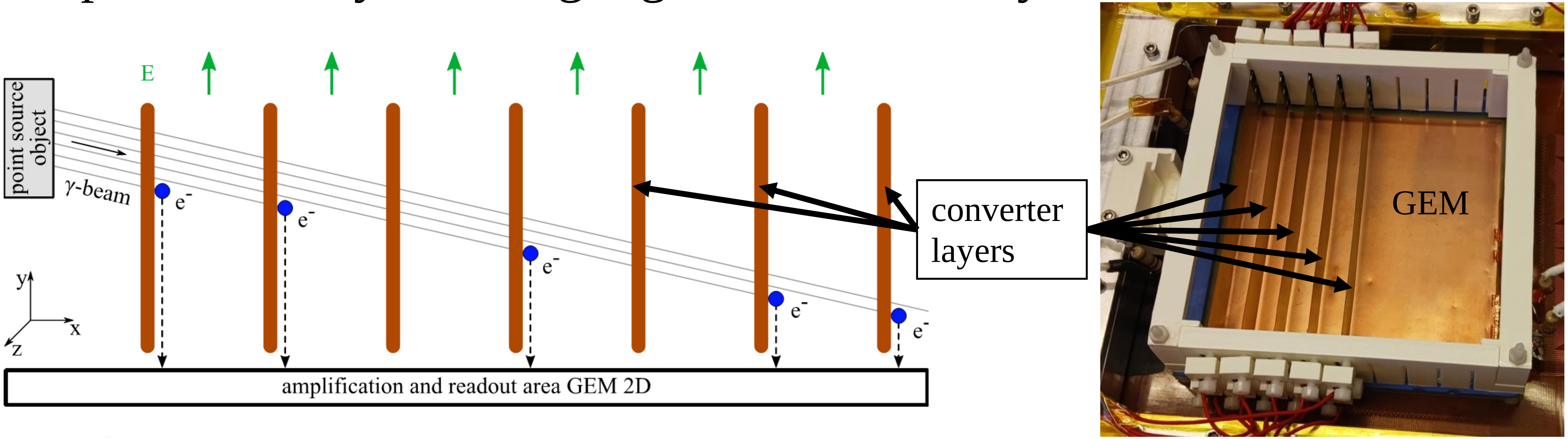
LMU
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

FSP ATLAS
Erforschung von
Universum und Materie

TUM LMU
ORIGINS
Excellence Cluster
ESO
lrz

Motivation

- Micro-Pattern Gaseous Detectors:
  - Extremely good spatial and temporal resolution
  - High-rate capability
  - But: naturally low gas density ⇒ poor detection of neutral particles as photons
- Improvement by inserting high-Z converter layers

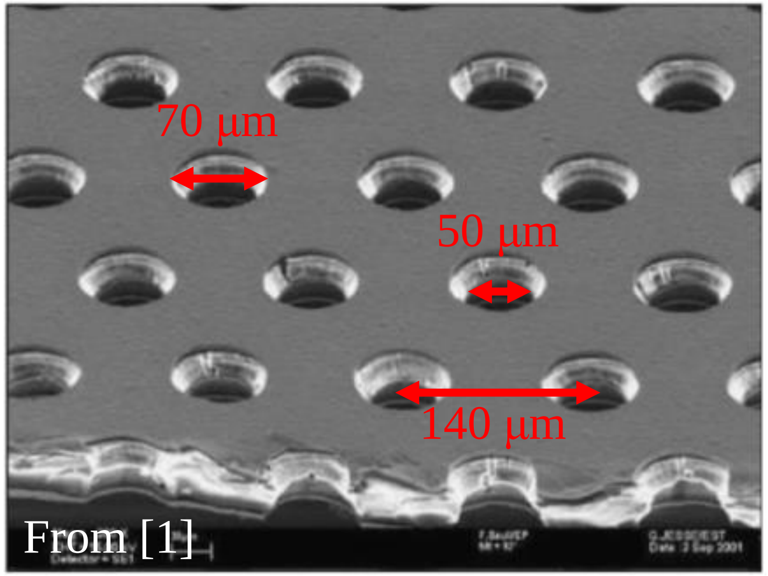


converter layers sketch

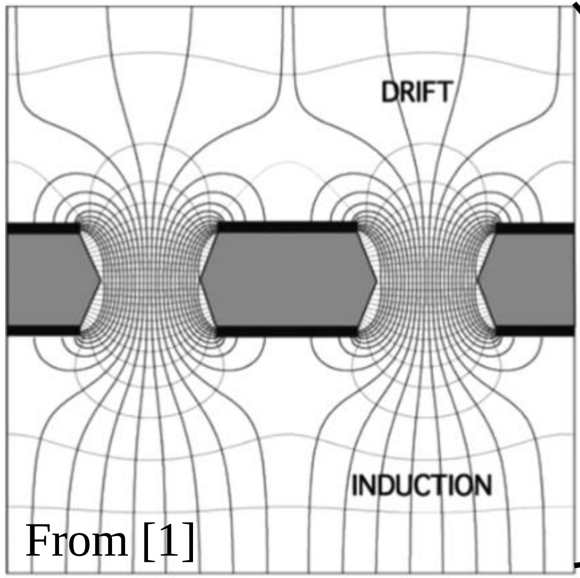
converter layers in detector

GEM Detector

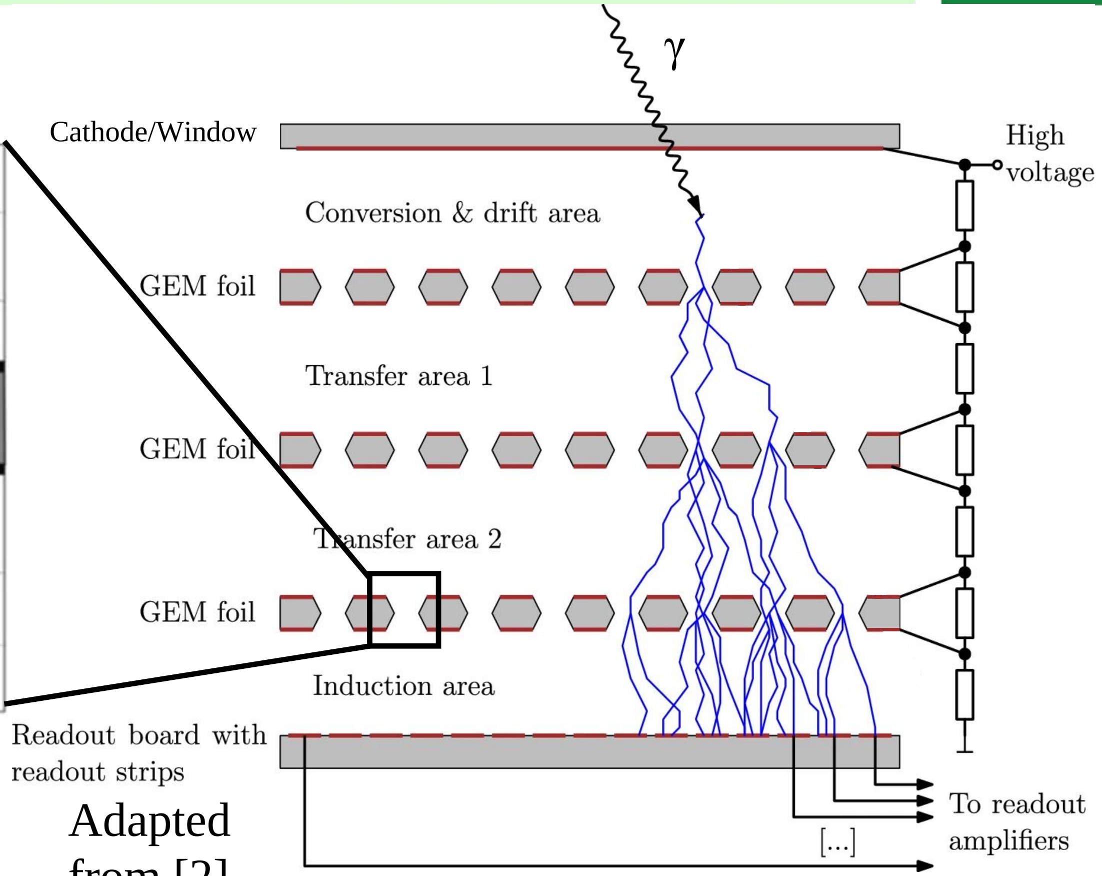
- **G**aseous **E**lectron **M**ultiplier



From [1]



From [1]



Adapted from [2]

- Copper plated Kapton foil with holes
- Amplification via locally strong e-fields
  - Amplification factor of 20 per Foil
  - 3 foils ⇒ $20^3 = 8000$

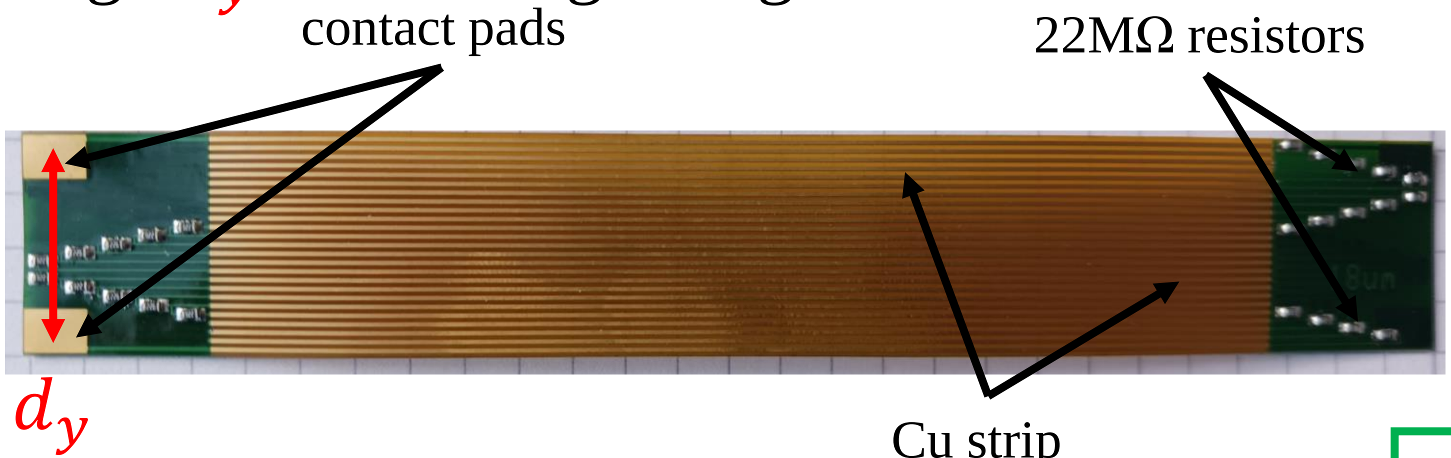
advantages:

⇒ excellent spatial resolution (< 100 µm)

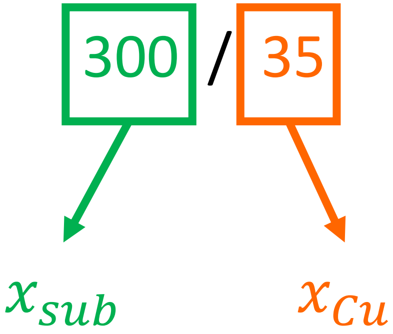
⇒ high-rate capability

Converter Layers

- Substrate material is FR4 or Flex-PCB (Polyimide similar to Kapton)
- Copper strips (0.4 mm width & distance) each connected over $22M\Omega$ resistors
- Applied voltage d_y results in guiding field

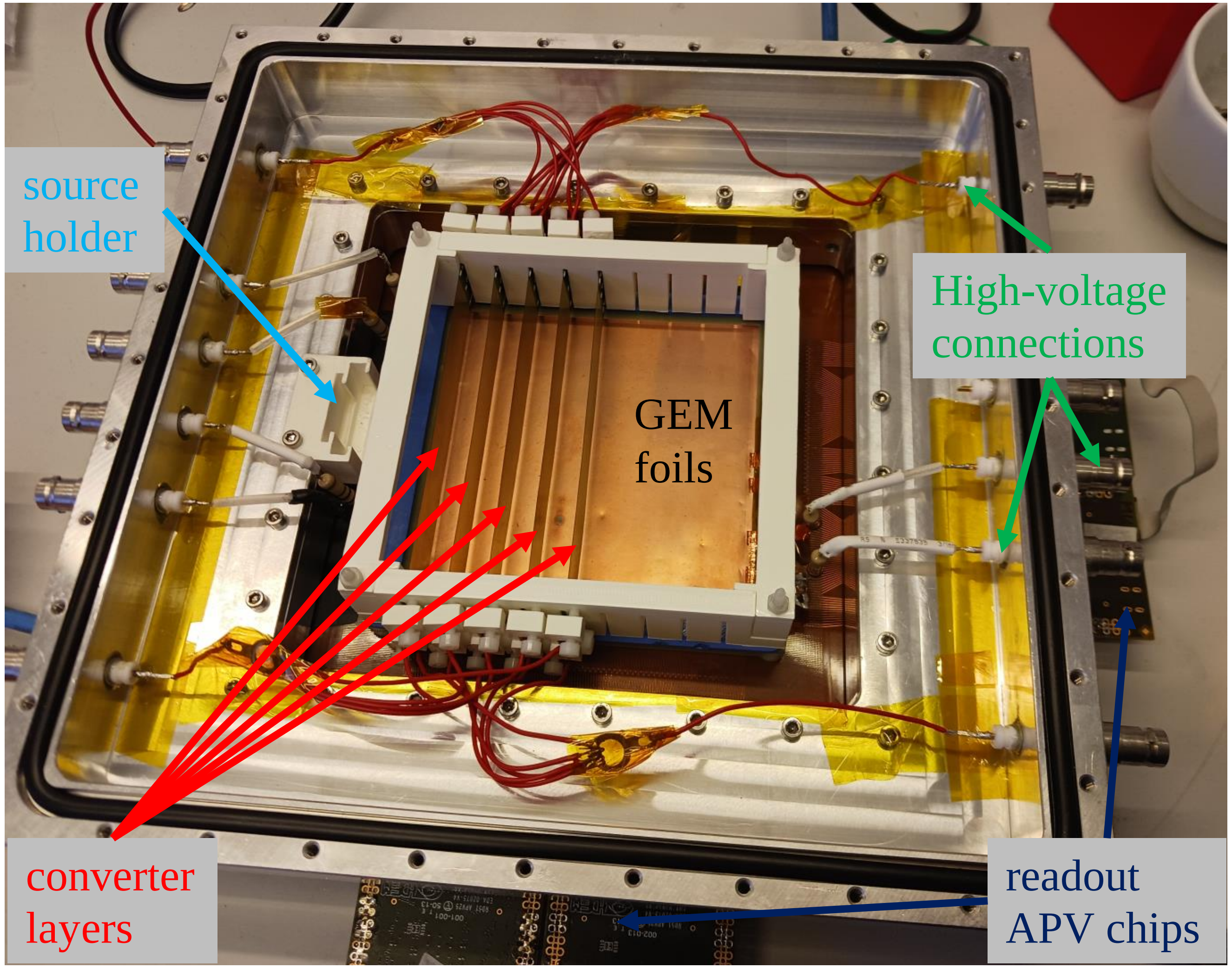


  - Effective area: $20mm * 100mm$
  - Combinations off:
    - 50/100 μm Flex-PCB or 300/1550 μm FR4
    - 18/35 μm copper



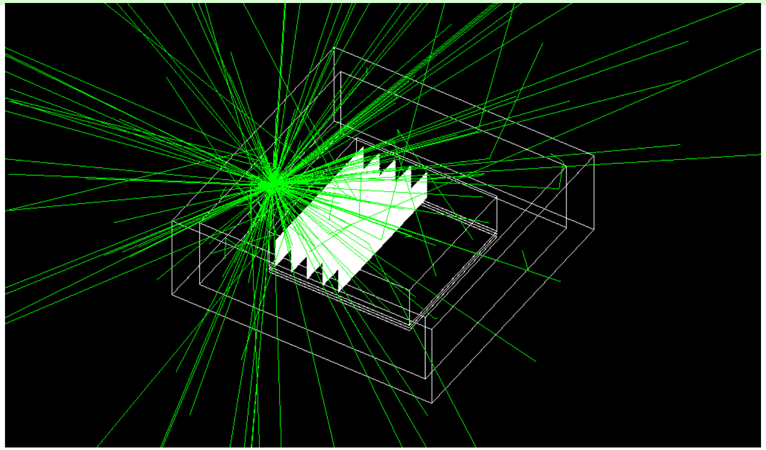
Detector Setup

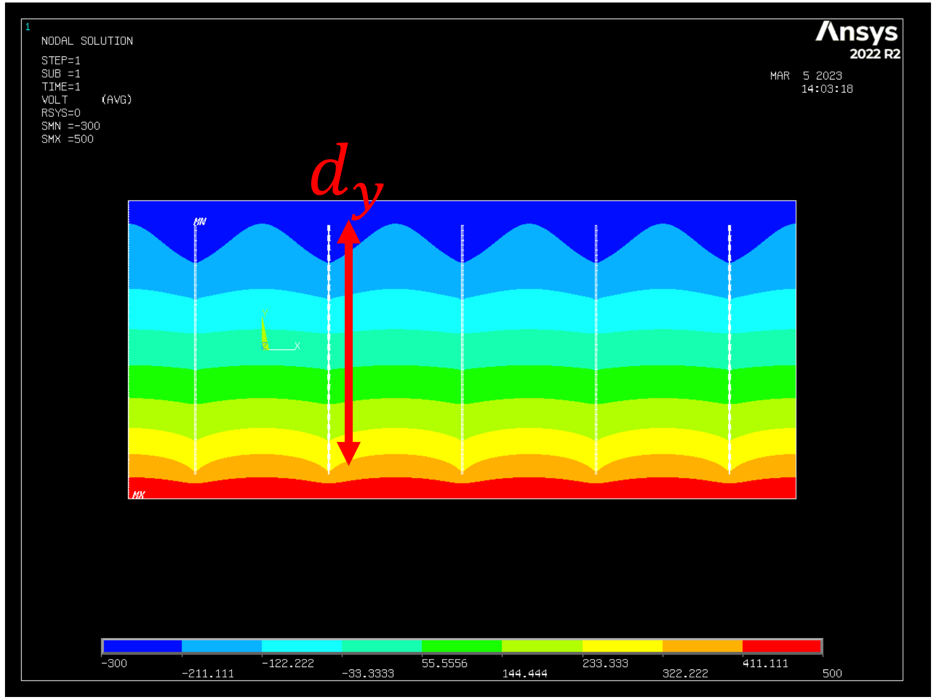
- Gas mixture: Ar/CO_2 93/7 %
- Am-241 source
- Here shown: 100/18 layers
- The layers are put under stress to pull them straight
  - ⇒ Better guiding properties
- Self-triggering on the bottom side of the lowest GEM foil
- Readout via APV chips connected to a scalable readout system



Simulation

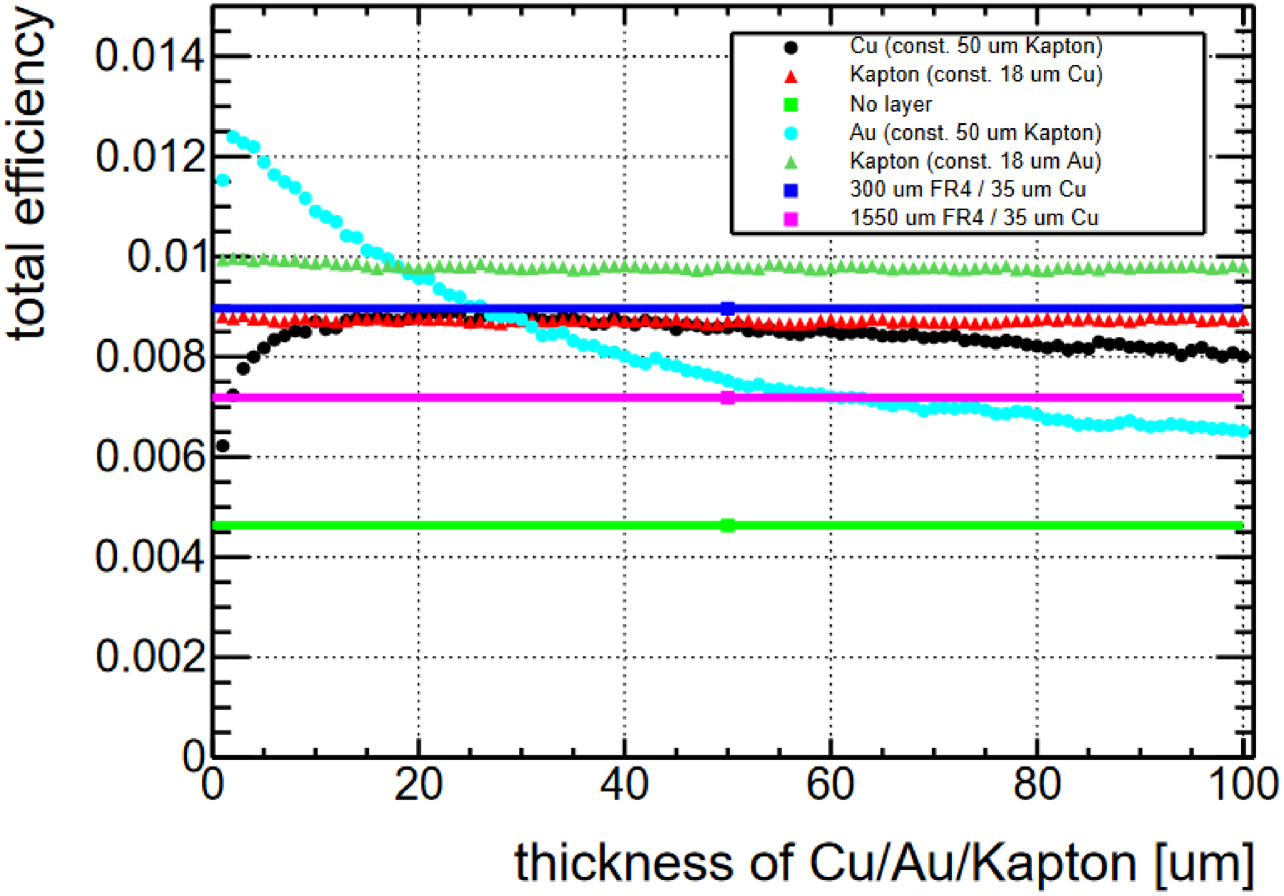
- Geant4:
  - Photon-Matter interaction
  - Position & energy of created electrons
  - Modelled after real detector setup
- ANSYS:
  - Application of electrical potential
  - Electrical fields between converter layers
  - Equipotential lines shown for $d_y = 600\text{V}$ along layers + 200V drift
- Garfield++:
  - Import electrons from Geant4
  - Import electric fields from ANSYS
  - Simulates resulting drift



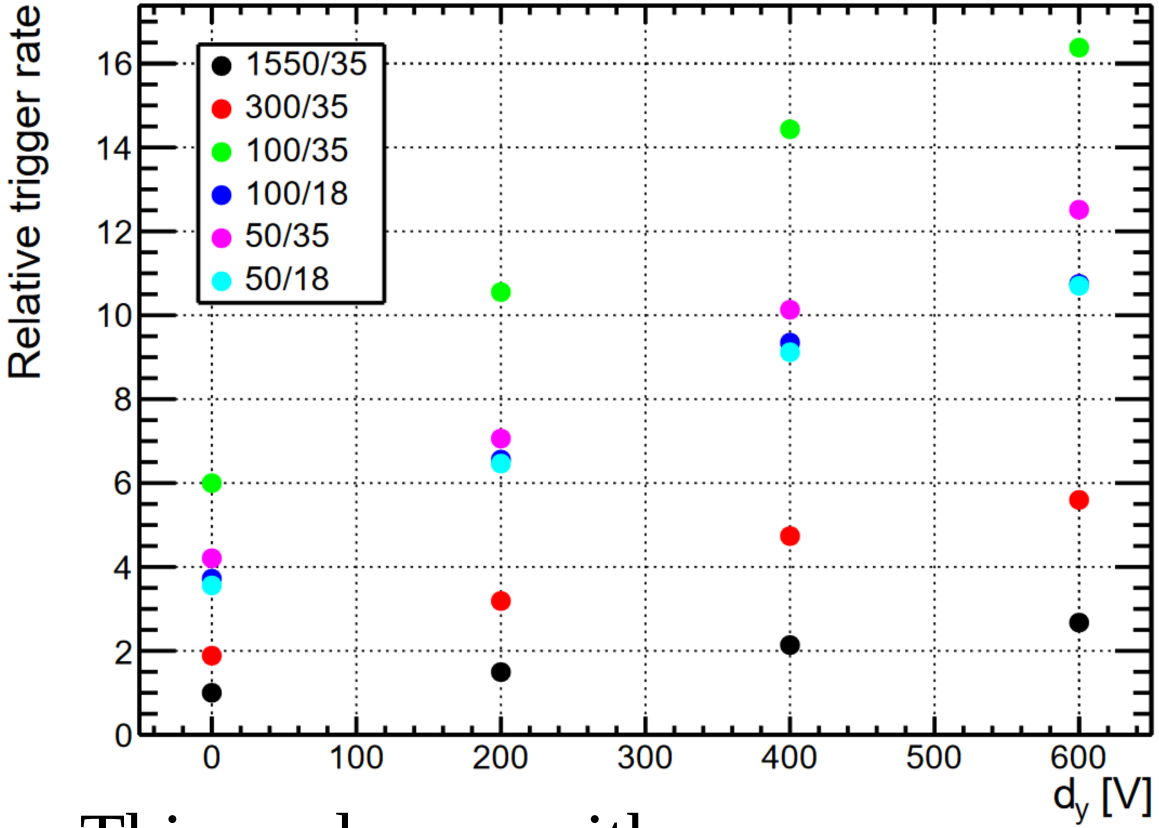


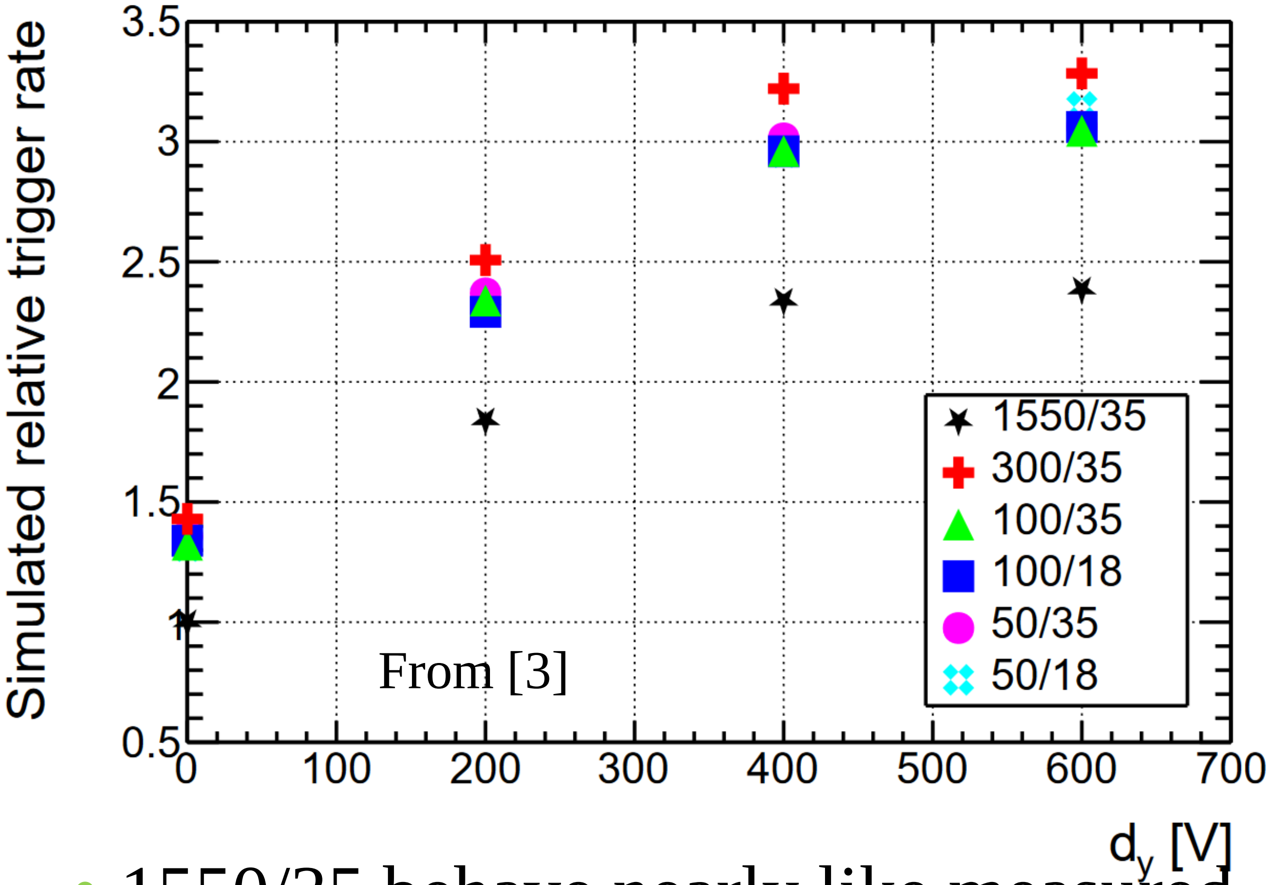
Simulation: Thickness

- Total conversion efficiency = $\frac{\#\ Events\ with > 1\ e^{-}\ reaching\ active\ gas\ volume}{\#\ Events\ with\ \gamma\ entering\ active\ gas\ volume}$
- Au exceeds Cu for $\lesssim 30\ \mu m$
  - But: Too much metal is detrimental
- Steep rise at the beginning
  - Thickness smaller than the range of e- in Cu/Au
- Kapton has nearly no effect
- Without layers: 0.46 %
  - Cu layers: 0.88% ⇒ 1.9x w/o
  - Au layers: 1.24% ⇒ 2.7x w/o
- 50/18 and 50/35 as good as 300/35



Measurements





From [3]

- Thinner layers with more copper perform better

⇒ Improvement by a factor of up to ≈ 7 compared with 1550/35

- 1550/35 behave nearly like measured
- All other layers differ strongly from measurements

⇒ Further investigation needed

Conclusion & Outlook

- Conversion simulations indicate potential to increase the efficiency from ≈ 0.46% to ≈ 0.88% with copper or to ≈ 1.24% with gold
- The measurements indicate that FR4 that thinner substrates with more copper are favourable, due to less passive material and more active material
  - But mechanical stability must be considered for optimal guiding fields
- A maximum increase in trigger rate of a factor ≈ 7 is achieved between standard (1550/35) and optimized converter layers
- Trigger rate simulations predict all layers behaving the same except for 1550/35, which isn't reflected in the measurements
- Further investigation of the simulation and potential unknown measurement effects

Literature

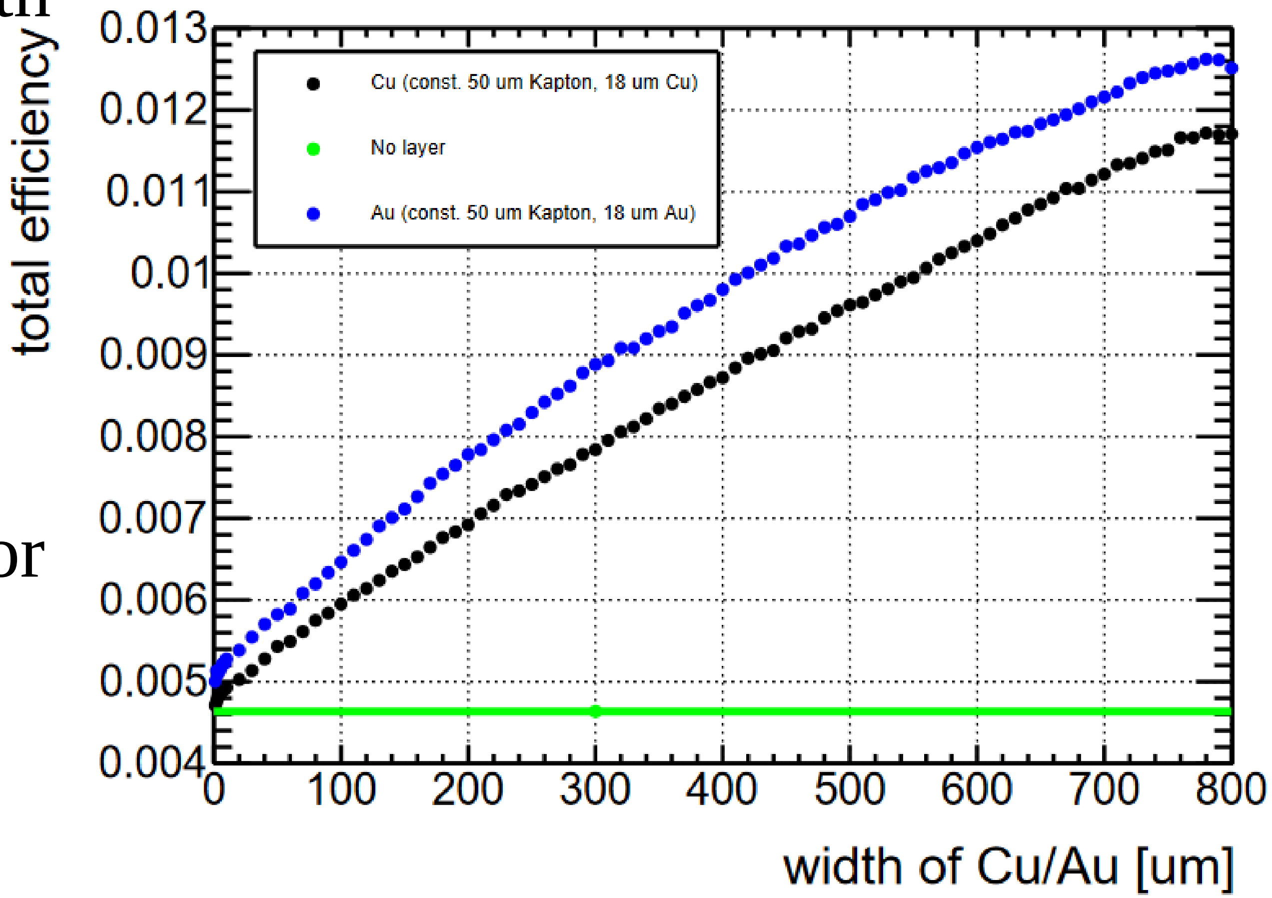
[1]:The gas electron multiplier (GEM): Operating principles and applications“. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (7. Aug. 2015). doi: https://doi.org/10.1016/J.NIMA.2015.07.060

[2]: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). https://doi.org/10.1007/s10894-018-0181-2

[3]: Katrin Penski, Work in progress (internal communication)

Simulation: Width

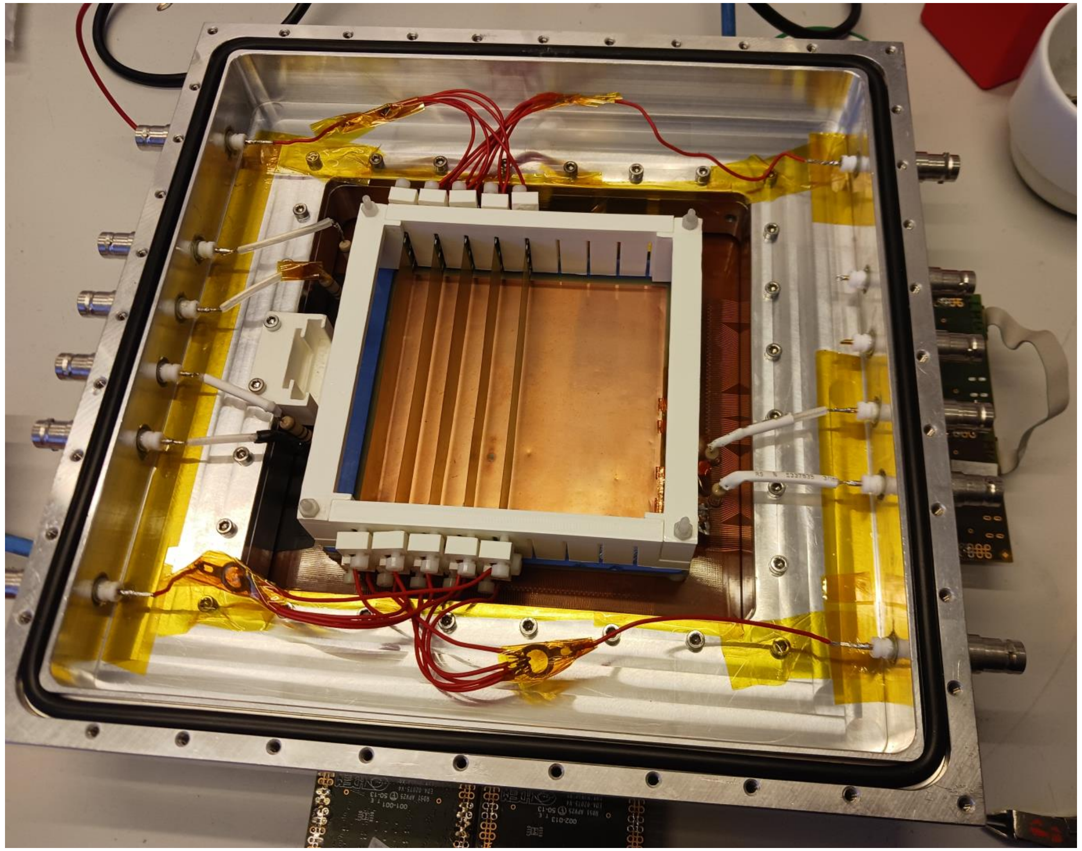
- The efficiency for Au is higher than for Cu, as expected
- Efficiency rises with increasing width and decreasing distance between the strips
- Small dip at the end
  - Loss of surface area due to connecting strips
- Further improvement by over a factor of 2
  - Cu layers: 1.17% ⇒ 2.5x w/o
  - Au layers: 1.26% ⇒ 2.7x w/o



Motivation

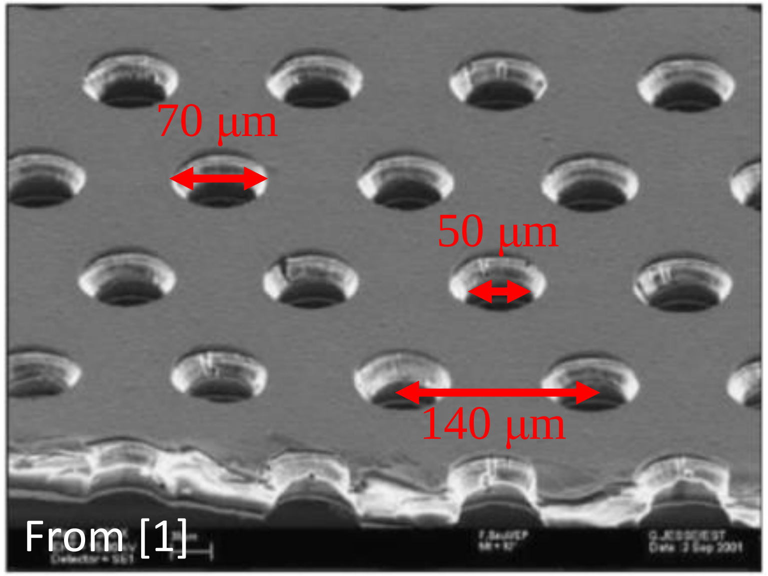
- For detecting neutral particles semiconductor and scintillator detectors are mostly used
  - Both have the drawback, that they are costly and aren’t easily scalable
- Gaseous detectors are cheaper to produce and can get scaled to m² dimensions
  - But they suffer from poor detection efficiency for neutral particles due to the low density of gases

⇒ Aim: Increase the photon detection efficiency by using converter layers

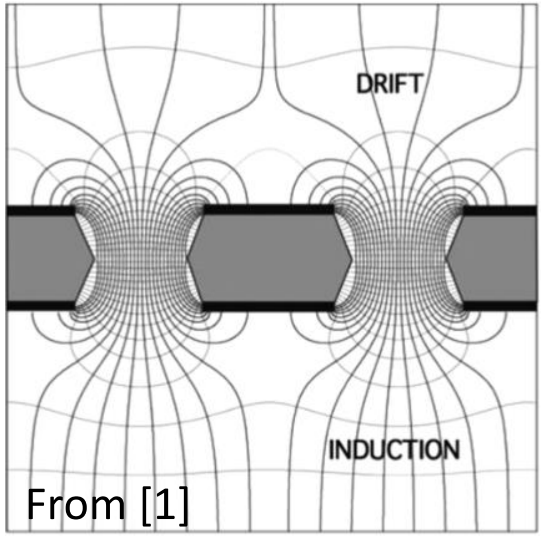


Detector Setup: GEM foil

- **G**aseous **E**lectron **M**ultiplier
- Double sided copper plated Kapton foil with holes
- Electrical potential difference of ~300V is applied
- Amplification via resulting locally strong e-fields
  - Amplification factor of 20 per Foil



From [1]



From [1]

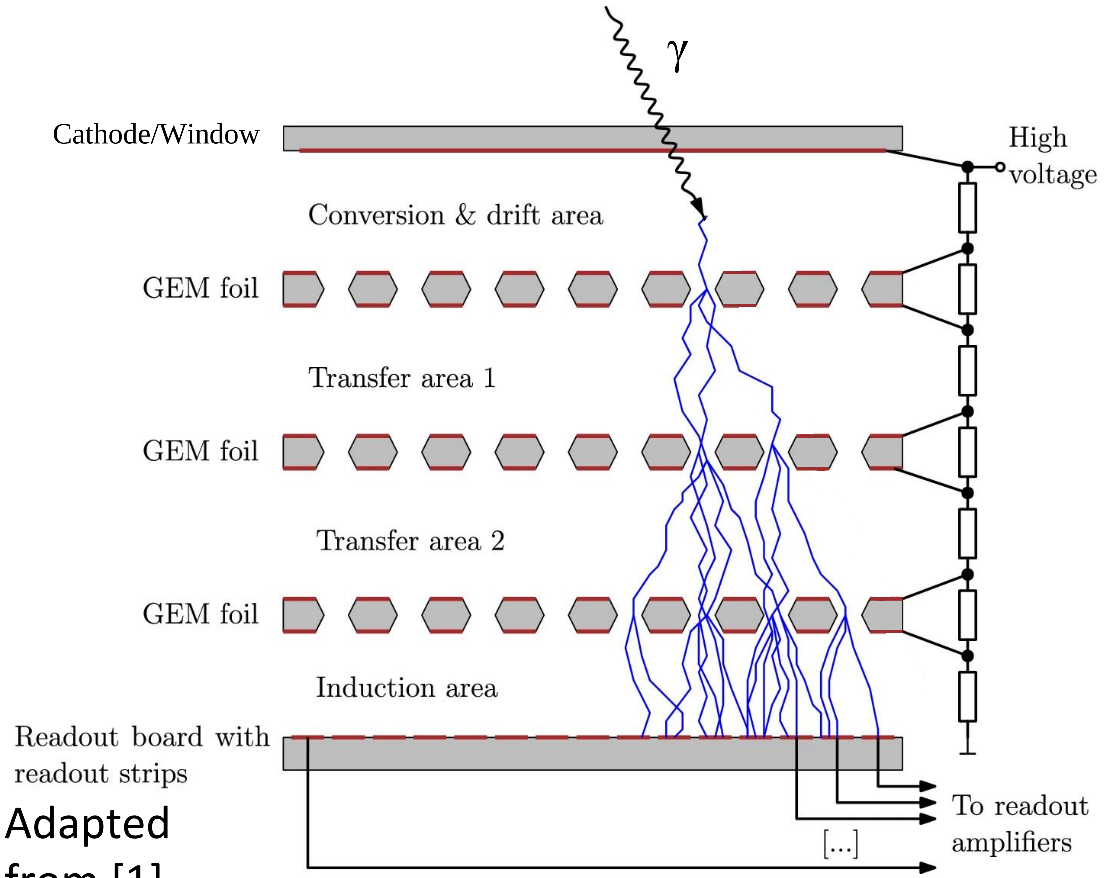
Detector Setup: Triple GEM Setup

- 3 GEM foils

  ⇒ Amplification of $20^3 = 8000$

- Advantages:
  - Excellent spatial resolution (< 100 µm)
  - High-rate capability
  - No resistive coating on readout strips needed

- Disadvantage:
  - A discharge could melt through a GEM foil and render it useless



Adapted from [1]

Photon Detection

- Optimization for 60 keV photons

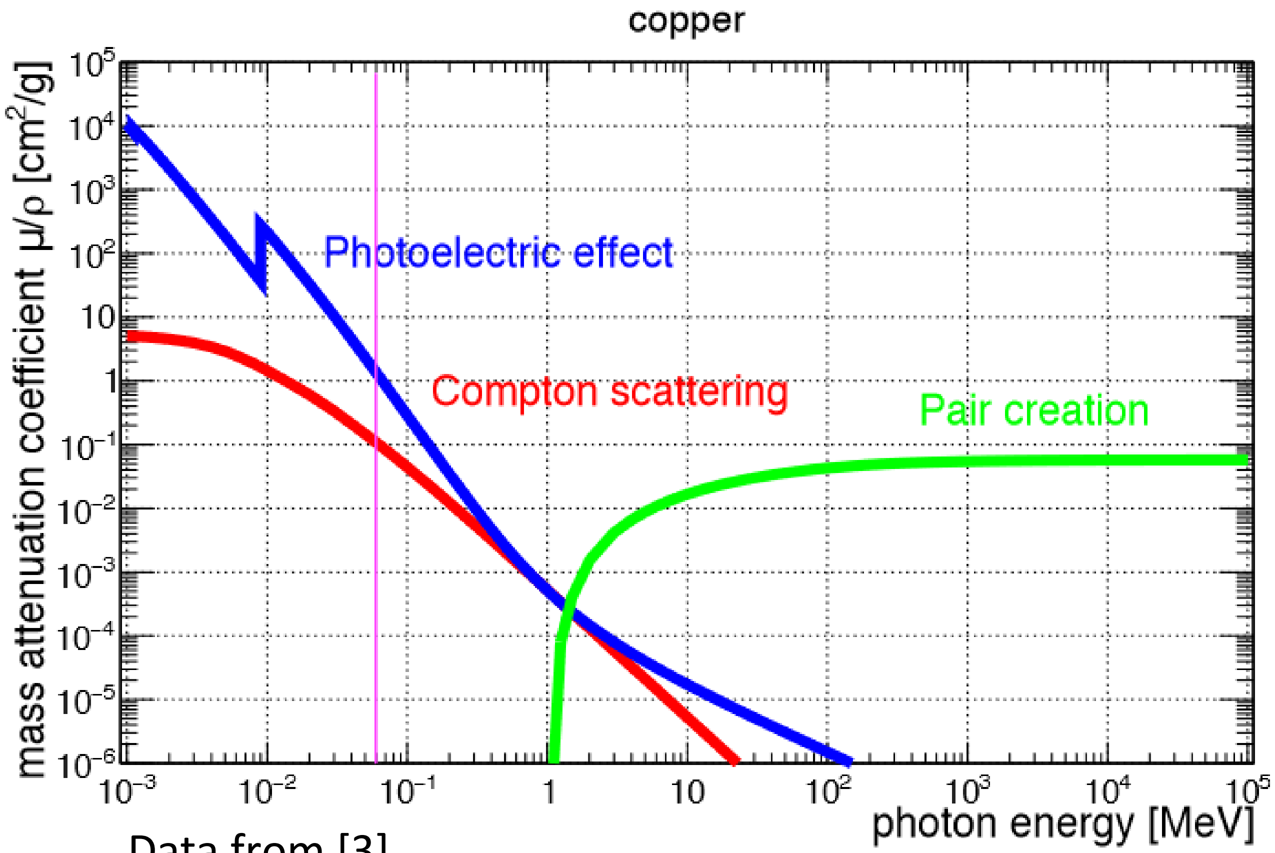
- 60 keV photons mainly undergo photoelectric effect

$$\sigma_{Photo} \sim Z^5$$

⇒ a high-Z materials are better

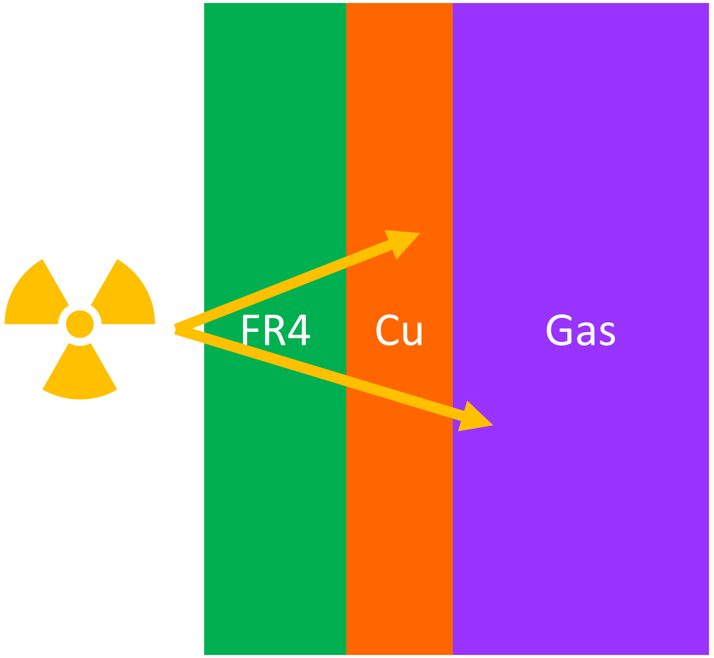
- Idea: Insert solid converter layers in a GEM Detector to better convert 60 keV photons into electrons

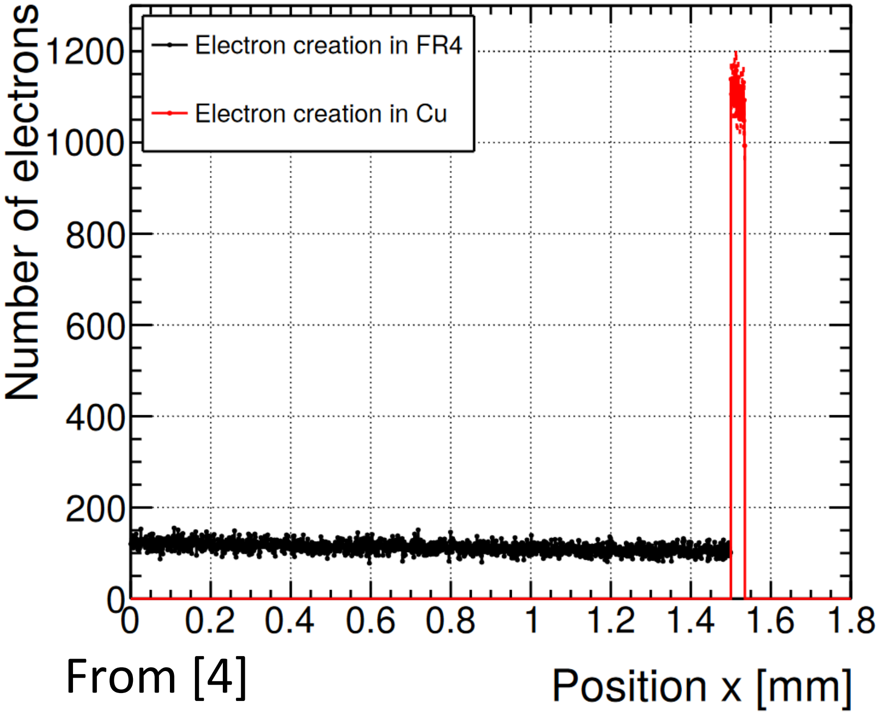
⇒ use copper plated layers



Data from [3]

Simulation: Converter Layers

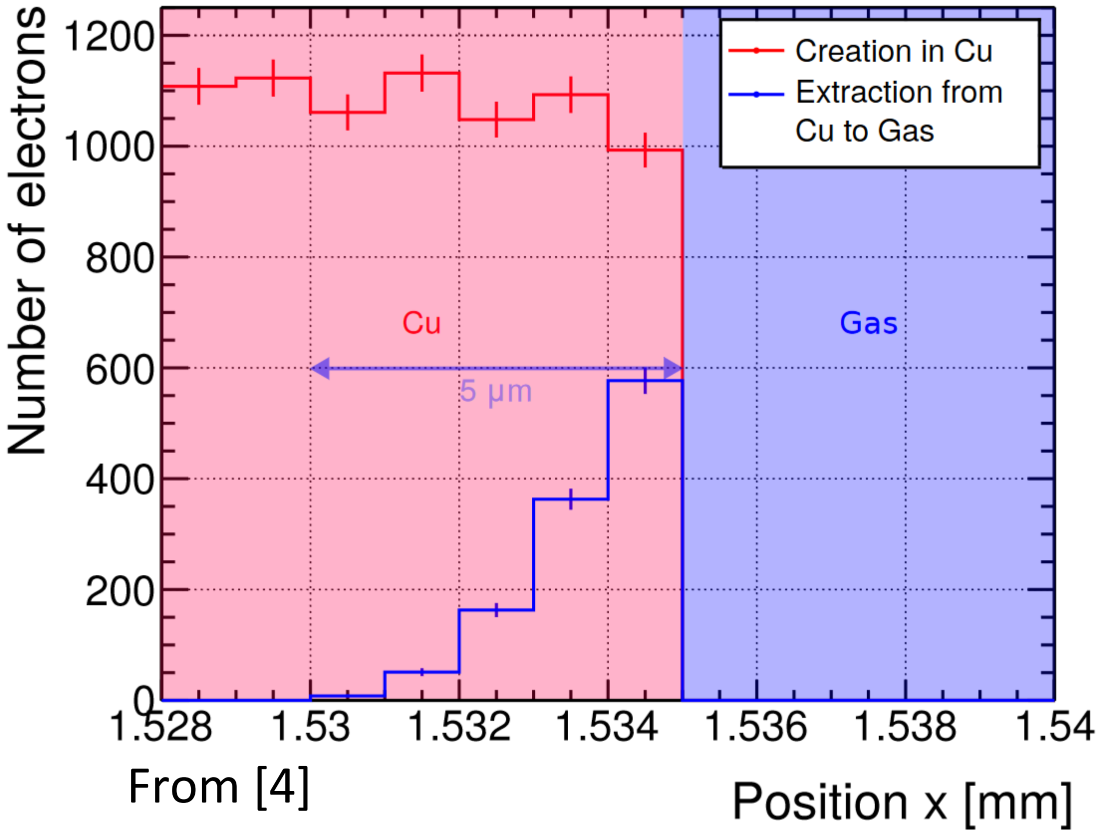




From [4]

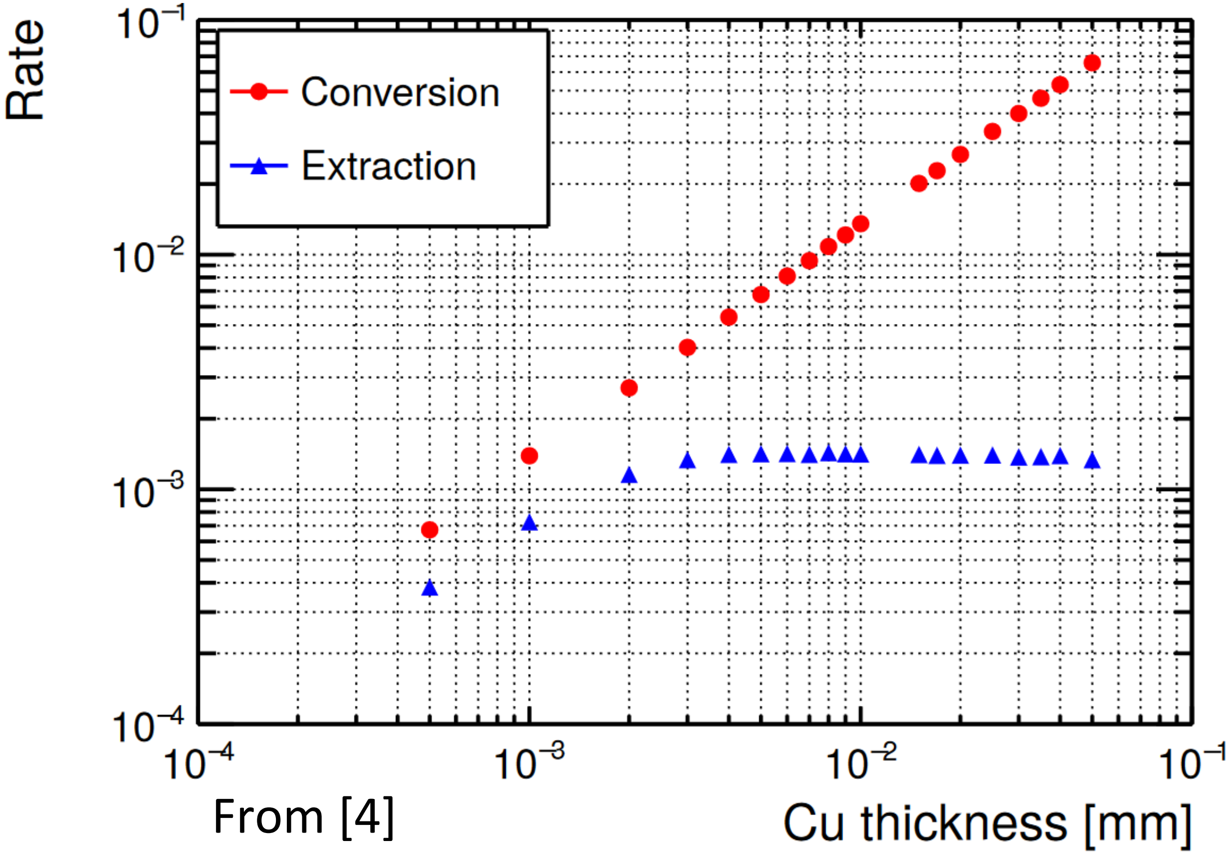
- FR4 material as carrier material
- Cu as main converter material
- Here: 1550 µm FR4 + 35 µm Cu

Simulation: Electron Extraction



From [4]

- No extraction out of the FR4

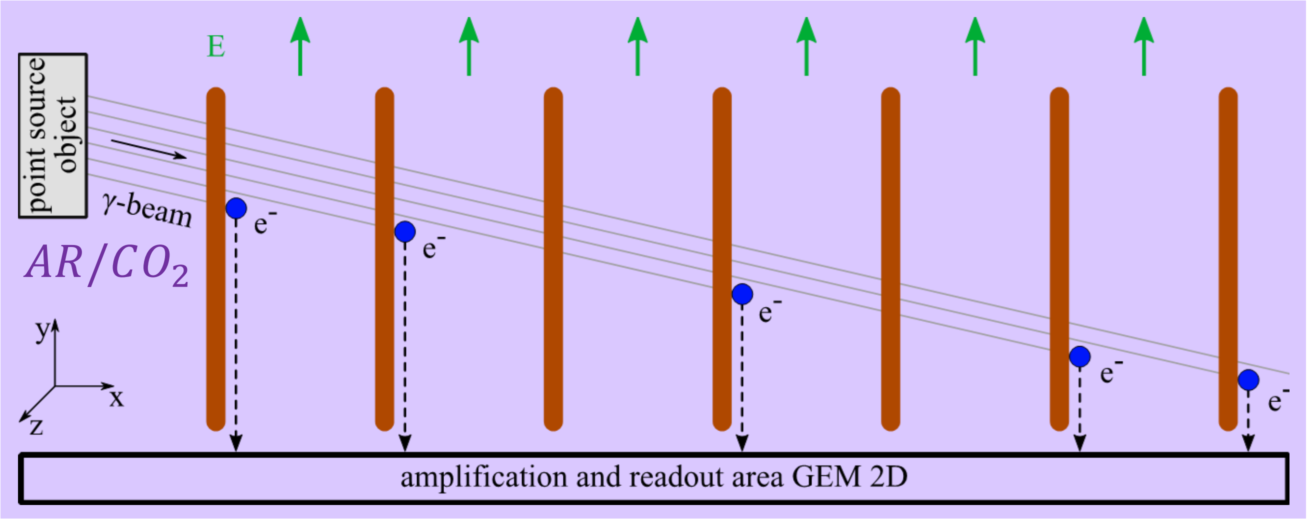


From [4]

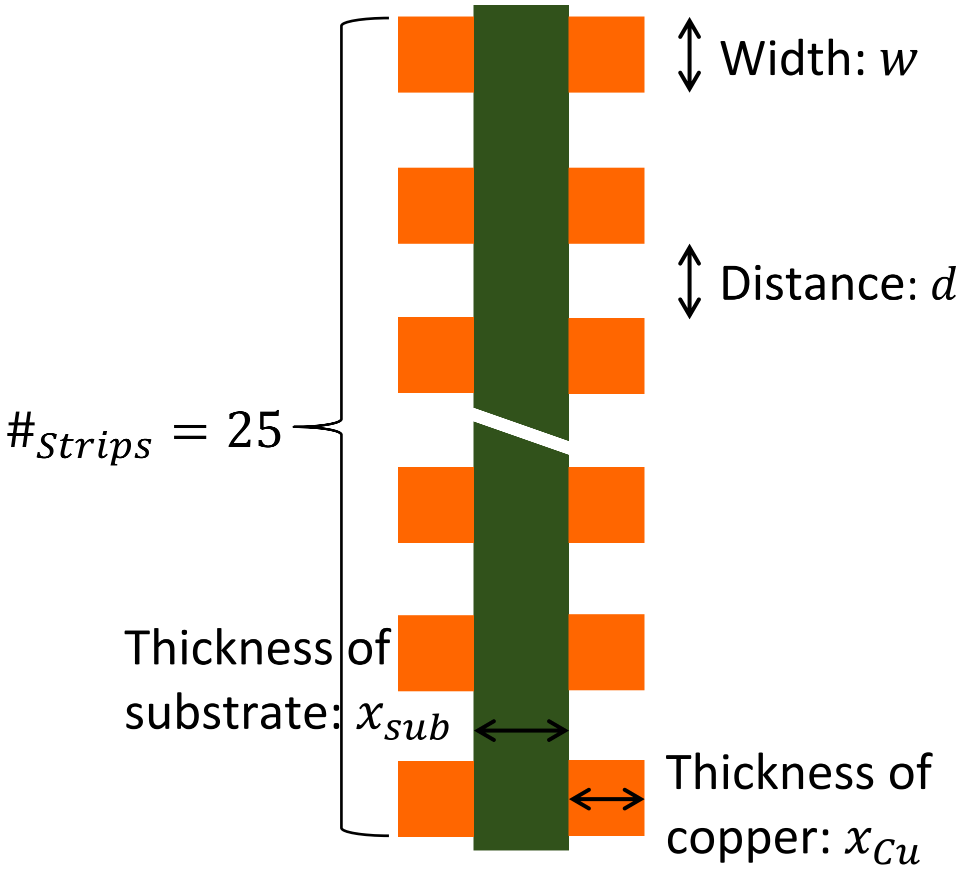
- Only the last 5 µm are effective ⇒ Material optimization necessary

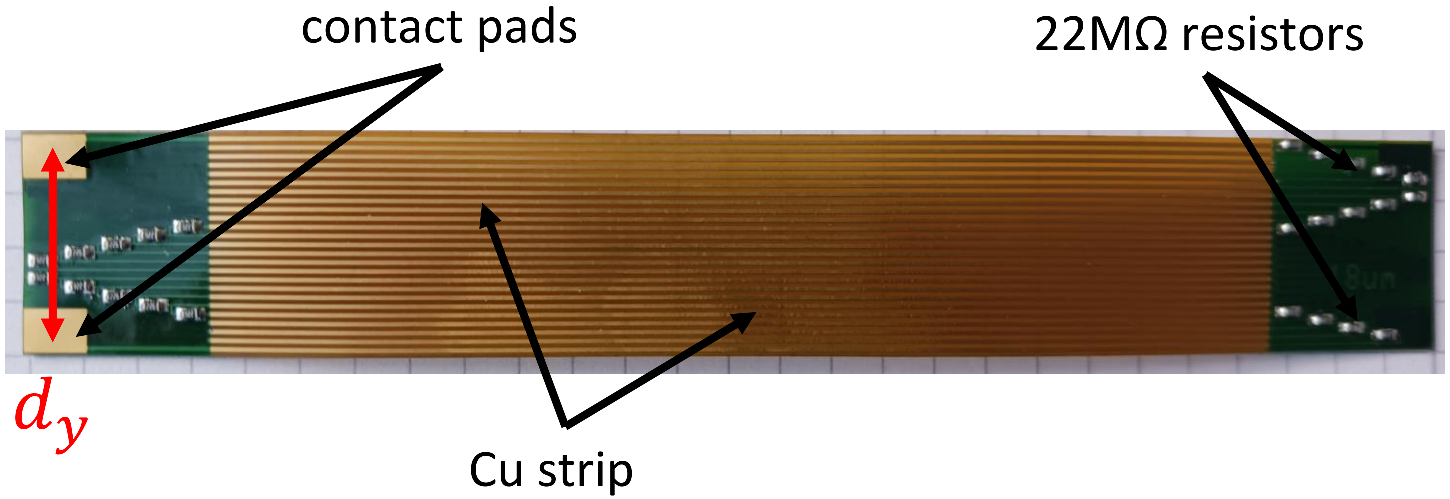
Detector setup

- GEM Detector filled with a gas mixture of Ar/CO_2 $93/7\%$
- 370 kBq Am^{241} source emitting 60 keV photons inside the detector
- Converter layers are placed perpendicular to the photons
  - Electron guiding is crucial for detection ⇒ use of electric guidance field



Layer geometry

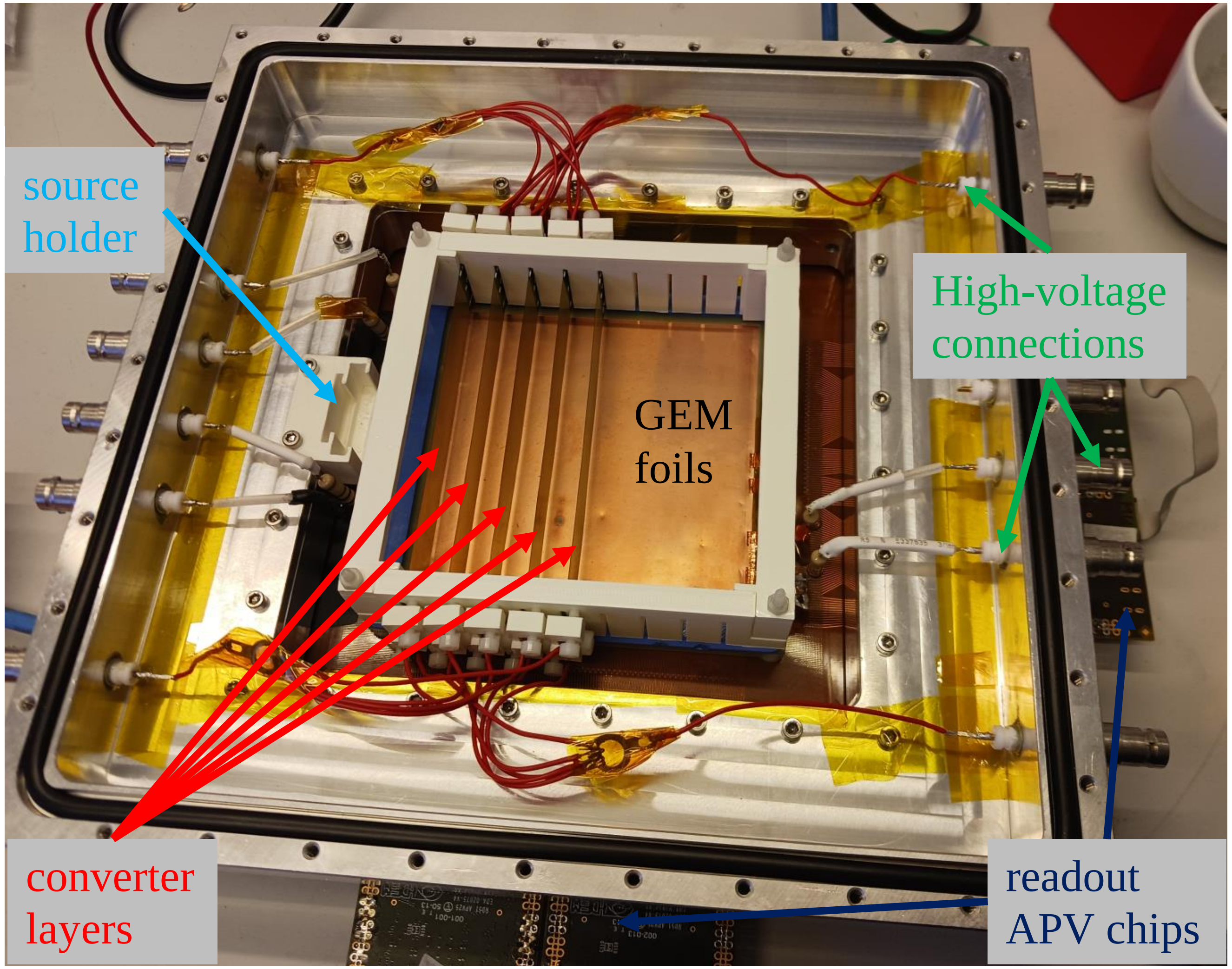




- Effective area: $20\ mm * 100\ mm$
- Layer total hight: $h_L = 20.4\ mm$
- Layer total length: $l_L = 135\ mm$
- Potential d_y applicable for electron guidance field

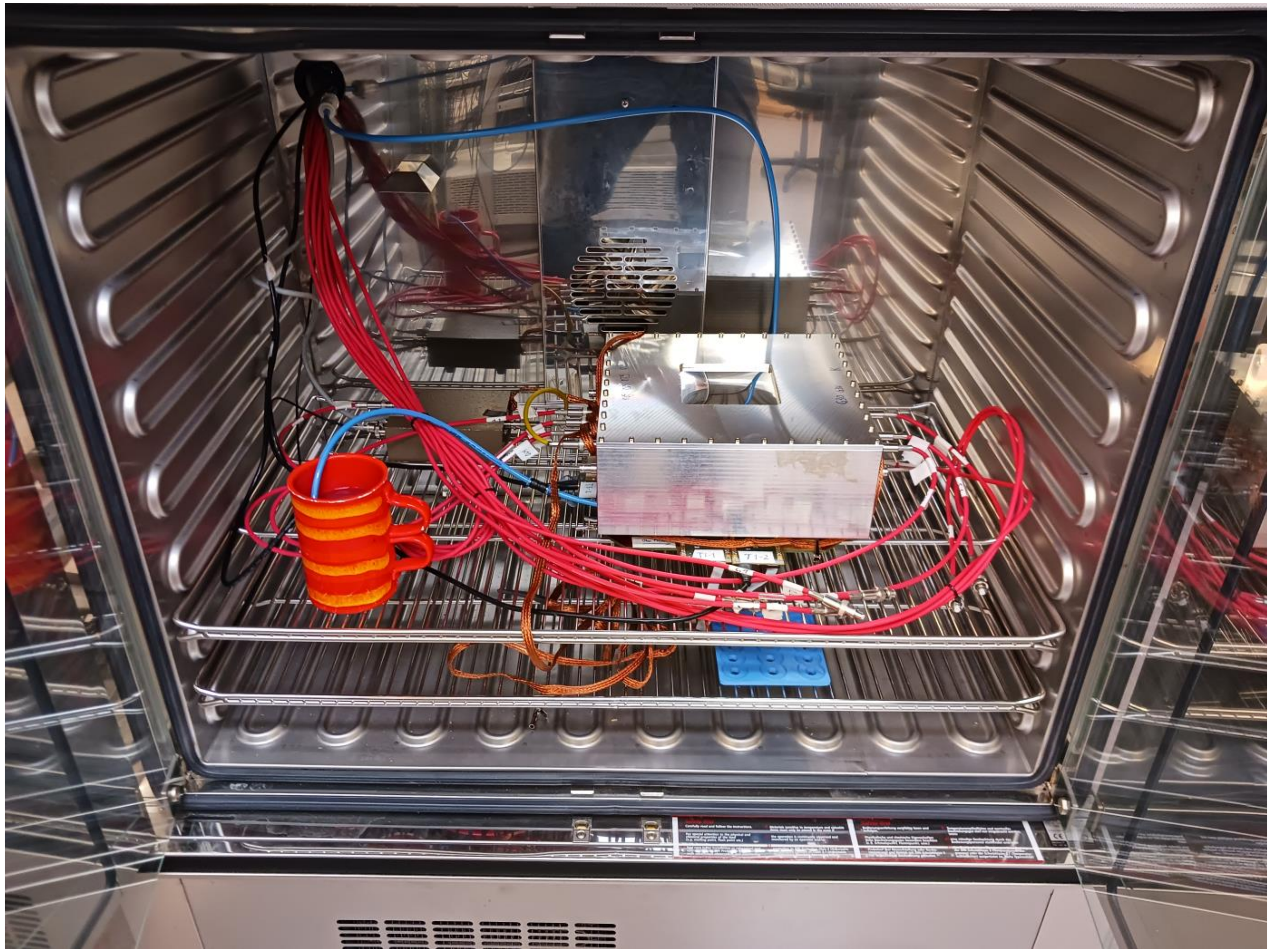
Detector Setup

- Here shown: 100/18
- The layers are put under stress to pull them straight
  ⇒ Better guiding properties
- Self-triggering on the bottom side of the lowest GEM foil
- Readout via APV chips connected to a scalable readout system



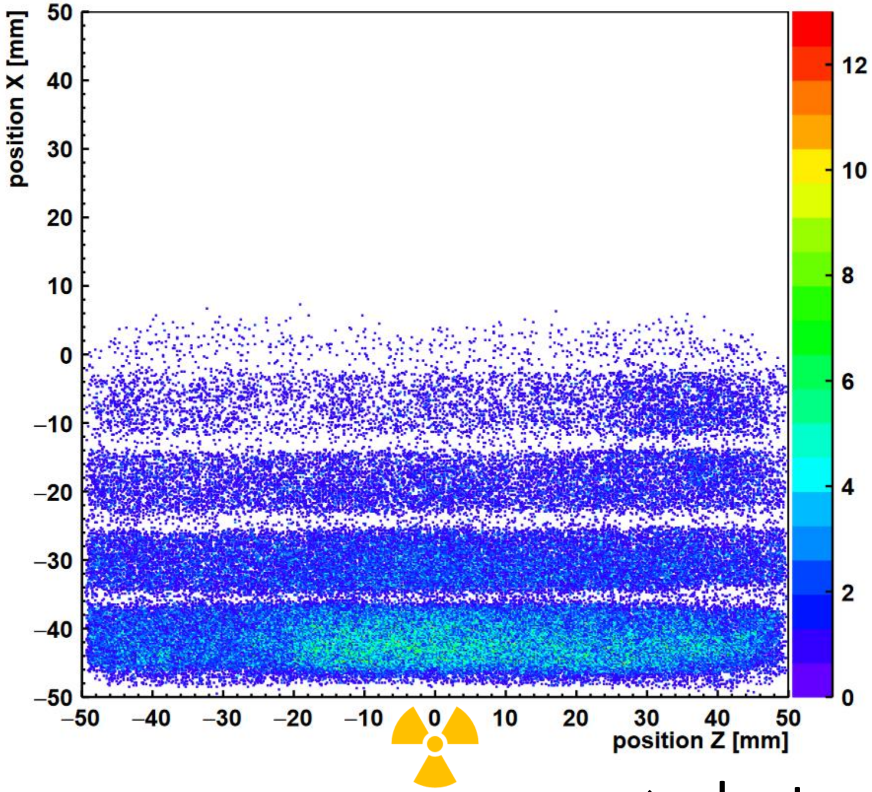
Detector Setup

- Detector is built up in climatised cabinet
- Able to control air temperature and relative moisture
- Standard operating conditions:
  - $T = 25 \pm 0.3\,°C$
  - $RH = 25 \pm 3\,\%$
- Pressure still dependent on environment

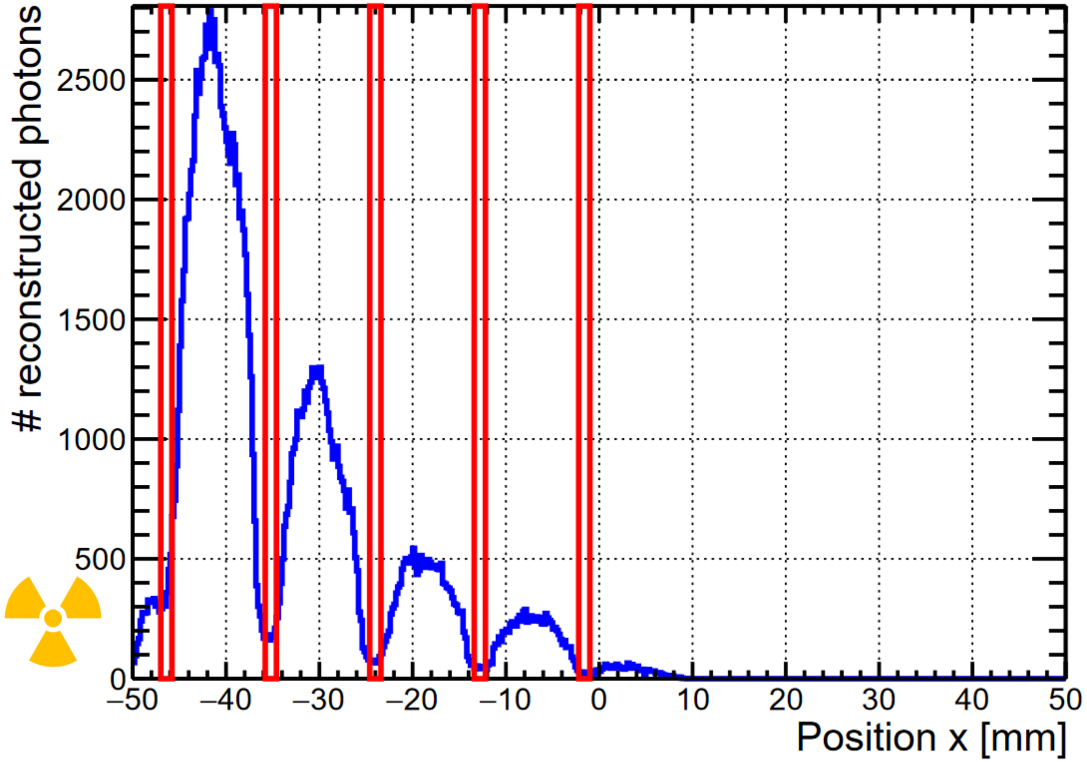


Measurement

2D reconstructed photon position



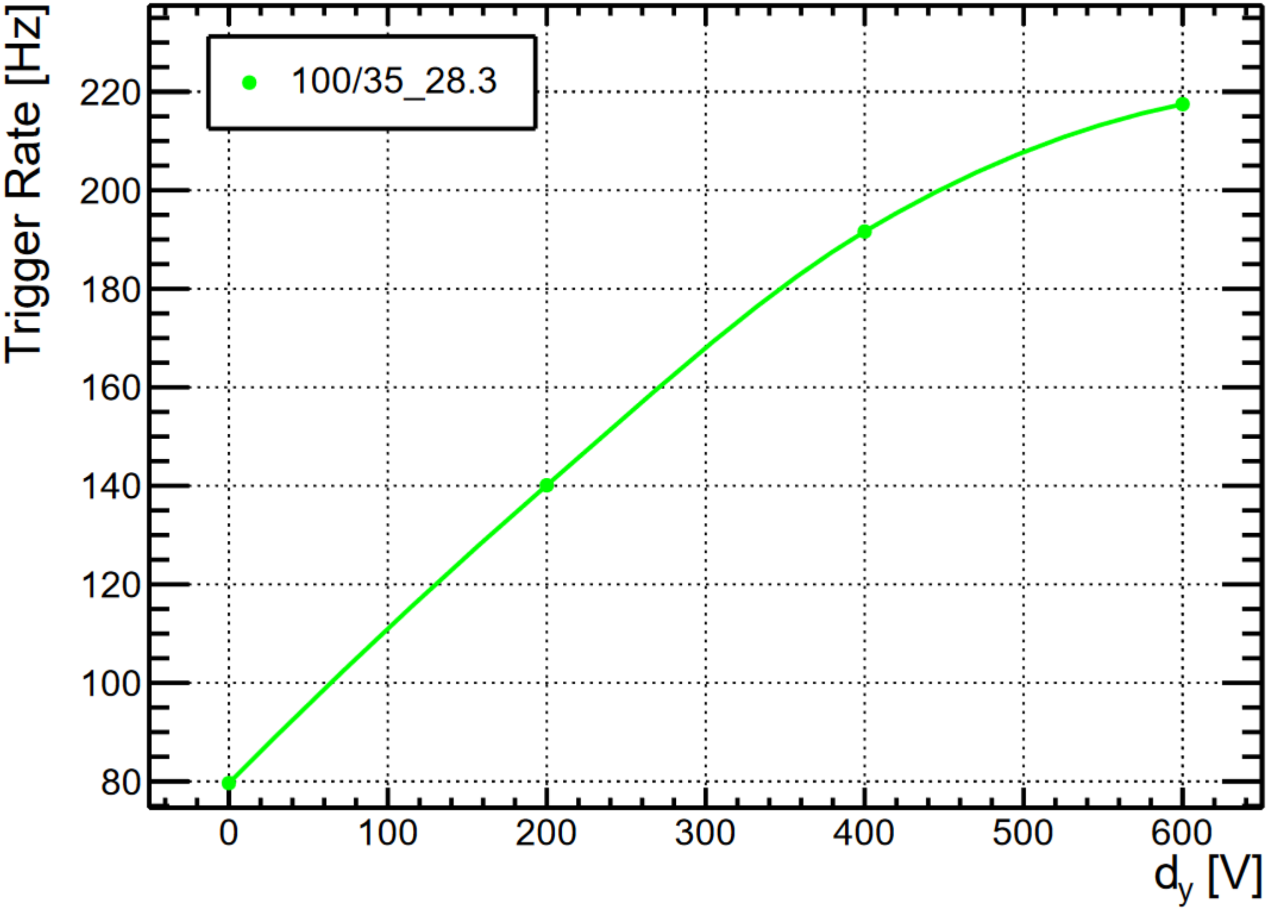
1D reconstructed photon position profile



⇒ electron guiding is working

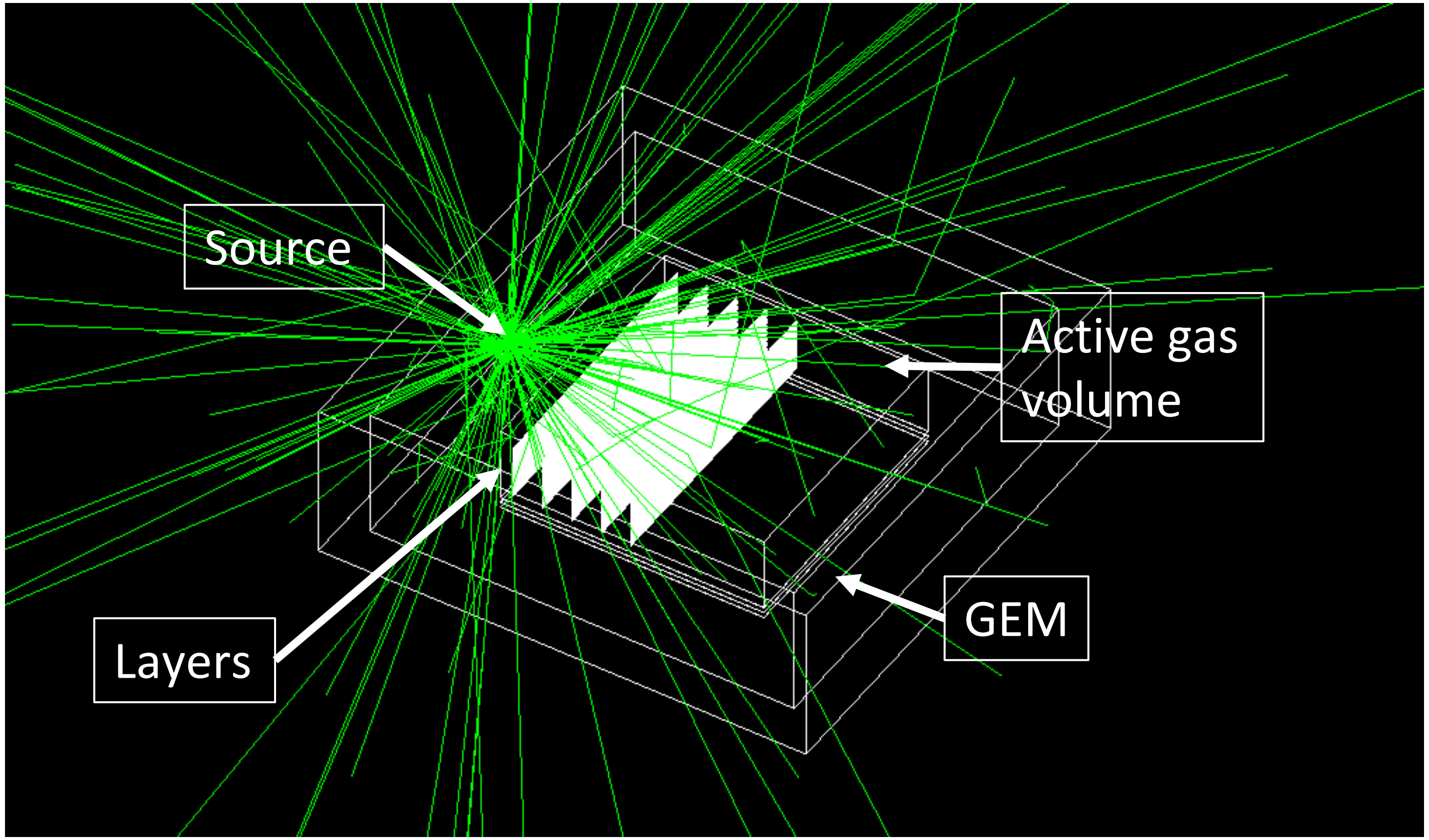
Layer Geometry: d_y

- d_y produces the drift field guiding the electrons to the amplification region
- The higher d_y the higher the drift velocity
- With constant production rate of electrons, higher d_y values lead to saturation of trigger rate



Simulation: Geant4

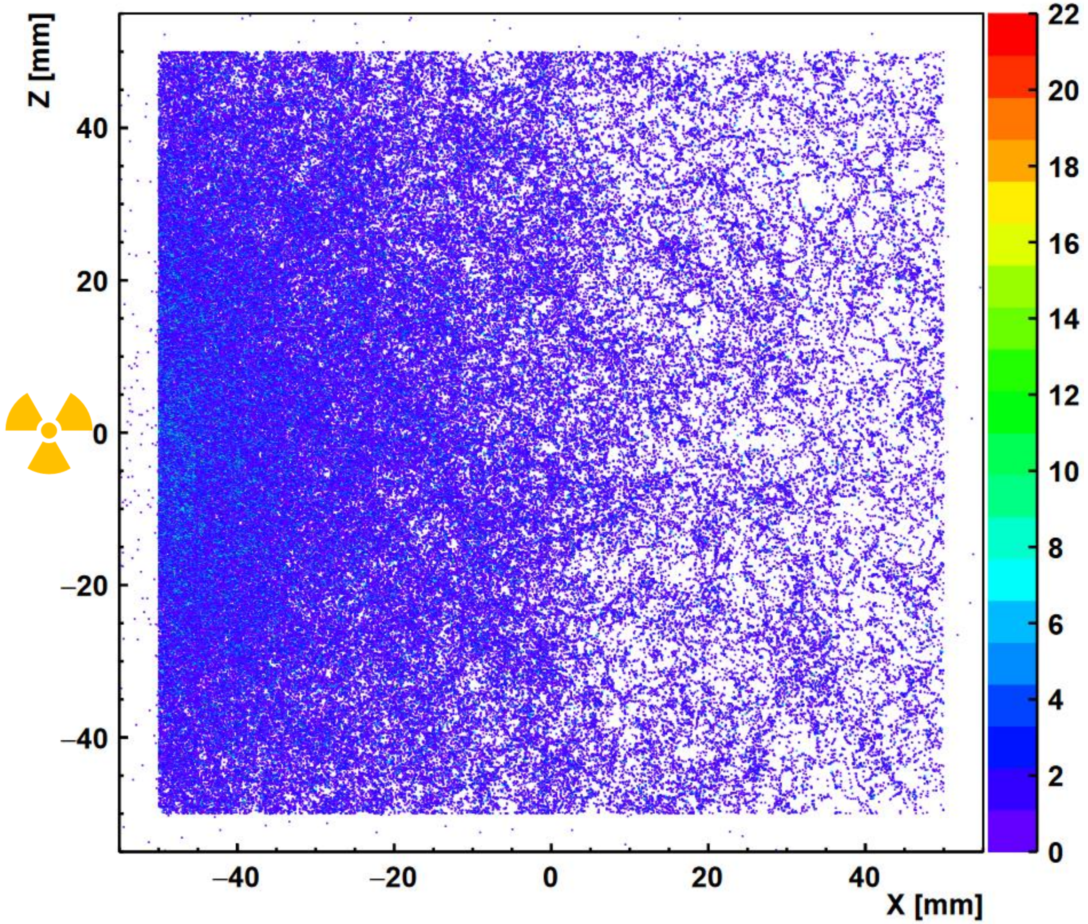
- Photon-Matter interaction
- Position of created electrons
- Modelled after real detector setup
- Spherical source emitting 60 keV photon in 4π



Simulation: Geant4: Electron Creation

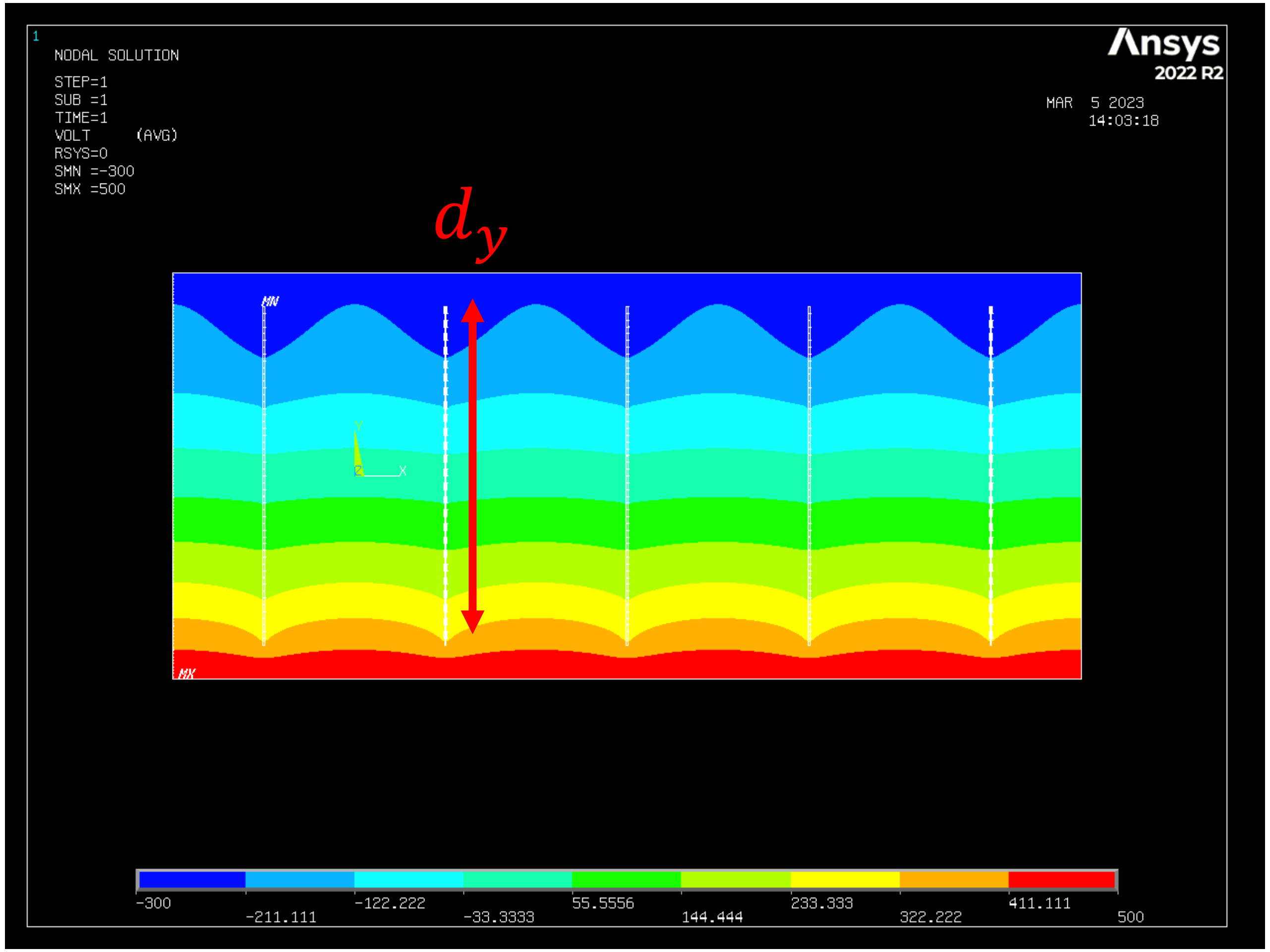
- Position of all electrons that reach the active gas volume
- Layers are nearly not visible due to them being 100 µm thick

⇒ all electrons need to be guided down to the amplification stage



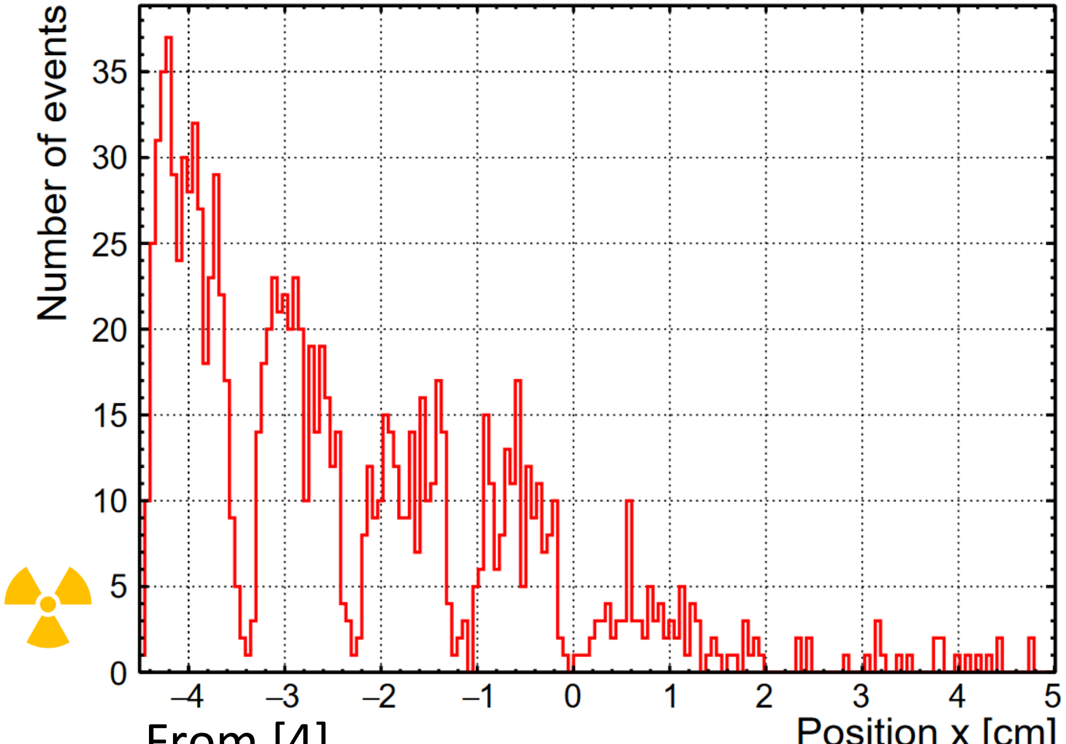
Simulation: ANSYS & Garfield++

- ANSYS
  - Calculation of the E-field between the layers
- Garfield++
  - Takes the field of ANSYS and the positions of Geant4
  - Simulates the electron drift in gas



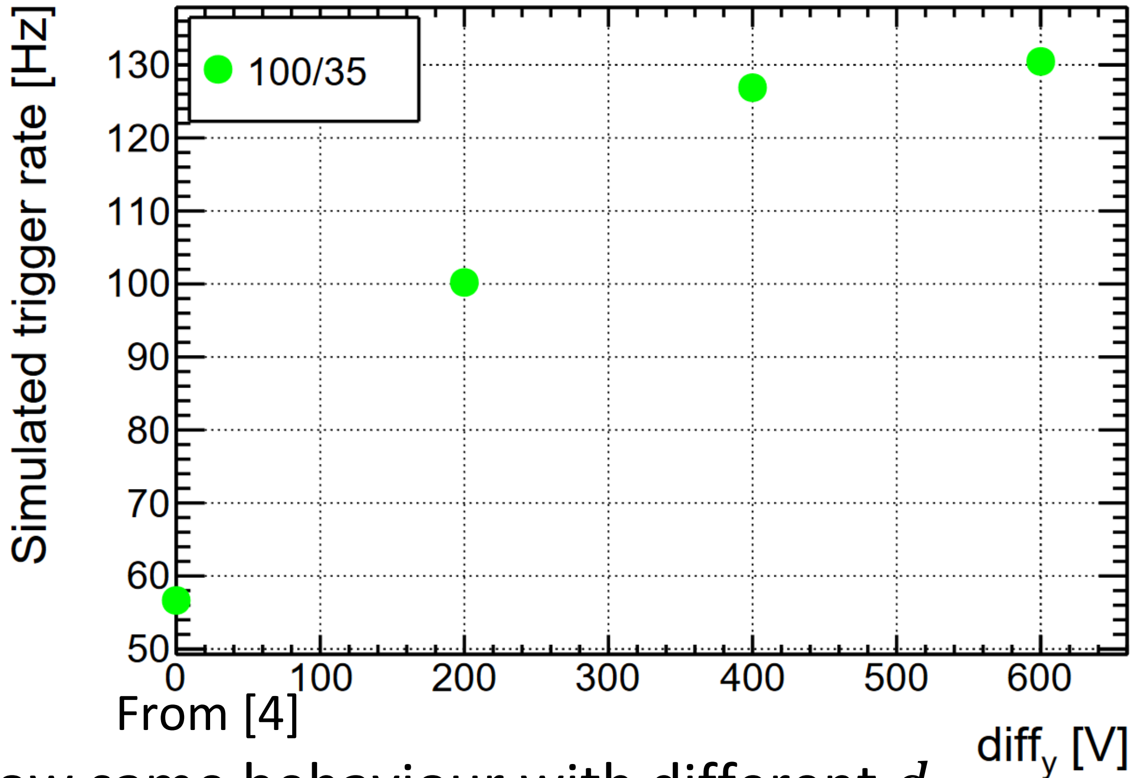
Simulation: Results

1D e- end-position after drift (after Garfield++)



From [4]

1D e- end-position after drift (after Garfield++)

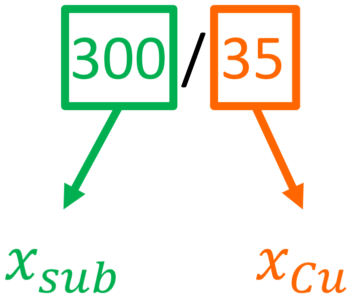


From [4]

⇒ Simulation and measurement show same behaviour with different d_y

Material Investigation

Terminology:



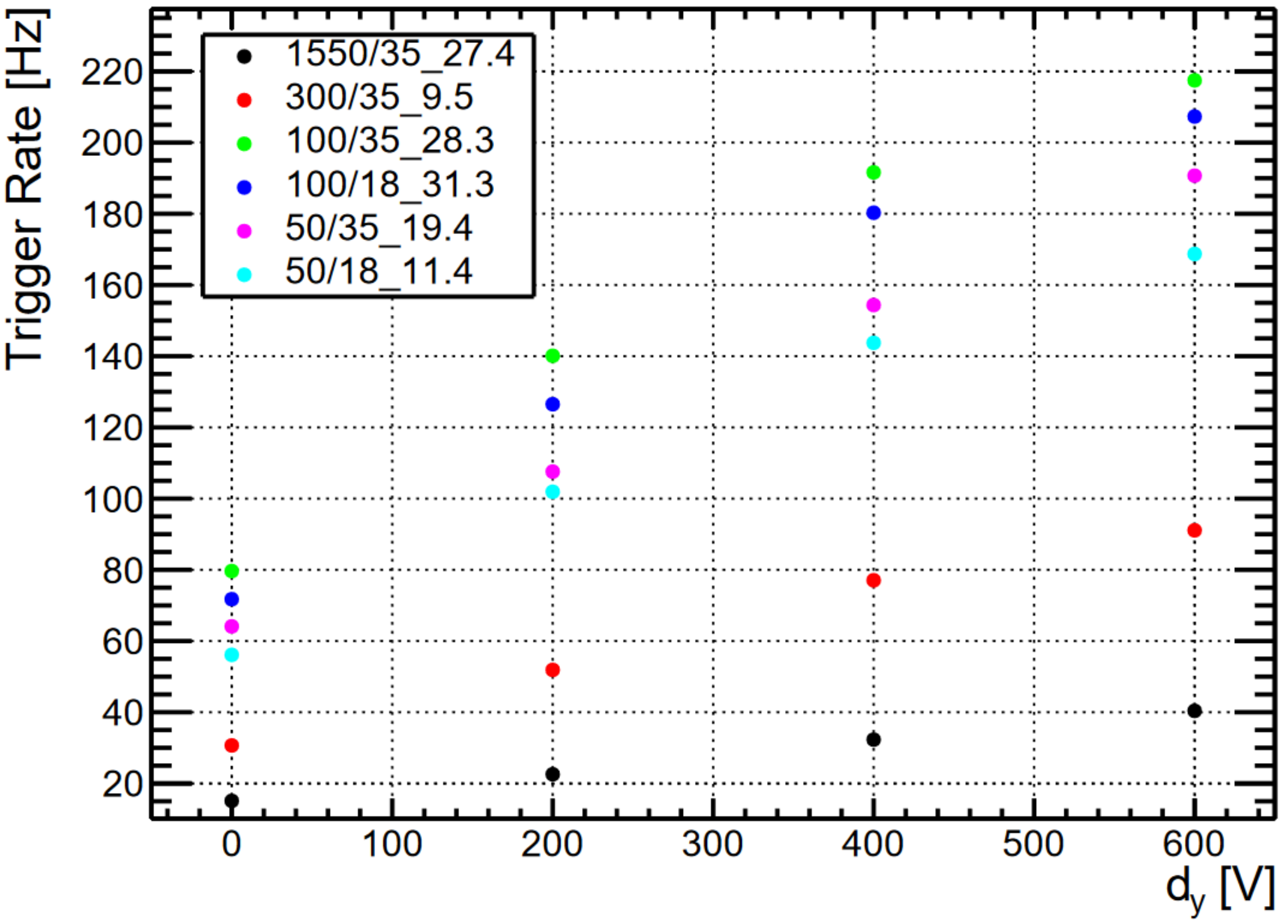
	x_{sub}, material	x_{Cu}
1550/35	$1550\ \mu m$, FR4	$35\ \mu m$
300/35	$300\ \mu m$, FR4	$35\ \mu m$
100/18	$100\ \mu m$, Kapton	$18\ \mu m$
100/35	$100\ \mu m$, Kapton	$35\ \mu m$
50/18	$50\ \mu m$, Kapton	$18\ \mu m$
50/35	$50\ \mu m$, Kapton	$35\ \mu m$

- All layers have $w = 0.4\ mm$ and $d = 0.4\ mm$

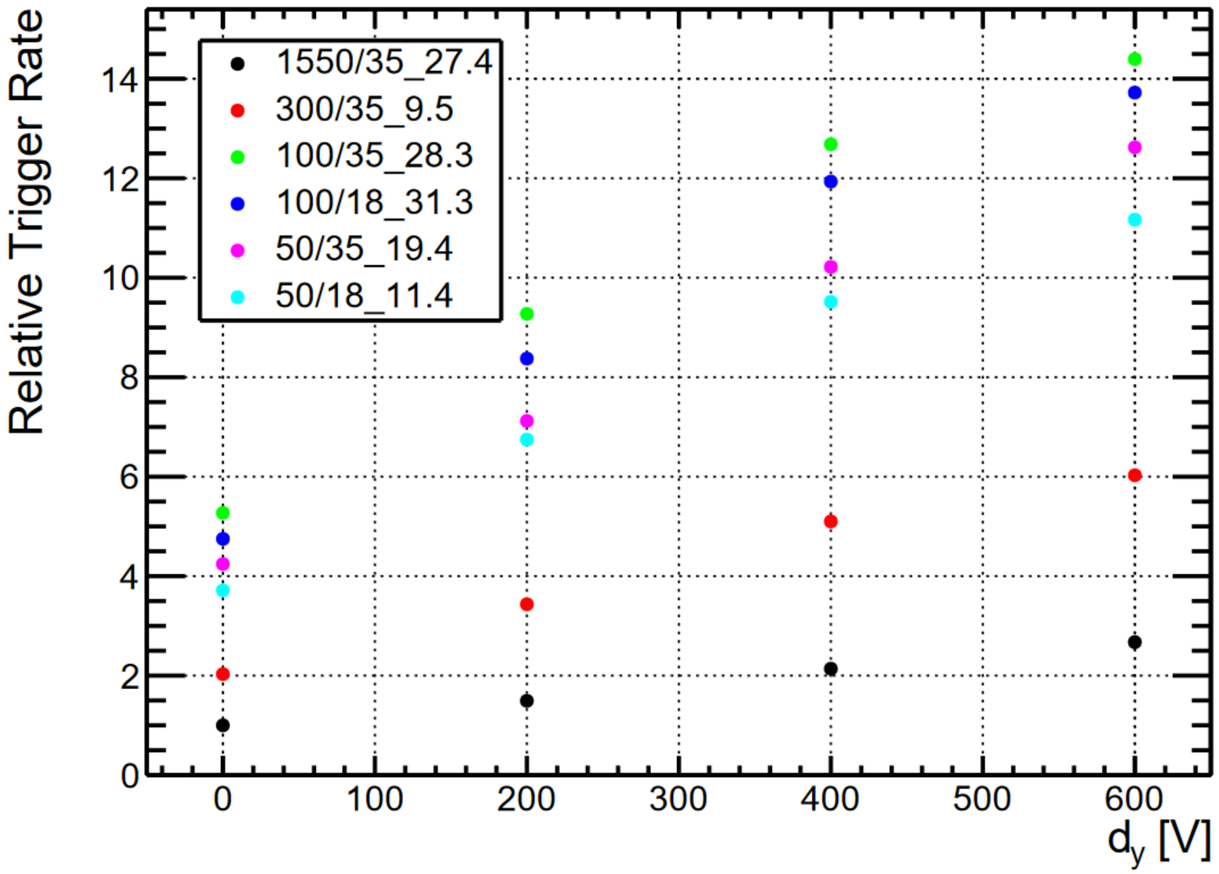
Measurement: Layer Investigation

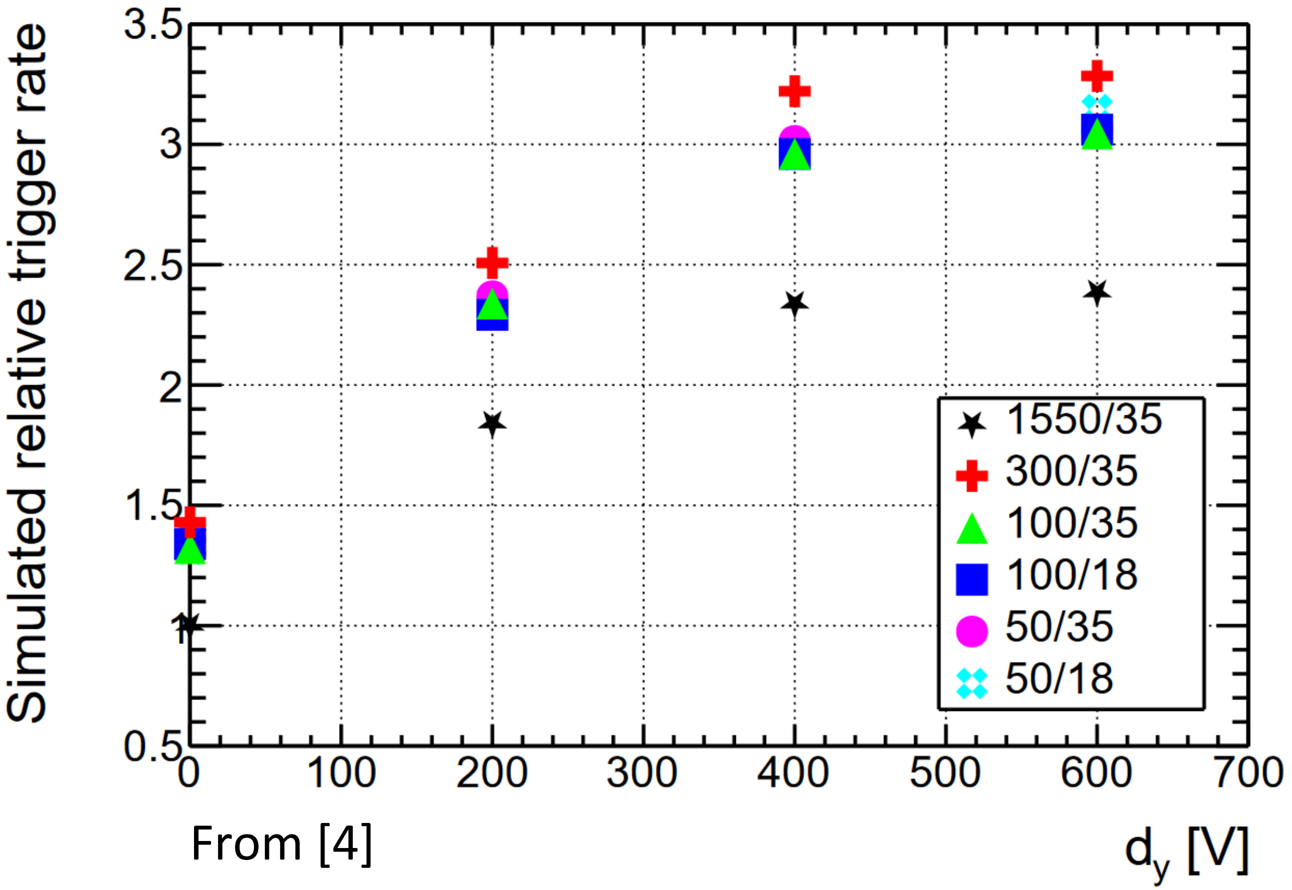
- Worst performance for 1550 μm and 300 μm thick FR4 layers
  - More passive material
- 35 μm of Cu perform better than 18 μm of Cu
  - More active material
- 50 μm thick layers are slightly worse than 100 μm thick layers
  - Less geometrically stable ⇒ Less efficient guiding

⇒ Improvement by a factor of up to ≈ 5.5 compare with 1550/35



Measurement: Comparison with Simulation



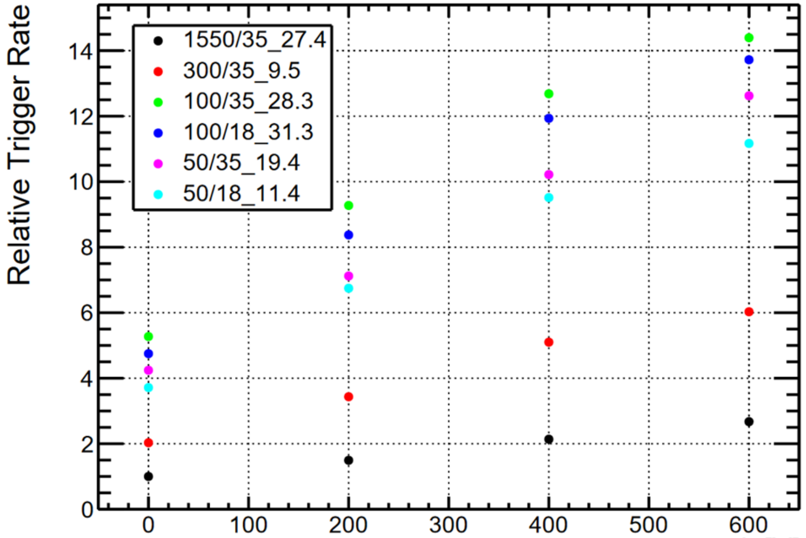


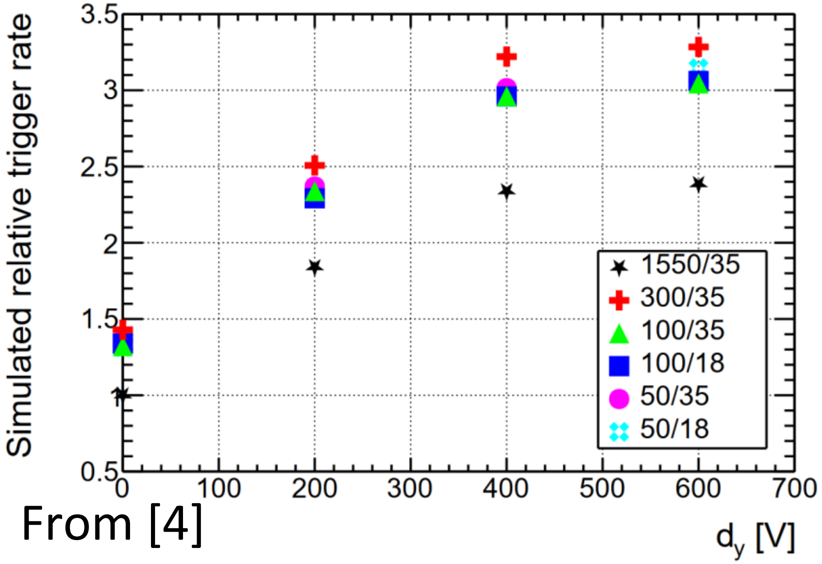
From [4]

Measurement: Comparison with Simulation

- All normalised to 1550/35 (get rid of systematics)
- 1550/35 behave nearly identical
- In the simulation all but 1550/35 perform very similar
  - More difference in the measured data
- Simulation and measurement disagree on the performance of 300/35
- Simulation indicates that 50/18 & 50/35 would ideally be as efficient as 100/35
  - Not ideal guiding in the measurement

⇒ Work in progress ⇒ further investigations needed

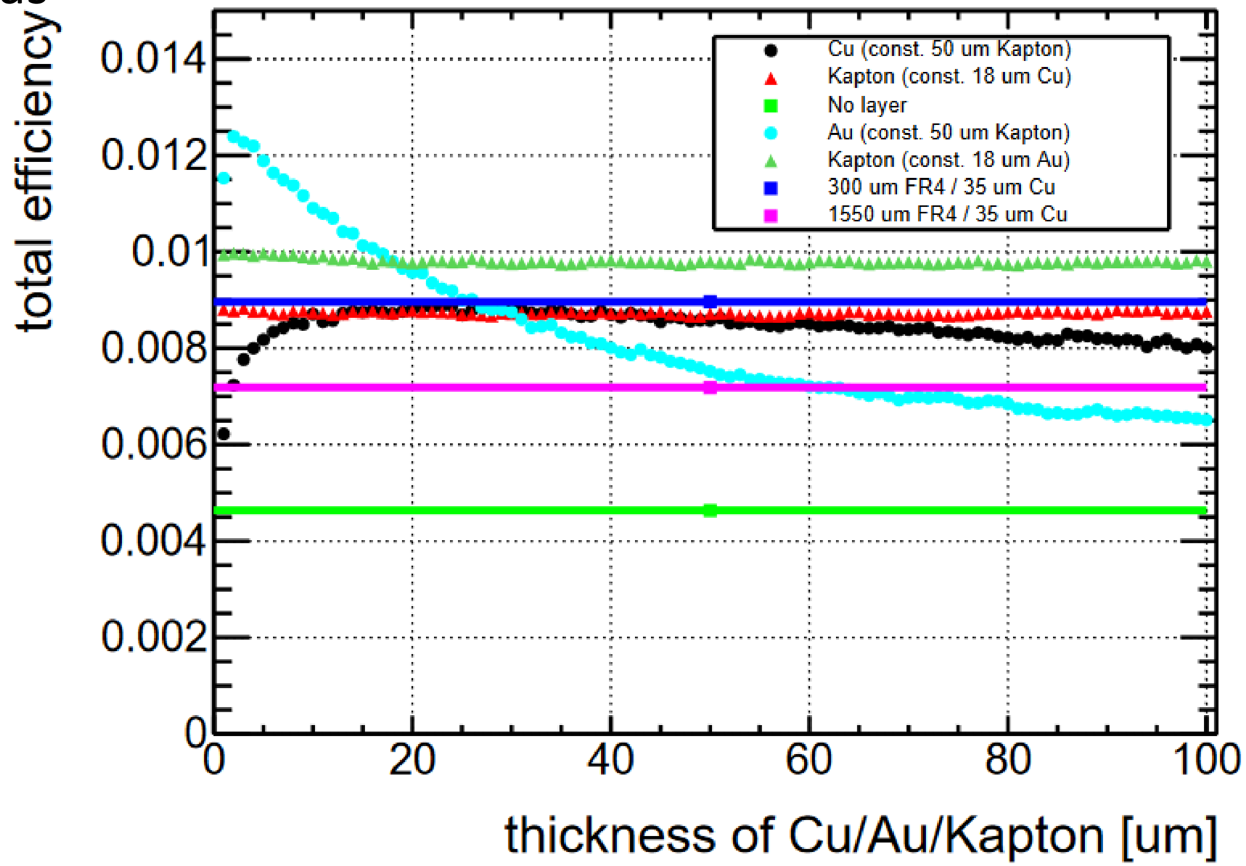




From [4]

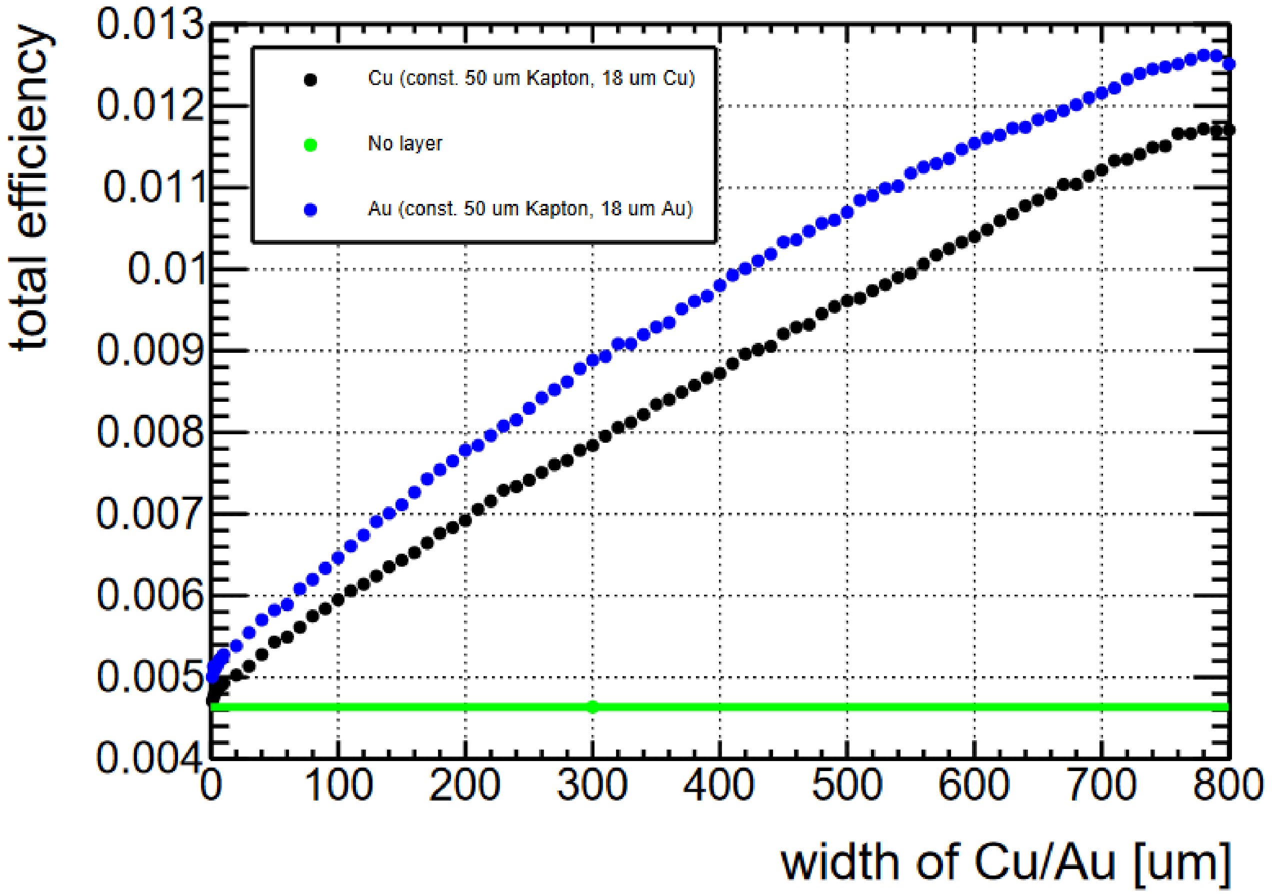
Simulation: Geant4: Thickness & Material

- Total efficiency: a least 1 electron reaches gas
- Au exceeds Cu for $\lesssim 30\ \mu m$
  - But: Too much metal is detrimental
- Steep rise at the beginning
  - Thickness smaller than the range of e- in Cu
- Kapton has nearly no effect
- Without layers: 0.46 %
  - Cu layers: 0.88% ⇒ 1.9x w/o
  - Au layers: 1.24% ⇒ 2.7x w/o
- 50/18 and 50/35 as good as 300/35



Simulation: Geant4: Width & Distance

- The efficiency for Au is higher than for Cu, as expected
- Efficiency rises with increasing width and decreasing distance between the strips
- Small dip at the end
  - Loss of surface area due to connecting strips
- Further improvement by over a factor of 2
  - Cu layers: 1.17% ⇒ 2.5x w/o
  - Au layers: 1.26% ⇒ 2.7x w/o

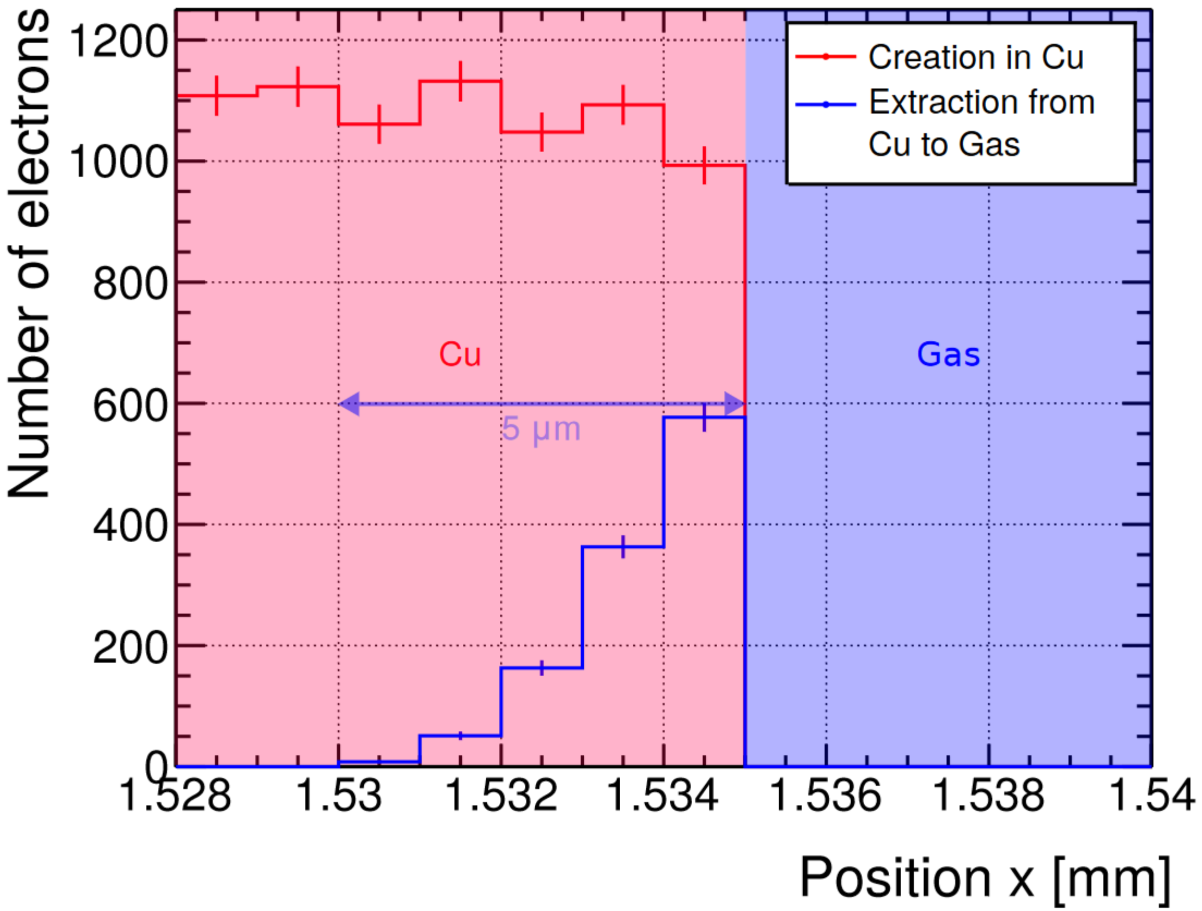


Literature

- [1]:The gas electron multiplier (GEM): Operating principles and applications“. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (7. Aug. 2015). doi: https://doi.org/10.1016/J.NIMA.2015.07.060
- [2]: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). https://doi.org/10.1007/s10894-018-0181-2
- [3]: National Institute of Standards and Technology: XCOM: Photon Cross Sections Database. https://www.nist.gov/pml/xcom-photon-cross-sections-database, [Online, Accessed: 7.6.2023]
- [4]: Katrin Penski, Work in progress (internal communication)
- [5]: National Institute of Standards and Technology: ESTAR: Stopping-Power Range Tables for Electrons, Protons, and Helium Ions. https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions, [Online, Accessed: 7.6.2023]

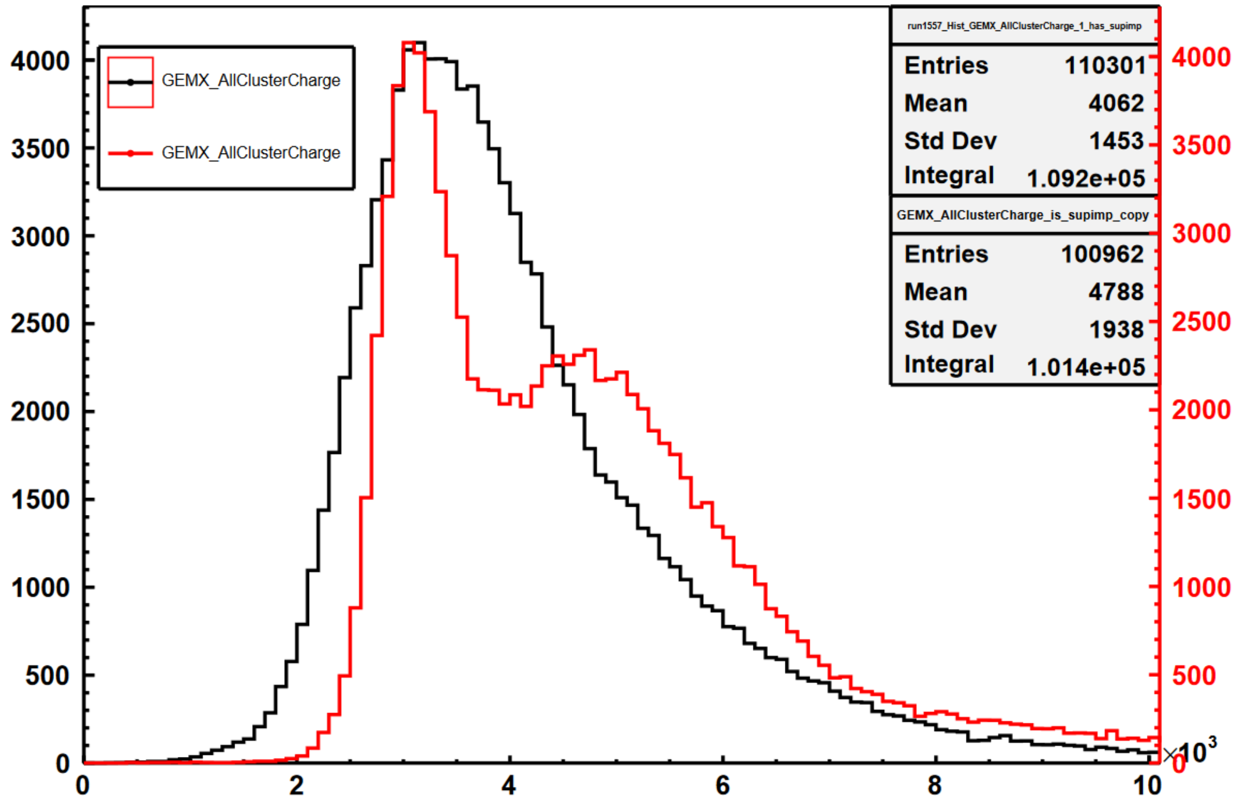
Motivation

- Problem: Not all produced electrons reach the gas
- CSDA-range of 50 keV electrons in Cu is $\approx 7.75\ \mu m$ [5]
  - $50\ keV\ \approx 59.5\ keV\ -\ E_{K-shell}$
- CSDA-range of 50 keV electrons in Kapton is $\approx 1.369\ \mu m$ [5]

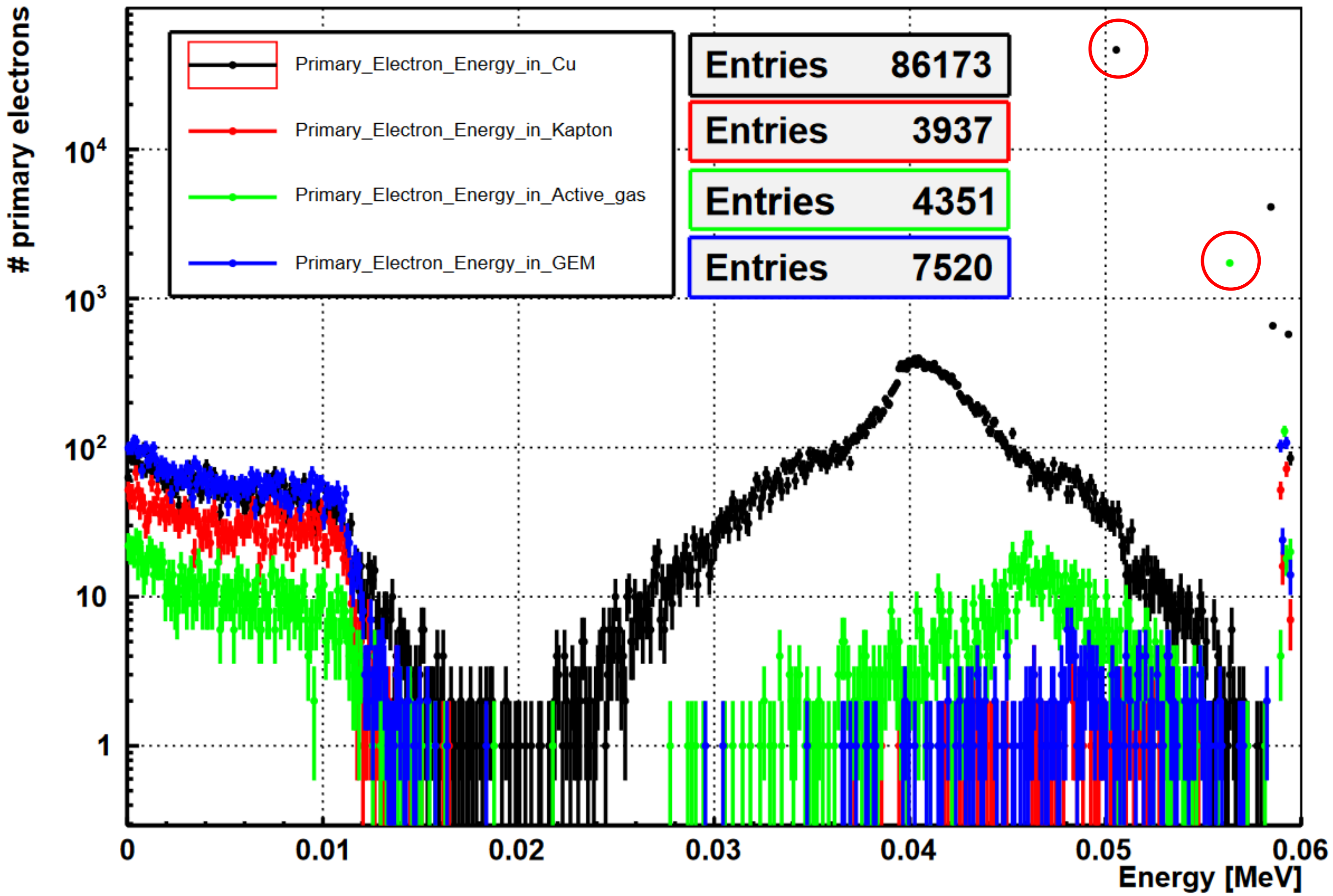


Measurement: AllClusterCharge

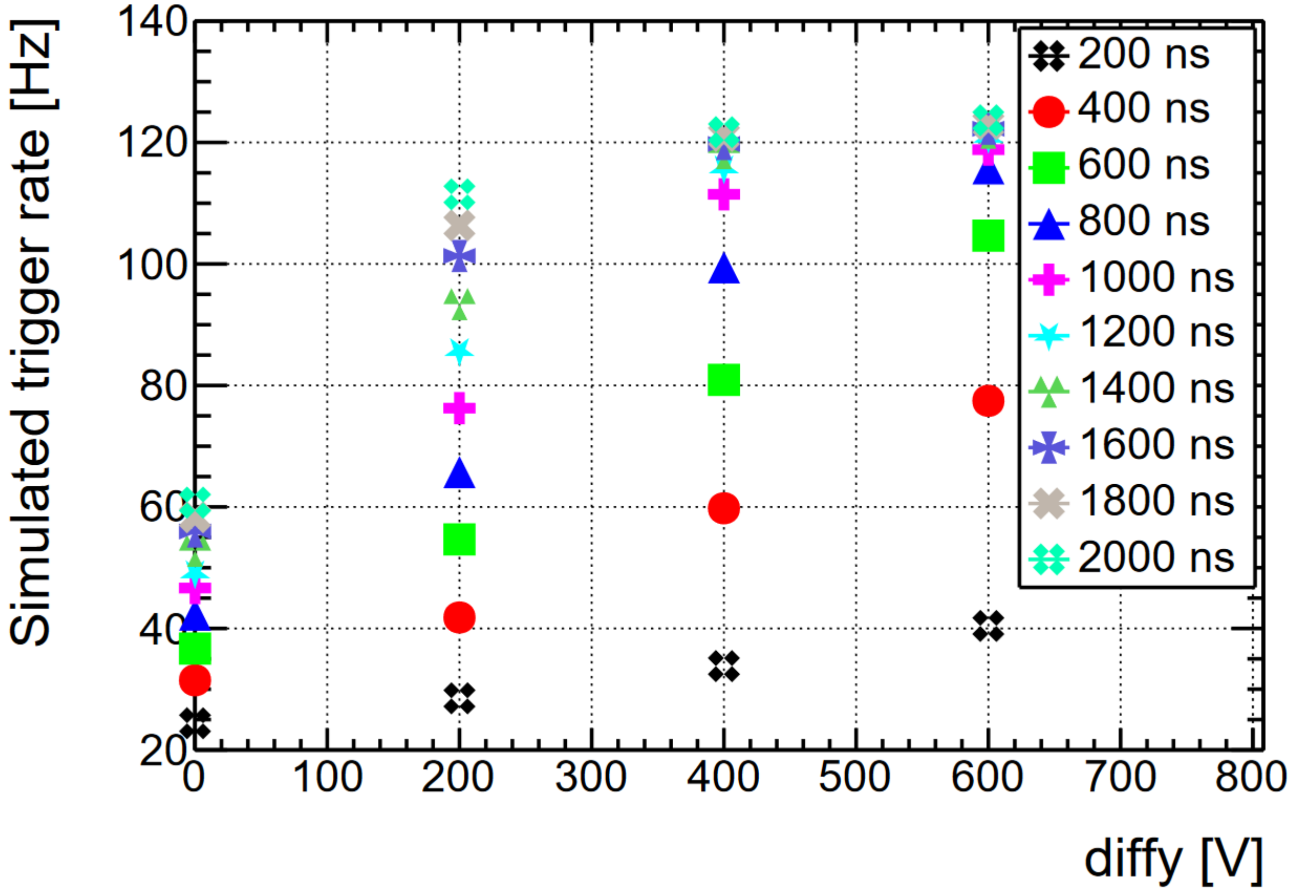
- Black: AllClusterCharge, large Det., 50/18 layers, $d_y = 400\ V$
- Red: AllClusterCharge, small Det., 50/18 layers, $d_y = 400\ V$
- Would expect two peaks
  - 50 keV from Cu (k-shell)
  - 60 keV from Ar



Measurement: AllClusterCharge



Simulation


Simulated trigger rate [Hz]
140
120
100
80
60
40
20
0
100
200
300
400
500
600
700
800
diffy [V]
200 ns
400 ns
600 ns
800 ns
1000 ns
1200 ns
1400 ns
1600 ns
1800 ns
2000 ns