EDIT 2020

Track 4: Gas Detectors

Introduction

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Gas Detector Track

Introduction

- Organization
- Gas Detectors Basics
- Amplification
  - MPGD: GEM & Micromegas

- Signal Reconstruction

- Experiments
  - Basics: Fe55 spectrum
  - Gain measurement 1+2
  - GridPix gain studies
  - Fitting and pad Size studies

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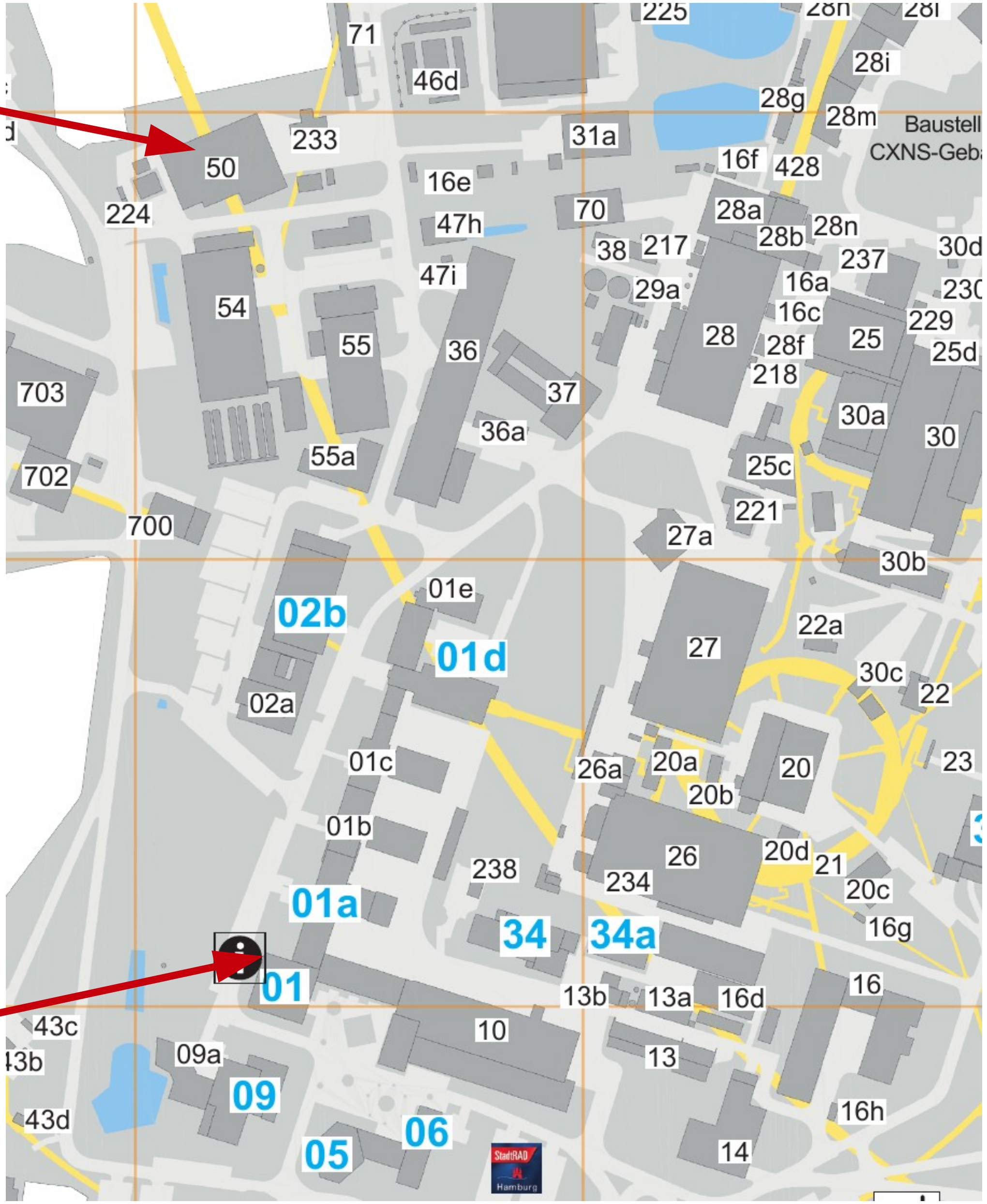
Organization

- Locations:
  - Introduction lecture + simulation/analysis: seminar room 1b
  - All other tasks:
    detector lab in HERA hall west / building 50
    - 7 floors underground
    - Access with DACHS card:
      Everyone has to check in when entering and out when leaving
      - ← We need to track how many people are down

Hall west
Building 50



Seminar
room 1b

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Tutors/Supervisors

- Hall West - Lab
  - Ralf Diener
  - Markus Gruber (Task 14: GridPix - Measuring Single Electrons)
  - Christoph Krieger
  - Felix Müller (Task 13: The Iron-55 Spectrum)
  - Oliver Schäfer (Task 15: Gain Determination by Measuring GEM Currents)

- Seminar Room 1b - Analysis
  - Engin Eren
  - Remi Ete
  - Lennart Huth (Task 16: Impact of Readout Granularity)

Gas Detectors

"old-school"?

- Low material, low energy loss, low multiple scattering
- Comparably cheap to cover large areas/volumes
- Quasi continuous tracking i.e. in a time projection chamber → excellent pattern recognition
- Particle identification via dE/dx measurement
- Resolution about 100 μm, time 1-10 ns
  - Moderate single point resolution ↔ # of measurement points
  - Glückstern equation
    - Uniform medium
    - Equally spaced measurements
    - Negligible multiple scattering
    - valid for N ≥ 10

$$\frac{\delta_{p_T}}{p_T^2} = \frac{\sigma_{r\phi}}{0.3\, B\, L^2}\sqrt{\frac{720}{N+4}} \left[\frac{T\, m}{GeV/c}\right]$$

$\frac{\delta_{P_T}}{P_T^2}$: momentum resolution
$\sigma_{r\phi}$: single point resolution ($\perp$ to bending plane)
L: length of tracker (radius)
B: magnetic field N
N: number of measurement points

- Gas detector used in: CMS, ATLAS, ALICE, LHCb, Belle 2, TOTEM, COMPASS, CAST, T2K, NA48, DIRAC,...

Gas Detectors

Basic Principle

- The detectors discussed here work on the same principles (not covered: Cherenkov etc.)
- Charged particle or photon passes through the sensitive gas volume and ionizes the gas atoms or molecules, resp.
  - In the volume a sufficient electric field is applied to
    - Separate ions and electrons
    - Drift the electrons towards the readout
  - # of electrons too small to be read out directly:
    - Amplification in a strong electric field (avalanche effect)
  - Readout
    - Motion of electrons and ions close to the readout induces a current on the electrodes

Example: Time Projection Chamber (TPC)

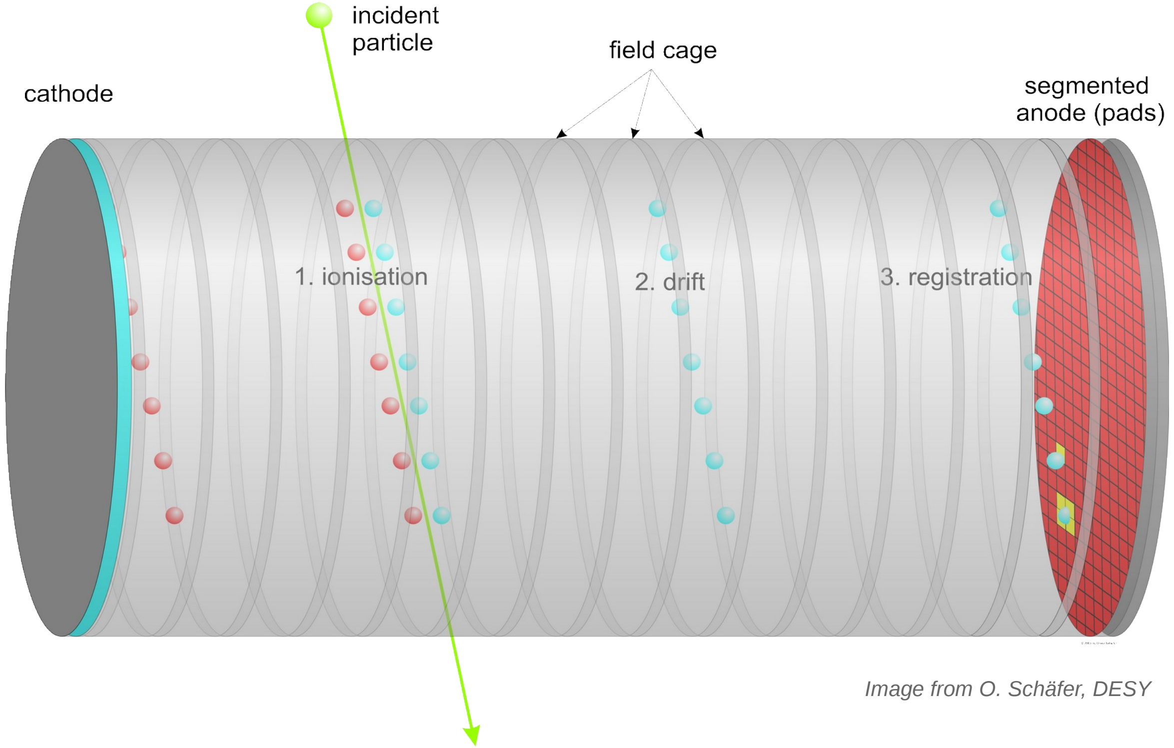


Image from O. Schäfer, DESY

- For tracking: magnetic field → momentum determination from curvature/charge measurement

Ionization

Energy Loss

- Average energy loss: Bethe-Bloch

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{n z^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\epsilon_0}\right)^2\left[\ln\frac{2 m_e c^2 \beta^2}{I\cdot(1-\beta^2)}-\beta^2\right]$$

with $n=\frac{N_A\cdot Z\cdot\rho}{A\cdot M_u}$

  - Mostly depends on particle characteristics charge and momentum (dependence on medium rather weak: Z/A ~ 1/2)
- Straggling functions in moderate thin layers of medium:
  - Landau'ish behaviour: Long tail towards higher energy depositions (delta electrons)
- Ionization
  - Primary: electrons liberated from atoms/molecules
  - Secondary: all processes that need mediator process like e.g. ionization by energetic primary e⁻ → delta electrons

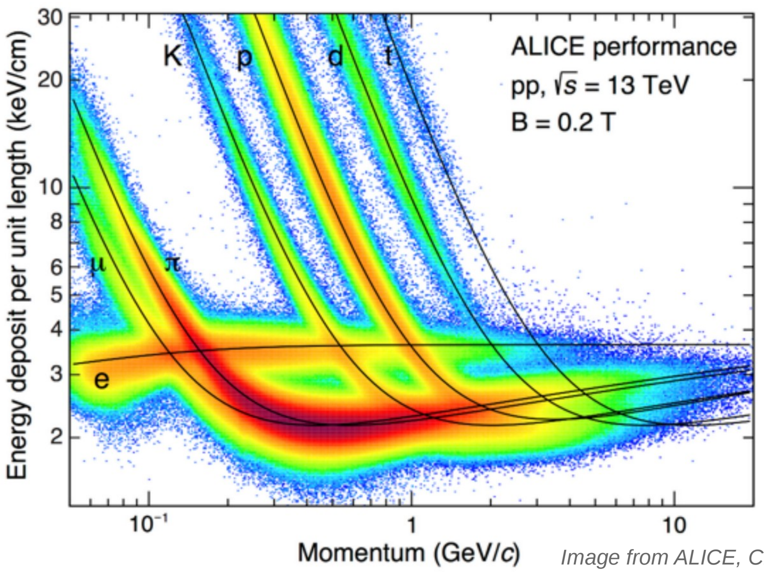


Image from ALICE, CERN

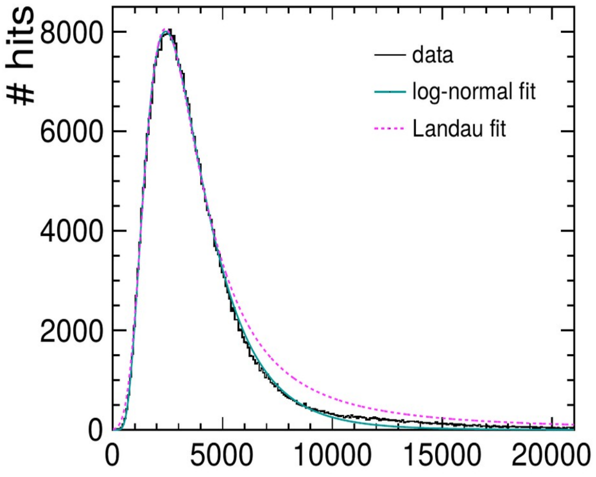


Image from P. Malek

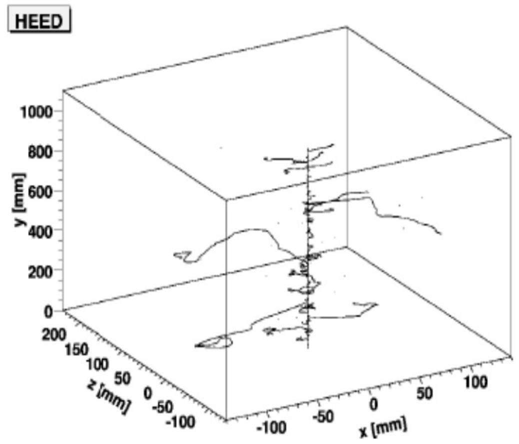


Image from HEED simulation by A. Münnich

Ionization

Producing electrons

- Deposited energy derived from number of produced electrons
- Number of electrons produced: $n_e(dx) = \frac{dE}{dx} \cdot I^{-1}$
  - Depends linearly on transferred energy,
    I: average ionization energy (larger than I_{min}, excitation processes and energy of e^- / ion pair)
  - Number constrained by energy conservation and quantized liberation of shell e-
  - Standard deviation: $\sigma_{n_e} = \sqrt{F * n_e}$
    F: Fano factor

- In Argon based gases at atm. pressure
  - Interactions/clusters per cm ~ 25
  - Average # e^- per cluster ~ 3-4

  → #e^-/cm ~ 90
  - F = 0.21

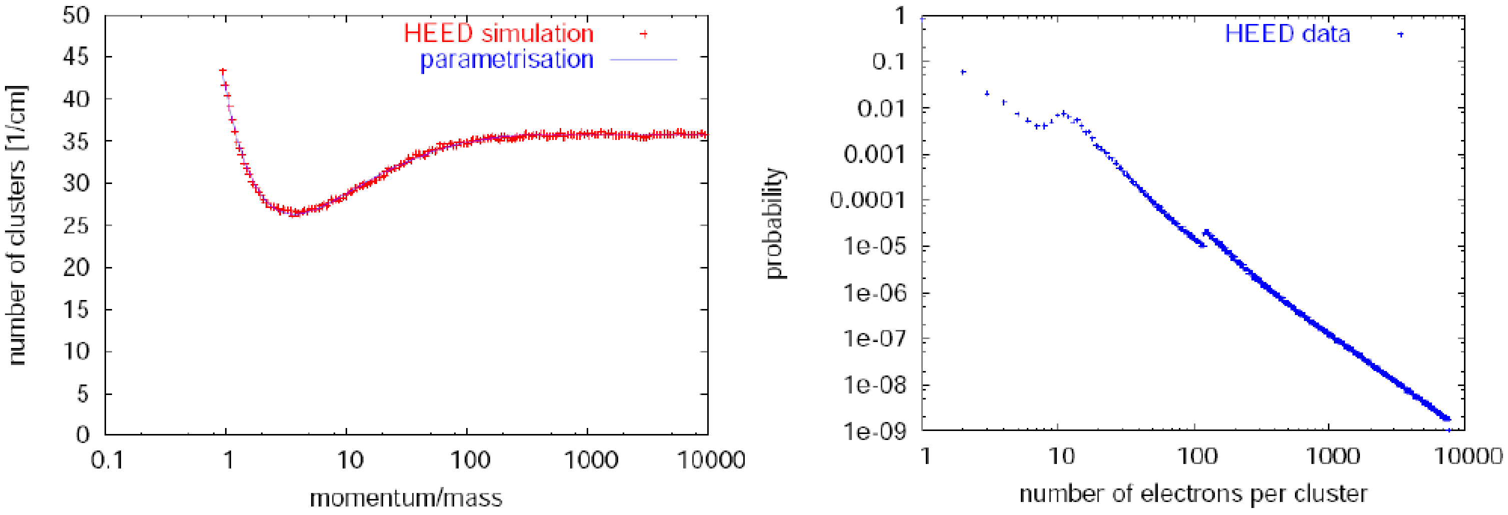


Image from HEED simulation done by A. Münnich

Drift

Basics

- In the applied field the primary/secondary electrons drift towards the readout at the anode
- Movement described by the Langevin equation

$$m_e \frac{d\vec{v}}{dt} = e\vec{E} + e\left(\vec{v} \times \vec{B}\right) - K\vec{v}$$

m_e : electron mass
e : electron charge
$\vec{v}$: electron velocity
$\vec{E}$: electric field
$\vec{B}$: magnetic field
K : frictional force coefficient caused by interaction with gas molecules

- Important parameters
  - Drift velocity: depends on gas mixture, E field
  - Diffusion: depends on gas mixture, E field, B field

$$\sigma = \sqrt{\sigma_0 + D\,z}$$

σ : charge cloud width
σ_0 : initial width
D : diffusion coefficient
z : drift distnce

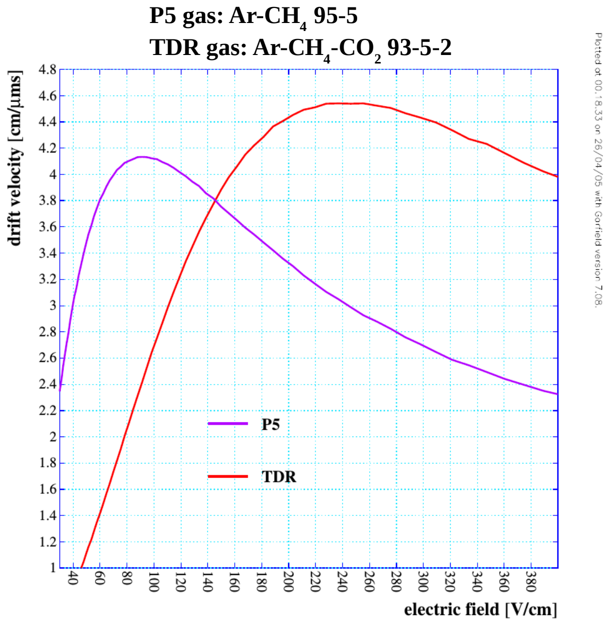
Detector Gas

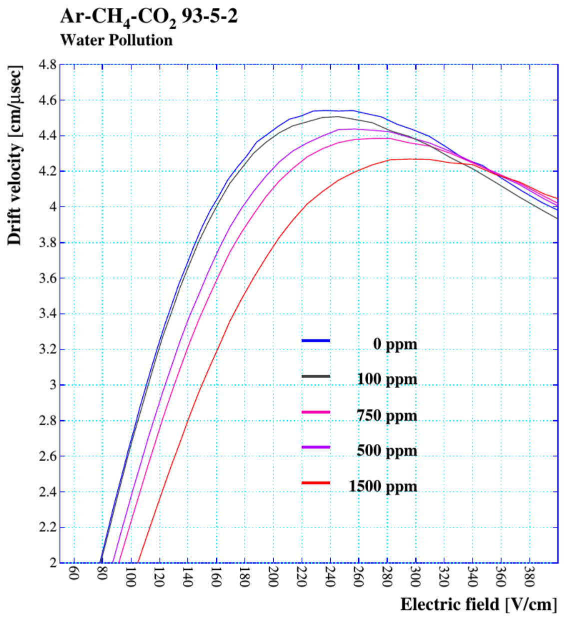
Choosing the Medium

- Usually a noble gas (inert) combined with a additions of quencher gases

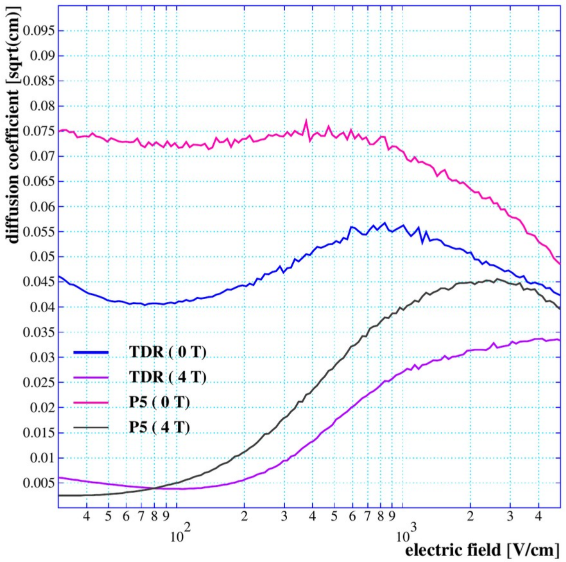
- Commonly Argon is used
  - Cheap (3rd most common gas in athmospere)
  - Non toxic, non flammable/explosive

- Quenching gas - Preventing discharges
  - Absorbtion of photons produced in avalanches before the produce new e^- at cathode
  - Often organic molecules:
    CO_2, CH_4, iC_4H_{10} (isobutane), C_5H_{12} (pentane),….
    - Choice should consider of polymerization → aging
  - Sometimes additional additives to influence drift velocity, diffusion





Images from T. Lux
FLC group, DESY



Gas Amplification

Basics, Amplification Structures

- Amplification in high electric field
  - Electrons gain enough energy between collisions to ionize gas
  - Avalanche process
  - Often proportional region used

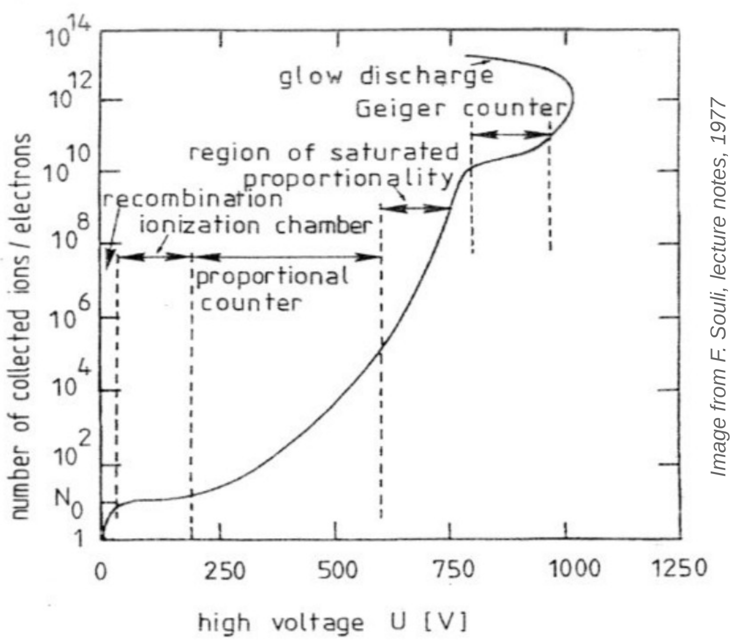
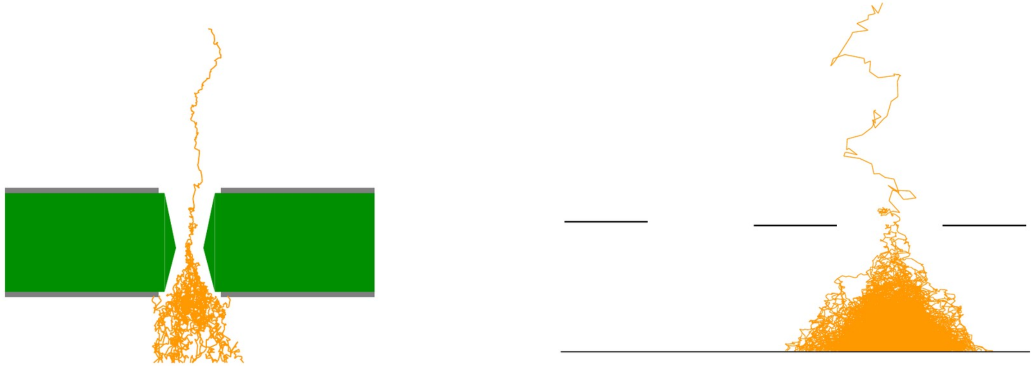


Image from F. Souli, lecture notes, 1977

- Resistive Plate Chamber (RPC) / Drift tube

- MPGDs: Gas Electron Multiplier / Micromegas



Images from “Basics of Gaseous Detectors” lecture @ EDIT2011
S. F. Biagi, H. Schindler, R. Veenhof

GEM: Gas Electron Multiplier

Principle

- Introduced by F. Sauli (1996)
- Some 10 µm thick insulator (Kapton) coated on both sides with a few µm of conductor (copper)
- Highly perforated (CERN standard: 140 µm pitch, 70 µm hole diameter)
- Voltage of a few hundred volts applied between copper layers
  → high field in holes (10's kV) → amplification within the holes
- Gain up to about 10^3 for a single GEM feasible
- Higher stability (at high integrated gain) with Multi-GEM-Structure

  + more flexibility

  → Intrinsic ion feedback suppression

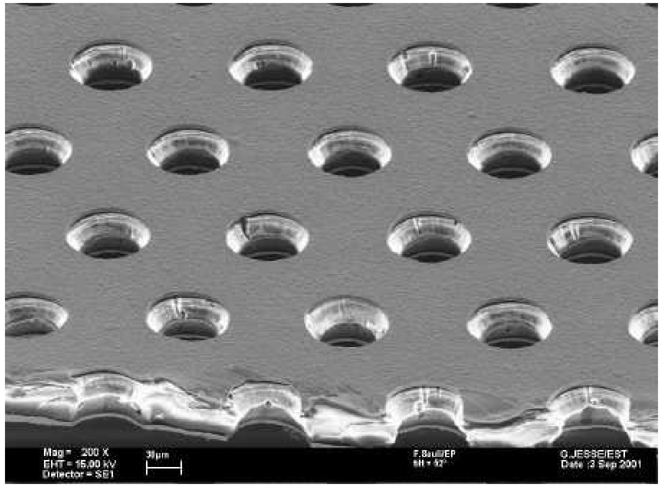
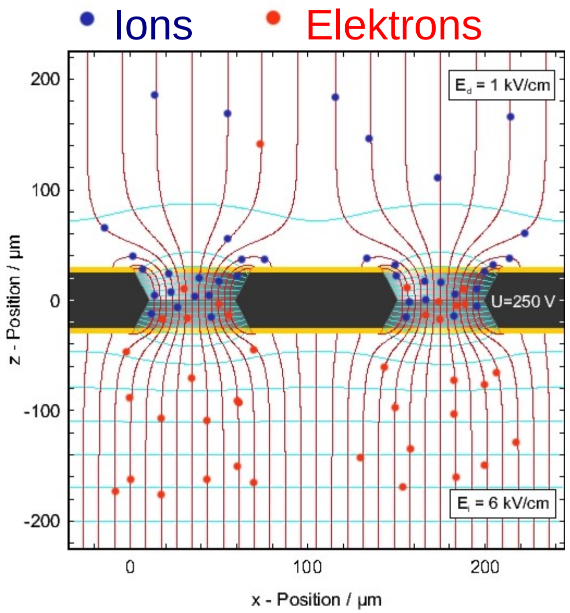
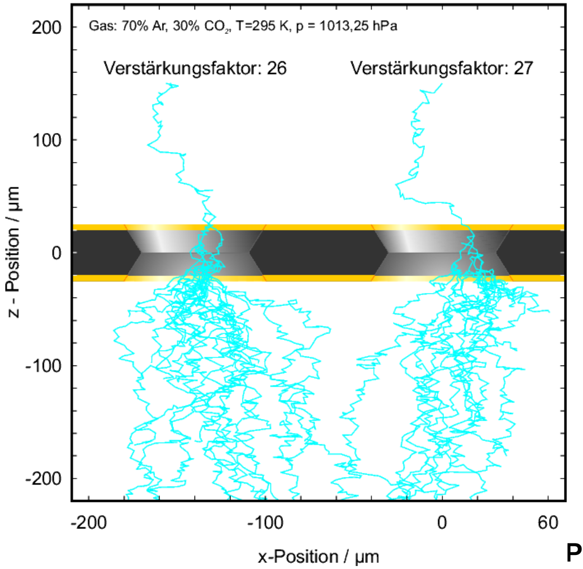


Image from Gas Detectors Development group CERN, 2014, url: www.cern.ch/GDD.



Images from FLC group, DESY



GEM: Gas Electron Multiplier

Gain & Efficiency

- Gain usually means the effective Gain G_{eff}

$$G_{eff} = C \cdot G \cdot X$$

C: collection efficiency to pull incoming e^- into the hole

G: gas gain inside the hole

X: extraction efficiency to drift e^- from the hole

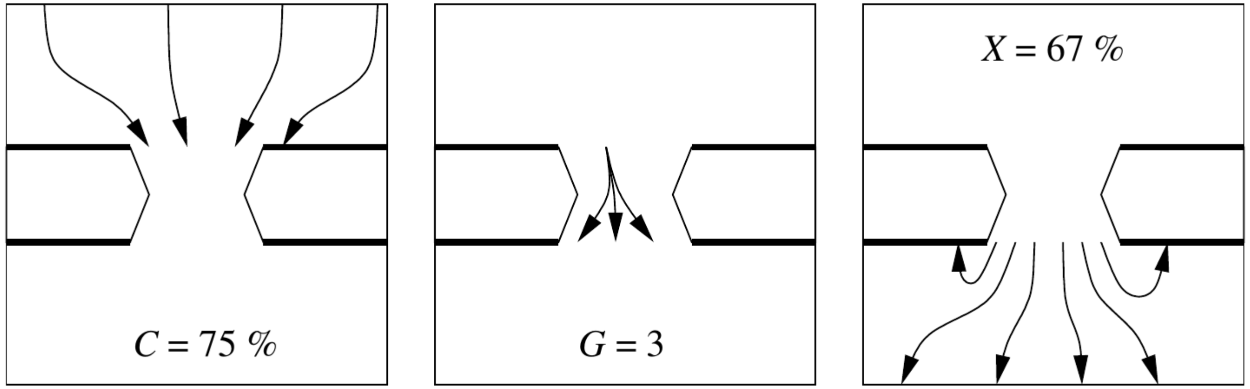


Image from A. Vogel

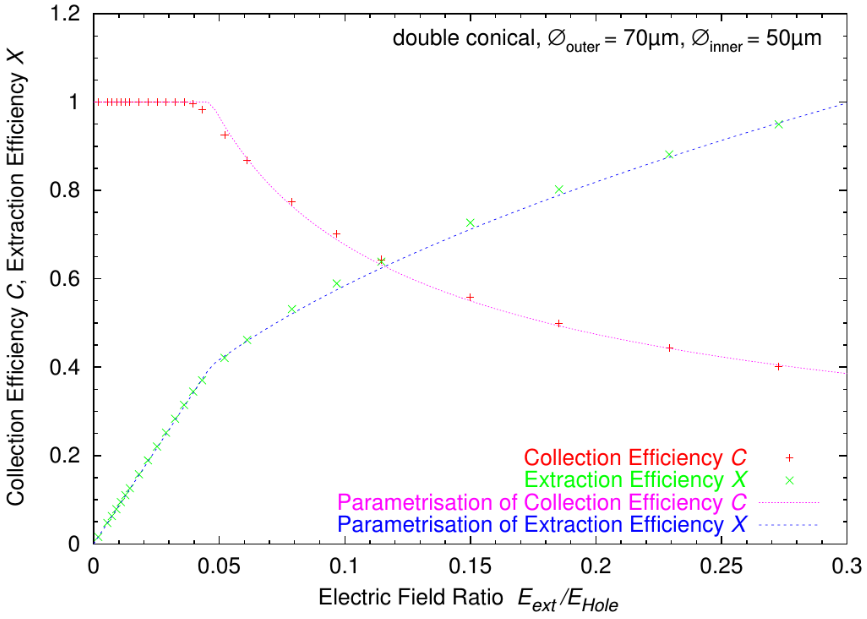


Image from desy-thesis-10-015, L. Hallermann: "Analysis of GEM Properties and Development of a GEM Support Structure for the ILD Time Projection Chamber"

GEM: Gas Electron Multiplier

Ions

- Ion backflow
  - Ions produced in the amplification drift back into the drift volume
  - Unwanted: distort field, catch electrons
  - Ion backflow $$IB = \frac{I_{cathode}}{I_{anode}}$$
  - ALICE-TPC GEM Upgrade
    - IB ~ 0.6 % at energy resolution of $\sigma/E < 12$ %
    - Ion backflow suppression of a
      - Single GEM ~ 10^{-1}
      - GEM stack ~ 10^{-2}-10^{-3}

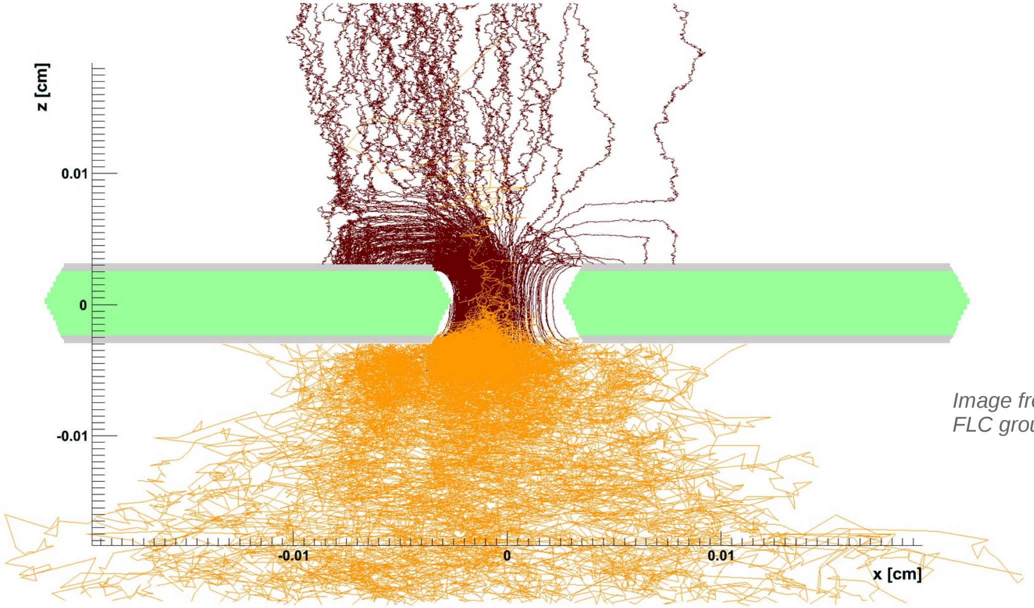
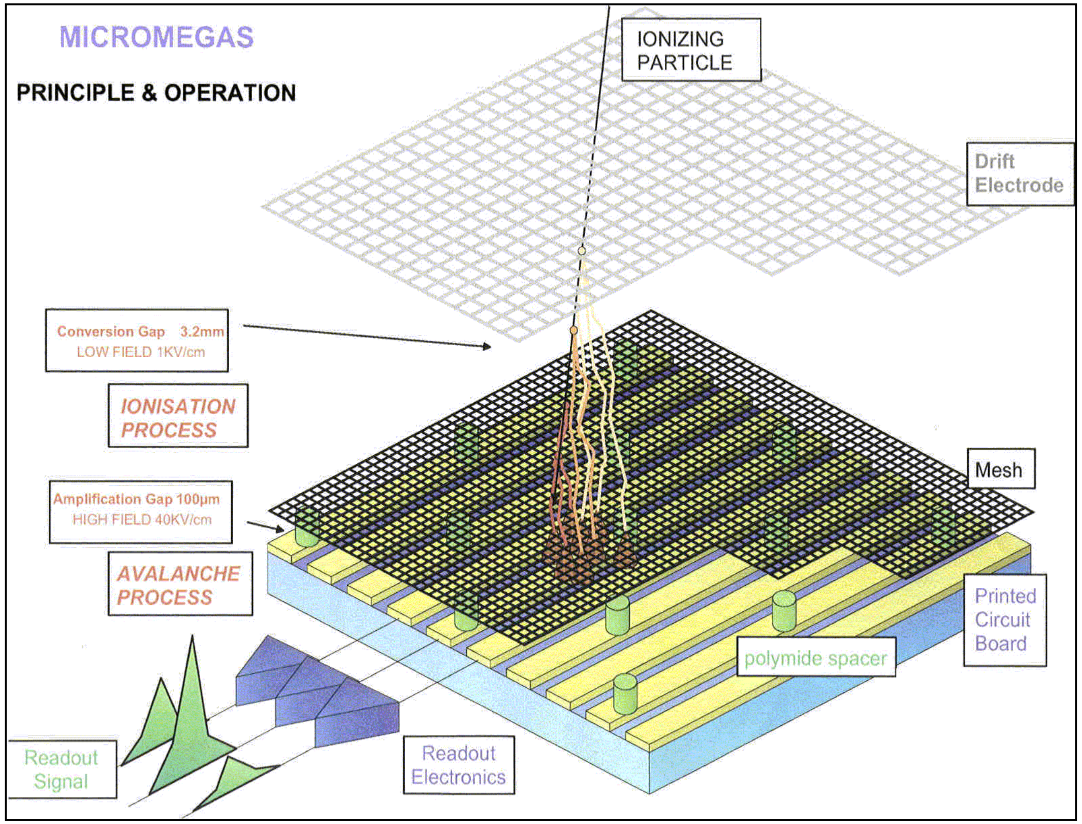


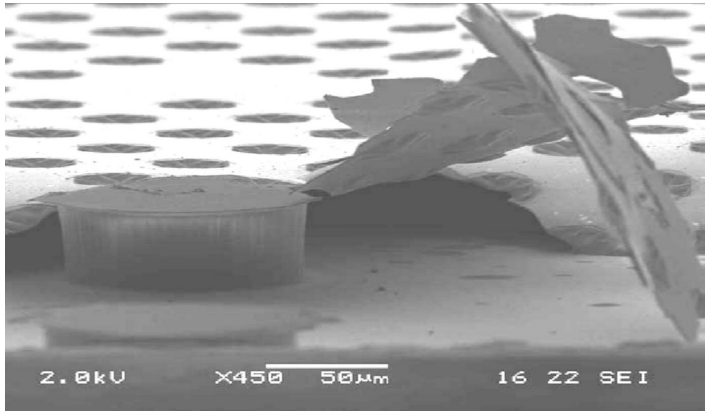
Image from K. Zenker FLC group, DESY

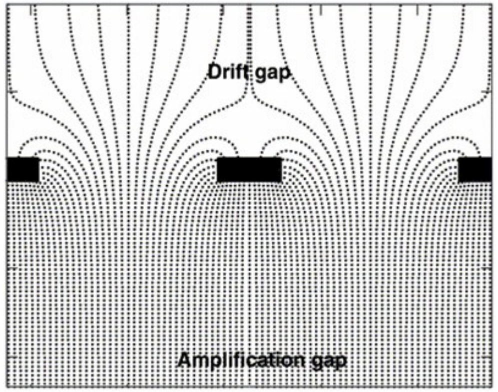
Micromegas

Principle

- Introduced by I. Giomataris, G. Charpak et al. (1995)
- Parallel plate gas avalanche detector with a small gap
- Micromesh held by pillars 50 µm above the anode plane
- Several kV/cm between mesh and anode
  → gas amplification
- Additional resistive layer on anode protects against discharges



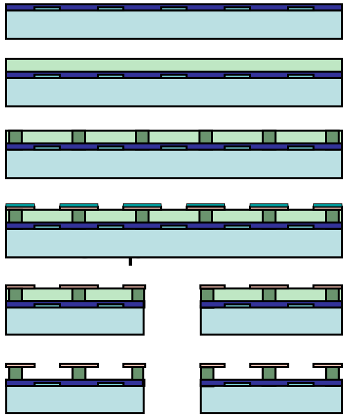




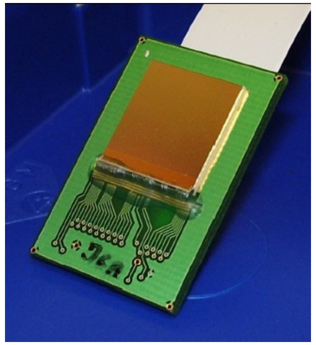
GridPix

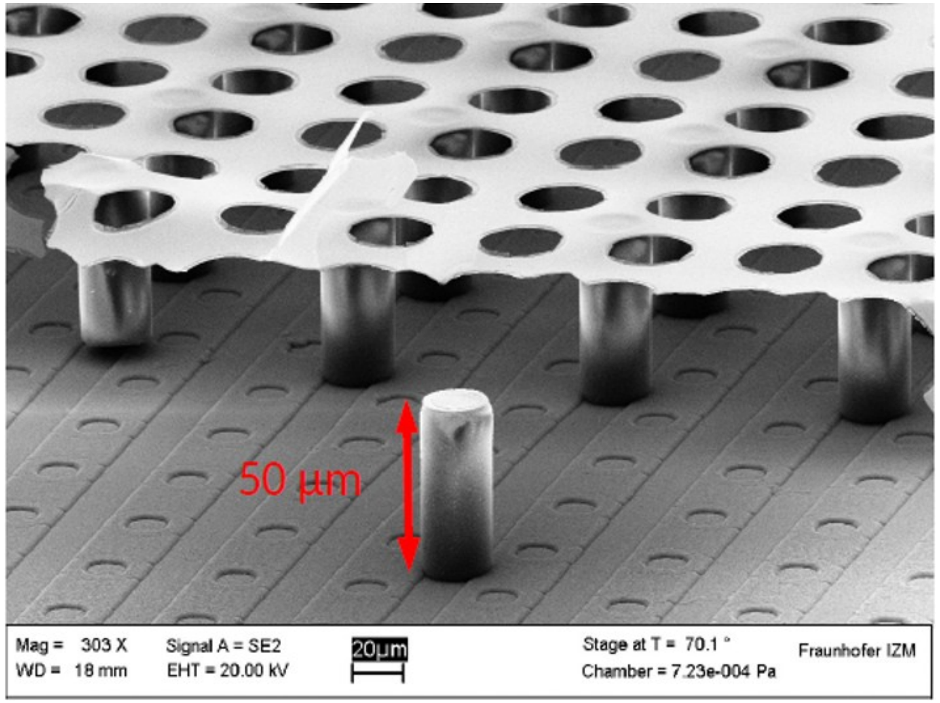
Micromegas and Pixels

- InGrid: Micromegas on a Timepix chip
- Produced with wafer post-processing
- Mesh holes aligned with pixels of the chip: single e$^-$ measurement



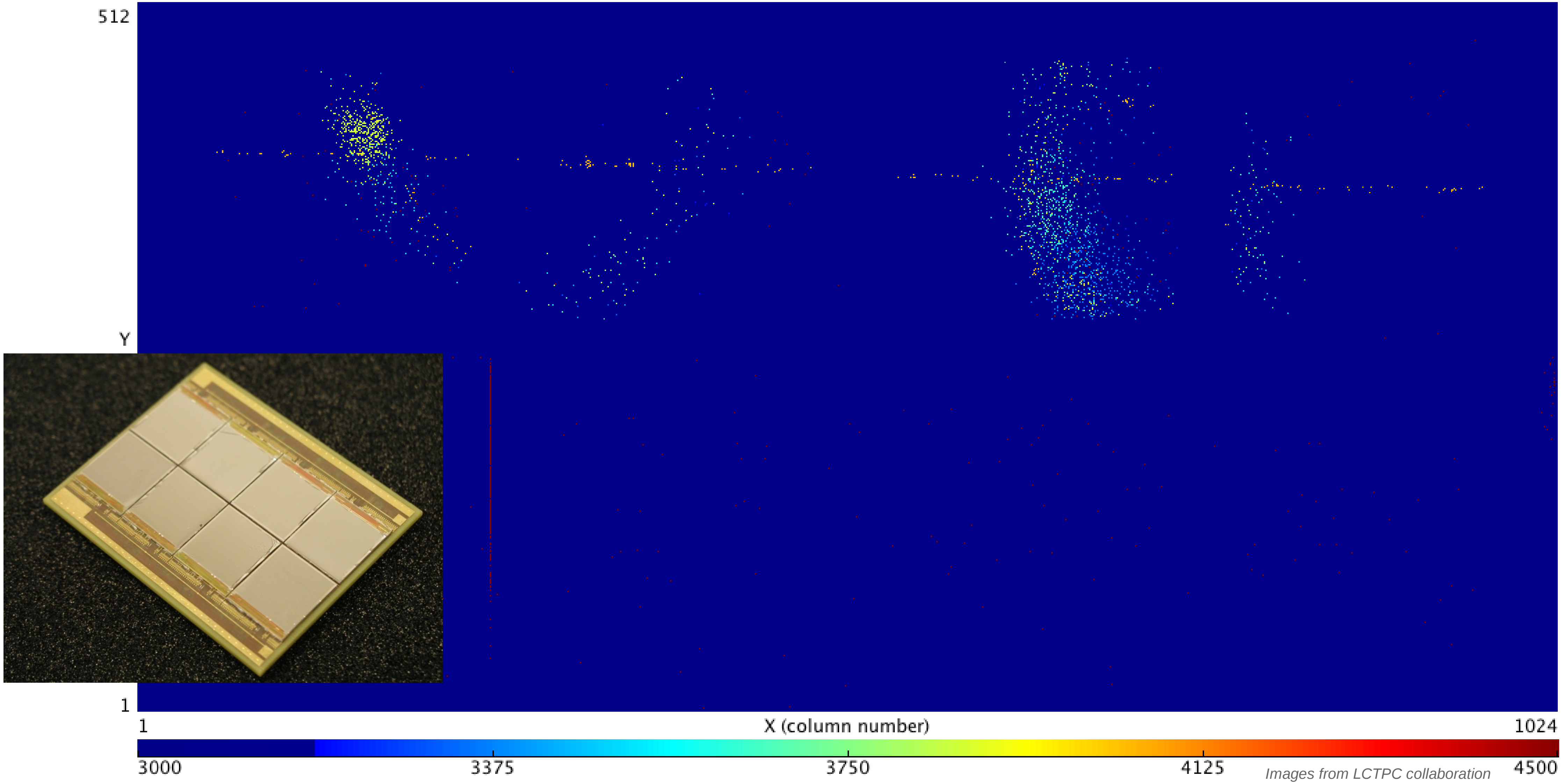
1. Formation of Si_xN_y protection layer
2. Deposition of SU-8
3. Pillar structure formation
4. Formation of Al grid
5. Dicing of Wafer
6. Development of SU-8





GridPix

Octopuce, He/iC4H10 (80/20), B = 1T, 5 GeV beam electron with two delta curlers, Dec 2010

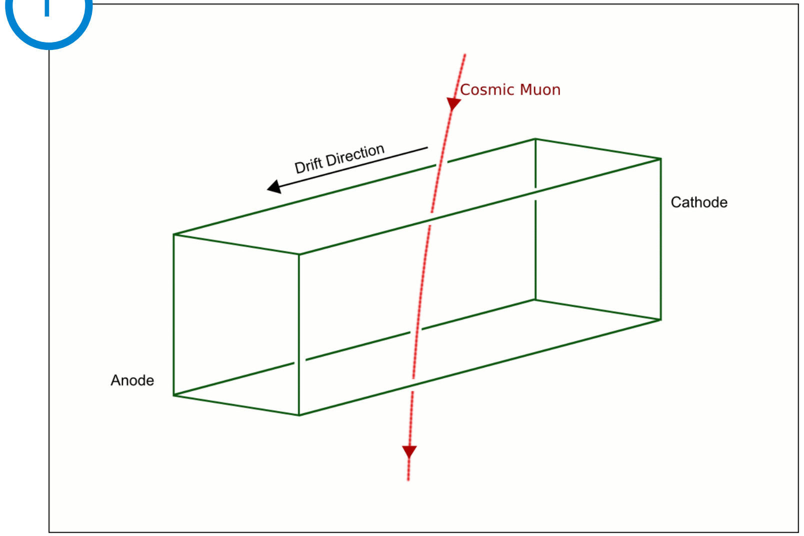


Images from LCTPC collaboration

Time Projection Chamber

Charge Signals

①



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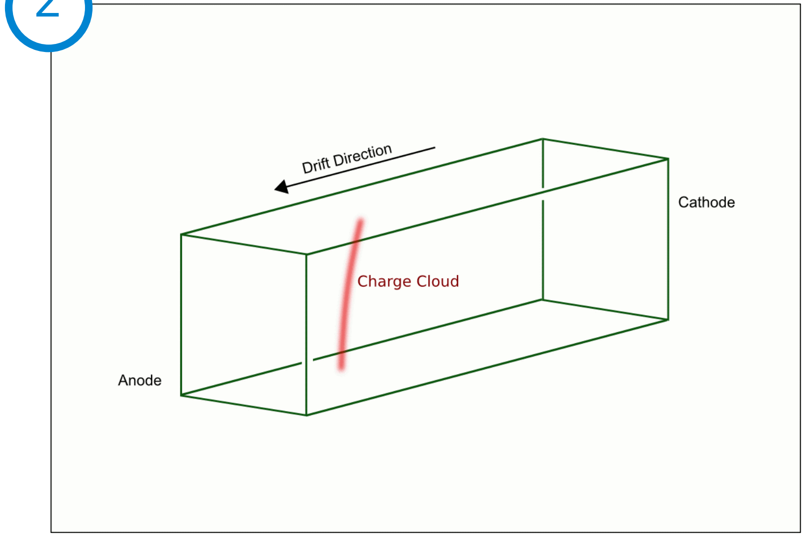

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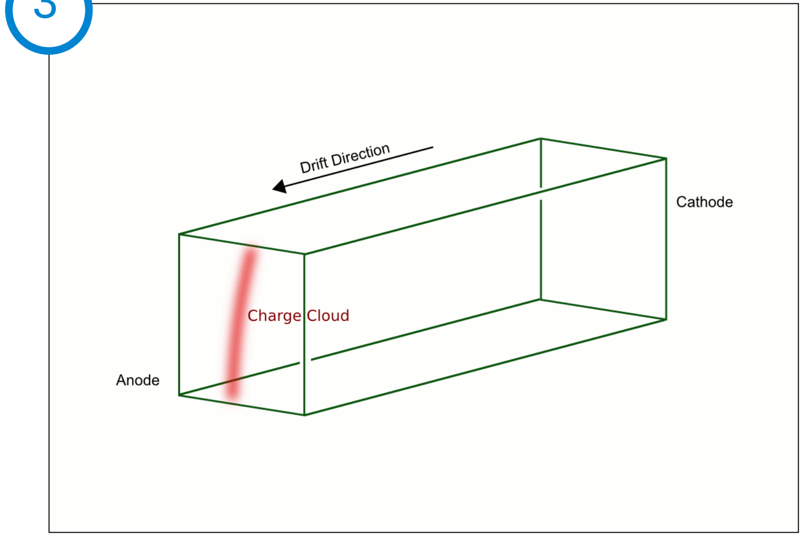

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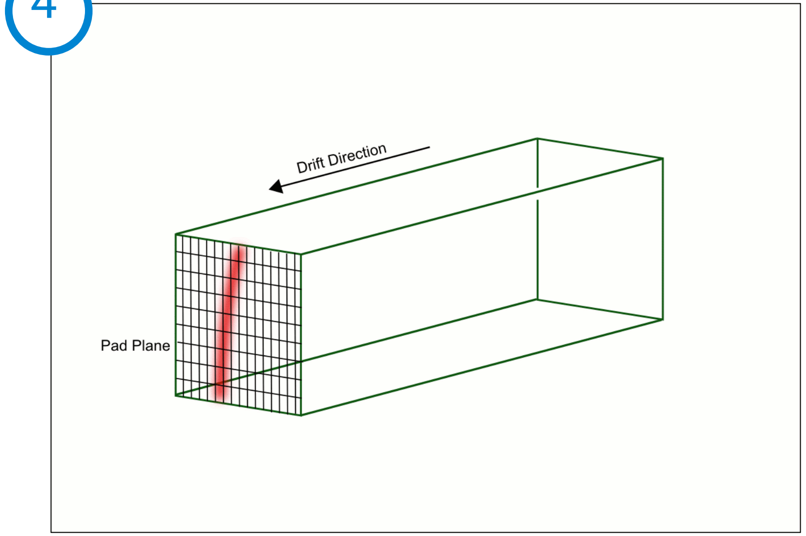
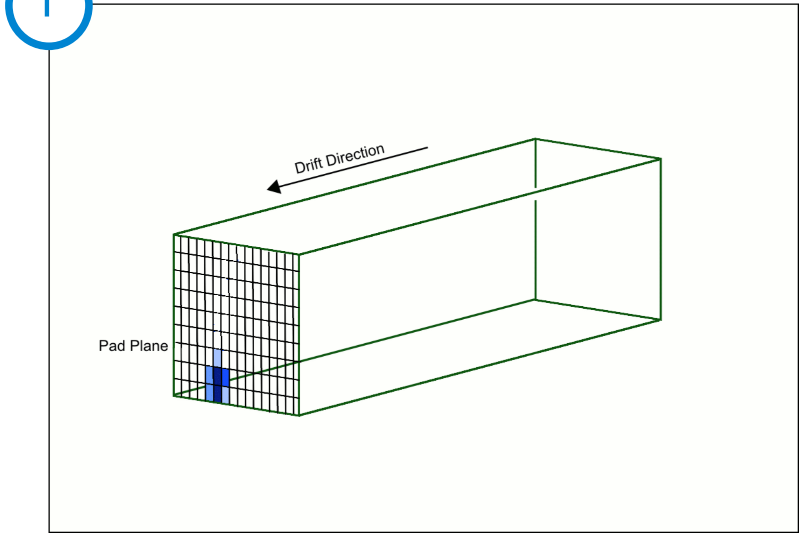


Time Projection Chamber

Recorded Signals

1



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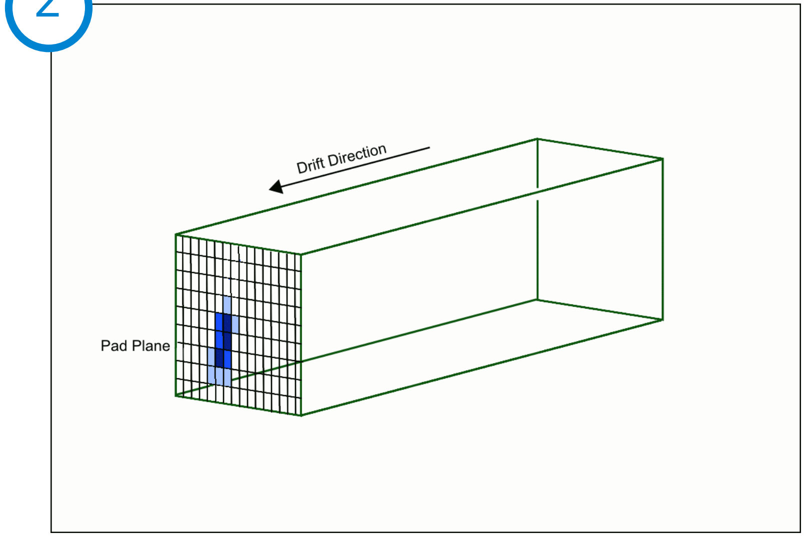

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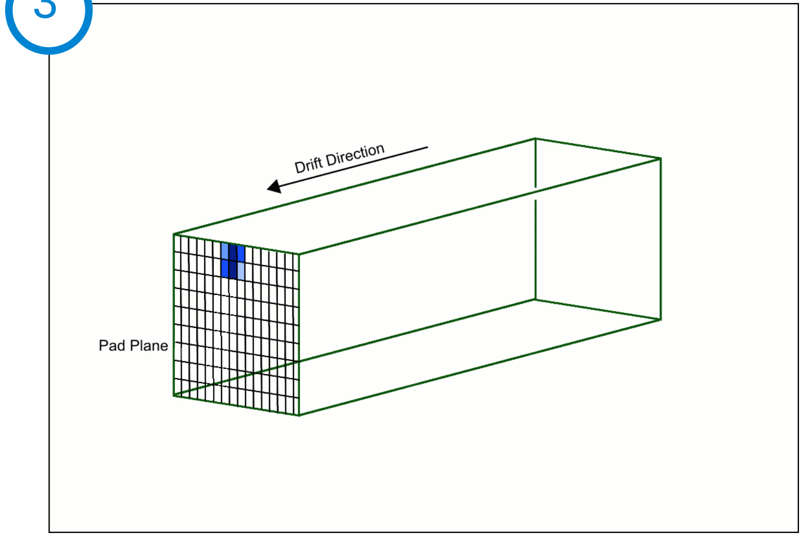

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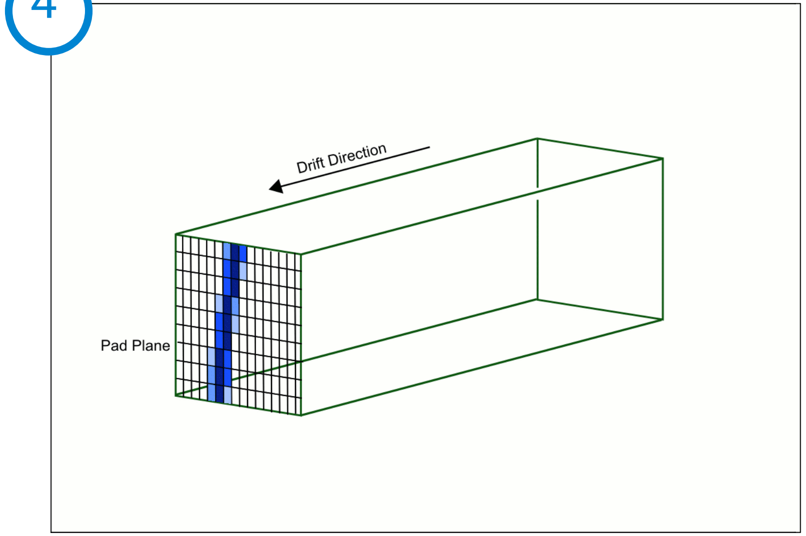


Time Projection Chamber

Reconstruction

- Straight line

$$x = f(y) = a\,y + b$$

- 2nd degree polynomial

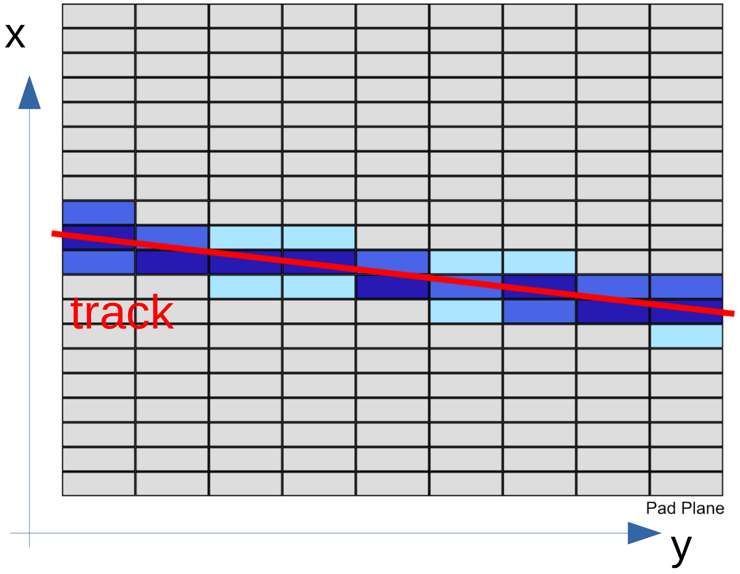
$$x = f(y) = a\,y^2 + b\,y + c$$

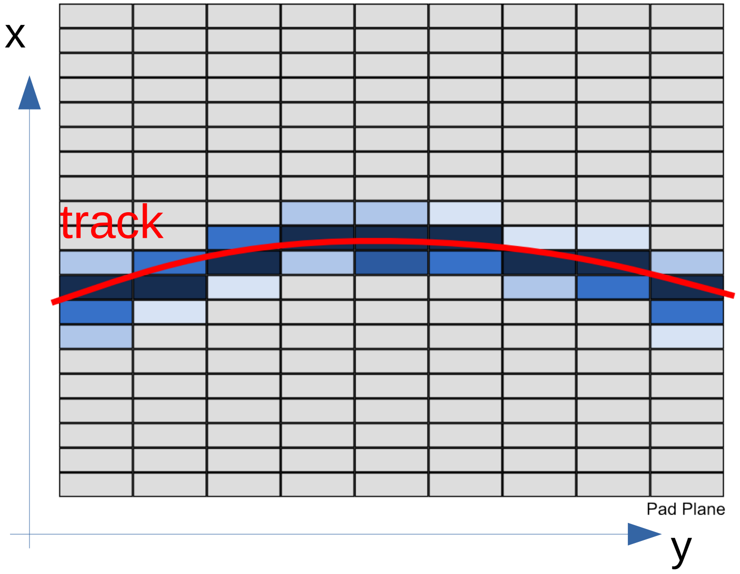
- Circle

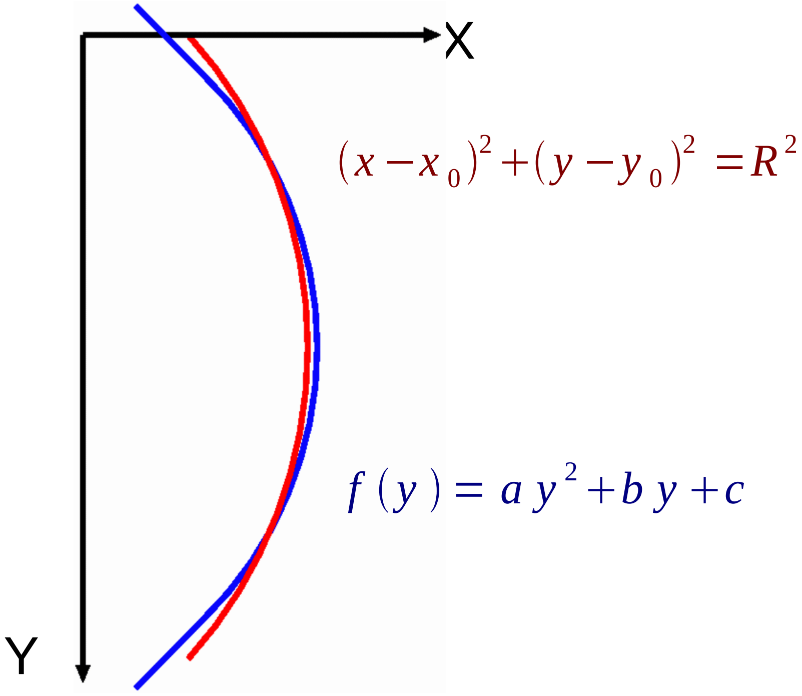
$$(x - x_0)^2 + (y - y_0)^2 = R^2$$

$$\rightarrow$$

$$x = f(y) = x_0 \pm \sqrt{\frac{1}{C^2} - (y - y_0)^2}$$







Iron-55

Basics

- ^{55}Fe is a radioactive isotope of iron with a nucleus containing 26 protons and 29 neutrons
  - Decays by electron capture to manganese-55, half-life of 2.737 yrs

$$^{55}Fe + e^- \rightarrow {}^{55}Mn^*$$

(^{55}Mn exited since e$^-$ in K shell missing)

  - 24.4% : disexitation of ^{55}Mn* via e$^-$ coming from L shell
    → γ at 5.9 keV

- At used activities of a few 100 kBq relatively safe
  → low penetration depth, easy to shield

- Safety here in lab: sources build in prototypes
  - Handling of sources only by trained tutors
    → Do not open the prototype setups!

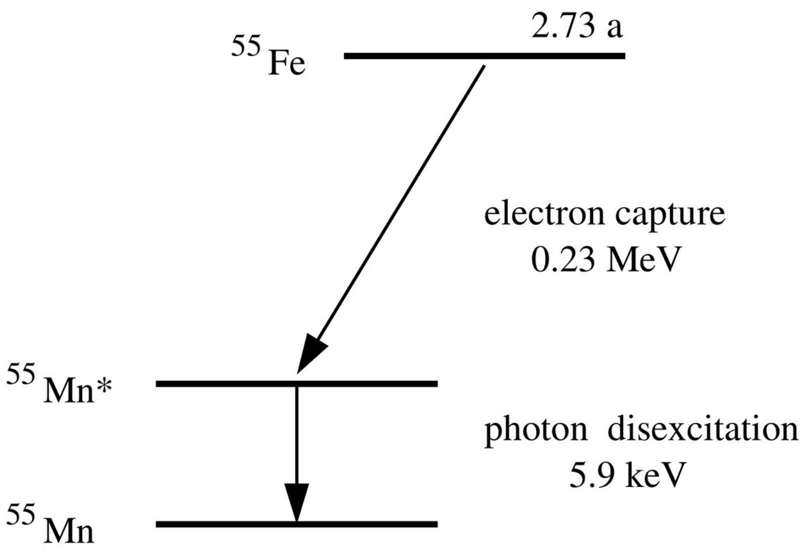


Image from desy-thesis-10-015
L. Hallermann: "Analysis of GEM Properties and Development of a GEM Support Structure for the ILD Time Projection Chamber"

Iron-55

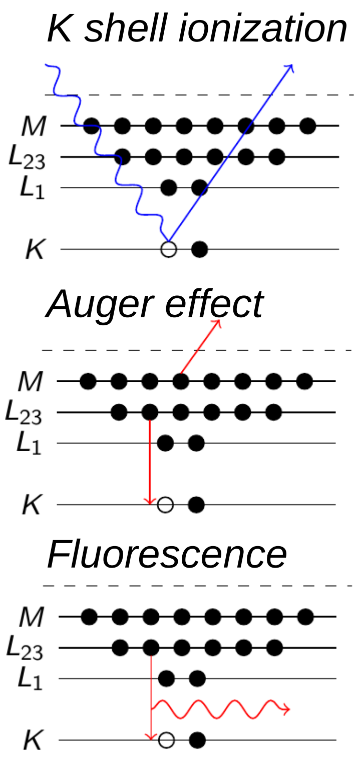
Spectrum

- Processes in Argon: K shell 3.2 keV binding energy → e^- obtain E_{kin} of 2.7 keV
- Gap in K shell filled by 2 different processes
  - Photo effect with K shell $W_{kin} = 2.7$ keV

    1) Auger effect $W_{kin} = 3.2$ keV
    Prob.: 80 %

    2) K-L fluorescence $W\gamma = 2.9$ keV
    → large absorption length → escape undetected
    Auger effect $W_{kin} = 0.3$ keV
    Prob.: 16 %
- 3) Photo effect with L shell $W_{kin} = 5.6$ keV

  Auger effect $W_{kin} = 0.3$ keV
  Prob.: 4 %



Images from "Basics of Gaseous Detectors" lecture @ EDIT2011
S. F. Biagi, H. Schindler, R. Veenhof

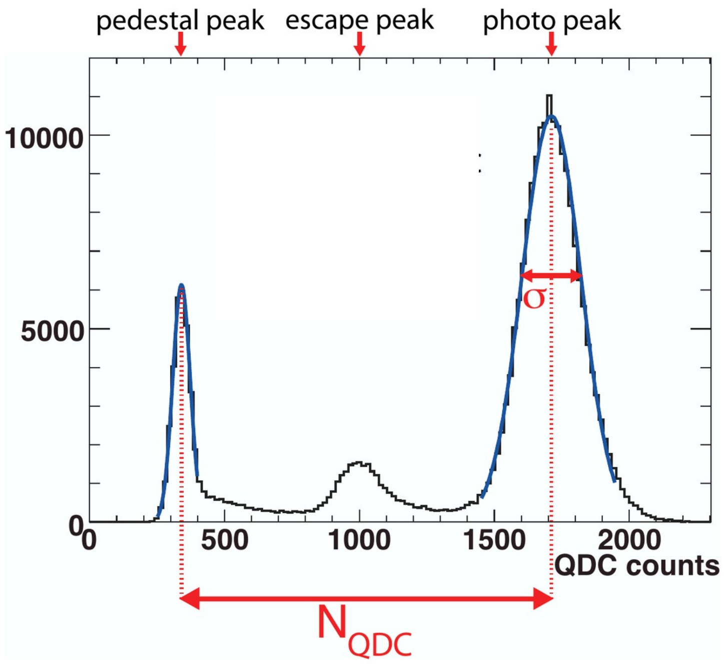


Image from desy-thesis-10-015
L. Hallermann: "Analysis of GEM Properties and Development of a GEM Support Structure for the ILD Time Projection Chamber"

- Case 1+3: 5.9 keV photo peak (in Ar: 234 e^-)
- Case 2: 3.0 keV escape peak (in Ar: 119 e^-)

Iron-55

Electrons

- Released electrons
  - In pure Argon
    - W_{Argon} = 25.2 eV
      →
      - 5.9 keV photo peak : 234 e^-
      - 3.0 keV escape peak : 119 e^-

$$Np = \frac{{}^{55}Fe_{emission}[keV]}{W_{Ar}}$$

  - For P5 gas:
    - W_{Argon} = 25.2 eV
    - W_{CH4} = 12.6 eV

      → e^- per peak?

$$Np = {}^{55}Fe_{emission}[keV] \times \left(\frac{\%_{Ar}}{W_{Ar}}\right) + {}^{55}Fe_{emission}[keV] \times \left(\frac{\%_{CH_4}}{W_{CH_4}}\right)$$

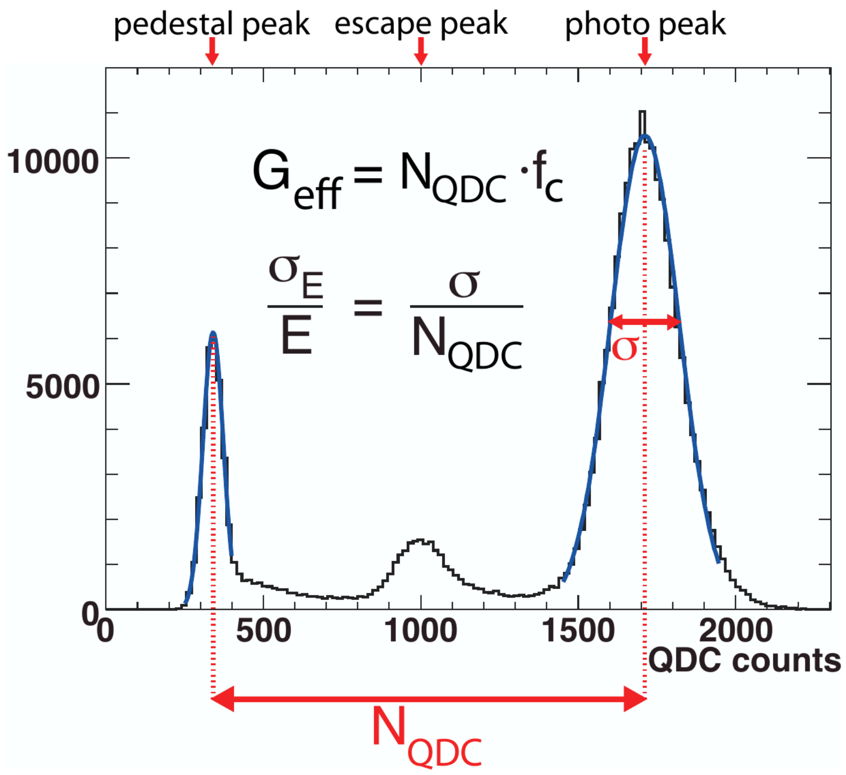
  - Isobutane
    - $W_{i\text{-}C4H10}$ = 23.4 eV

Gain

Why?

- Via the gain one gets an estimate of signal over noise S/N
- Optimization of readout electronics

- Charge in the detector should be under control
- Ion backflow should be known and controlled
- Charged particle flow is one of the main factors in aging
  Too much charge can become a problem



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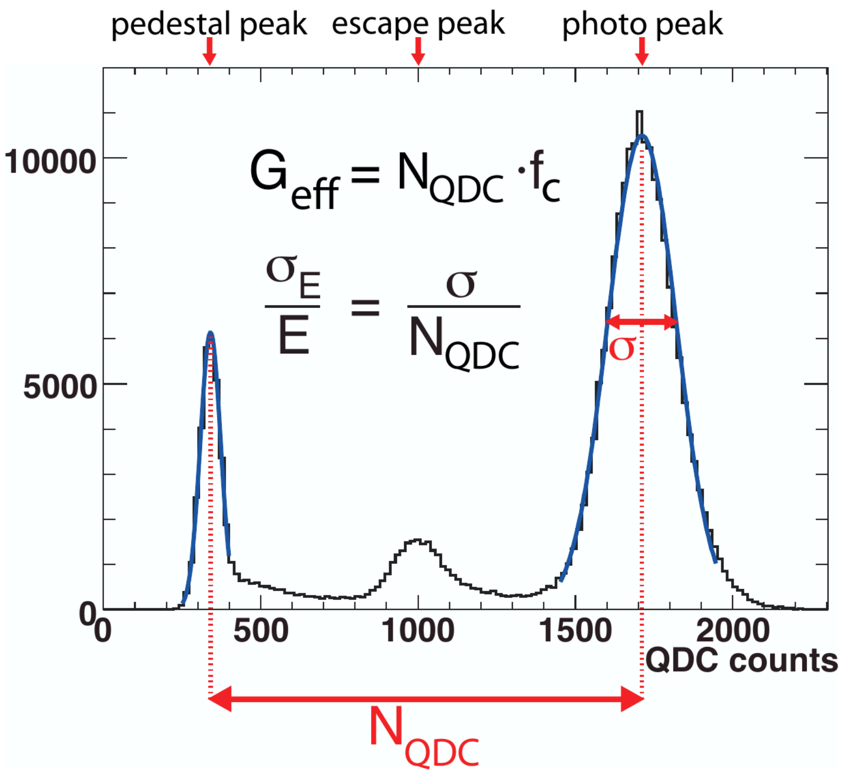
Iron-55

Gain Determination

- Determine Gain:
  - Calibrate preamplifier
    - Determine how much charge corresponds to a QDC count (QDC: charge to digital converter) using a defined input
  - Pedestal
    - Determine 0 of charge measurement by subtraction of noise peak position
  - Effective gain G_{eff}

$$G_{eff} = \frac{Q_{Anode,meas}}{Q_{Fe,initial}}$$

- Q_{Anode} : measured charge after GEM amplification
- Q_{Fe}: initially produced charge by iron-55 source (Np * e)



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Iron-55

Energy Resolution

- Energy resolution: width σ of photo peak
  - The “Fano factor” describes the uncertainty on # of e^- produced though ionization
  - So energy resolution cannot be better than

$$\frac{\sigma_E}{E} = \frac{\sigma_{n_e}}{n_e} = \frac{\sqrt{F * n_e}}{n_e}$$

which is ~3% in Argon
($n_{e,\text{Fe55, Argon}}$ = 234, F_{Argon} ~ 0.2)

  - With the iron-55 spectra setup used here:
a bit better than 10 % for high gains achievable

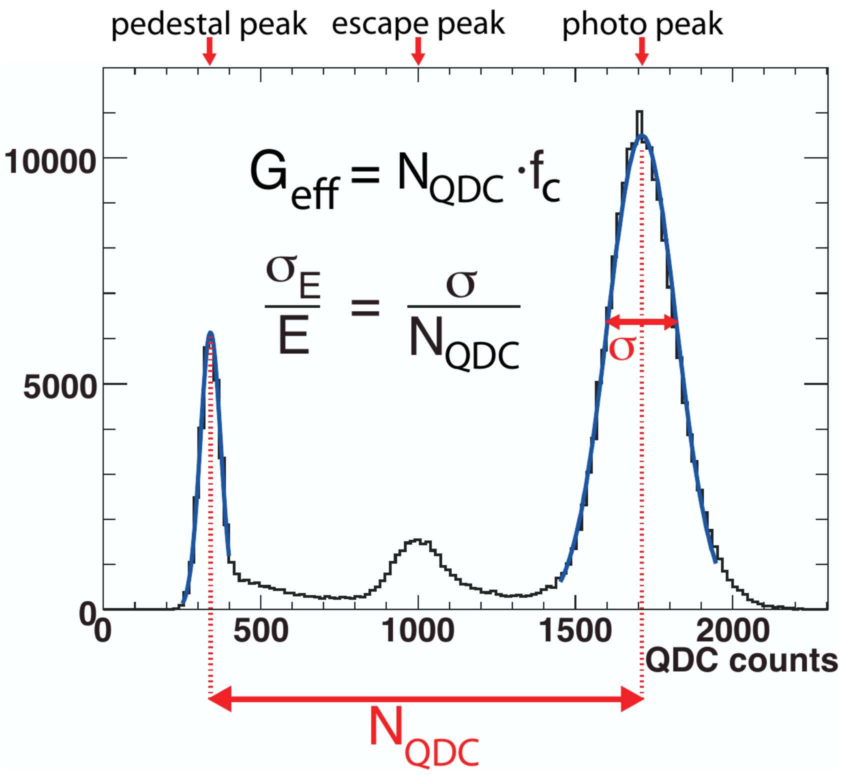


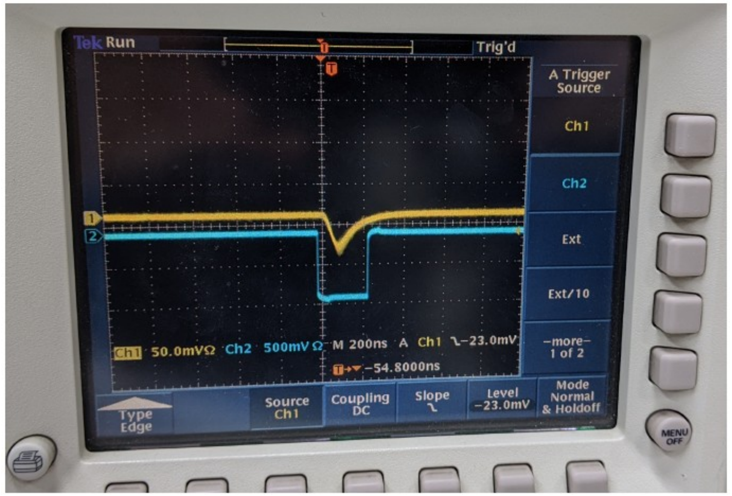
Image from desy-thesis-10-015
L. Hallermann: “Analysis of GEM Properties and Development of a GEM Support Structure for the ILD Time Projection Chamber”

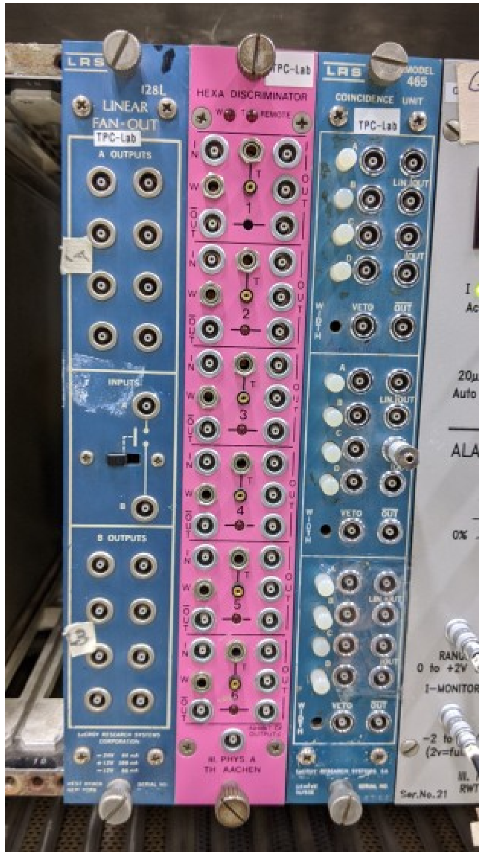
Task 13: Iron-55 spectrum

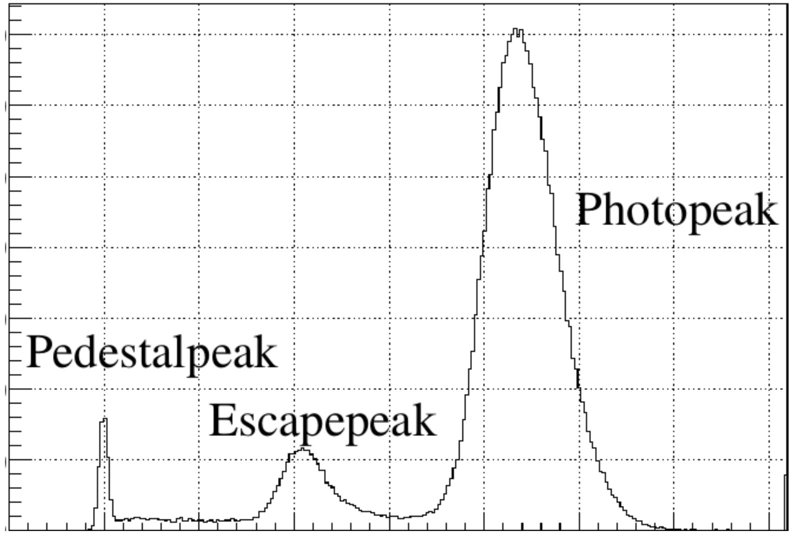
The Iron-55 Spectrum

- Fe55 Iron Spectra Measurement
- Small TPC with iron-55 source
- One pad connected to a preamplifier and QDC (charge digitizer)

- Tasks
  - Build up trigger system and readout
  - Calibrate preamplifier and QDC
  - Analyze spectrum and plot gain curve
  - Determine the energy resolution



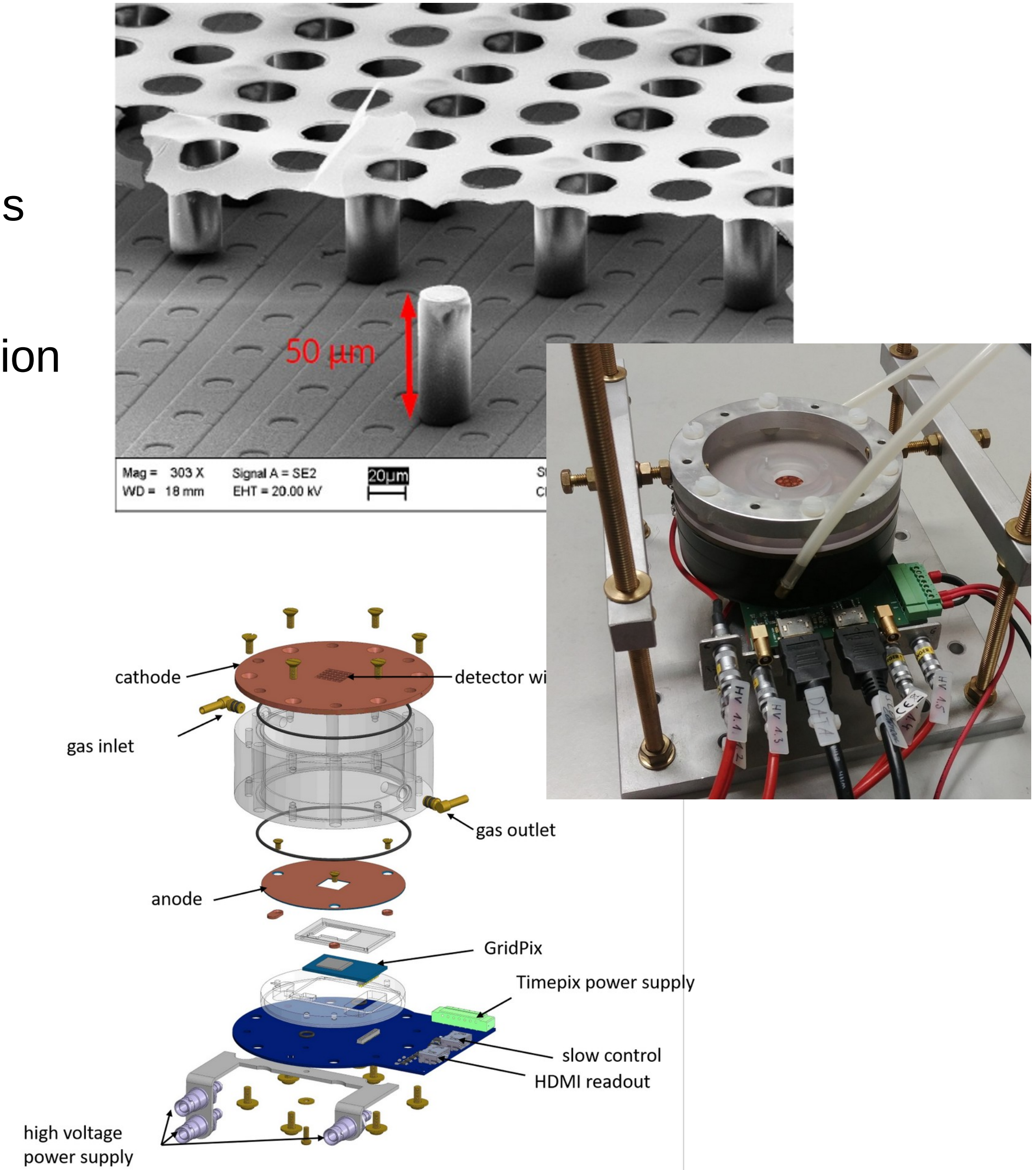




Task 14: GridPix

Measuring Single Electrons

- The GridPix is a Timepix pixel chip with a Micromegas gas amplification grid produced on top → can detect single electrons
- Using a CAST-type GridPix detector, X-ray photons will be reconstructed to determine the gas gain and the energy resolution
- Tasks
  - Prepare the setup
  - Use monitoring tool to understand the data.
  - Analysis using python scripts, understanding cuts
  - Fit the resulting spectra to determine
    - Energy resolution
    - Gas gain

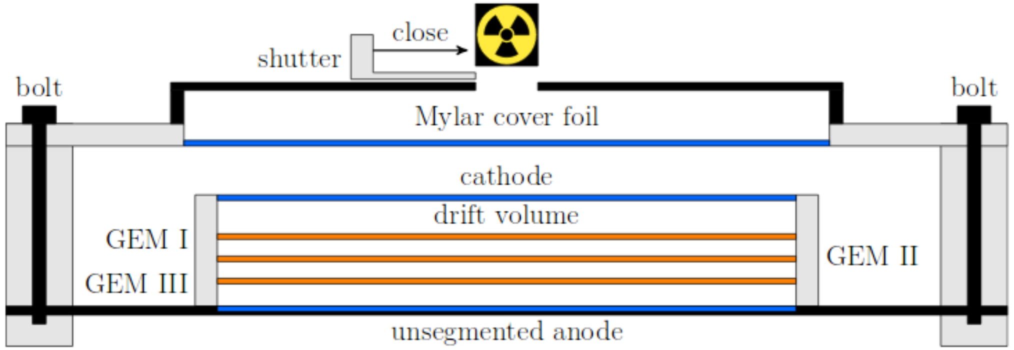


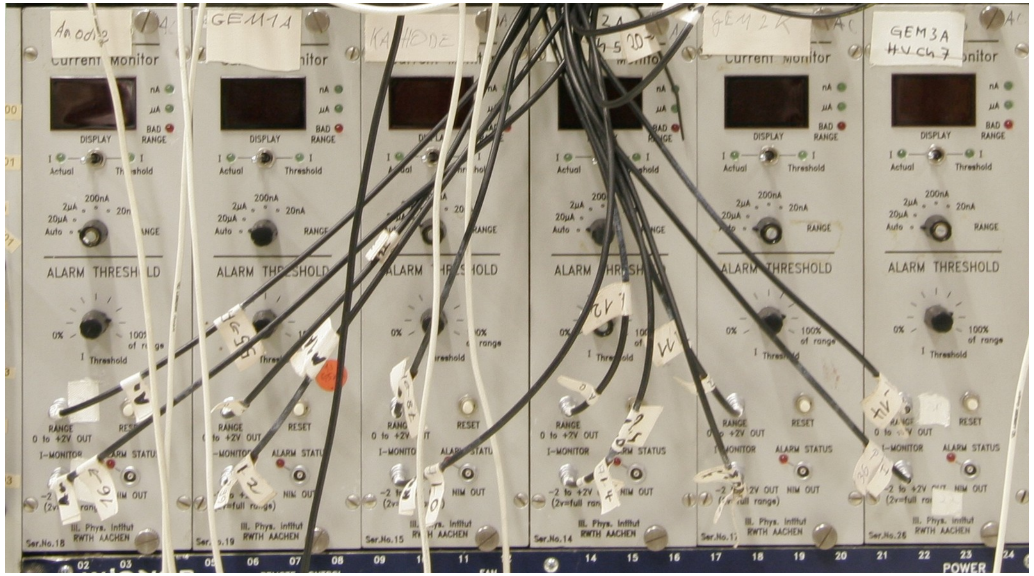
Task 15: Gain Determination by Measuring GEM Currents

CUMOS - NIM Modules to measure Nanoamperes

- CUMOS are specifically developed NIM modules able to measure currents in the nanoampere regime at several kilovolts
- They are used to determine GEM gain and ion backflow depending on triple GEM stack voltage settings

- Tasks
  - Set up the prototype
  - Determine by varying voltage settings of the setup:
    - Gain curve
    - Optimized ion backflow settings





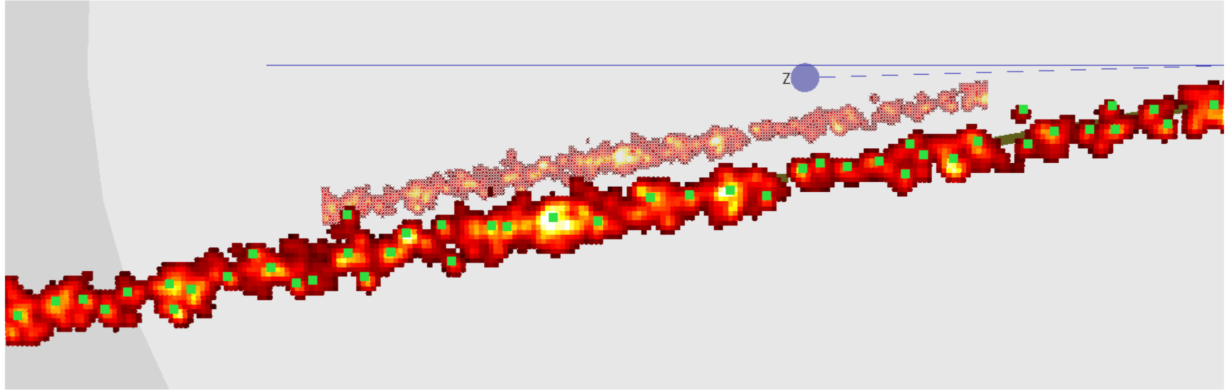
GEM voltage [V]

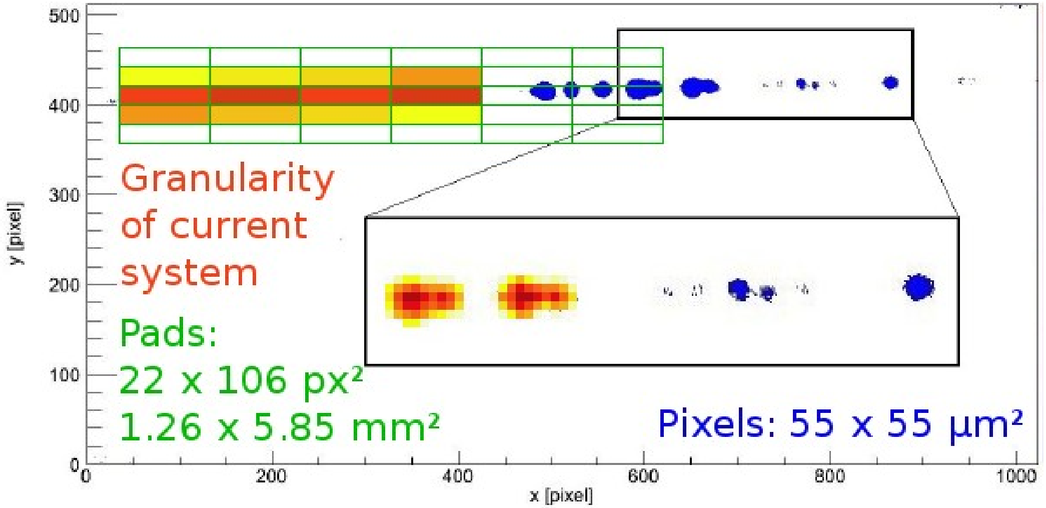
Task 16: Impact of Readout Granularity

Analysis on Simulated Data - Reconstruction and Resolution

- A detailed time projection chamber simulation has been used to simulate kaons and pions including the drift, amplification and charge readout on the level of single electrons
- This has been done for different readout granularities, meaning pad sizes
- Tasks
  - Understand python and Root
  - Implement a track fit
  - Determine the single point resolution and compare the results for different pad sizes to find the optimal working point

Please bring your laptop to the task





Closing Slide

Final remarks

- Have fun!
  - But think first before doing things.
    In the lab there are several dangers ranging
    from high voltage to radioactive sources
- Do not hesitate to ask the tutors if you have questions.
  We'll try to help where we can.