Gaseous radiation detectors

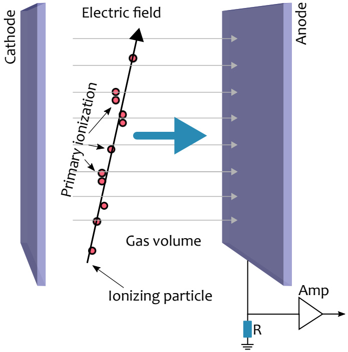
Introduction

From introduction lecture

Gaseous radiation detectors

- Material that interacts with incoming radiation is the gas inside the detector.
- Gas ionizes along particle trajectory ⇒ electron – ion-pairs.
- Principle: Primary ionization → secondary ionization → drift to electrodes → (gas multiplication) → charge induction → signal.
- All kind of configurations possible: Proportional counter, drift chamber, Time Projection Chamber (TPC), etc.
- Good for large area tracking detectors (economical).

⇒ Let's go into more details!



Ionization processes

Remember from last lecture

- Electromagnetic radiation interacts mostly via photoelectric effect, Compton scattering and pair production:
- Charged particles loosing energy via inelastic collisions (excitation, ionization), Bremsstrahlung and Cerenkov radiation.
- Primary ionization: $X \underset{\text{rad.}}{\longrightarrow} X^+ + e^-$
- Secondary ionization if $E_{e^-} > E_i$ (called δ electrons)

Average ionization in gases

- The mean number of electron-ion -pairs $\langle n_T \rangle$ can be calculated by

$$\langle n_T \rangle = \frac{L \cdot \left\langle \frac{dE}{dx} \right\rangle_i}{W_i}$$

  with the thickness of the gas layer L, the ionization energy E and the average energy needed to produce an electron-ion pair W_i.

- Ionization is Poissonian process,

$$P(n, \langle n \rangle) = \frac{\langle n \rangle^n \exp\{-\langle n \rangle\}}{n!}.$$

  Here the mean number of ionization processes $\langle n \rangle) = L/\lambda$ with $\lambda = 1/(n_e \sigma_I)$ and σ_I the ionization cross-section.

Ionization processes

Characteristics of common gases

Gas	ρ [g/cm^3]	I_0 [eV]	W_i [eV]	$\frac{dE}{dx}$ [$\frac{\text{kev}}{\text{cm}}$]	n_P [$\frac{\text{I.P}}{\text{cm}}$]	n_T [$\frac{\text{I.P}}{\text{cm}}$]
H_2	8.38×10^{-5}	15.4	37	0.34	5.2	9.2
He	1.66×10^{-4}	24.6	41	0.32	5.9	7.8
N_2	1.17×10^{-3}	15.5	35	1.96	10.0	56.0
O_2	1.33×10^{-3}	12.2	31	2.26	22.0	73.0
Ne	8.39×10^{-4}	21.6	36	1.41	12.0	39.0
Ar	1.66×10^{-3}	15.8	26	2.44	29.4	94.0
Kr	3.49×10^{-3}	14.0	24	4.60	22.0	192.0
Xe	5.49×10^{-3}	12.1	22	6.76	44.0	307.0
CO_2	1.86×10^{-3}	13.7	33	3.01	34.0	91.0
CH_4	6.70×10^{-4}	13.1	28	1.48	16.0	53.0

Table: Characteristic numbers of common gases: a.o. the average energy to produce electron-ion pair W_i, the number of primary and total electron-ion pairs per length n_P, n_T and the energy loss per length dE/dx. Values extracted from K. Kleinknecht, *Detektoren für Teilchenstrahlung*, Teubner (2005)

Note: Factor 2 – 6 between n_P to n_T.

Electron-ion movements in gas

Transport of ions in gas

- Ions move with thermal motion in random directions

$$\langle T_{\text{ion(thermal)}} \rangle = \frac{3}{2} kT.$$

- In case of external electric field ions additionally drift along field lines

$$\nu_D^+ = \mu^+ \frac{EP_0}{P}.$$

  with μ^+ being the ion mobility, E the field strength, P the pressure andP_0 the normal pressure. More or less linear dependence on field strength.

- Typical speed of ions $\mathcal{O}(\frac{\text{cm}}{\text{ms}})$.

Transport of electrons in gas

- Electron drift more complicated due to their larger mean free path. The higher mobility allows them to gain higher velocities between collisions.
- No linear dependence on electric field strength. Saturation effects, even decreasing possible.

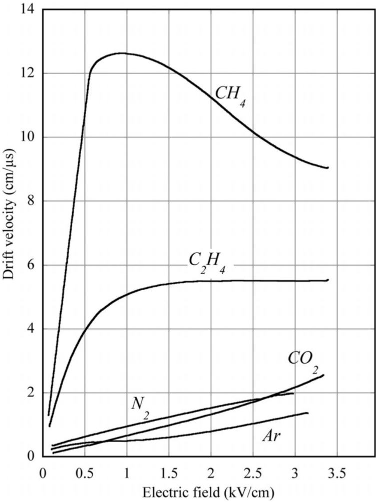
Electron-ion movements in gas

- Townsend formula

$$\nu_D^- = k\frac{qE}{m}\tau$$

  with electron energy distribution coefficient k and the average time between collisions τ.

- Quantitatively not very useful. Strong dependence on gas mixture and field strength.
- Cold gas: Kin energy $\approx$ termal energy. $\nu_D \sim E$, mobility const.
- Hot gas: Kin energy $\gg$ termal energy. $\nu_D \approx const.$, mobility not const.
- Typical speed of ions $\mathcal{O}(\frac{\text{cm}}{\mu\text{s}})$



Electron-ion movements in gas

Drift velocities in gas mixtures

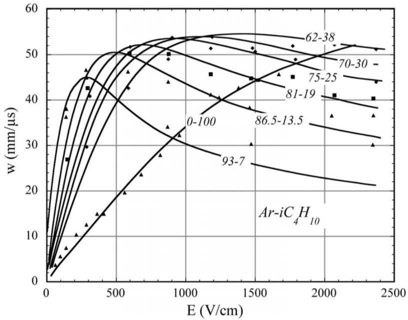


Figure: Drift speed of electrons in various Ar-isobutane mixtures (Breskin et al., 1974b).

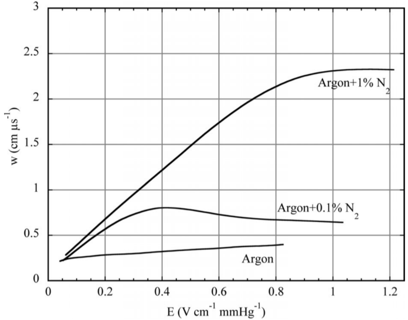


Figure: Drift speed dependence on small gas mixture changes (Colli & Fachini, 1952).

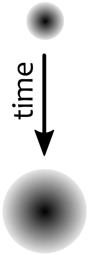
Electron-ion movements in gas

Diffusion

- Based on classical kinetic theory of gases.
- Can use Fick's second law

$$\frac{\partial \phi}{\partial t} = D\nabla^2\phi$$

Here ϕ is the concentration of particles and D the diffusion coefficient.



- In case diffusion starts from a point it behaves Gaussian like with

$$\sigma_x = \sqrt{2Dt}$$

- Diffusion coefficient D depends on thermal velocity ν,

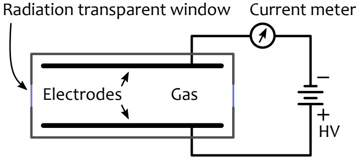
$$\nu = \sqrt{\frac{3k_BT}{m}}$$

with k_B being the Boltzmann constant and T the temperature.

- E field acts on longitudinal diffusion, B field on transverse component.

Ionization chamber

Most simple gaseous detector



- Parallel plates in gas enclosure.
- High voltage source.
- Current meter.
- Electric field in chamber

$$E = \frac{U}{d}$$

  where U is the potential difference between plates and d the distance of the plates.
- Can be used in direct current mode and in pulse mode.

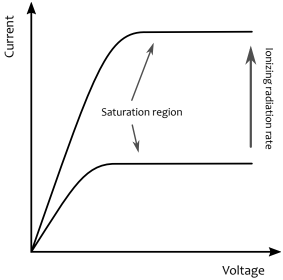
Figure: Ionisation chamber made by Pierre Curie (CC BY-SA 2.0).

Current mode

- Ionizing radiation generates continuously electron-ion pairs.
- Their drift towards electrodes generates steady dc current.

Ionization chamber

Current mode (cont.)



- Current measured by picoammeter.
- Increasing voltage reduces recombination effects (columnar and volume)
  $\Rightarrow$ measured current increases.
- Saturation effect takes place when effectively no recombination anymore and all ionization charge contributes to the current.
- Large gas variety for ionization chambers (e.g. also air possible).

What are recombination?

- Electrons and ions from the ionization processes can be captured before reaching the electrodes.
- Positive ions get neutralized by free electrons or negative ions.
- Electrons get captured by negative ions or electronegative gas atoms (e.g. O_2).

Ionization chamber

Pulse mode

- Possible to do spectroscopy, measuring single ionization processes (energy).
- Signal by measured voltage over load resistor.
- Starting with $E = U/d$ and energy conservation,

$$\frac{1}{2}CU^2 = \frac{1}{2}CU_0^2 - n\int_{x_0}^{x} qE_x dx$$

we get

$$\Delta U = -\frac{nq}{Cd}(x - x_0).$$

- Assuming const. drift velocity we get for ions

$$\Delta U^+ = -\frac{ne}{Cd}\nu_D^+\Delta t^+$$

and for electrons

$$\Delta U^- = -\frac{n(-e)}{Cd}(-\nu_D^+)\Delta t^-.$$

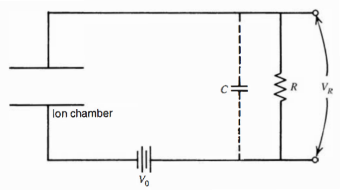


Figure: Ion chamber with in pulse readout (Knoll 2014).

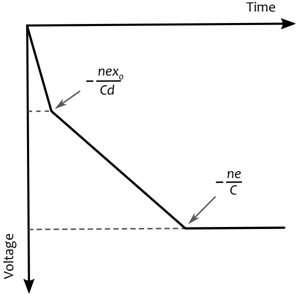
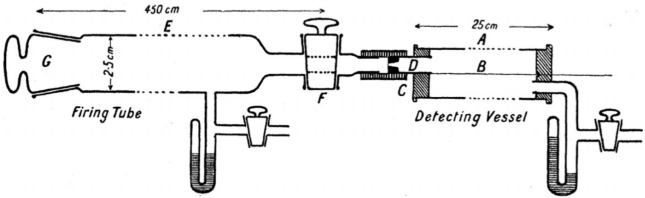


Figure: Ion chamber pulse shape.

Proportional counter

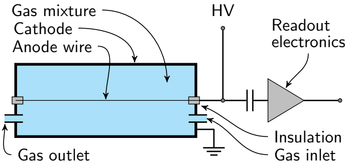
Original design – Rutherford & Geiger (1908)



- Electric field in chamber

$$E(r) = \frac{U}{r \ln\left(\frac{r_c}{r_a}\right)}$$

  where U is the potential difference between plates and r_a, r_c the radii of the anode and cathode.



- Configuration with a thin wire allows for high fields close to the anode.

Proportional counter

Avalanche formation

- Due to high electric field strength around anode primary electrons gain high velocity ($10^4 - 10^5$ V/cm).
- Now electrons have enough kinetic energy – between collision – to ionize themselves atoms.
- Thus an electron avalanche is generated.

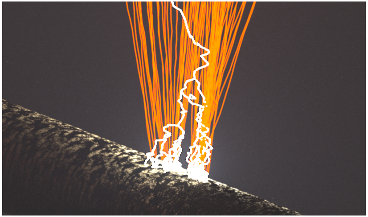


Figure: Simulation of avalanche in proportional counter.

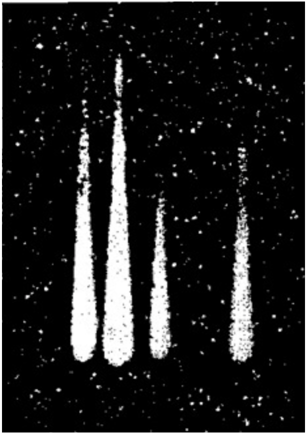


Figure: Electron avalanches in cloud chamber (H. Raether, Butterworth (1964))

Proportional counter

Avalanche formation

- The probability of having a secondary ionization per unit path length in gas can be expressed by the Townsend coefficient

$$\alpha = \frac{1}{\lambda_{\text{ion}}} = \sigma_i N$$

where λ_{ion} is the mean free path of ions, σ_i the ionization cross section and N the atom/molecule density.

- The change of number of electrons n_0 after path x

$$\frac{dn}{dx} = \alpha n$$

leads to the following expression in case the Townsend coefficient is independent of x

$$n(x) = n_0 \exp(\alpha x).$$

- In case of $\alpha(x)$

$$n(x) = n_0 \exp\left(\int \alpha(x) dx\right).$$

- The ratio $n(x)/n_0$ is gas amplification (gain).

Proportional counter

Avalanche evolution

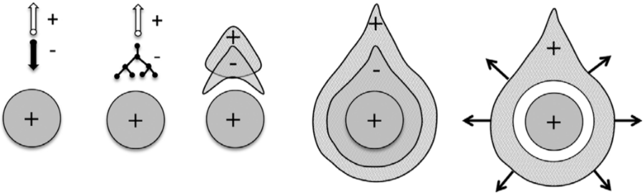


Figure: Evolution of avalanche around wire (F. Sauli, *Gaseous Radiation Detectors – Fundamentals and Applications*, Cambridge).

1. "Primary" electron drifts towards anode.
2. Electron accelerates in high fields close to anode and ionizes surrounding atoms (gas multiplication).
3. Diffusion of electrons and ions take part.
4. Avalanche develops around anode wire.
5. Electrons quickly recombined at anode ($\mathcal{O}$(1ns)). Positive ions drift towards cathode and induce "large" signal on anode.

Proportional counter

Regions of operation

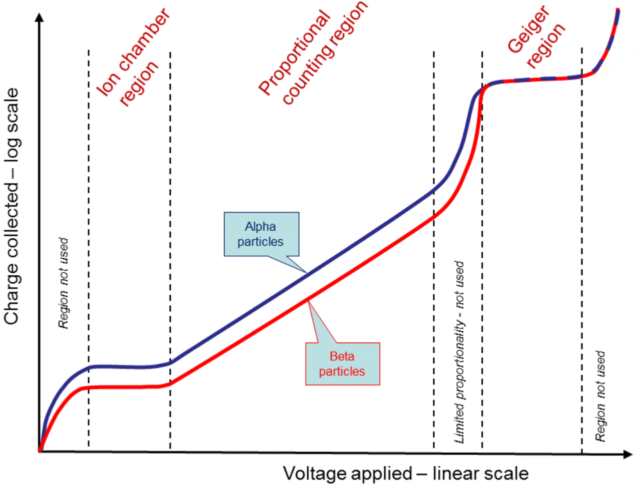


Figure: Region of operation of gas-filled detectors (taken from Wikipedia).

Proportional counter

Gas multiplication factor (following Knoll)

- Total charge assuming independent avalanches and minimal space charge effects

$$Q = n_0 e M.$$

  Here M is the gas multiplication factor and n_0 the number of primary ion pairs.

- Using the electric field expression for cylindrical tubes with $\alpha(r)$, M can be written

$$\ln M = \int_a^{r_{\mathbf{critical}}} \alpha(r) dr.$$

  The Townsend coefficient α is depending on the gas type and the electric field.

- Equation can be written in term of the electric field $\mathcal{E}(r)$

$$\ln M = \int_{\mathcal{E}(a)}^{\mathcal{E}(r_{\mathbf{critical}})} \alpha(\mathcal{E}) \frac{\partial r}{\partial \mathcal{E}} d\mathcal{E}.$$

- Using the electric field equation for the cylindrical configuration $E(r) = U/r \ln(r_\mathrm{c}/r_\mathrm{a})$ we get,

$$\ln M = \frac{U}{\ln(b/a)} \int_{\mathcal{E}(a)}^{\mathcal{E}(r_{\mathbf{critical}})} \frac{\alpha(\mathcal{E})}{\mathcal{E}} \frac{d\mathcal{E}}{\mathcal{E}}.$$

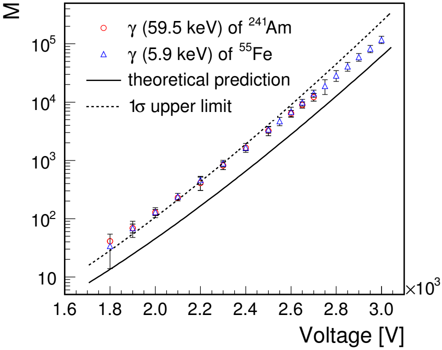
Proportional counter

Gas multiplication factor (cont.)

- Diethorn further developed the equation assuming linearity between α and $\mathcal{E}$ (details found in references listed in Knoll),

$$\ln M = \frac{V}{\ln(b/a)} \frac{\ln 2}{\Delta U} \left(\ln \frac{V}{pa \ln(b/a)} - \ln K \right).$$

- Here:
  $p \to$ gas pressure.
  $K \to$ minimum value of $\mathcal{E}/p$ for gas multiplication (found in tables).
  $\Delta V \to$ potential difference an electron undergoes between ionization points (found in tables).
- Figure: Comparison of measured gas multiplication factor to theoretical using the Diethorn formula.



Proportional counter

Space charge

- The ions from the avalanches that move slowly towards the cathode, cause space charge.
- Space charge is spread throughout the camber due to diffusion and will distort the field.
- Close to the anode wire space charge can reduce the field strength.
- Signal can be reduced, it has an effect on the energy resolution.
- Not dramatic in proportional counters we build here in the lab but we will see later that space has a major affect on large Time Projection Chambers used at LHC.

Energy resolution (Knoll 2014)

- There is naturally a charge fluctuation in the readout pulses from detectors. For gas filled detectors we have independent fluctuation of produced ion-pairs and avalanche variations,

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2$$

Proportional counter

Energy resolution

- Rewriting the equation for single avalanche multiplication factor

$$\sigma_M^2 = \left(\frac{1}{n_0}\right)^2 \sum_{i=1}^{n_0} \sigma_A^2 = \frac{1}{n_0}\sigma_{A_{\mathbf{typical}}}^2$$

$$\Rightarrow \left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \frac{1}{n_0}\left(\frac{\sigma_{A_{\mathbf{typical}}}}{A_{\text{typical}}}\right)^2$$

1. The fluctuations of primary ion-pairs (first part of eq.) can be estimated to some extent with the Fano factor

$$\sigma_{n_0} = F n_0.$$

(Fano factor: additional factor multiplied to the variance of the Poission distribution describing the ionization process. Measured the variance is usually smaller than models predict. Therefore Fano factor < 1)

Proportional counter

Energy resolution

2. Avalanche variations: The number of electrons in avalanche can be described by Polya distribution with Θ being a related to electron fraction exceeding the ionization threshold energy ($0 < \Theta < 1$)

$$P(A) = \left(\frac{A(1+\Theta)}{\overline{A}}\right)^{\Theta} \exp\left(\frac{-A(1+\Theta)}{\overline{A}}\right) \Rightarrow \left(\frac{\sigma_A}{\overline{A}}\right)^2 = \frac{1}{\overline{A}} + b.$$

Here $b = 1/(1+\Theta)$ with values around 0.5.

- Summing up (for large $\overline{A}$) we get for the charge variance

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \frac{1}{n_0}(F+b)$$

- Using the the energy of the ionizing radiation and the mean energy for ion-pairs in gas, which give the number of ion-pairs, we get

$$\frac{\sigma_Q}{Q} = \sqrt{\frac{W(F+b)}{E}}.$$

- Theoretical values – with grain of salt – of energy resolution for Ar gas and the ^{55}Fe photo-peak is 12.8% (using the factor 2.35 to convert from stddev to usual FHWM based definition).

Something additional about gases

Quenching

- The gas emits photons when excited by electron impacts. Typically from 150 nm to visible light.
- These photons may cause spurious pulses via photoelectric effect in the electrodes of the detector.
- May cause interactions in the gas - loss of proportionality of avalanches.
- Depends on gas mixture, detector geometry, pressure and electric field.
- Fixed by adding a molecular gas into the mixture - absorbs the photons.
- Different in Geiger-Müller tubes.

Pennning effect

- Sometimes the quenching gas (or another additional gas component) has excitations that are lower than the ionization energy of the bulk gas.
- Exitations are effectively transferred in collisions and may cause additional ionization: W is lowered for the mixture.
- Depends on the field strength.

Case study of proportional counter

Setup

- Using a self build proportional counter from a beverage can with a strand of a normal electric wire ($\varnothing \approx 100\mu$m) serving as anode.

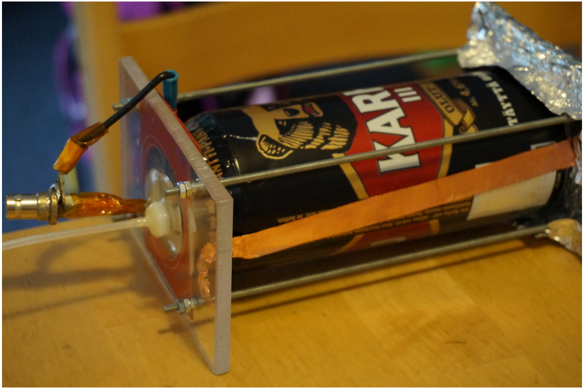
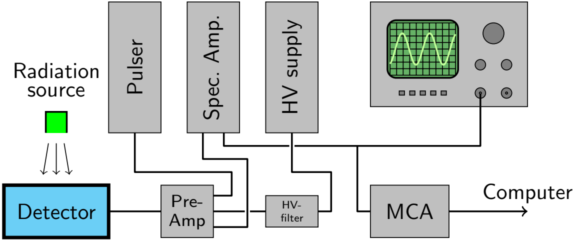


Figure: Proportional counter: Visible also the high voltage connector, the ground connection to the cathode, the gas supply tube and shielding alufoil.

Case study of proportional counter

Setup

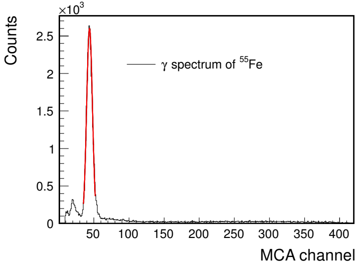
- Gas mixture: P10, consisting of 90% Ar and 10% methane (quenching gas).
- Operational voltage region from 1 to more than 3 kV (over 4 kV glowing discharge observed).
- Used ionizing radiation sources: ^{55}Fe and ^{241}Am.
- Measurement setup:

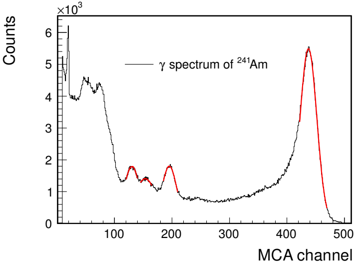


Case study of proportional counter

Results

- Spectra of ^{55}Fe and ^{241}Am. Detector at moderate voltage of 2.25 kV.
- Not shown: How to calibrate measurement setup (part of labwork)





- What small peak left of photopeak of ^{55}Fe spectrum?

Case study of proportional counter

Escape peak

- Remember from last lecture: Photoelectric effect most important for low energy spectroscopy.
- Full absorbtion of X-ray leads to so-called photo-peak.
- Absorbtion of photons in noble gases show discontinuities (absorbtion edges).
- Characteristic x-rays from exited gas atoms (mostly K shell) after photoelectric process.
- Those x-rays may escape detector which leads to the so-called escape peaks.
- Position of escape peak lower to photo-peak with distance of escaping x-ray energy.

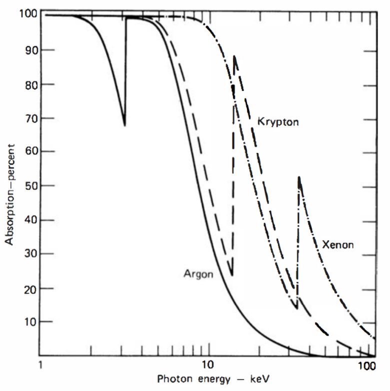


Figure: Absorbtion of photons in various noble gases (Knoll 2014).

Geiger-Müller counter

Principle

- Usage of similar gases as in proportional counter.
- Configuration of detector such that operates above the proportional region.
- In avalanches surrounding atoms get excited and radiate soft photons that generate via photoelectric effect electron-ion pairs that form additional avalanches.
- Within a few microsecond we get a total discharge and a large signal.

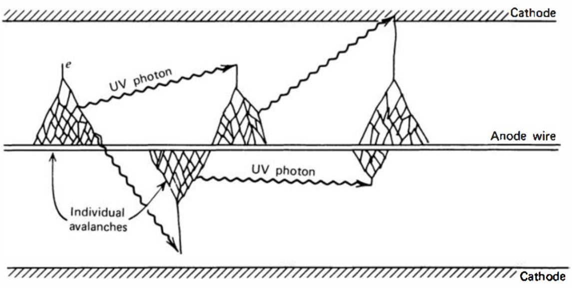


Figure: Discharge mechanism in Geiger-Müller counter (Knoll 2014).

Geiger-Müller counter

Readout

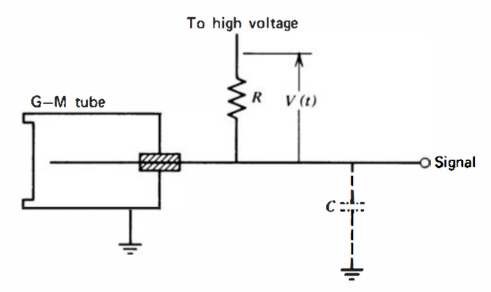
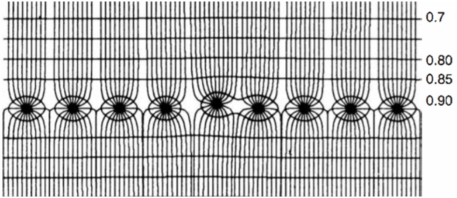


Figure: Circuit for fast voltage restoration in G-M tube (Knoll 2014).

Multiwire chamber

The next step

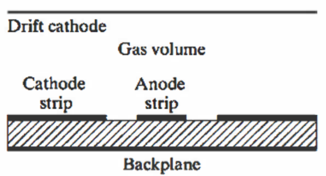
- George Charpak invented this idea (1968).
- Introducing independent wires between planar electrodes, each working as proportional counter..
- First truly position sensitive gas detector.
- Short drift allows for fast detector – up to 100 ns timing resolution.
- 2d detectors by using multiple chambers with crossed wires.
- Got a nobel prize 1992.

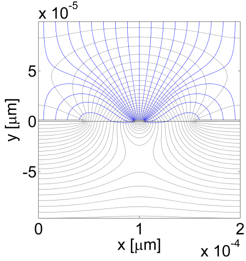


Microstrip detector

First micropattern gas detector type (MPGD)

- Alternating cathode – anode strips on a resistive surface.
- Basically works like a multiwire chamber.
- Easy to manufacture with litography – a huge development over multiwire chamber when pitch in hundreds of microns is needed.
- Field strength increases in the edges of the strips – sparking and eventually aging (destructiuon of the anode structure).

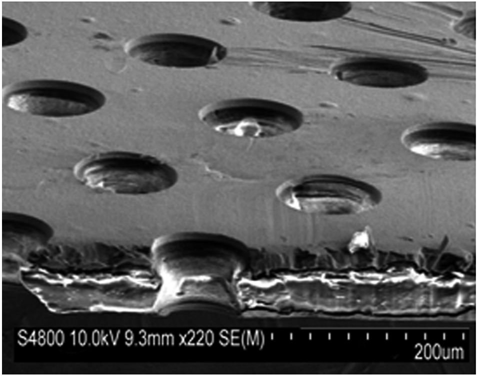




Gas Electron Multiplier

GEM

- Versatile and robust type of micropattern gaseous radiation detectors.
- Active component: Thin (50 μm) polyimide foil coated with copper (5 μm) from both sides.
- Microscopic holes with a typical diameter of 70 μm are etched chemically through the foil.



Gas Electron Multiplier

Electric field configurations

- When high voltage is applied over the copper electrodes, a strong electrostatic field inside the holes allows gas multiplication of electrons.

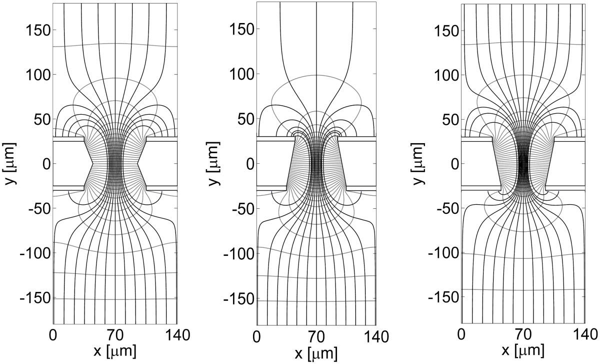
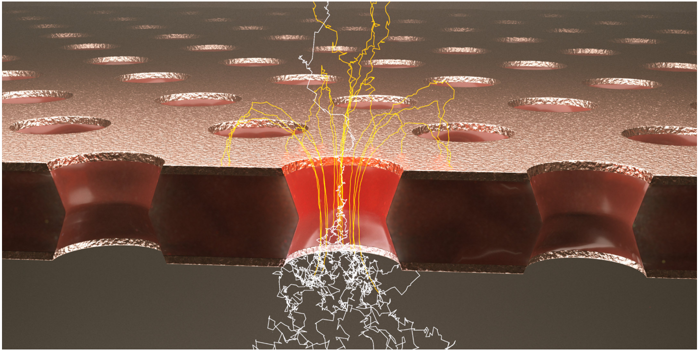


Figure: 2d plot of field lines in and close by a GEM hole, made with double mask technique (left) and single mask technique (middle, right).

Gas Electron Multiplier

GEM simulation

- Simulation of an avalanche produced by a single drifting electron using the Garfield++ tool (`https://garfieldpp.web.cern.ch/garfieldpp/`).

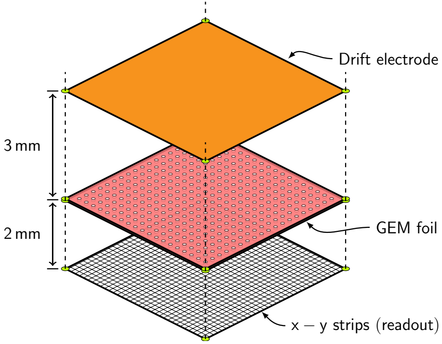


- Note: Backflowing ions are to some extend captured by copper electrodes which reduces space-charge in drift space.

Gas Electron Multiplier

Example setup of a GEM detector

- Most simple example consists of: Drift electrode, GEM foil, readout strip/pad -plane and gas tight box.
- Negative voltages are applied to all layers in decreasing order to generate electric field of one direction inside chamber.
- Ionization of interest occurs in drift space between drift electrode and GEM.



- Avalanches that occur in GEM holes drift through induction space towards readout plane and induce current.
- Very important for the operation is the voltage setup that defines the gas multiplication, the collection efficiency and the extraction efficiency.
- Will come back with special lecture about GEM based detectors if time allows. . . .

Simulation of gas filled detectors

- Very few field configurations can be analytically solved (parallel plate, radial symmetry).
- Need numerical methods to solve the field for MPGD detectors: Finite Element Method (FEM) solvers, such as ANSYS or COMSOL.
- Electron/ion transport and avalanche formation are not trivial processes.
- Practically the only simulation tool that exists today is GARFIELD++ (old GARFIELD was written in Fortran and not actively maintained anymore).
- Microscopic (Monte Carlo) and analytic solvers.
- GARFIELD uses MAGBOLTZ to calculate electron transport in gas.
- HEED to produce primary electrons (Can be imported from another simulation tool, such as Geant4.
- Need a field map by a FEM solver.
- Still better solutions needed for complicated dynamic effects, such as charge-up, space charge generation etc.