

Gas Ionisation Detectors

- *ionisation*
- *movement of electrons and ions in electric fields*
- *charge signal*
- *ionisation chamber*
- *proportional chamber*
- *position sensitive detectors*
 - *multi-wire proportional chamber*
 - *drift chamber*
 - *time projection chamber*

Gas Ionisation Detectors

Incoming ionizing radiation (charged particles) creates electron-ion pairs in gas filled volume.

	Excitation potential [eV]	Ionization potential [eV]	Mean energy for ion-electron pair creation [eV]
H ₂	10.8	15.4	37
He	19.8	24.6	41
N ₂	8.1	15.5	35
O ₂	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO ₂	10.0	13.7	33
CH ₄		13.1	28
C ₄ H ₁₀		10.8	23

*energy loss due to excitation and ionization
free electrons and ions are created by ionization*

Gas Ionisation Detectors

Electrons and ions move due to the impact of diffusion randomly and the impact of an external electric field. Signal currents are induced at anode and cathode.

consider drift velocity v of electrons, determined by random collisions of electrons in gas along path

τ : average time between collisions

$\langle v_r \rangle$: average velocity due to random movement

n : number density

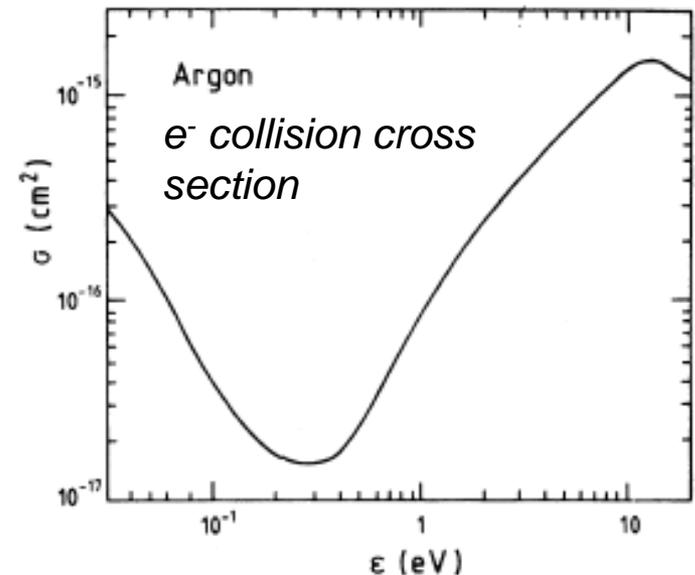
σ : cross section

collision rate: $\frac{1}{\tau} = n\sigma\langle v_r \rangle$

between collisions acceleration by electric field E :

$$m \frac{dv_e}{dt} = q_e E$$

$$x(t) = \frac{1}{2} \frac{q_e E}{m} t^2$$



Gas Ionisation Detectors

collision probability dP for time interval dt :

$$dP = \frac{1}{\tau} e^{-t/\tau} dt$$

average transport

$$\langle x \rangle = \int_0^{\infty} \frac{1}{2} \frac{q_e E}{m} t^2 \frac{1}{\tau} e^{-t/\tau} dt = \frac{q_e E}{m} \tau^2$$

$\langle v_d \rangle$: average drift velocity

$$\langle v_d \rangle = \frac{\langle x \rangle}{\tau} = \frac{q_e E}{m} \tau \equiv \mu E$$

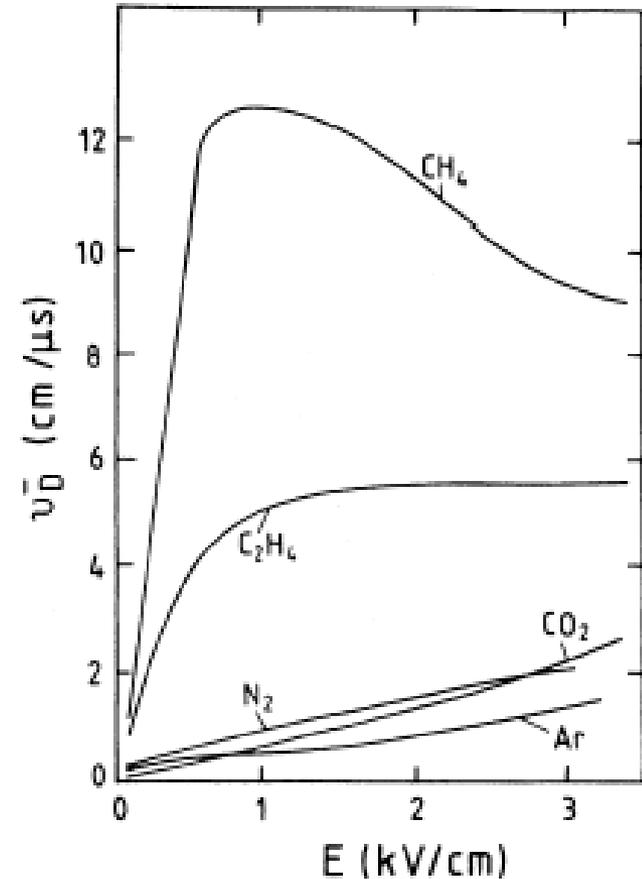
μ : mobility

τ is inverse proportional to density \sim pressure :

$$v_d \propto \frac{E}{p} \propto \mu p_0 \frac{E}{p} \quad \text{with } p_0 : \text{standard pressure}$$

$$\int_0^{\infty} t^n e^{-at} dt = \frac{\Gamma(n+1)}{a^{n+1}}$$

$$\int_0^{\infty} t^2 e^{-t/\tau} dt = \frac{\Gamma(2)}{(1/\tau)^3} = 2\tau^3$$



Gas Ionisation Detector

Electron drift velocity vs. reduced field E/p for different mixture of Argon and Methan

- drift velocity of ions is much lower due to high mass than electron drift velocity.*
- drift velocity: $v^+ = \mu^+ E p_0/p$ at reduced field strength $E/p \sim 1 \text{ kV/cm}$ ions are ~ 1000 times slower.*

compare:

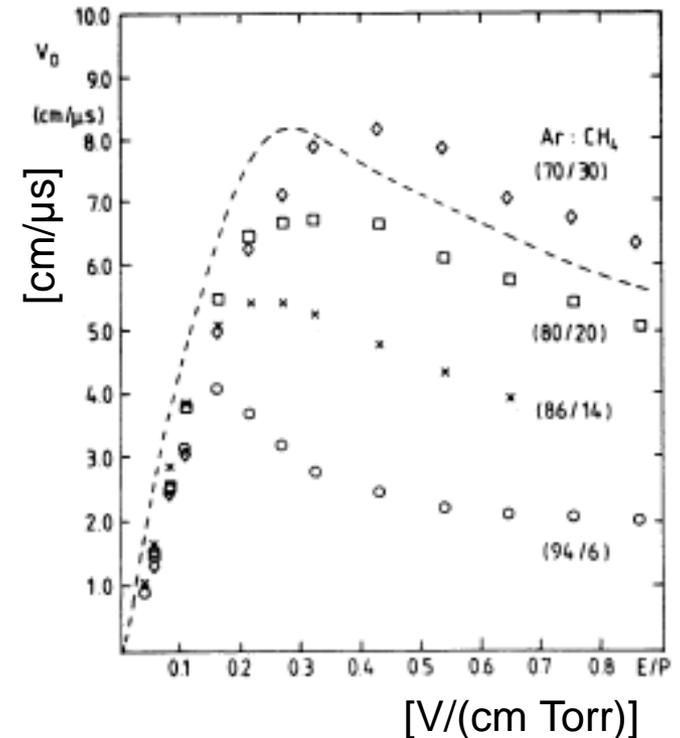
electrons: $v^+ \sim \text{cm}/\mu\text{s} = 10^6 \text{ cm/s}$

ions: $v^- \sim \text{cm/ms} = 10^3 \text{ cm/s}$

Losses

electrons are lost by recombination and electron attachment at electronegative gases e.g. O_2 , Cl_2^- , NH_3 , $\text{H}_2\text{O}..$,

Strong reduction of e^- - signal. Purity of counting gases is important.



Gas Ionisation Detectors

Ionisation chamber

Uniform electric field: $\mathcal{E} = V/d$

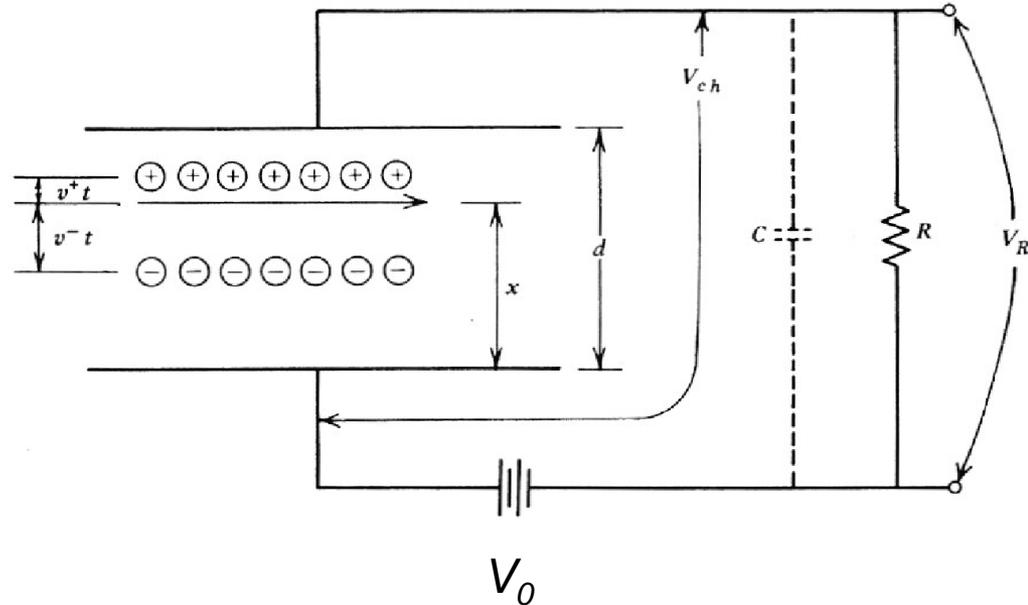
Energy of electrons, ions

$$E = Q \Delta\phi = n_0 e \mathcal{E} x = n_0 e \mathcal{E} v t$$

V_0 *applied high voltage*

V_{ch} *reduced voltage*

$V_R = (V_0 - V_{ch})$ *small signal voltage*



Energy conservation in capacitance:

$$\frac{1}{2} C V_0^2 = n_0 e \mathcal{E} v^+ t + n_0 e \mathcal{E} v^- t + \frac{1}{2} C V_{ch}^2$$

full energy ions electrons remaining energy

$$\frac{1}{2} C (V_0^2 - V_{ch}^2) = n_0 e \mathcal{E} t (v^+ + v^-)$$

with $2V_0 \sim (V_0 + V_{ch})$ and $V_{ch}/d \sim V_0/d$

$$\frac{1}{2} C 2V_0 V_R = n_0 e V_0/d (v^+ + v^-) t$$

$$\Rightarrow V_R = n_0 e / (dC) (v^+ + v^-) t$$

Gas Ionisation Detectors

$$V_R = n_0 e / (dC) (v^+ + v) t$$

electrons arrive at anode: $t = x/v$

only ion part moves:

$$V_R = n_0 e / (dC) (v^+ t + x)$$

ions arrive at cathode: $t = (d-x)/v^+$

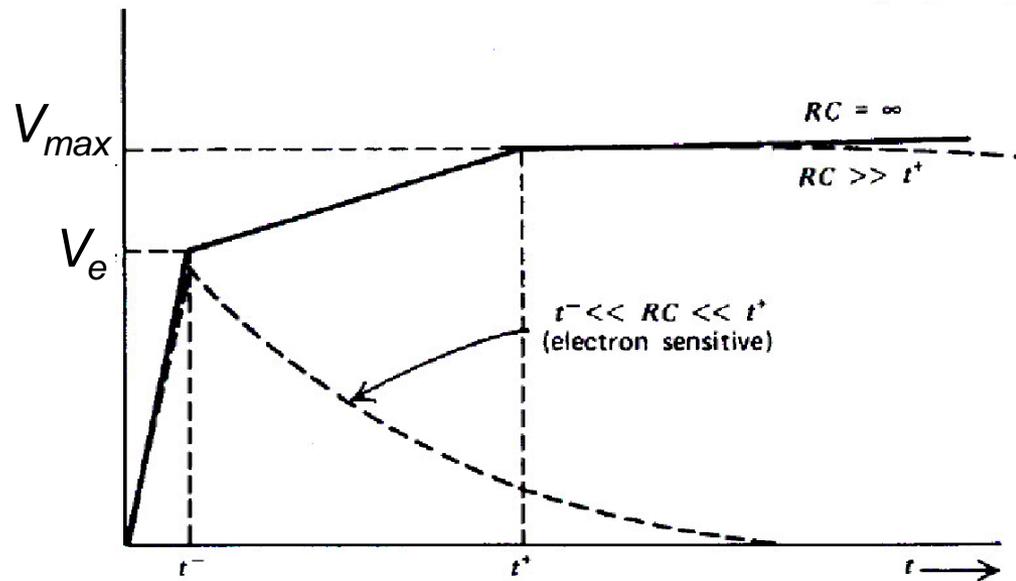
$$V_R = n_0 e / (dC) ((d-x) + x)$$

Signal stops at: $V_R = n_0 e / C$

Consider also coupling capacitance

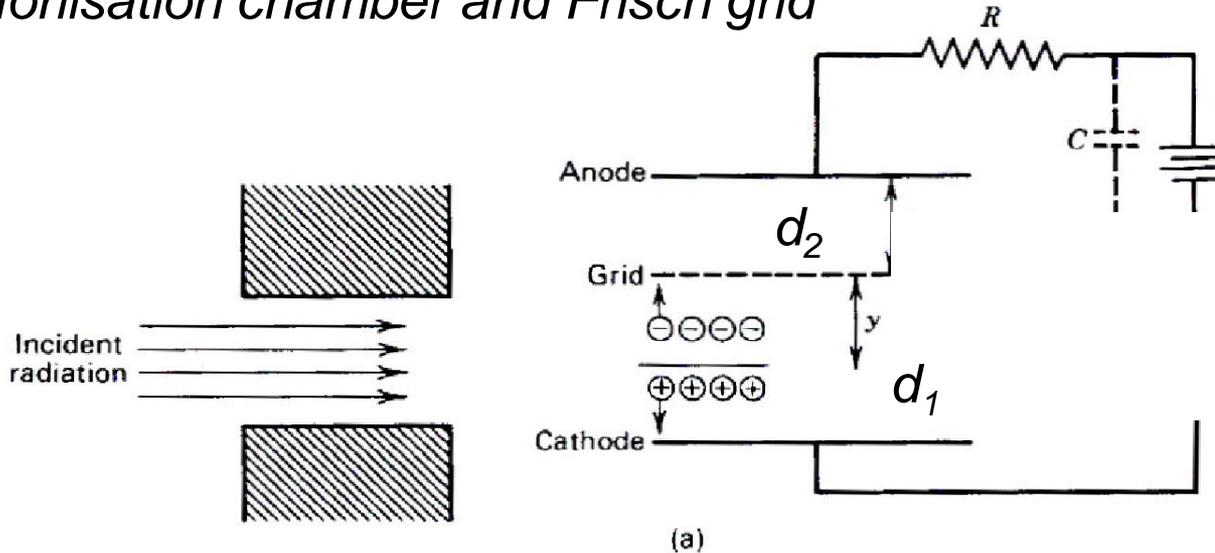
$$\text{for } RC \gg t^+ \quad V_{max} = V_R = n_0 e / C$$

$$t \ll RC \ll t^+ \quad V_R \sim V_e$$



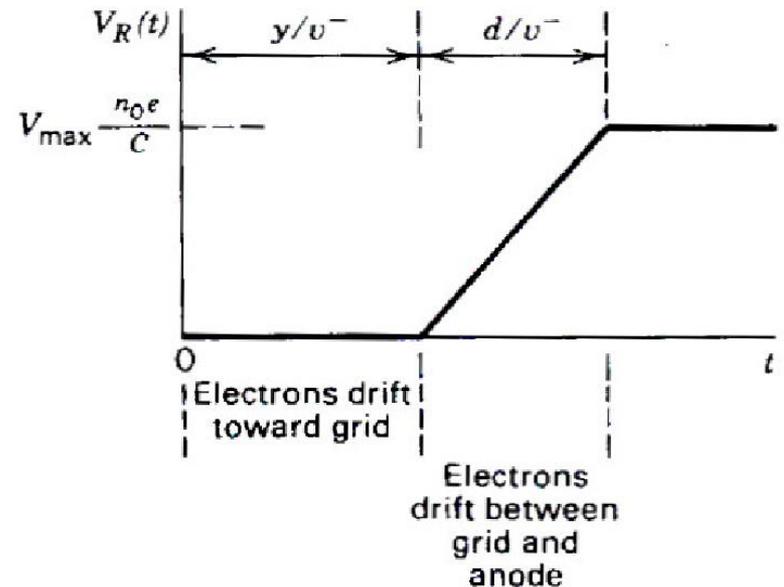
Gas Ionisation Detectors

Ionisation chamber and Frisch grid



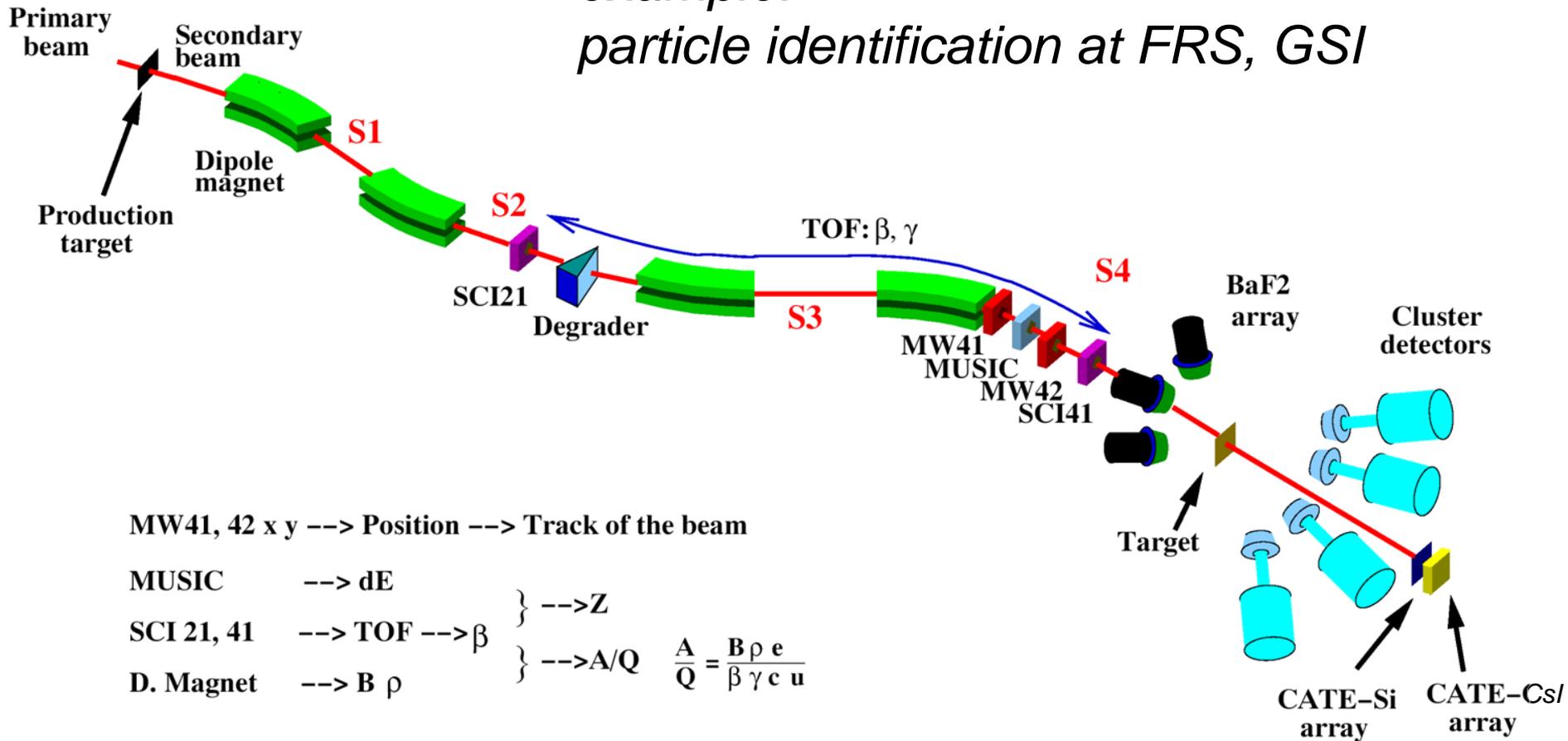
signal timing and amplitude

Ionisation chamber in nucl. physics
 + energy resolution $\sim 1\%$
 ($\Delta E/E = 1\%$ @ 5MeV α -particle)
 + flexible gas pressure/HV variation
 + uncomplicated, cheap
 + no radiation damage
 + large area 500 cm²
 + Bragg curve spectroscopy



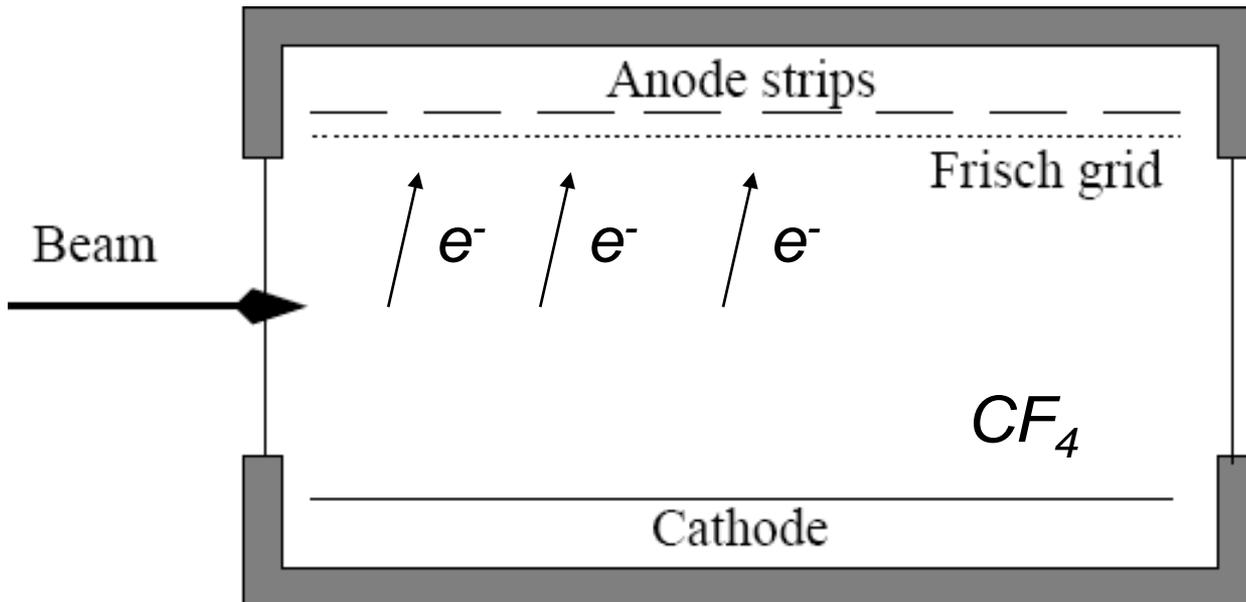
Gas Ionisation Detectors

*example:
particle identification at FRS, GSI*



Gas Ionisation Detectors

- MUSIC (Multi Sampling Ionisation Chamber) measures energy loss ΔE
- Z identification of incoming beam particles, amplitude independent of x
- Rate limitation



$$\#e^- \sim \Delta E$$

$$\frac{\Delta(\Delta E)}{\Delta E} \approx 1.6\%$$

Gas Ionisation Detectors

I recombination effects

II ionisation region

III gas amplification region

e^- - energy > ionisation energy

proportional region < 600 V

amplification is proportional to initial charge

increased voltage > 600 V

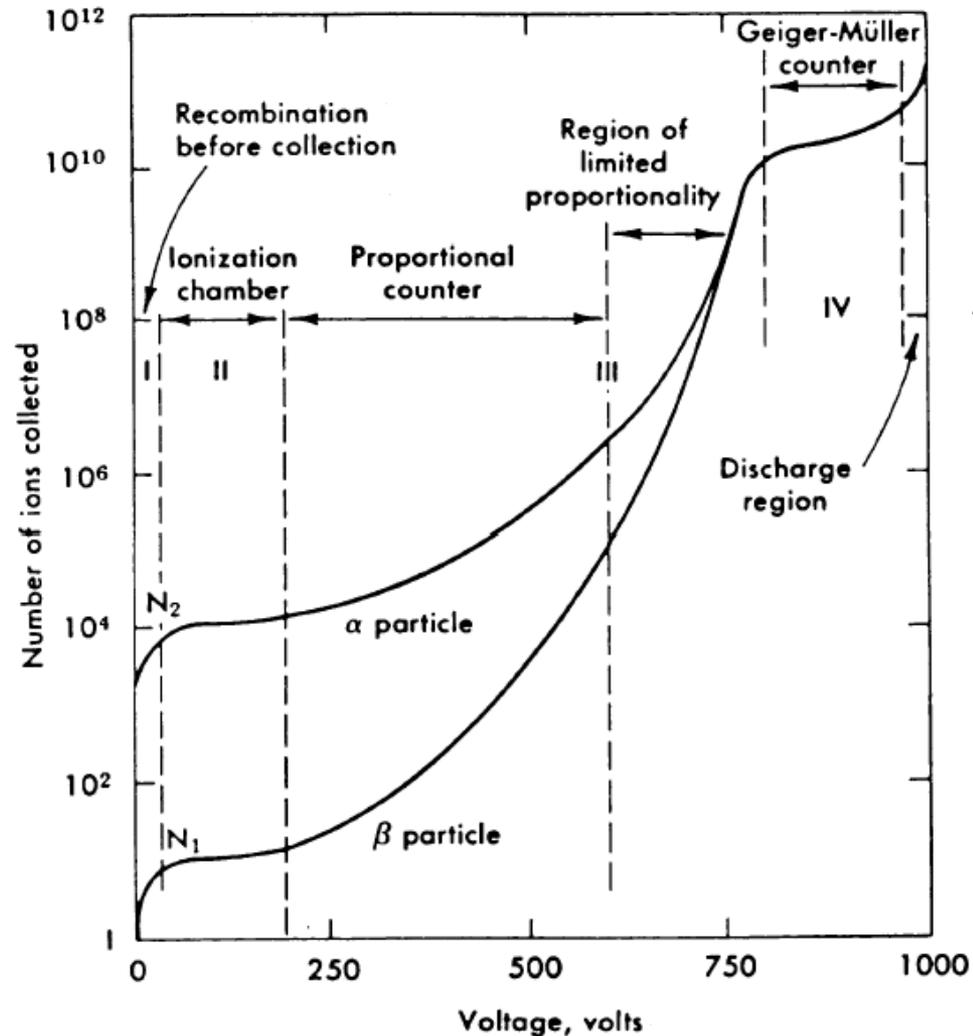
ampl is not proportional due to space charge of pos. ions

IV Geiger-Müller region

positive space charge limits

E-field strength, no additional amplification, same amplitude

V discharge region



Gas Ionisation Detectors

Proportional range: energy increase between collisions at high electrical field strength cause additional secondary ionisation.

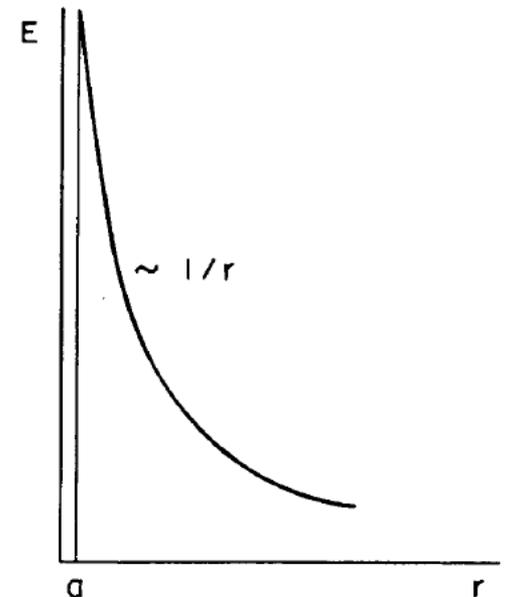
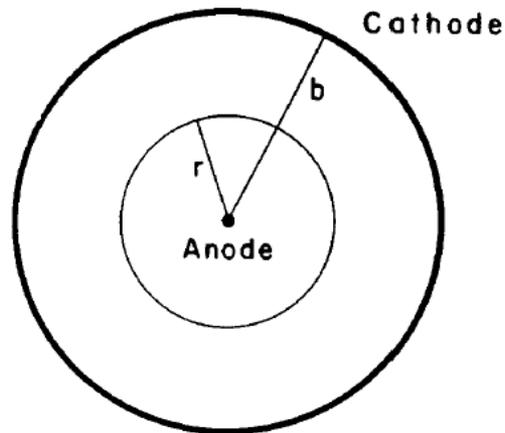
- *electron magnification along distance:*
- *requires high E- field strength*
- *use radial field strength dependence in vicinity of thin wires*

$$\vec{E}(r) = \frac{V_0}{r \ln \frac{r_2}{r_1}} = \frac{CV_0}{2\pi\epsilon} \frac{1}{r}$$

$$\varphi(r) = \frac{CV_0}{2\pi\epsilon} \ln\left(\frac{r}{r_1}\right)$$

r_1 radius wire

$r_2 = b$ inside radius zylinder



Gas amplification

Cylindrical geometry:

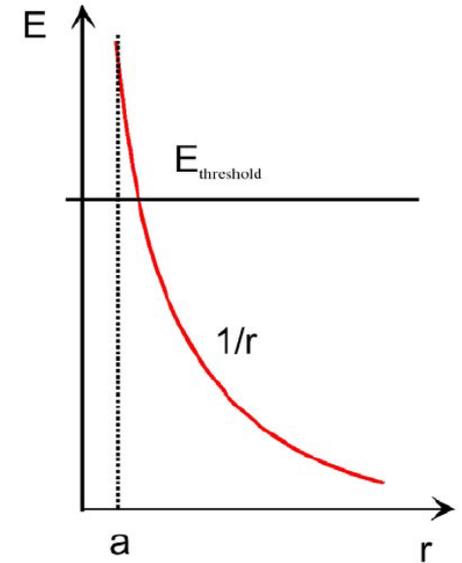
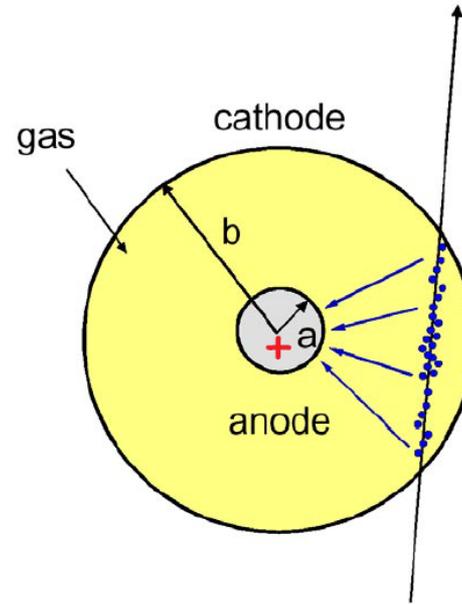
$$E(r) = \frac{CV_0}{2\pi\epsilon_0} \cdot \frac{1}{r} \text{ und } V(r) = \frac{CV_0}{2\pi\epsilon_0} \cdot \ln \frac{r}{a}$$

C =capacitance/length

Electrons drift in direction anode

Due to $1/r$ dependence of field strength in vicinity of thin wires $E > kV/cm$ and electrons can cause secondary ionisation of gas molecules

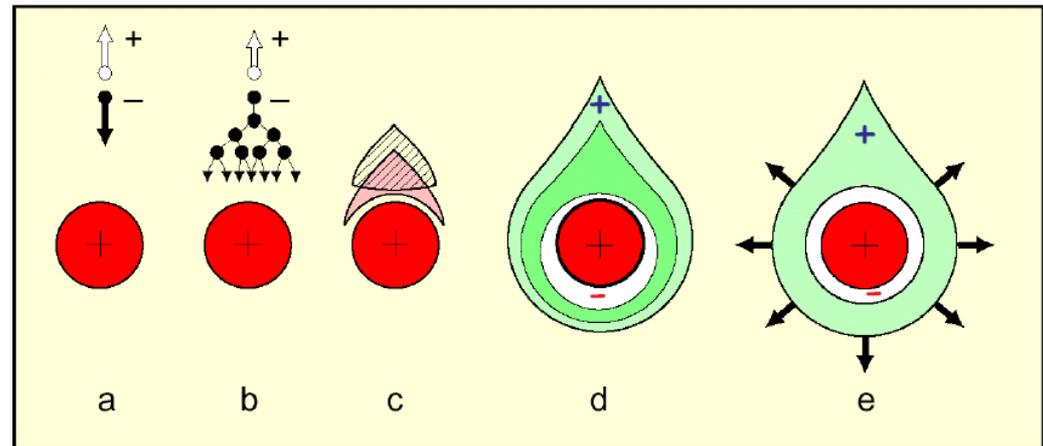
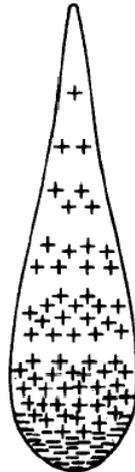
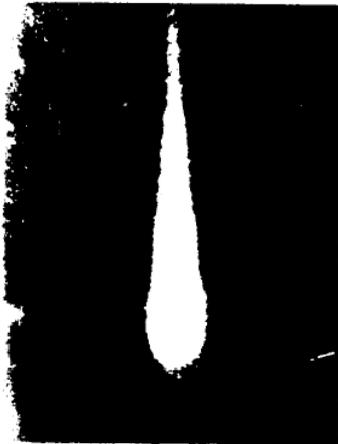
Exponential increase of electron-ion pairs only close to the wire!



Gas ionisation detector

Development of charge avalanche

Cloud chamber picture



- Transversale diffusion cause a drop like avalanche around the anode wire
- Electrons are collected within short time period of $\sim 1\text{ns}$
- Cloud of positive ions remains drifting slowly to cathode

Gas Ionisation Detectors

Gas amplification :

critical field strength ~ 50 kV/cm

$$r_c = \frac{V_0}{E_c \ln \frac{r_2}{r_1}}$$

Ionisations coefficient α depends on E -field and average free distance

\sim pressure: $\alpha = f(E/p) p$

Diethorn approxim.:

$$\alpha(E) \approx \frac{\ln 2}{\varepsilon_i} E$$

ε_i ionisation energy

Typical values:

wire diameter 25 μ m

outer radius 25 mm

high voltage 1 kV

-> critical radius 30 μ m

-> amplification vol./full vol. = 10^{-6}

Gas amplification

Number of electron-ion pairs per length unit produced in an avalanche is described by

Townsend coefficient α

which is related to the collision

ionisation cross section: $\alpha = \sigma_{ion} \cdot \frac{N_A}{V_{Mol}}$

Number of ions: $n(x) = n_0 \cdot \exp(\alpha(E) \cdot x)$

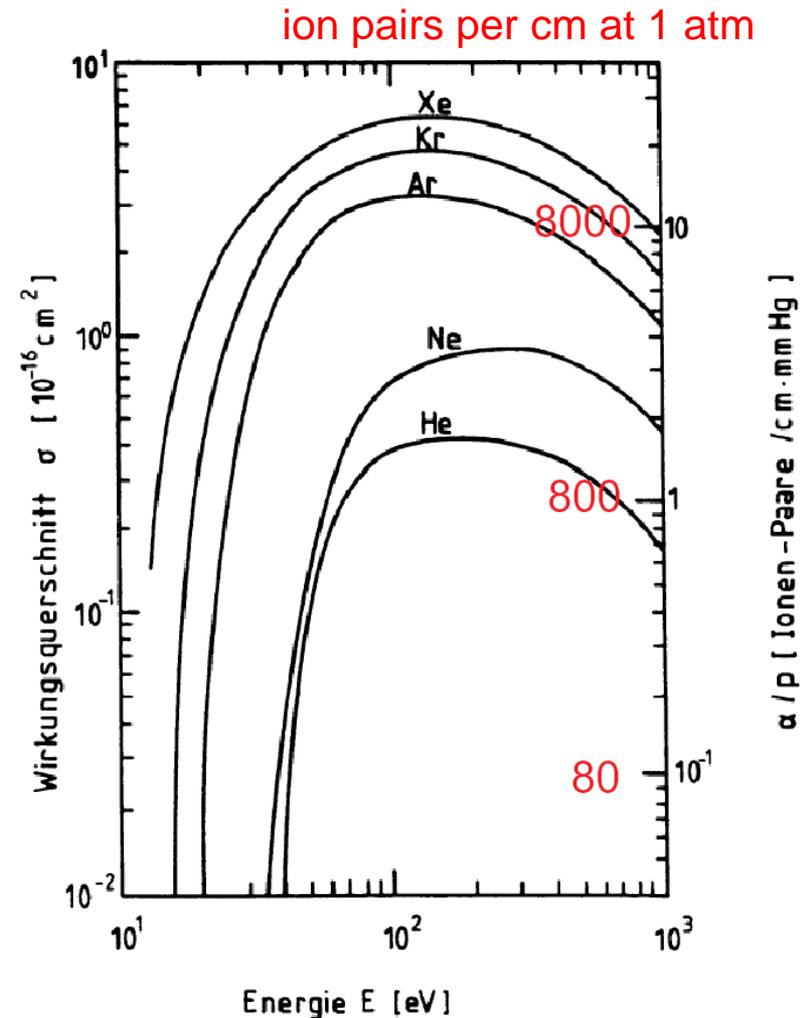
Gas amplification or gain:

$$A = \frac{n}{n_0} = \exp\left[\int_a^{r_c} \alpha(r) dr\right]$$

a anode diameter r_c critical distance for amplification

Exponential dependence between gain and applied high voltage

$$A \propto \exp\frac{U_o}{U_{Ref}}$$



Gas Ionisation Detectors

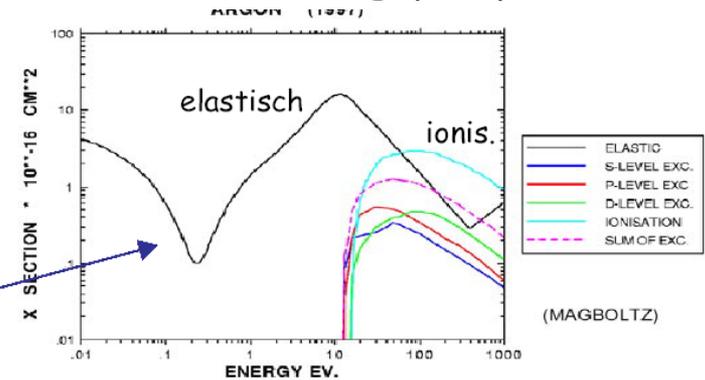
critical field strength and ionisation energy ε_i for different gas mixtures

Gas mixture	$E(r_c)$ [kV/cm]	ε_i [Volts]
90% Ar + 10% CH ₄	48 ± 3	23.6 ± 5.4
95% Ar + 5% CH ₄	45 ± 4	21.8 ± 4.4
92.1% Ar + 7.9% CH ₄	47.5	30.2
23.5% Ar + 76.5% CH ₄	196	36.2
9.7% Ar + 90.3% CH ₄	21.8	28.3
0.2% Ar + 99.8% CH ₄	171	38.3
CH ₄ (Hendricks)	69 ± 5	36.5 ± 5.0
CH ₄ (Diethorn)	144	40.3
C ₃ H ₈	100 ± 4	29.5 ± 2.0
75% Ar + 15% Xe + 10% CO ₂	51 ± 4	20.2 ± 0.3
90% Xe + 10% CH ₄	36.2	33.9
95% Xe + 5% CO ₂	36.6	31.4

Selection of counting gas

All gases show ionisation and amplification. However following properties are favorable:

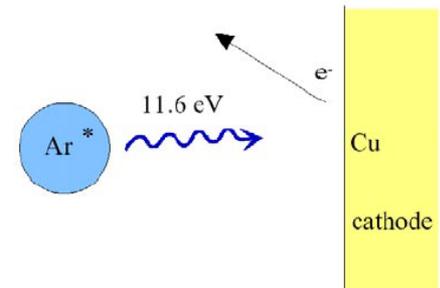
- Low high voltage
- Stable operation & high gain
- Count rate capability
- Long lifetime
- Short recovery time



Main component is typically nobel gas, which is mono-atomic and electrons show mainly elastic collisions with small energy losses. This enables gas amplification at relatively low voltages. Best Argon

Problem: In avalanche Ar atoms get excited and emit high energetic UV photons $E > 11.6$ eV. These photons hit cathode and cause electrons due to photoeffect (e.g. Al or Cu ~ 7.7 eV). Secondary electrons drift towards anode and creates another avalanche.

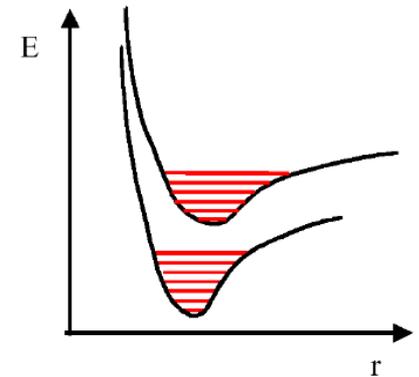
This effect causes with pure Ar gas already at low gas amplification a continuous current or 'break down'.



Additional gas components

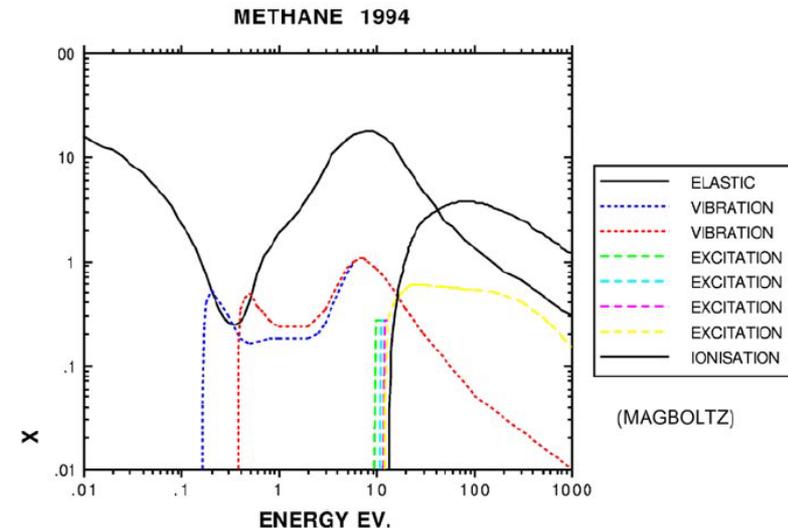
To get rid of this problem additional gas molecules are added.

- Molecules show many non-radiative vibrational and rotational states over a wide energy range.
- Molecules absorb UV photons at $\sim 100\text{-}200\text{ nm}$.
- Energy is released via collisions or dissociation
- Emission time is much longer than collision time and photons are effectively absorbed or quenched.



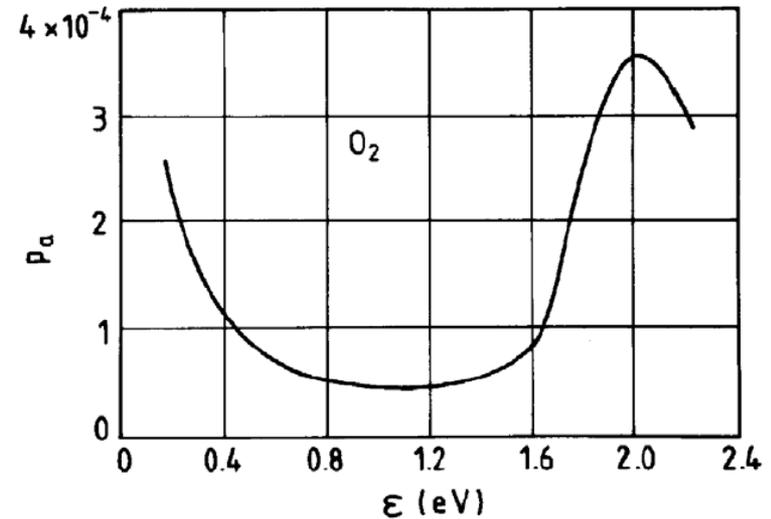
Most used molecules for 'quench gas'

- methane CH_4
- ethane C_2H_6
- isobutane iC_4H_{10}
- alcohol vapor



Recombination and electron capture

recombination probability per collision



Electro negative gases (without E field)

Gas	p_a	$n_s [s^{-1}]$	$t_a [ns]$
CO_2	6.2×10^{-9}	2.2×10^{11}	7.1×10^5
O_2	2.5×10^{-5}	2.1×10^{11}	190
H_2O	2.5×10^{-5}	2.8×10^{11}	140
Cl_2	4.8×10^{-4}	4.5×10^{11}	5

Recombination

Ions and electrons recombine and neutralize after production and detection. Depending on recombination coefficient

Highest recombination values for O_2 , CO_2 , Cl_2

Electron capture

Electron and molecules can combine to negative ions.

Depends on:

- p_a probability per collision
- n_s collision rate
- t_a average time for capture

Requires gas purification O_2 filter

Ion - and electron drift

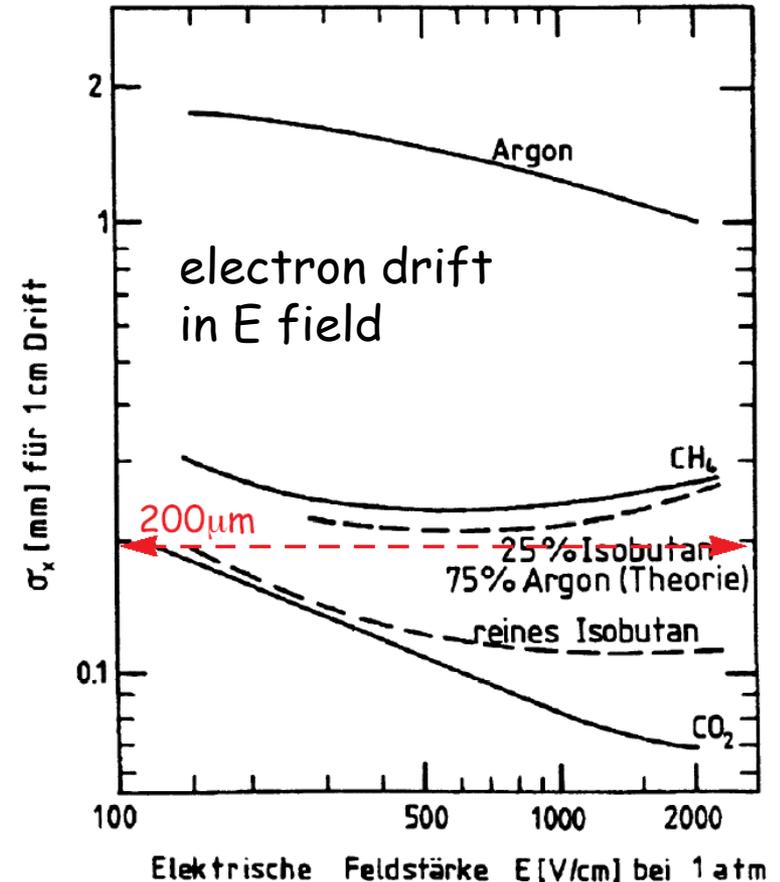
- Average mean free path
- Diffusion coefficient
- Mobility

For ions in gas, standard conditions

Gas	A	$\lambda_{Ion}[\text{cm}]$	$D_{Ion}[\text{cm}^2/\text{s}]$	$\mu_{Ion}\left[\frac{\text{cm/s}}{\text{V/cm}}\right]$
H ₂	2.02	1.8×10^{-5}	0.34	13.0
He	4.00	2.8×10^{-5}	0.26	10.2
Ar	39.95	1.0×10^{-5}	0.04	1.7
O ₂	32.00	1.0×10^{-5}	0.06	2.2
H ₂ O	18.02	1.0×10^{-5}	0.02	0.7

- Average mean free path of electrons six times ion path

- Mobility of electrons three order of magnitudes higher



Transversal width of electron cloud after 1 cm drift length as function of E field strength

summary gas ionisation detectors

Ionisation depends on:

- Ionisation energy
- Average energy per ion pair
- Average number of primary ion pairs per cm
- Average number of final ion pairs per cm (includes losses and amplification gain)

Important gas properties:

- Mobility of charges → timing properties
- Collisional ionisation → gas amplification
- Impact of electro negative gases (O_2, F, Cl, \dots) → efficiency
- Diffusion → position resolution

Multi Wire Proportional Chamber

Multi Wire Proportional Chamber: MWPC

George Charpak 1968

Enlarged concept of proportional counter and used wire planes.

Anode wires act as independent detector.

Capacitive coupling of electron pulses of avalanches at the anode wire L to neighbouring wires A is negligible with respect to the positive pulse caused by ions moving towards wires

Electronic instrumentation development in 1970's enabled fast read out of many channels (= wires)
→ 10^6 tracks per sec

Major breakthrough in detector development

Nobel price of physics in 1992

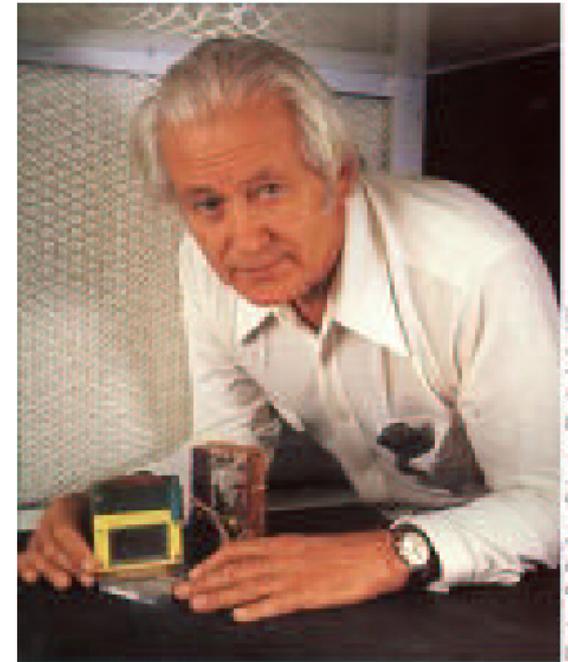
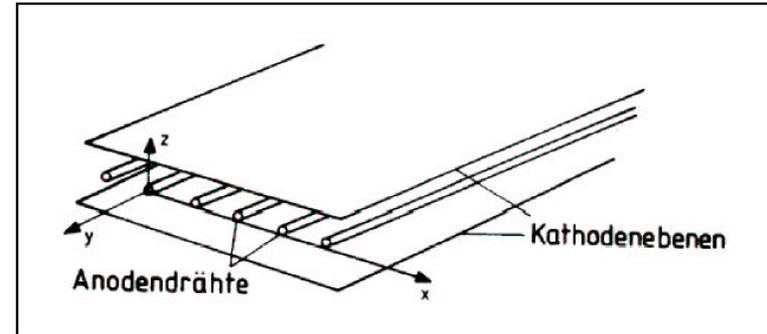


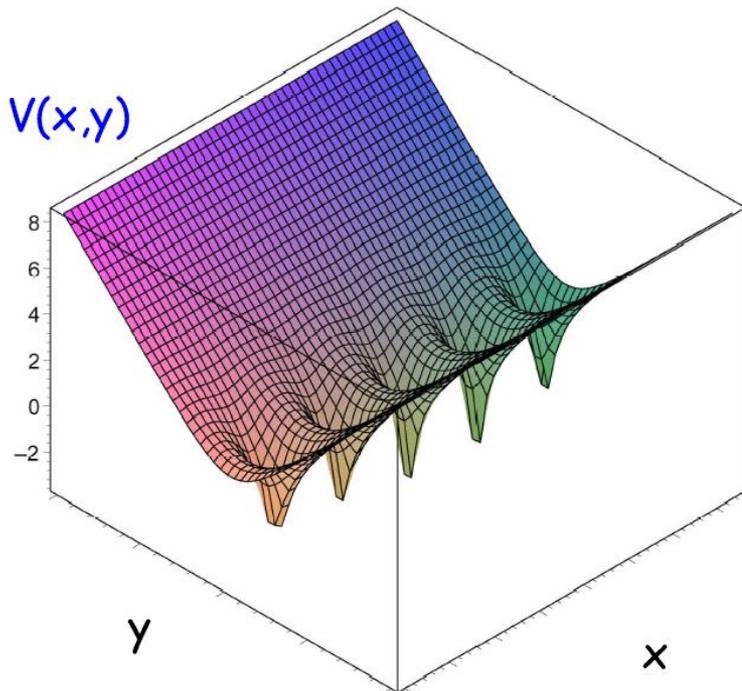
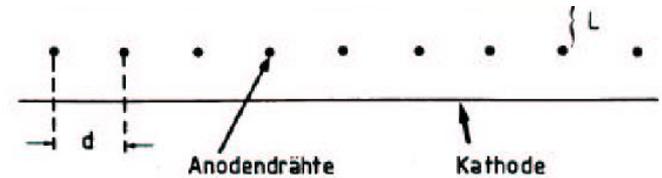
Photo: D. Pankov, Science Photo Lab, UK

Multi Wire Proportional Chamber

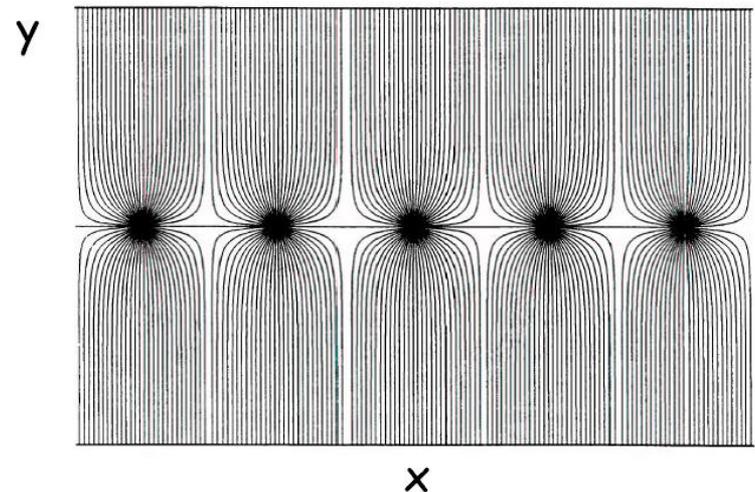
Anode wires are typically made of gold coated tungsten wires with a diameter of 15-30 μm . Chamber walls have to be light as possible e.g. fibre material, cathode planes are made of thin metall layers $\sim 50\mu\text{m}$. Typical distances: $d=2\text{mm}$, $L=4\text{mm}$

The potential within a plane MWPC is given by

$$V(x, y) = -\frac{q}{4\pi\epsilon_0} \ln \left\{ 4 \left[\sin^2\left(\frac{\pi x}{d}\right) + \sinh^2\left(\frac{\pi y}{d}\right) \right] \right\}$$



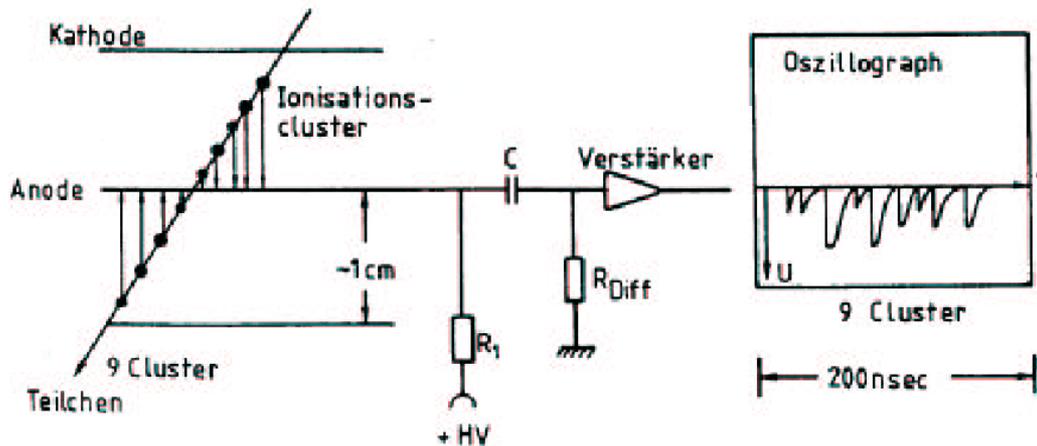
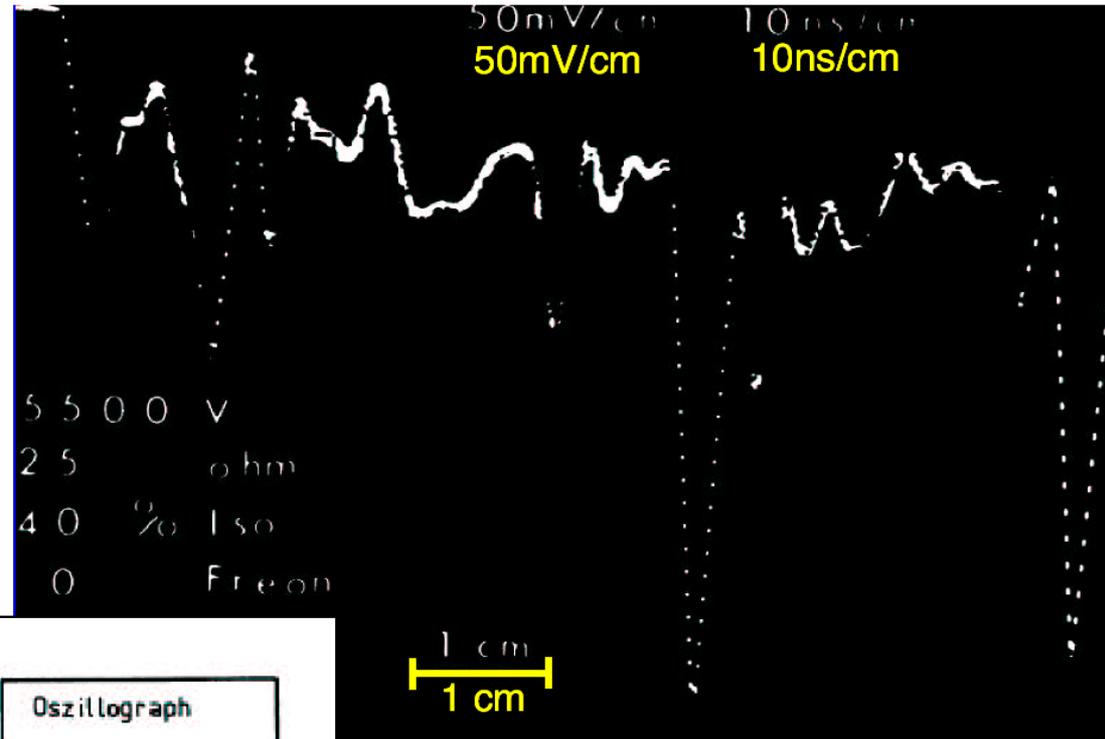
electric field lines



Mechanical tolerances are very limited! Precision of wire position needs to be high!

Multi Wire Proportional Chamber

Ionisation is not homogeneous along track. Single ionisation clusters can be made visible with fast electronics.



Multi Wire Proportional Chamber

Detector is triggered by pulses above threshold level. Efficiency depends on:

- high voltage level
- threshold voltage
- length of time window

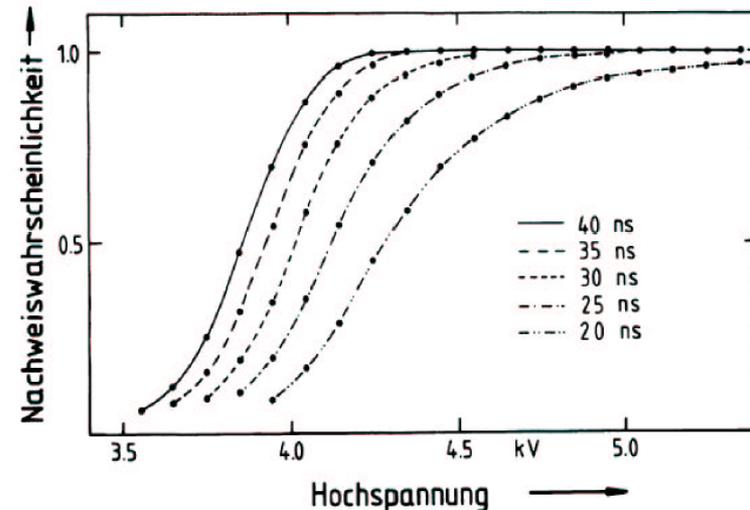
HV has to provide pulses above trigger level for 100% efficiency, but no continuous discharge may occur in detector volume.

Parameter depends on

- noise
- electronics sensitivity
- required time resolution

Ionisation/cm $1/\lambda$ t_{99} thickness for 99% probability of ionisation

	Encounters/cm	t_{99} (mm)	Free electrons/cm
He	5	9.2	16
Ne	12	3.8	42
Ar	25	1.8	103
Xe	46	1.0	340
CH ₄	27	1.7	62
CO ₂	35	1.3	107
C ₂ H ₆	43	1.1	113



Multi Wire Proportional Chamber

Advantages

- large area can be covered
- planar and cylindrical detector geometry
- simple position determination via digital read out
- can be used in high magnetic field
- fast electronic signal ($t \sim 20-50\text{ns}$)
Can be used for trigger

Disadvantages

- limitations in position resolution
- large tracking volume causes a Very high number of signal channels
- position determination limits momentum measurements
- at high count rates reduced local field strength due to space charge effects.

Drift chamber

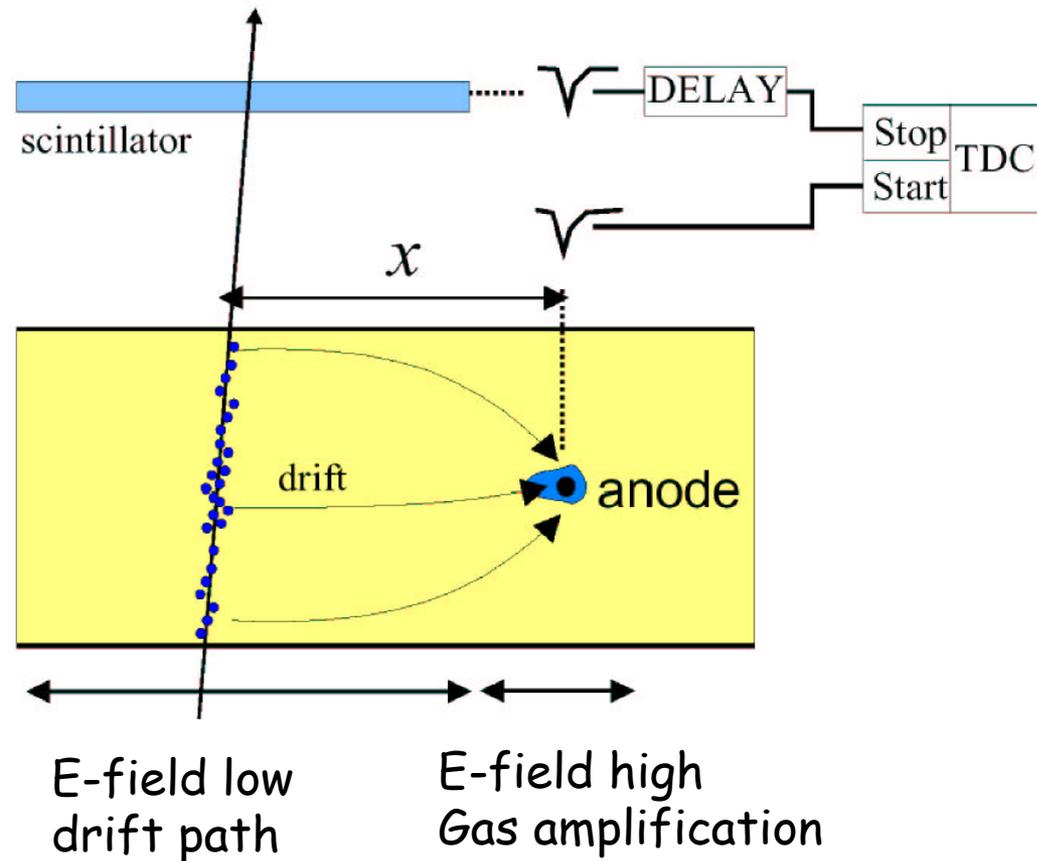
measure arrival time t_1 of electron avalanche with respect to external fast trigger signal t_0

The time t_0 must be given by same particle and other fast detector e.g. scintillator.

x-coordinate

$$x = \int_{t_0}^{t_1} v_D(t) dt$$

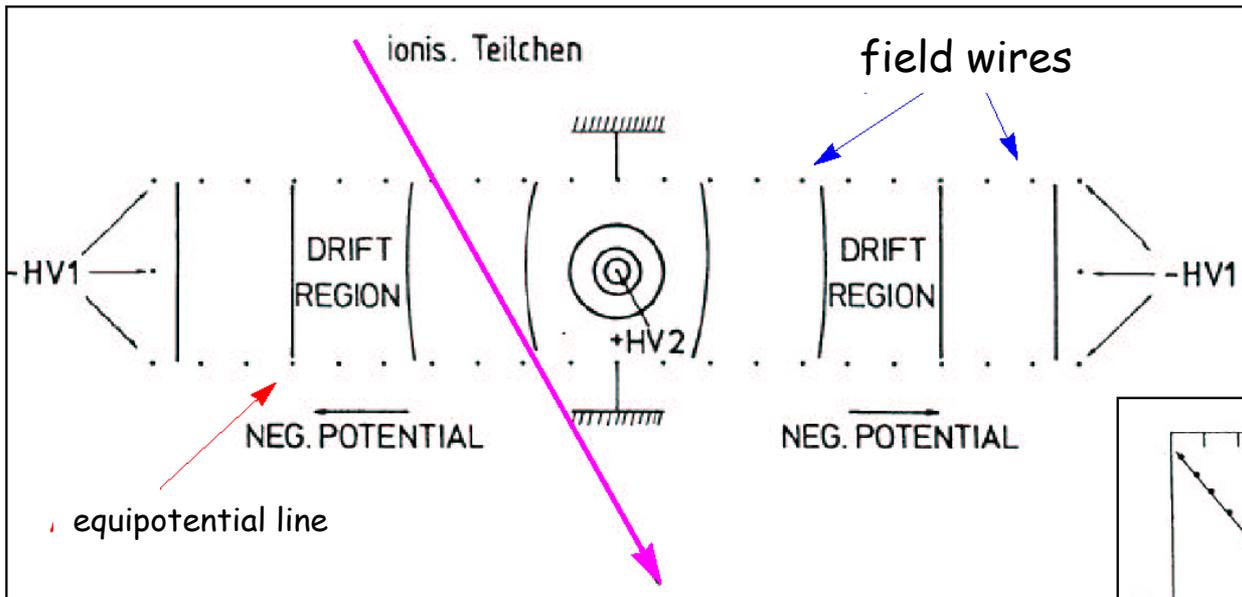
It is advantageous to have a constant drift velocity along the full drift distance for linear relationship time vs distance.



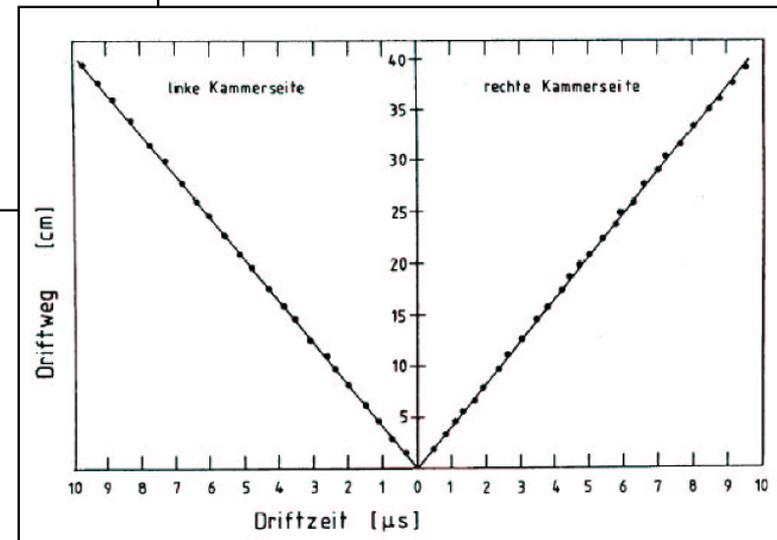
TDC: Time to Digital Converter

Drift chamber

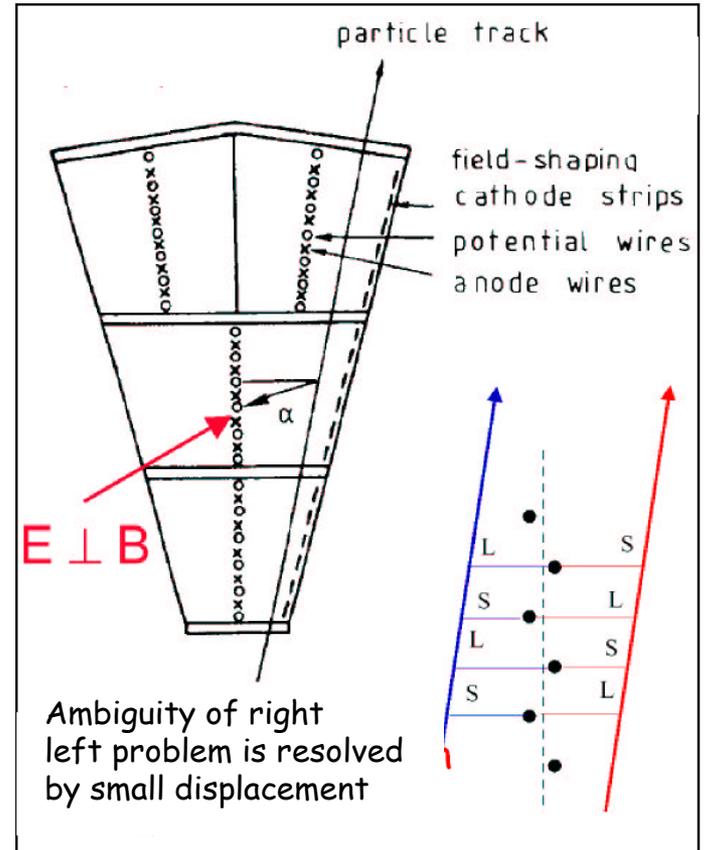
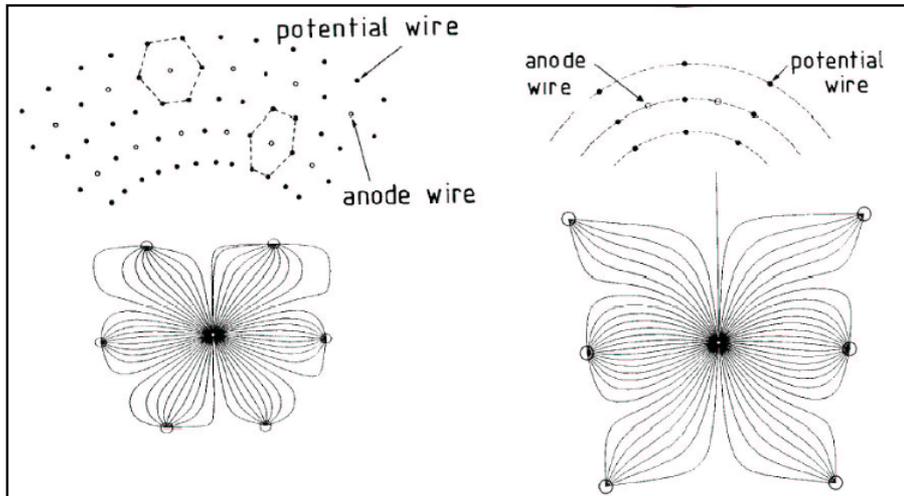
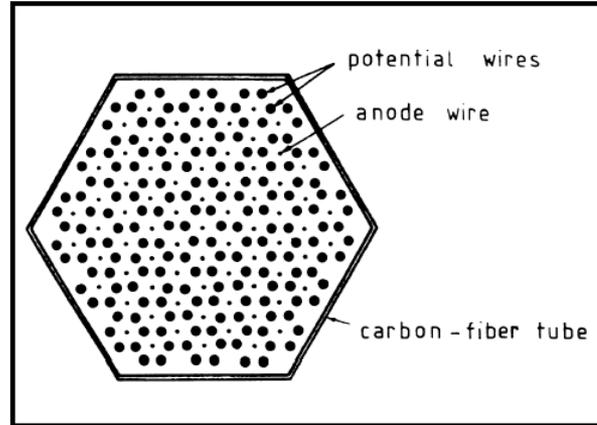
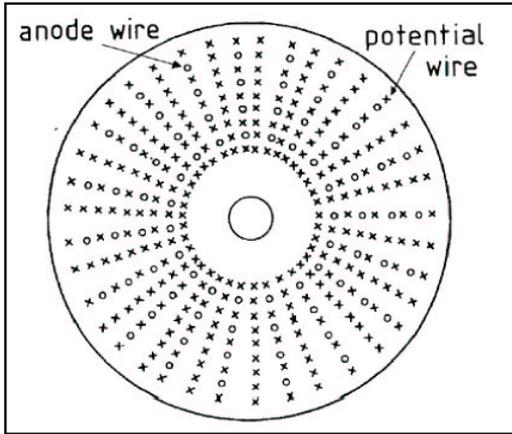
Position and potential of additional wires are used to shape the electric field. This can be done by resistors between the wires in order to achieve a constant electric field inside the drift volume and therewith a constant velocity.



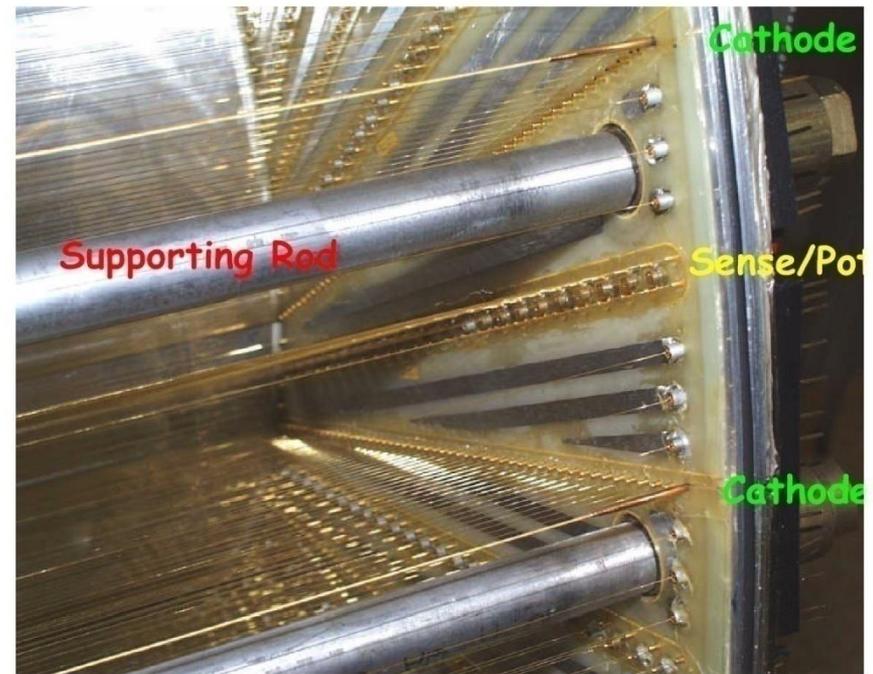
position time correlation



Drift chamber designs



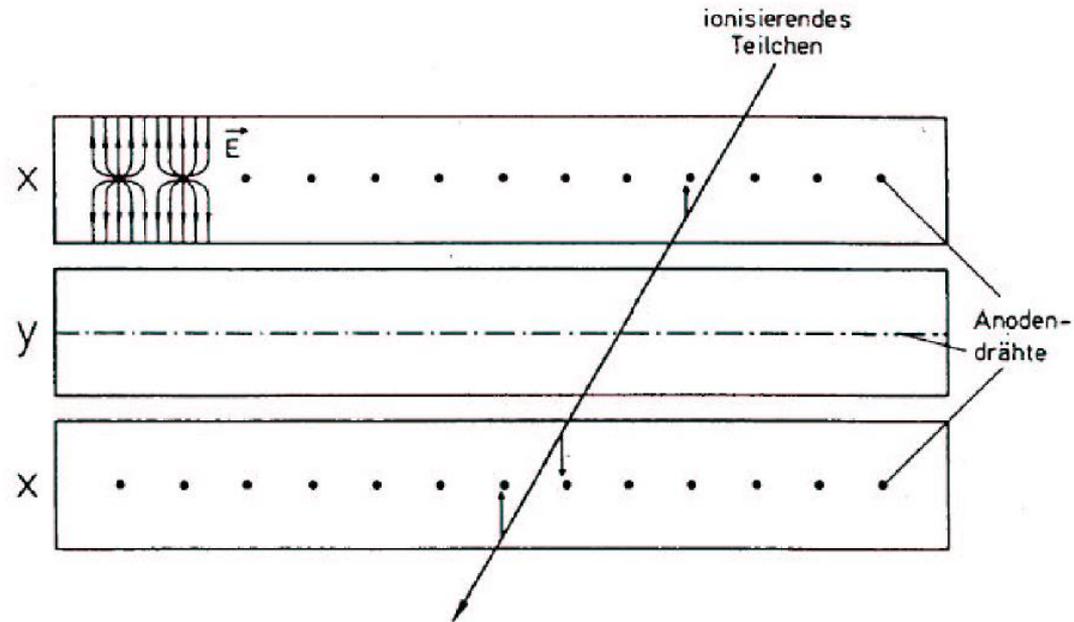
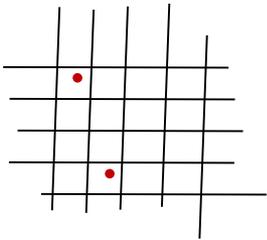
Drift chamber



Drift chamber

Two dimensional coordinates can be measured with crossed wire planes.

Ambiguity problem:
In case of several tracks each crossing point is candidate of particle. Combination increases quadratically with number of crossings.



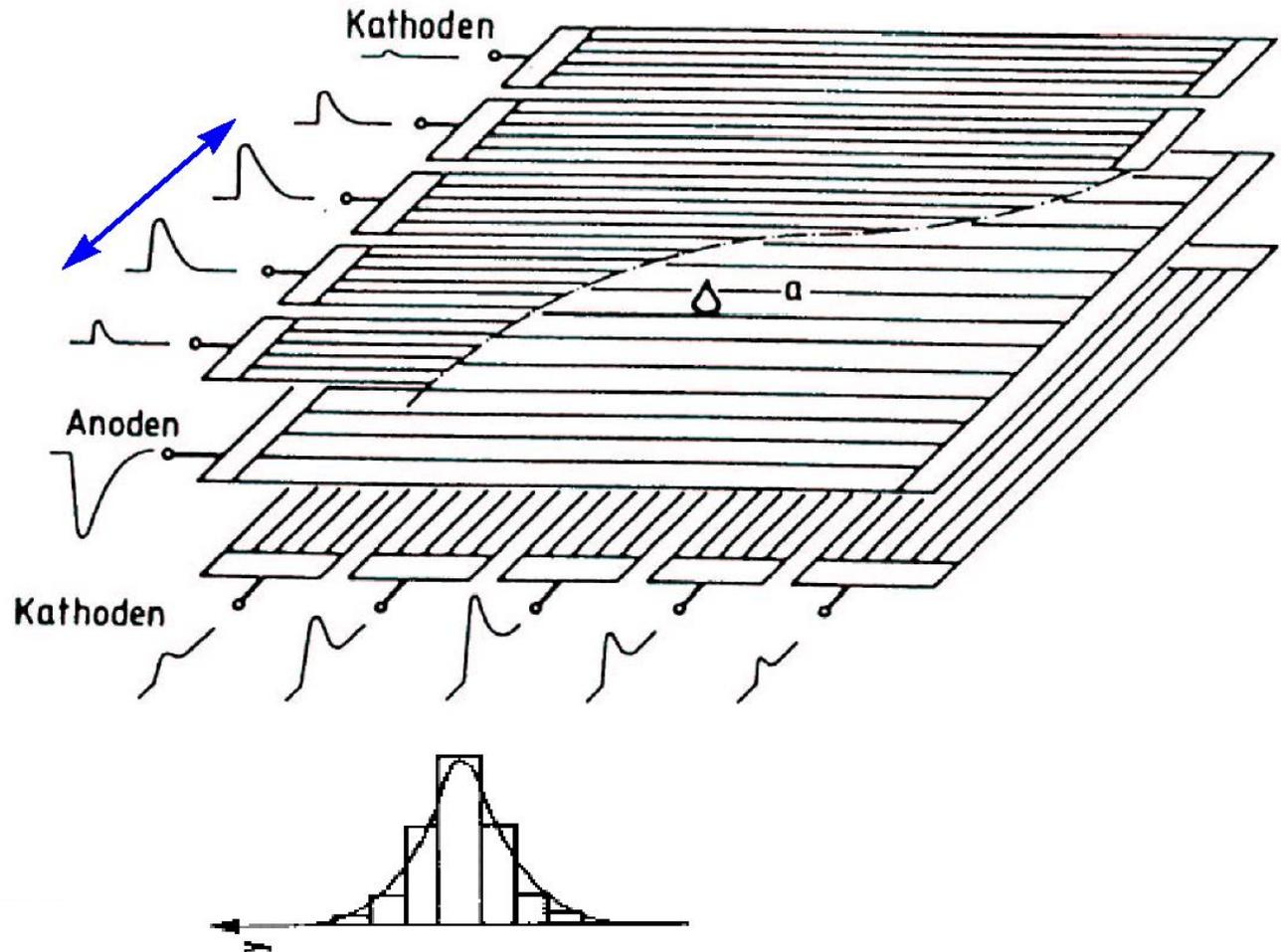
Drift chamber

At cathode a positive signal is induced by fast moving electron cloud.

Signal amplitude is decreasing with distance to location of avalanche.

Measure amplitude of neighbouring cathode stripes and determine centre of gravity.

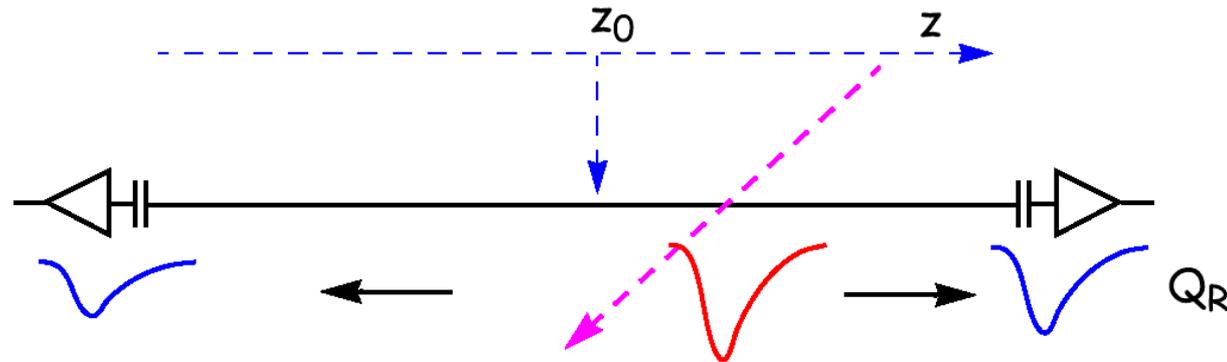
Allows resolution well below the width of the individual stripes
typical values:
 $\sim 30 - 40 \mu\text{m}$



Drift chamber

Position determination:
Charge at point z is divided
at both left/right side in
two parts. The charge ratio
is given by:

$$\frac{Q_L}{Q_R} = \frac{R_L}{R_R} = \frac{\frac{L_{eff}}{2} + (z - z_0)}{\frac{L_{eff}}{2} - (z - z_0)}$$



Effective length of wire L_{eff} depends on: resistivity, resistivity of add. network, coupling capacitance, electronics...

Typically a resolution of 1% is achieved, $\sigma \sim 2\text{cm}$ for 2 m wire length

Resolution depends strongly on pulse heights

A complementary method to measure position is possible by utilizing the different signal arrival times or timing differences between left/right, called: z-by-timing