Gaseous Detectors – Ionization Measurement

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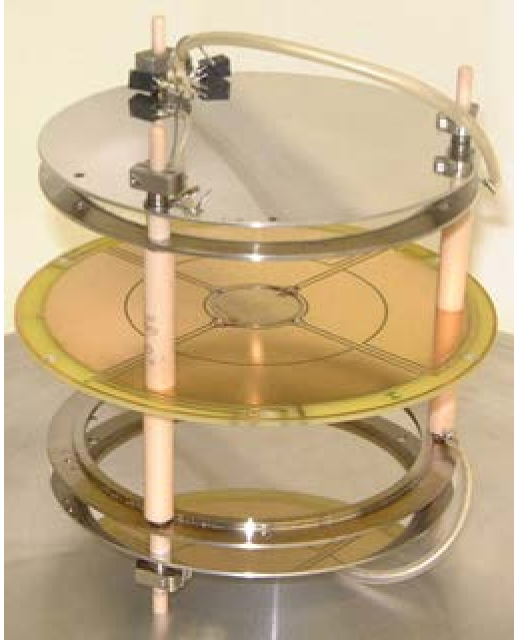
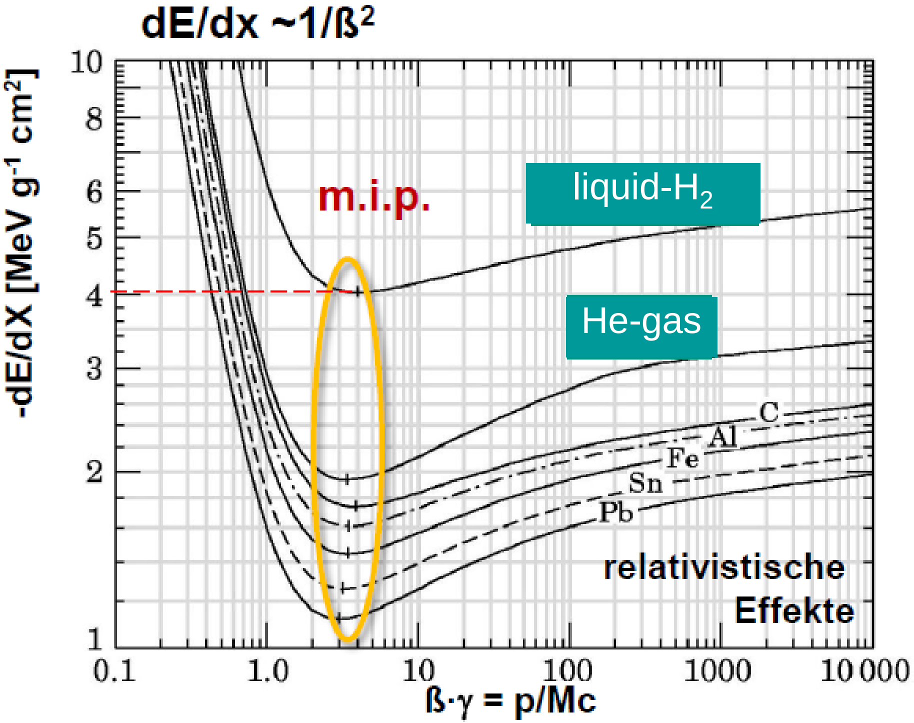


Interaction of charged particles in matter

Bethe-Bloch formula describes the energy loss of heavy particles passing through matter

$$-\frac{dE}{dx} = \underbrace{4\cdot\pi\cdot r_e^2\cdot N_a\cdot m_e c^2}_{= 0.3071\ \mathrm{MeV\ g^{-1}cm^2}}\cdot\rho\cdot\frac{Z}{A}\cdot\frac{z^2}{\beta^2}\cdot\left[\frac{1}{2}\ln\left(\frac{2\cdot m_e c^2\cdot\gamma^2\cdot\beta^2\cdot T_{max}}{I^2}\right)-\beta^2-\delta-2\cdot\frac{C}{Z}\right] \qquad \approx z^2\cdot\frac{Z}{A}\cdot f(\beta,I)$$

- energy loss of a particle is independent of its mass!
- energy loss is an important tool for particle identification
- for minimum ionizing particles **m.i.p.**
  dE/dx ~ 1-2 MeV g^{-1} cm^2
  i.e. for a target density ρ = 1 g/cm^3
  dE/dx ~ 2 MeV/cm

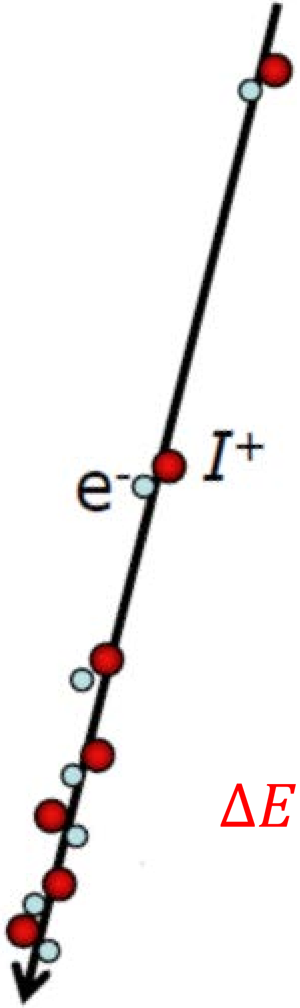


- for small β the term $1/\beta^2$ is dominant
- dE/dx has a minimum at βγ~3-4 (minimum ionizing particle)
- for high momenta dE/dx reaches a saturation

Ionization detectors

- incoming particle
- ionization track

➡ ion/e^- pairs



$$\Delta E \propto \langle n \rangle$$

$$\approx linear\ for\ \Delta E \ll E$$

Minimum-ionizing particles (Sauli. IEEE+NSS 2002)

different counting gases:

GAS (STP)	Helium	Argon	Xenon	CH_4	DME
dE/dx (keV/cm)	0.32	2.4	6.7	1.5	3.9
<n> (ion pairs/cm)	6	25	44	16	55

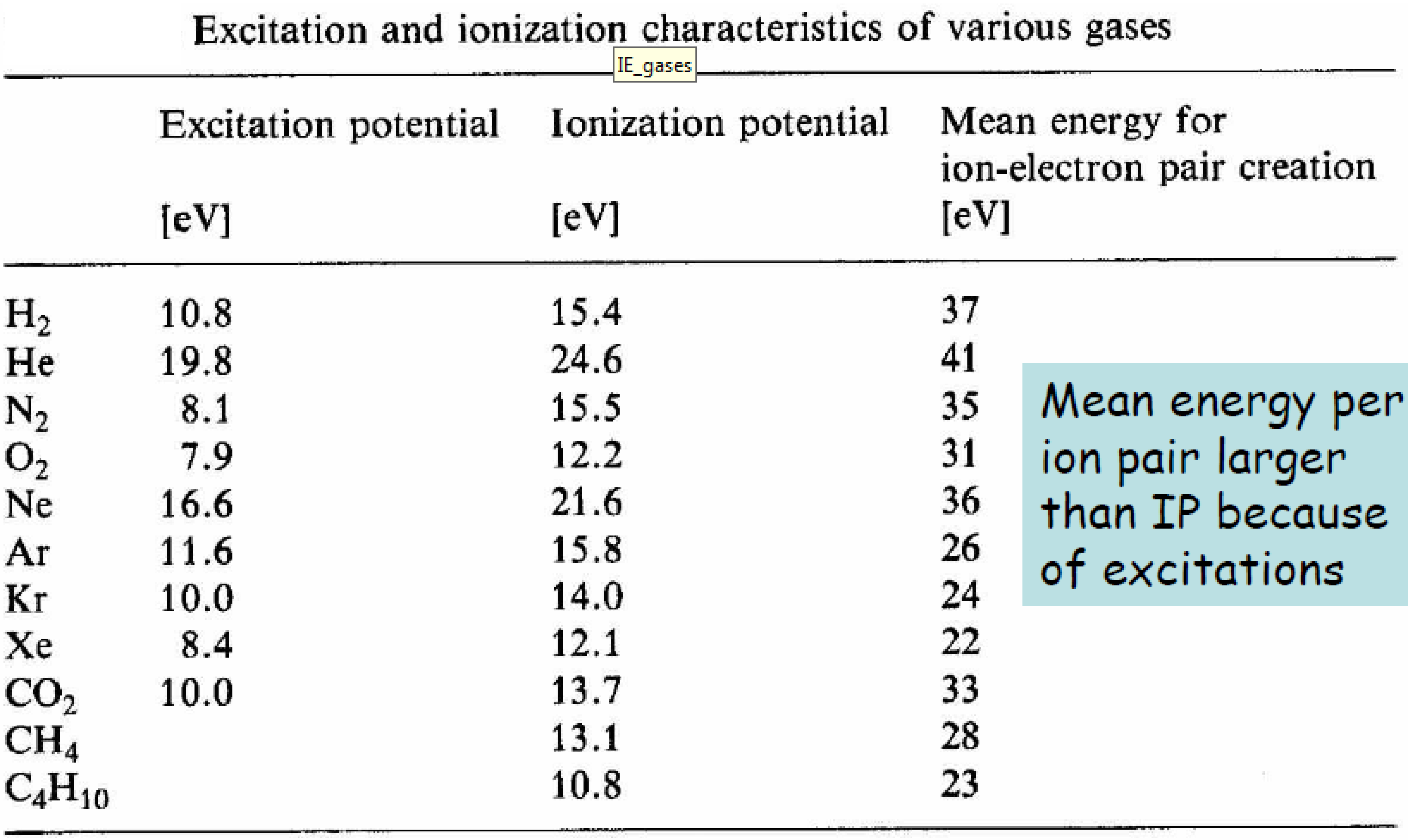
ionization process: Poisson statistics

detection efficiency ε depends on average number <n> of ion pairs

$$\boxed{\varepsilon \leq 1 - e^{-\langle n \rangle}}$$

GAS (STP)	thickness	$\varepsilon\,(\%)$
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

Effective ionization energies



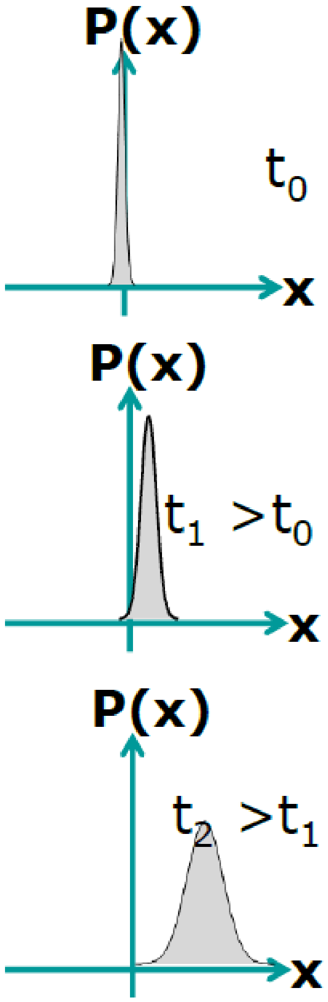
Excitation and ionization characteristics of various gases

	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_4H_{10}		10.8	23

Mean energy per ion pair larger than IP because of excitations

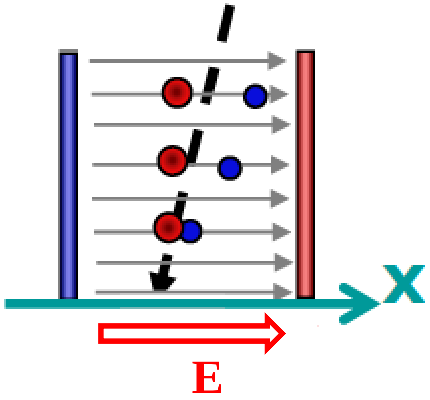
Large organic molecules have low-lying excited rotational states
⟶ excitation without ionization through collisions

Charge transport in gas



charge diffusion

Electric field **E = ΔU / Δx** separates positive and negative charges



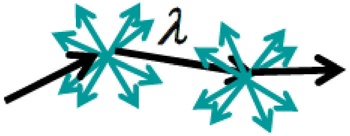
charge diffusion in electric field

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi\cdot\bar{D}\cdot t}}\cdot exp\left\{-\frac{(x-w\cdot t)^2}{4\cdot\bar{D}\cdot t}\right\}$$

$w = \frac{e}{2m}\cdot E\cdot\tau$ drift velocity

$\tau = \lambda/\langle v\rangle$ mean time between collisions

$\bar{D} = \mu\cdot\frac{k\cdot T}{e}$ $\mu = \frac{w}{E}$ mobility



There is a cycle of acceleration and scattering/ionization etc.

drift(w) and diffusion (D) depend on field strength E and gas pressure ρ

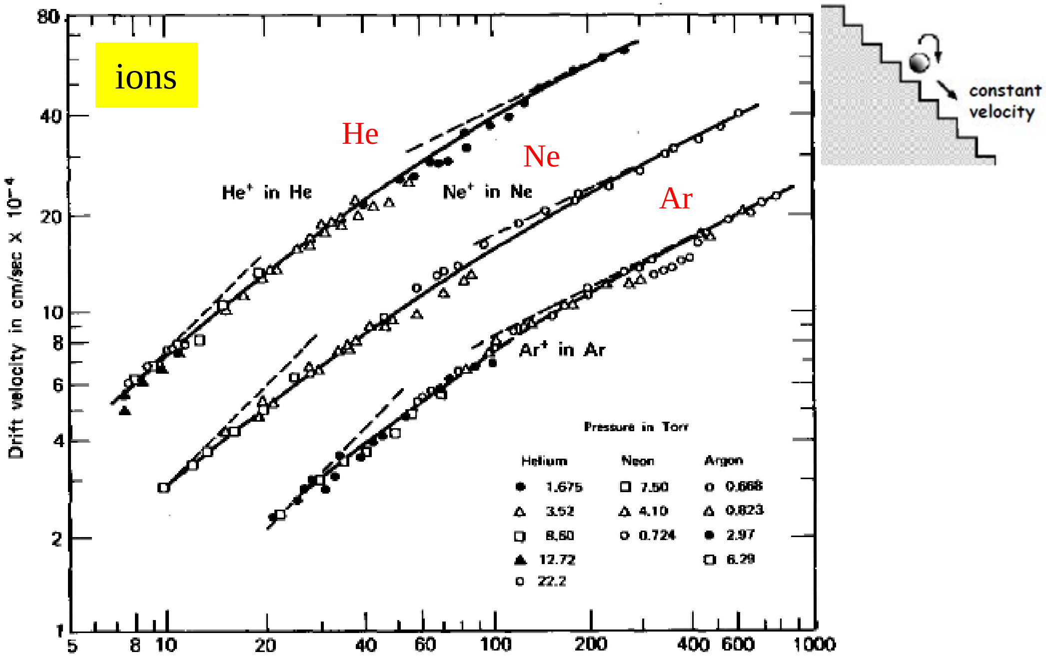
$w = w(E/\rho)$ $\bar{D} = \bar{D}(E/\rho)$

Ion mobility

GAS	ION	μ^+ ($cm^2 V^{-1} s^{+1}$) @STP
Ar	Ar^+	1.51
CH_4	CH_4^+	2.26
$Ar+CH_4$ 80+20	CH_4^+	1.61

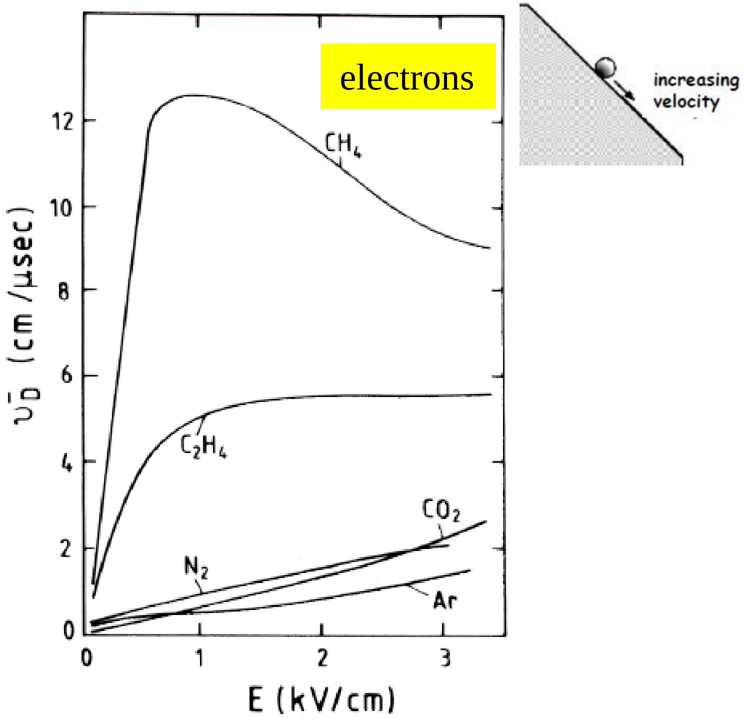
ion mobility $\mu^+ = w^+/E$

For ions there is an interplay between acceleration and collisions. Ion mobility is independent of field for a given gas at ρ, T = const.



E/ρ (V/cm/torr)

$w^+ \sim 10^{-2}$ cm/μs



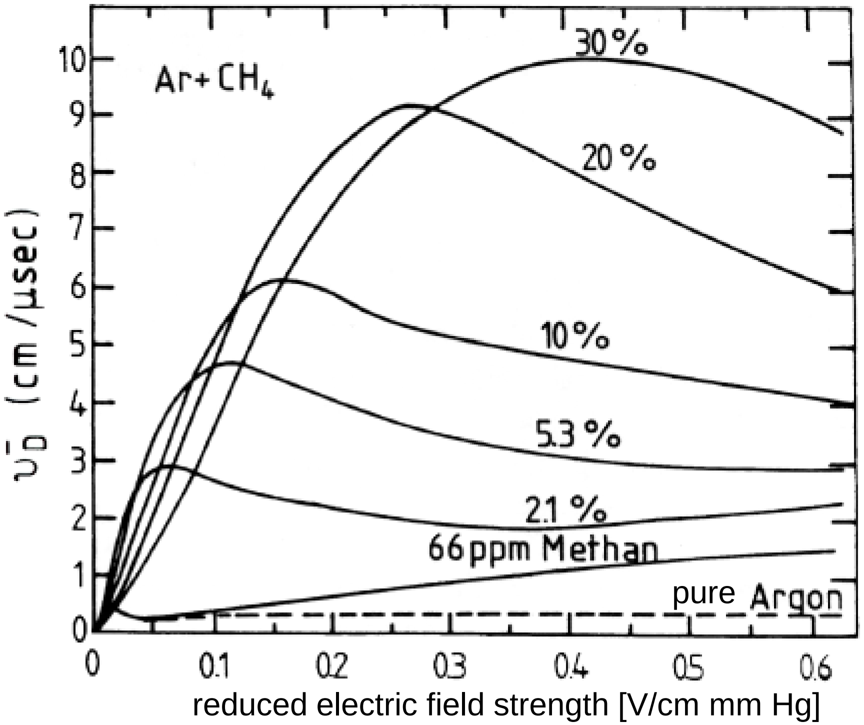
$w^- \sim 10^1$ cm/μs

E. McDaniel and E. Mason; The mobility and diffusion of ions in gases (Wiley 1973)

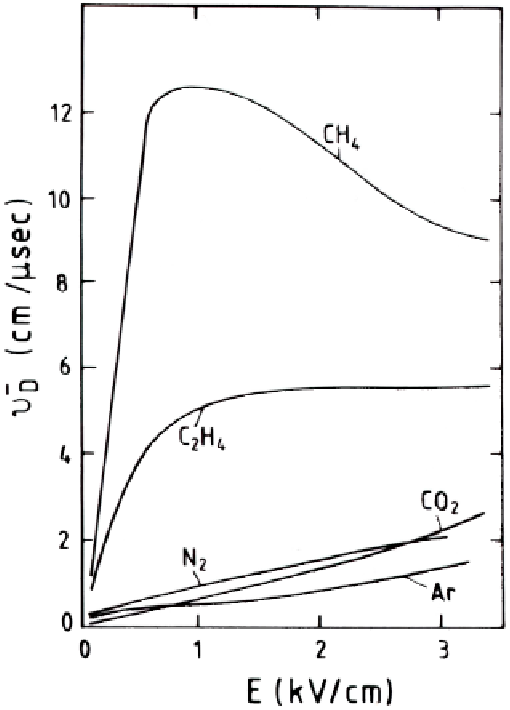
Electron mobility

In general, the mobility of electrons is not constant, but depend on their kinetic energy and varies with the electric field strength.

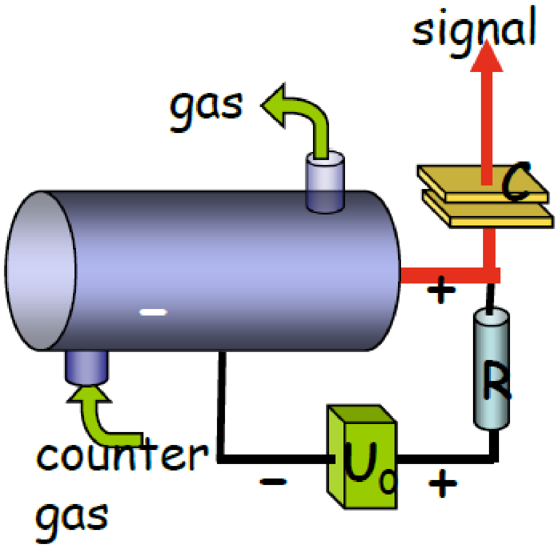
drift velocities of electrons in Argon-Methan mixture



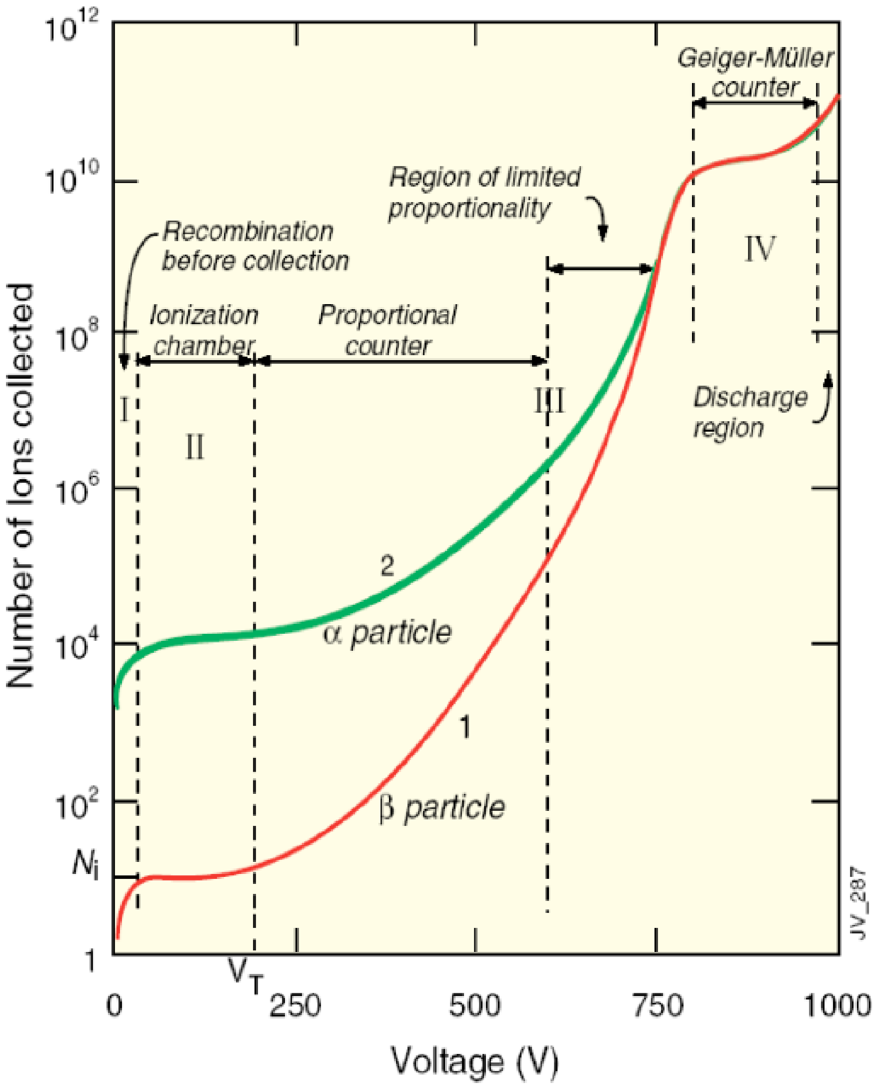
drift velocities of electrons in different gases



Amplification counters



single-wire gas counter



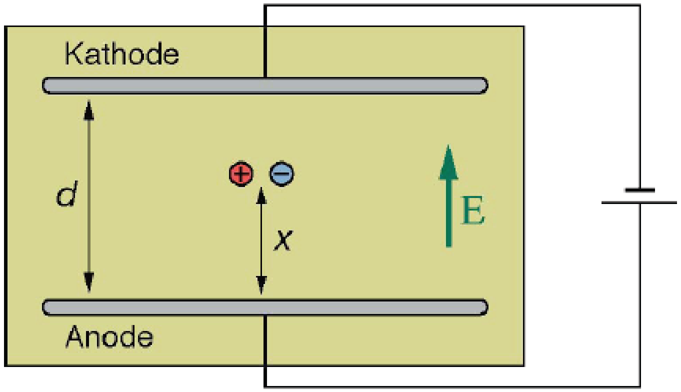
- gas counters may be operated in different operation modes depending on the applied high voltage.

Ionization chamber

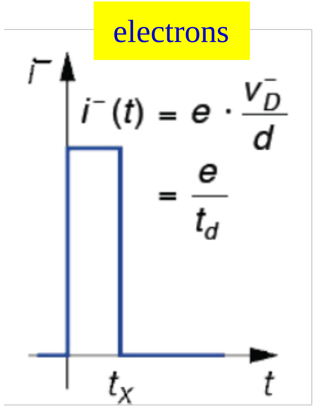
- An ionization chamber is operated at a voltage which allows full collection of charges, however below the threshold of secondary ionization (no amplification).

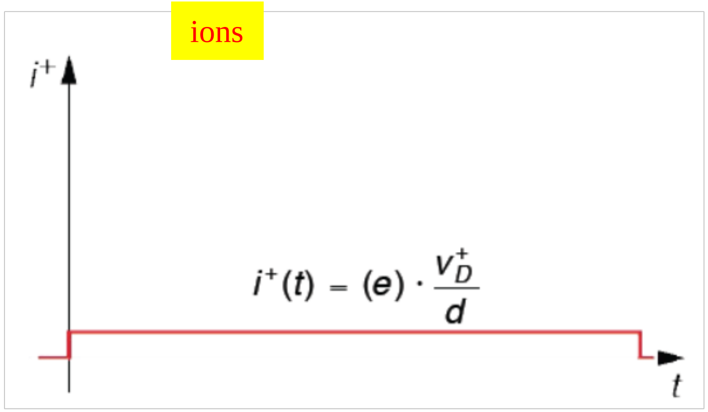
For a typical field strength 500 V/cm and typical drift velocities the collection time for 10 cm drift is about 2 μs for e⁻ and 2 ms for the ions.

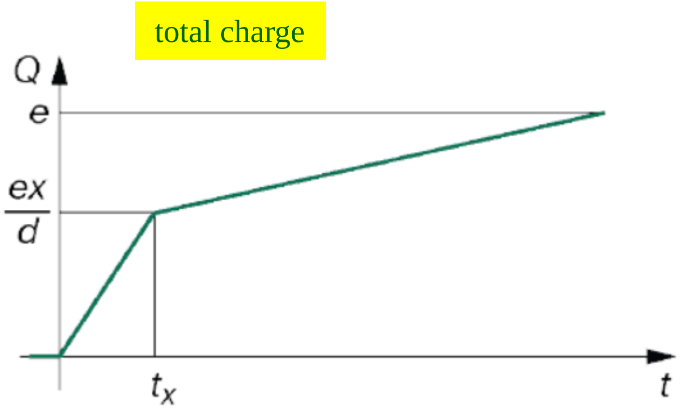
planar ionization chamber



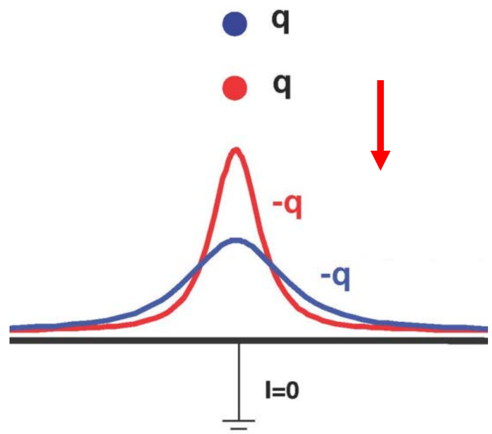
Time evolution of the signals for **one e⁻ ion pair**:


electrons


ions

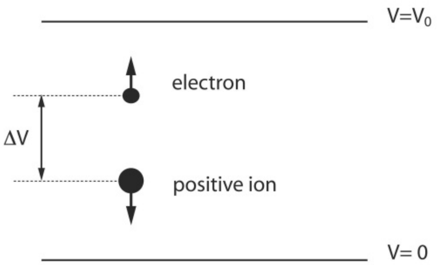

total charge

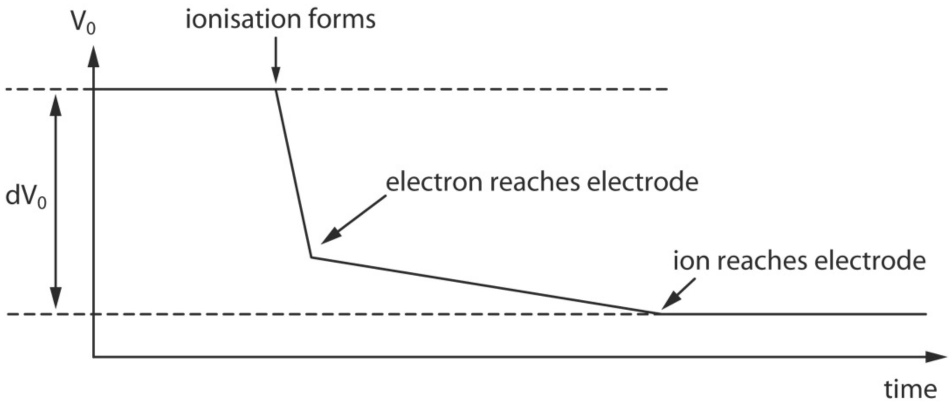
Signal collection

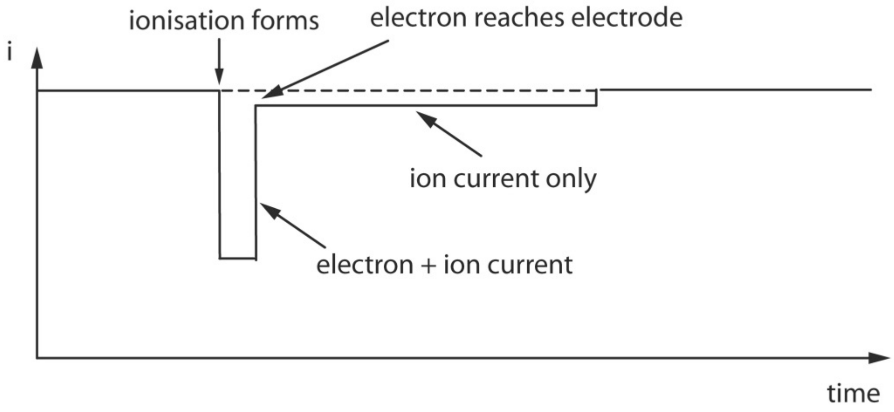


- ❖ The motion of charges induces an apparent current in the electrodes.
- ❖ Ion causes the same signal as the electron = same sign, same amplitude, but much slower

$$i = \frac{q}{V_0}\frac{dV}{ds}\frac{ds}{dt}$$

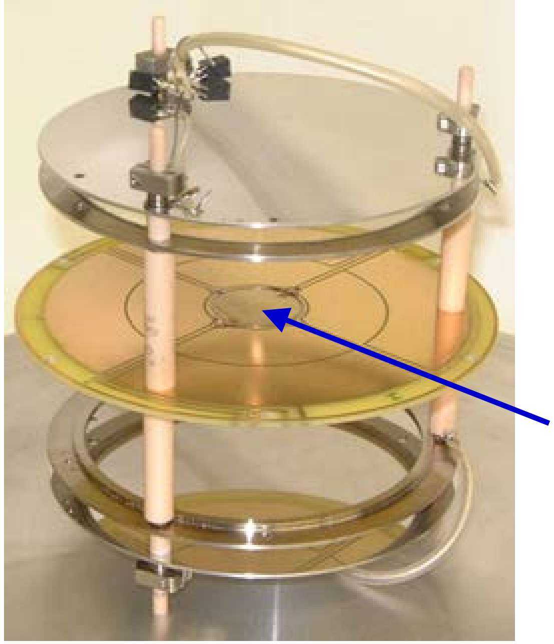






Ionization chamber

- no gas gain
- charges move in electric field
- induced signal is generated during drift of charges
- induced current ends when charges reach electrodes

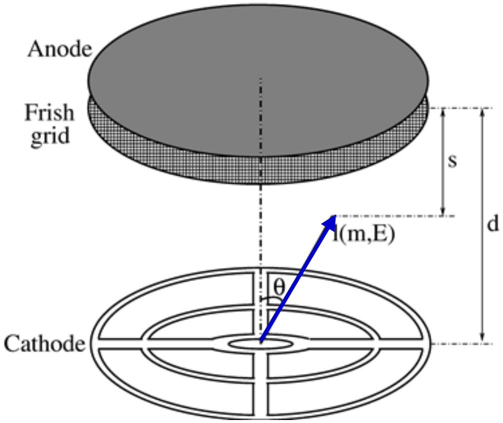


^{252}Cf source (25k f/s)

$T_{1/2}$=2.645 y

E_α = 6.118 and 6.076 MeV

binary fission/α-decay = 1/31



additional ´**Frisch grid**´:

- electrons drift towards Frisch grid and induce a signal but not on the anode.
- when electrons pass the Frisch grid, a signal is induced on anode.
- the angular dependence of the electrons is removed from anode signal

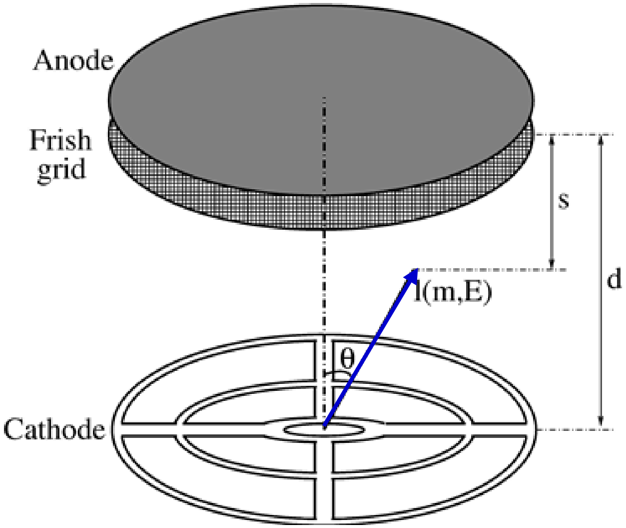
4π twin ionization chamber for fission fragments

measured quantities:

$\left.\begin{array}{l} E_H \\ E_L \end{array}\right\} \Rightarrow \begin{array}{l} \mathbf{A_H} \\ \mathbf{A_L} \end{array}$

e^- drift time ⇒ ϑ

segmented cathode ⇒ φ

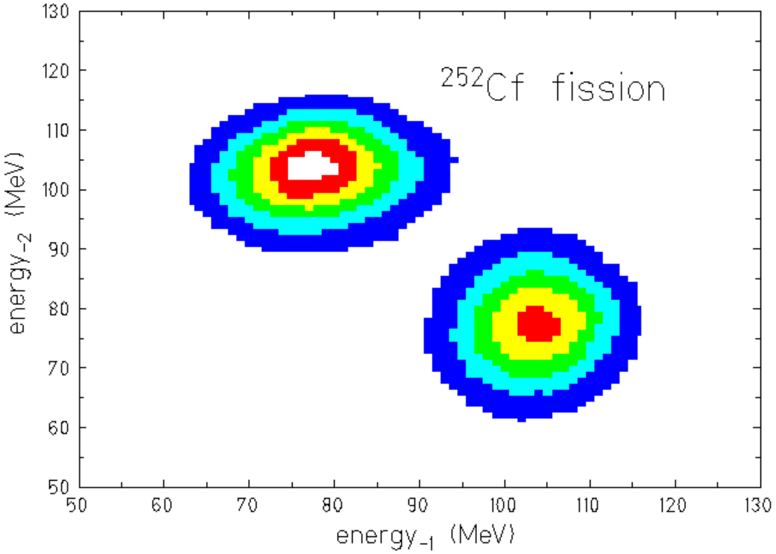


$$m_1 v_1 + m_2 v_2 = 0 \quad \rightarrow \quad m_1 E_1 = m_2 E_2$$

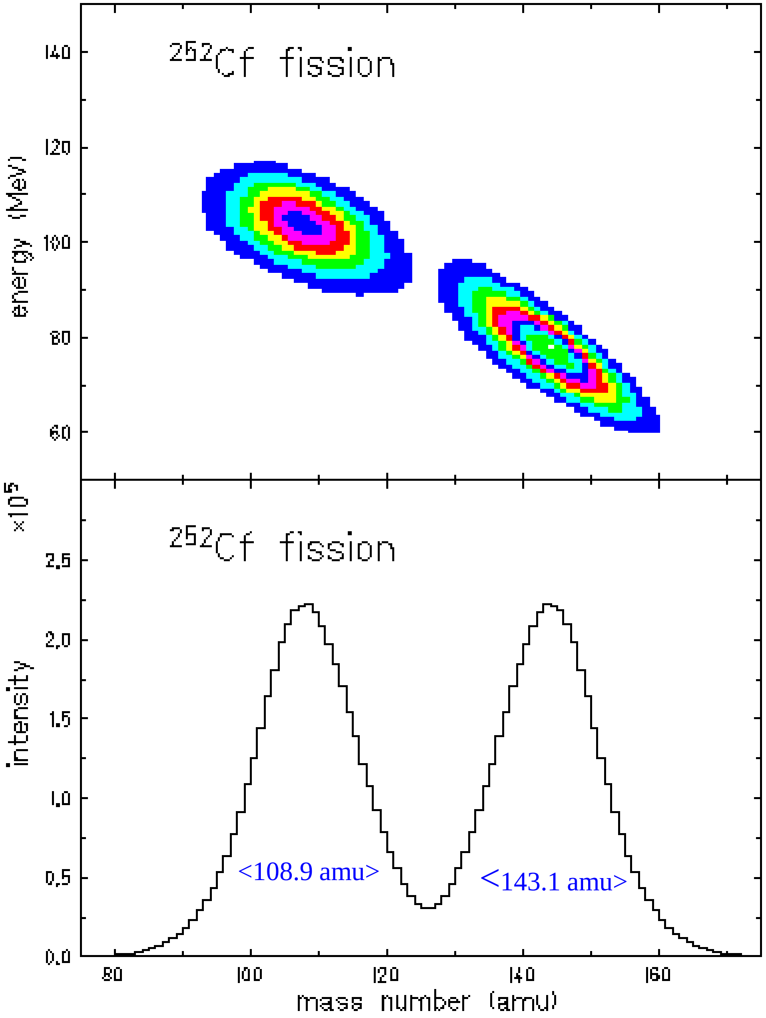
$$\boxed{m_1 = (m_1 + m_2)\frac{E_2}{E_1 + E_2}}$$

$$\langle E_L \rangle = 103.5 \pm 0.5\,MeV \;\rightarrow\; \langle A_L \rangle = 108.9 \pm 0.5$$

$$\langle E_H \rangle = 78.3 \pm 0.5\,MeV \;\rightarrow\; \langle A_H \rangle = 143.1 \pm 0.5$$



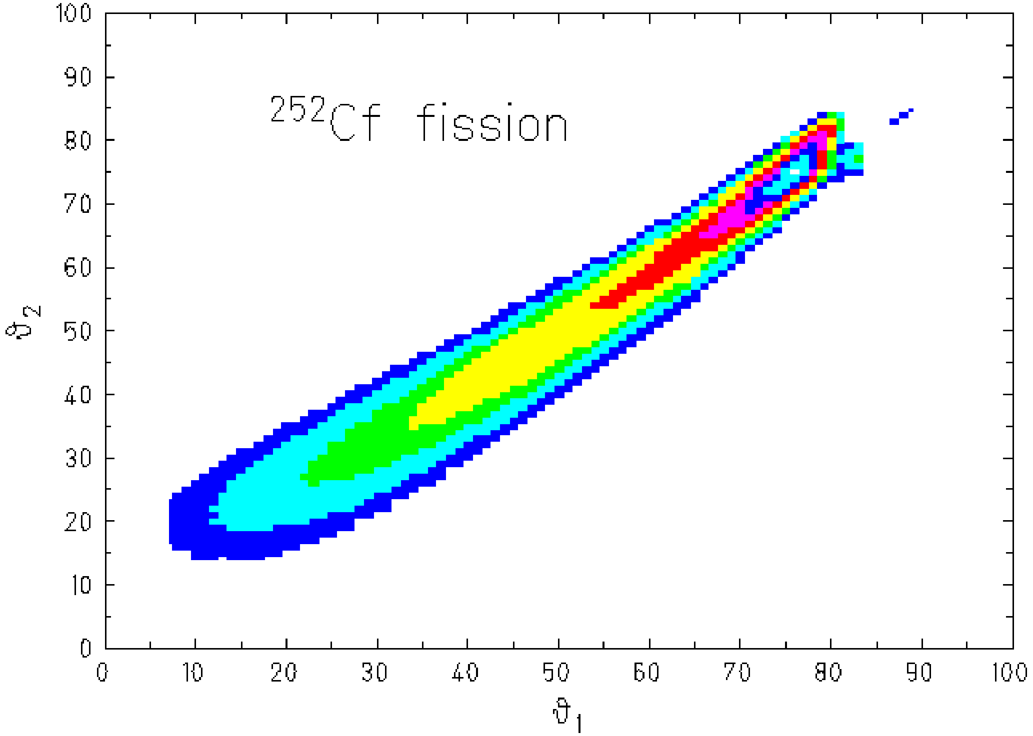
Fission fragment mass measurement

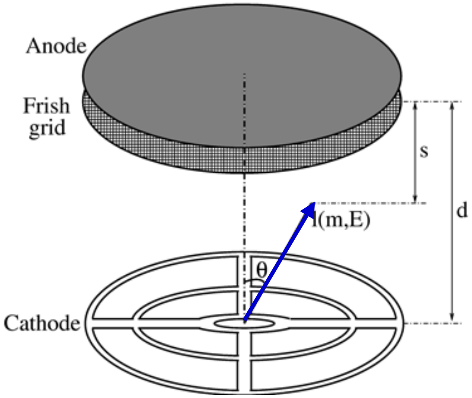


mass resolution σ = 3 amu

P. Adrich, diploma thesis (2000)

Determination of the polar angles





$$cos(\vartheta) = \frac{d - t \cdot v_{drift}}{\ell(E,A)}$$

drift velocity: $v_{drift} = 10$ (cm/μs)

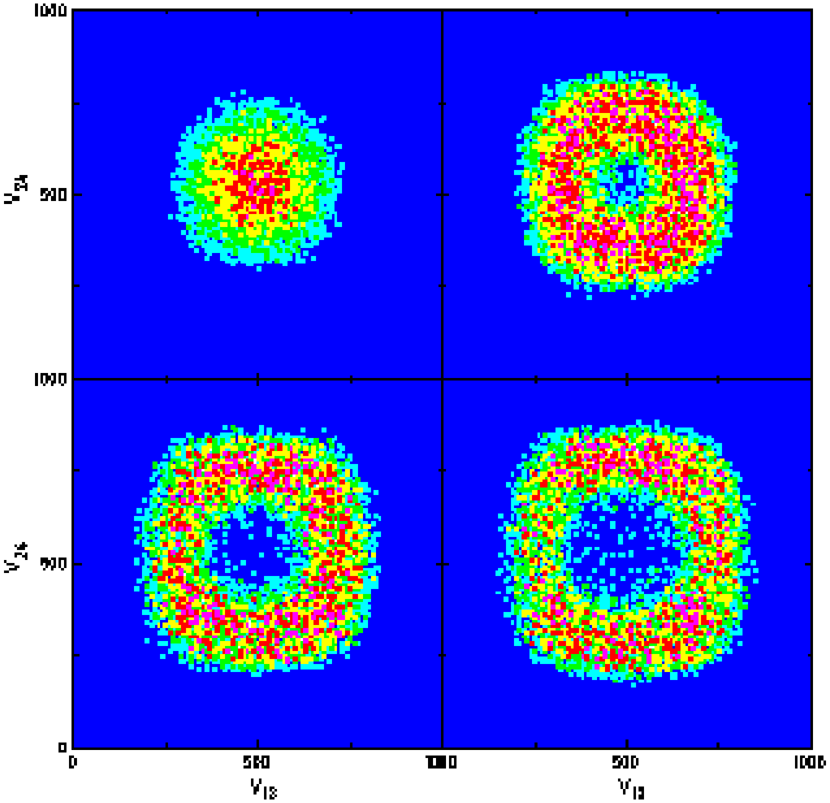
range of fragments in methan gas: $\ell(E,A)$

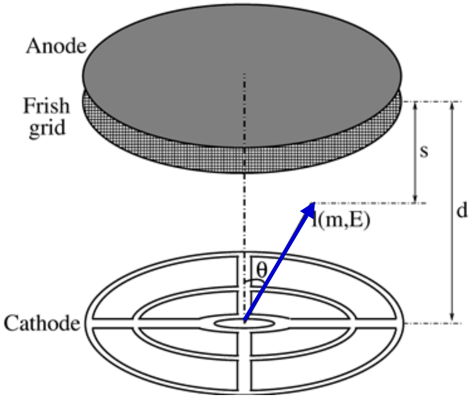
distance cathode-anode: d = 3.8cm

angular resolution	
ϑ	φ
30^0	4.2^0
50^0	2.5^0
70^0	2.3^0

P. Adrich, diploma thesis (2000)

Determination of the azimuthal angles





energy ratios for different emission angles ϑ

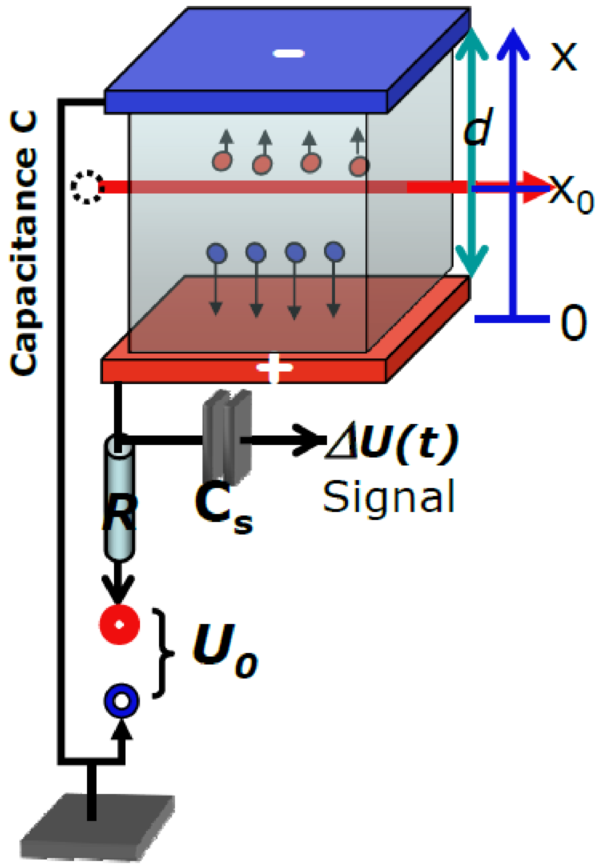
$$V_{13} = \frac{E_{S1}}{E_{S1} + E_{S3}} \qquad V_{24} = \frac{E_{S2}}{E_{S2} + E_{S4}}$$

$$\tan\varphi = \frac{V_{24} - 0.5}{V_{13} - 0.5}$$

P. Adrich, diploma thesis (2000)

Signal generation in ionization counters

primary ionization in gases: $I \approx$ 20-30 eV/IP



energy loss $\Delta\varepsilon$: $\mathbf{n} = n_I = n_e = \Delta\varepsilon / I$ of primary ion pairs **n** at x_0, t_0

force: $F_e = -eU_0/d = -F_I$

energy content of capacity C

1) $W(t) = \frac{C}{2}\left[U_0^2 - U^2(t)\right] \approx C \cdot U_0 \cdot \Delta U(t)$

2) $W(t) = n_e F_e [x_e(t) - x_0] + n_I F_I [x_I(t) - x_0]$

$$= +\frac{n \cdot eU_0}{d}[x_I(t) - x_e(t)]$$

$w^+(t)\cdot(t-t_0)$

1) + 2) $$\boxed{\Delta U(t) = \frac{W(t)}{C \cdot U_0} = \frac{n \cdot e}{C \cdot d}[w^+(t) - w^-(t)](t - t_0)}$$

total signal: electron & ion components

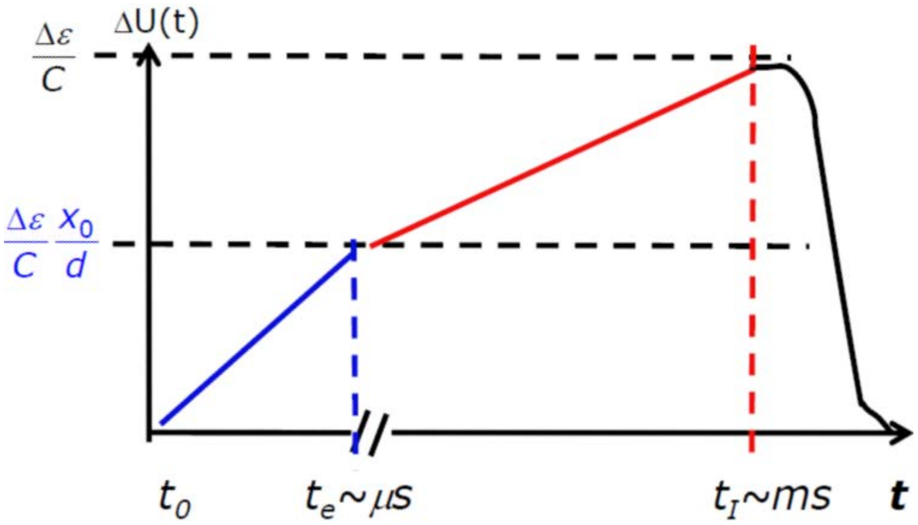
Time-dependent signal shape

total signal: electron & ion components

$$\Delta U(t) = \frac{\Delta\varepsilon}{C \cdot d}[w^+(t) - w^-(t)](t - t_0)$$

$$|w^+(t)| \sim 10^{-3} \cdot |w^-(t)|$$

drift velocities ($w^+ > 0$, $w^- < 0$)

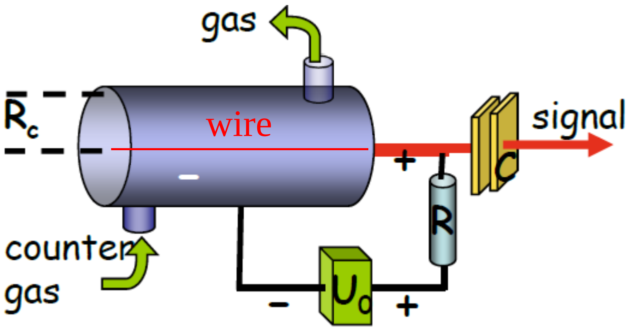


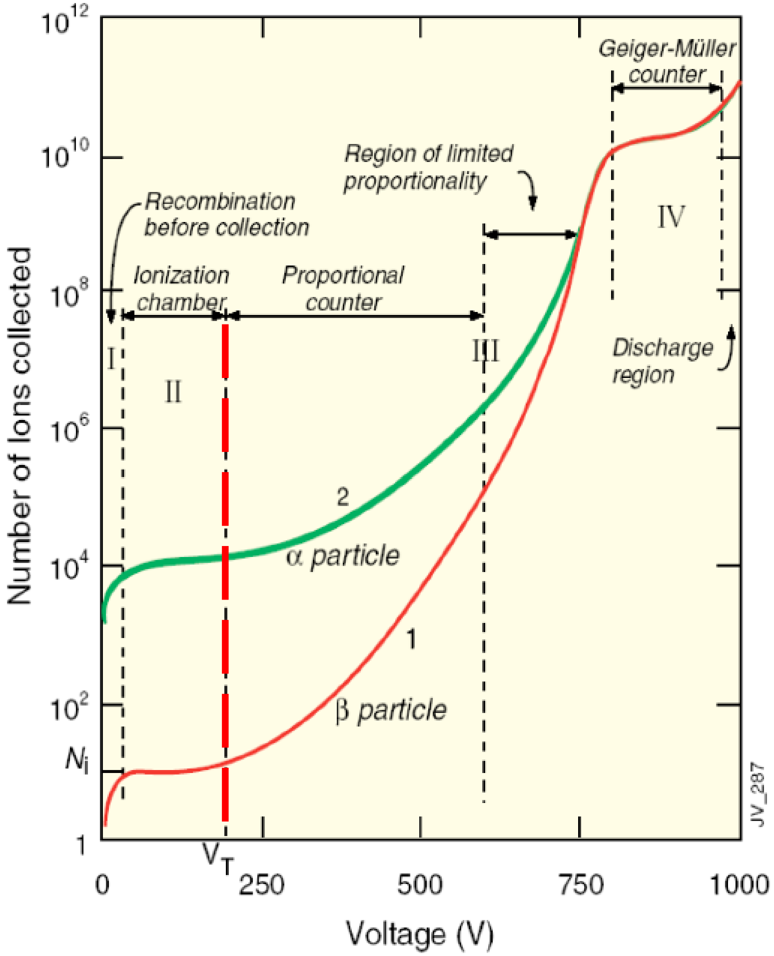
Both components measure Δε and depend on position of primary ion pair

$x_0 = w^- \cdot (t_e - t_0)$

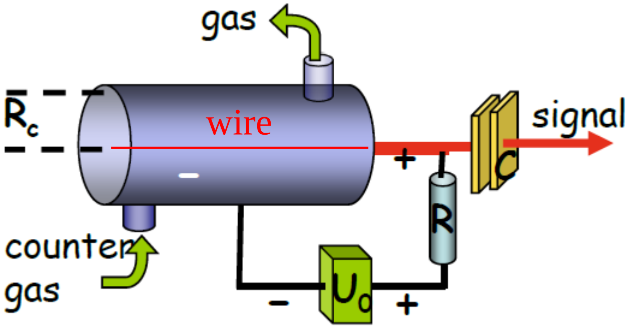
for fast counting use only electron component!

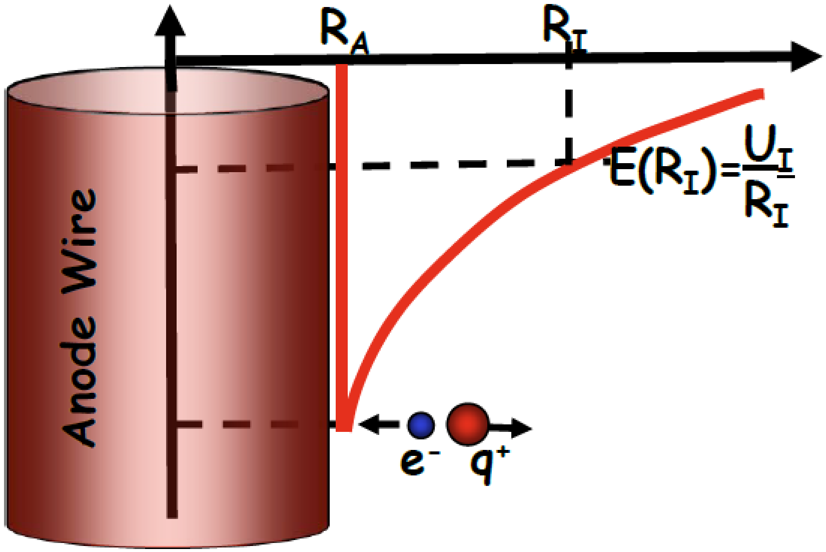
Proportional counter





Proportional counter





gas amplification factor (typical 10^4–10^6) is constant

anode wire: small radius $R_A \approx 50$ µm or less

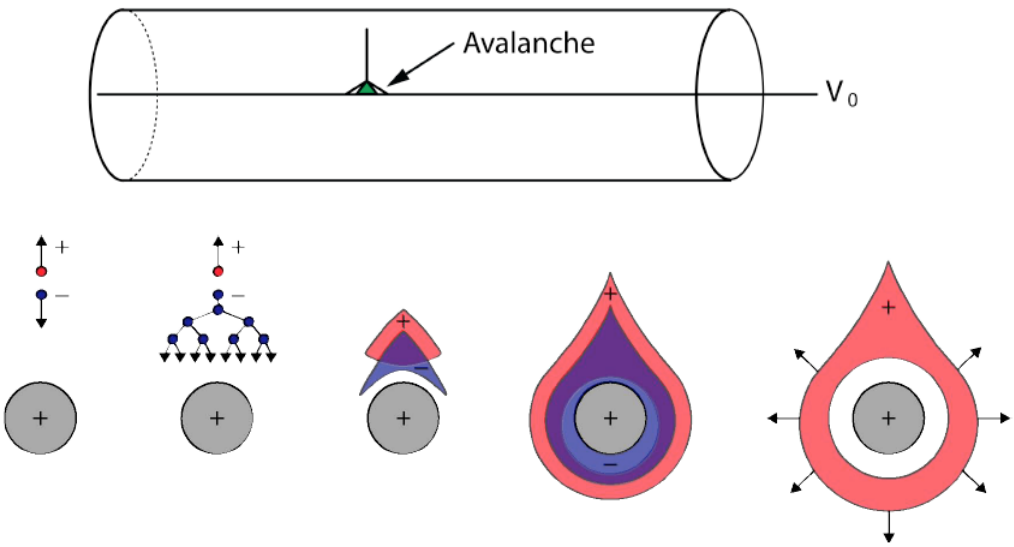
voltage $U_0 \approx$ (300-500) V

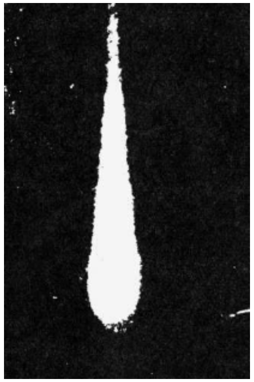
field at **r** from the wire

$$\boxed{E(r) = \frac{U_0}{ln(R_C/R_A)} \cdot \frac{1}{r}}$$

avalanche $R_I \rightarrow R_A$ (wire radius), several mean free paths needed pulse height mainly due to positive ions (q^+)

Proportional counter

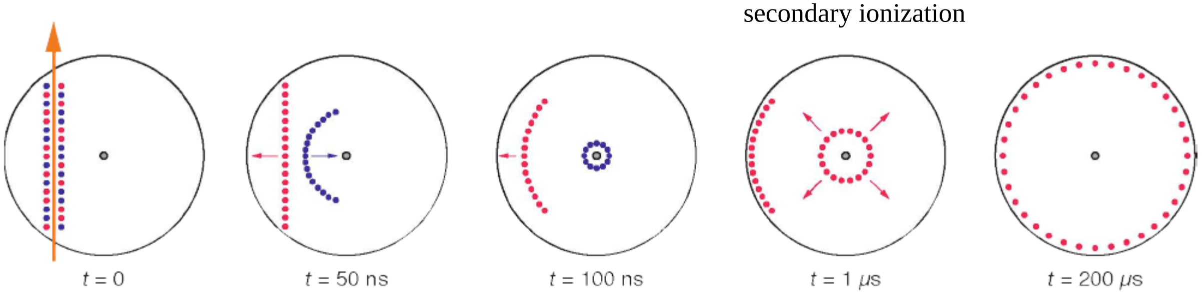




cloud chamber

The primary produced electrons drift the anode wire and reach the area of high electrical field strength. If a critical field strength is reached, a secondary ionization produces electrons in an avalanche.

time sequence of the signal evolution



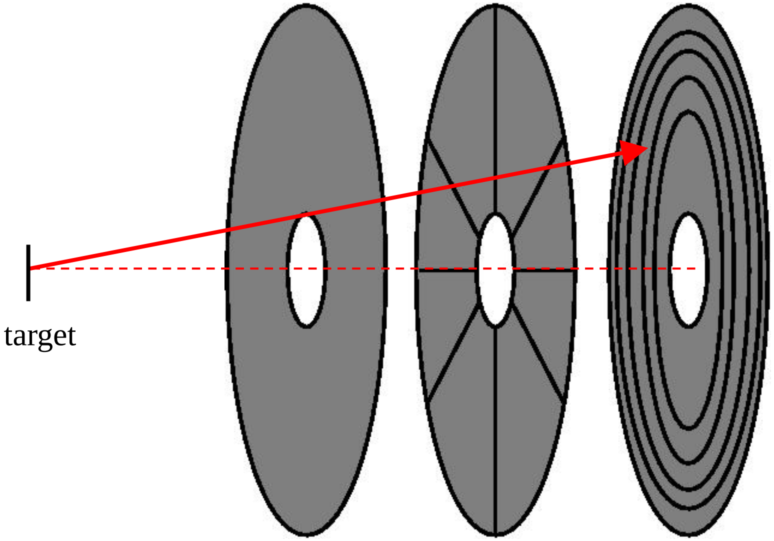
primary ionization

secondary ionization

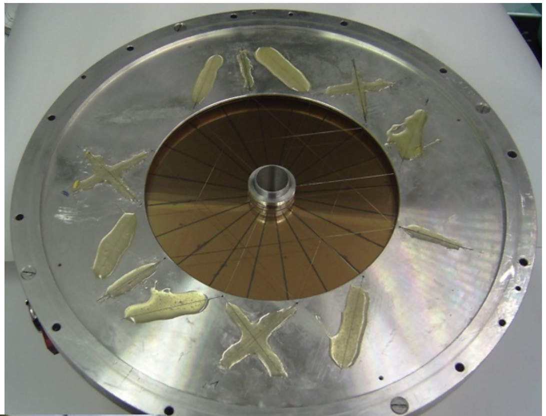
pos. ions drift due to secondary ionization

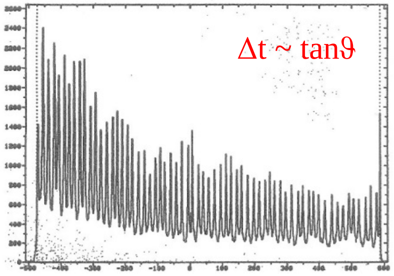
• pos. ion • electron

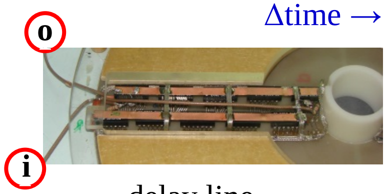
Proportional counter



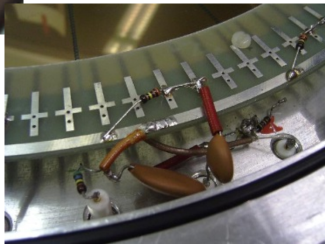
V_0 ~ 500 V
p = 5-10 Torr
~ 3 mm gap anode-cathode



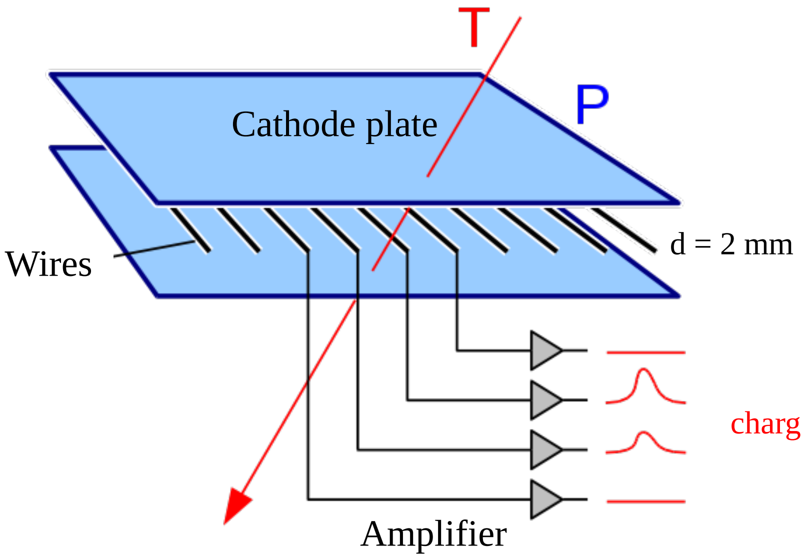




delay line

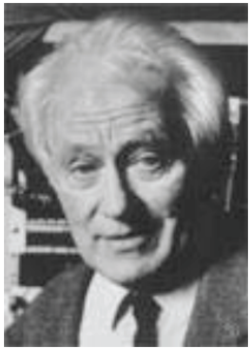


Multi-Wire Proportional Chamber

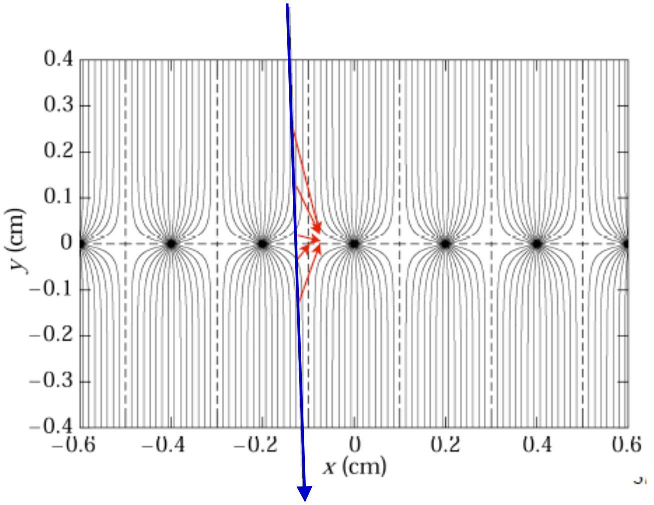


charge signals

A multi-wire proportional chamber detects charged particles and gives positional information on their trajectory.

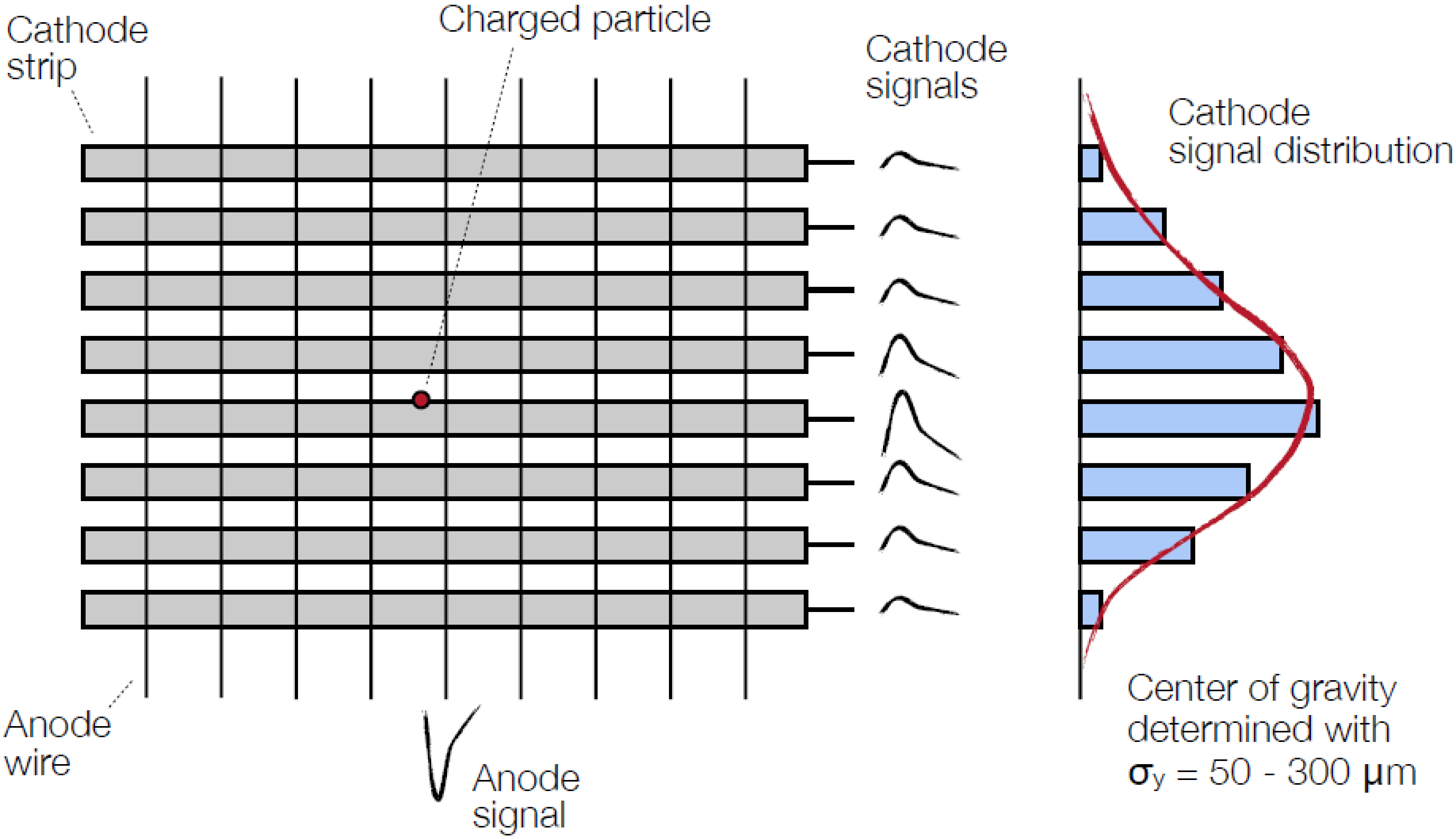


Georges Charpak
Nobel price 1992



- time resolution: fast anode signals ($t_{rise} \sim 0.1$ ns)
- position resolution: for d = 2 mm $\sigma_x = 50\text{-}300\ \mu m$ (weighted with charges)

Multi-Wire Proportional Chamber

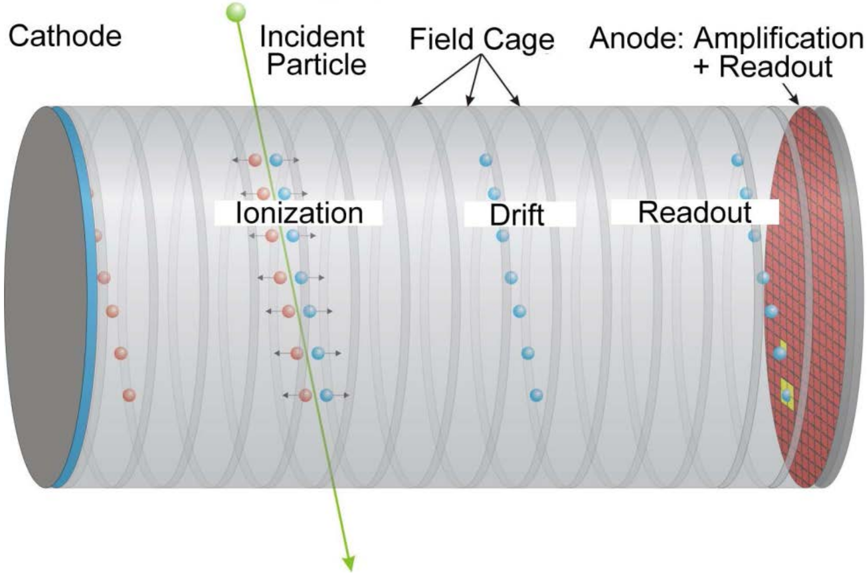


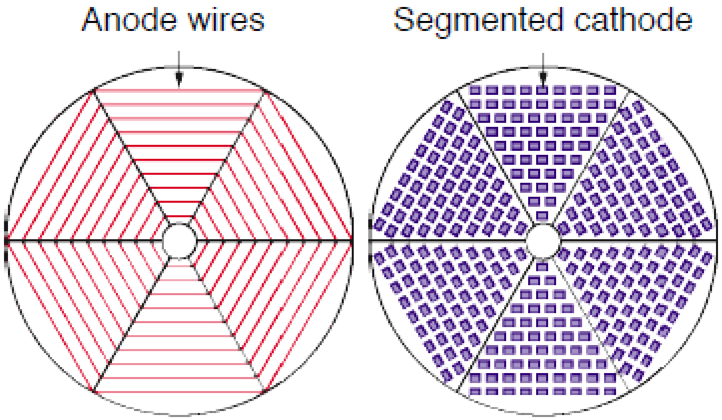
Center of gravity determined with σ_y = 50 - 300 µm

Time Projection Chamber

- Principle: Time Projection Chambers are based on the drift of the charge carriers with constant drift velocity v_D in a homogenous E-field (E = -dU/dz).

- typical parameters: E ~ 1 kV/cm, v_D ~ 1-4 cm/µs, Δz ~ 200 µm
- 3-dim. traces: z from the drift time, (x,y) from the segmented anode



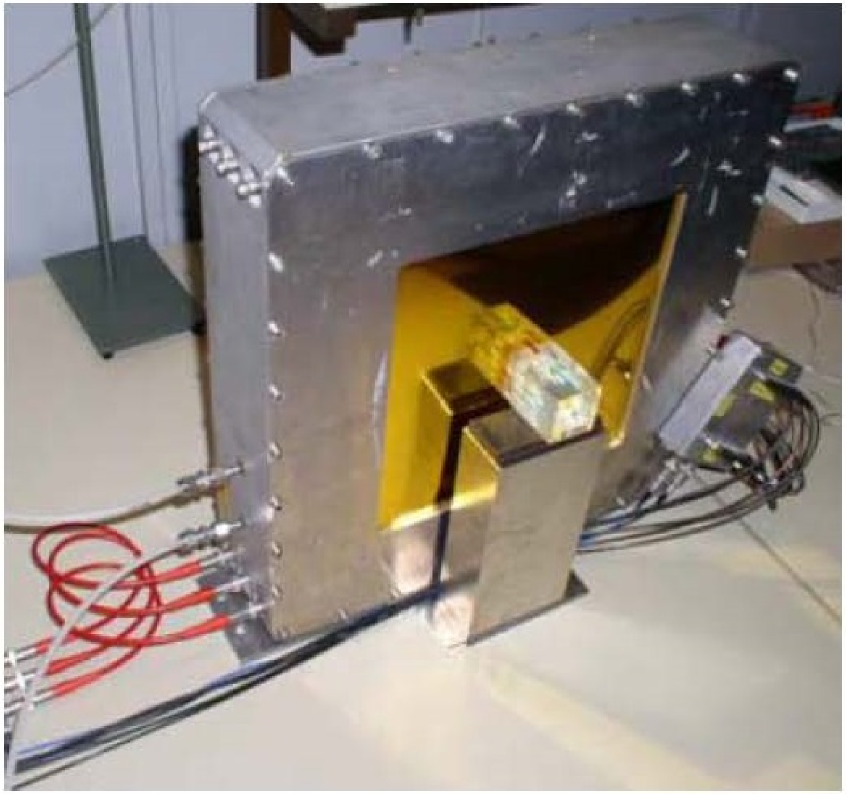


Time Projection Chamber

for position measurement (x + y)

MWPC

Δx= 0.5 mm (wire spacing 1 mm)
mounted as MW11,MW21+22, MW31, MW41



TPC

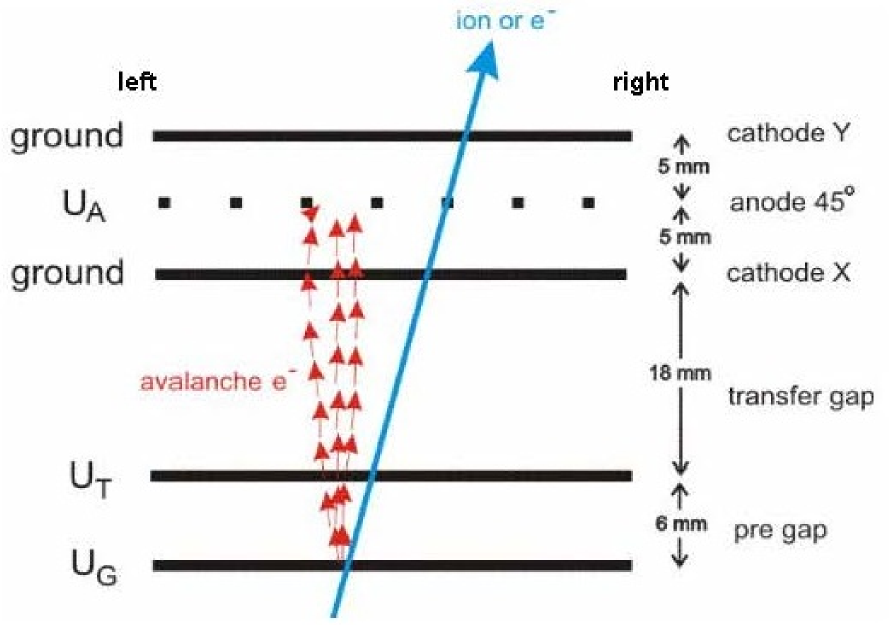
Δx= 0.2 mm (no wires in beam)
mounted as TPC21+22 and TPC41+42

Time Projection Chamber

for position measurement (x + y)

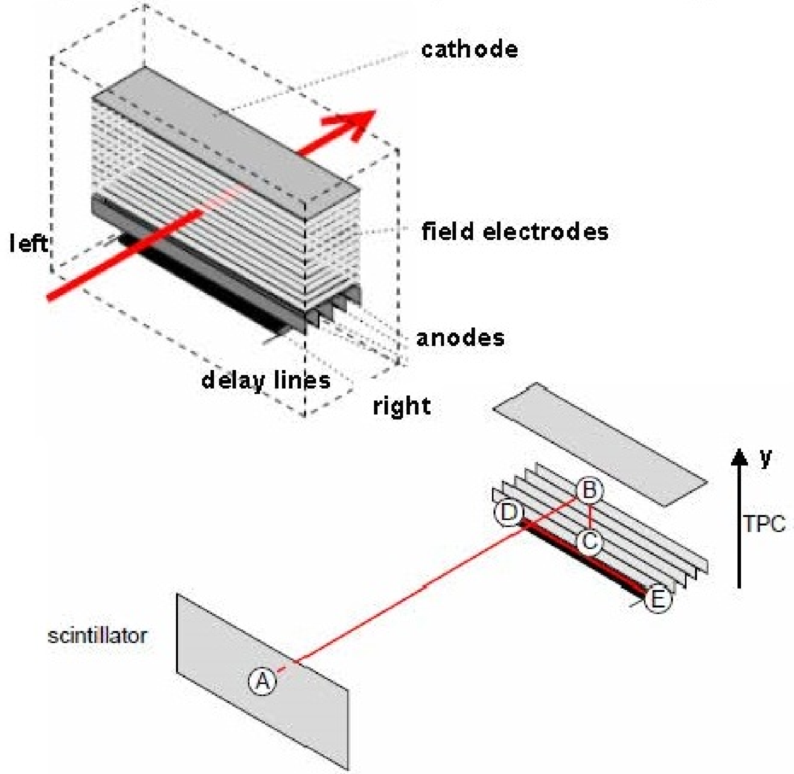
MWPC

Δx= 0.5 mm (anode wire spacing 1 mm)
mounted as MW11,MW21+22, MW31, MW41
delay-line readout in x+y

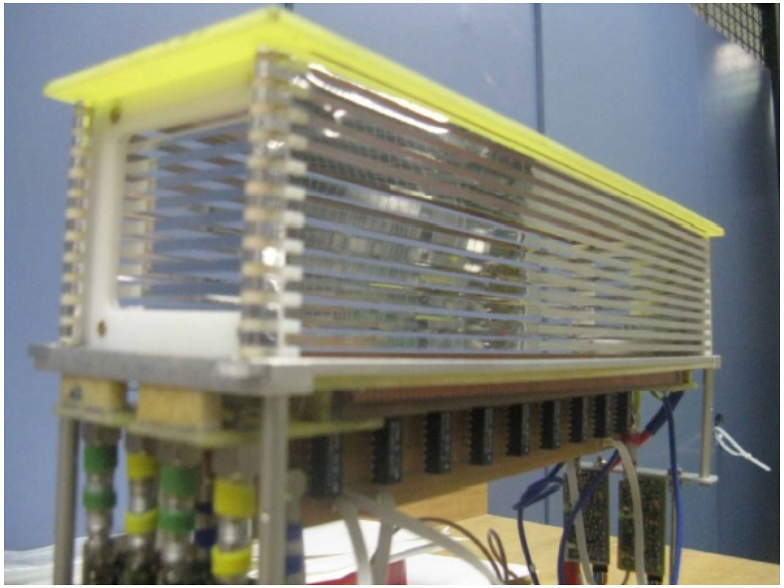


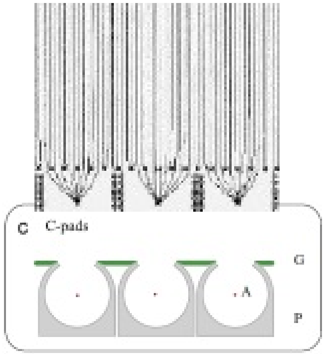
TPC

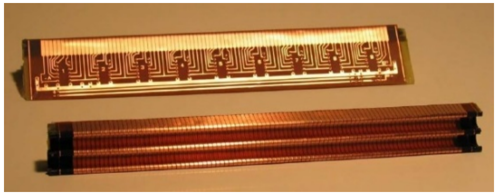
Δx= 0.2 mm (no wires in beam)
mounted as TPC21+22 and TPC41+42
delay-line readout in x, drift time in y

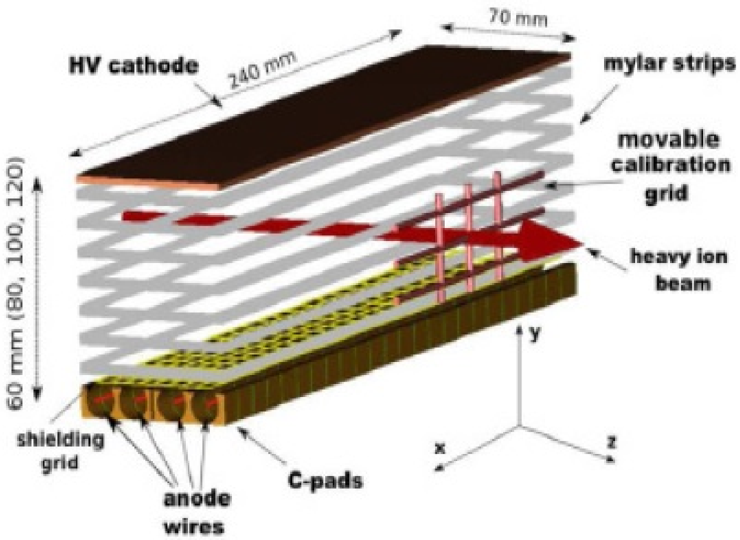


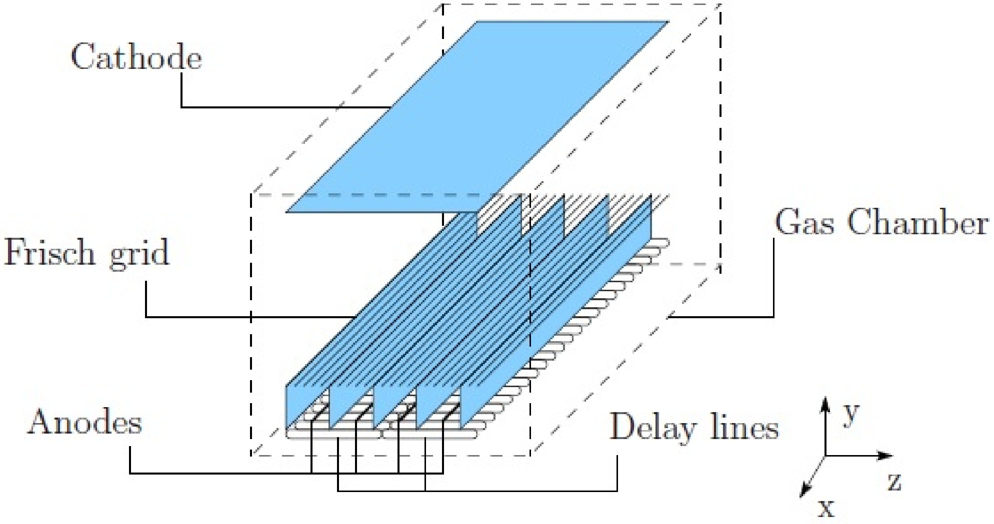
Time Projection Chamber



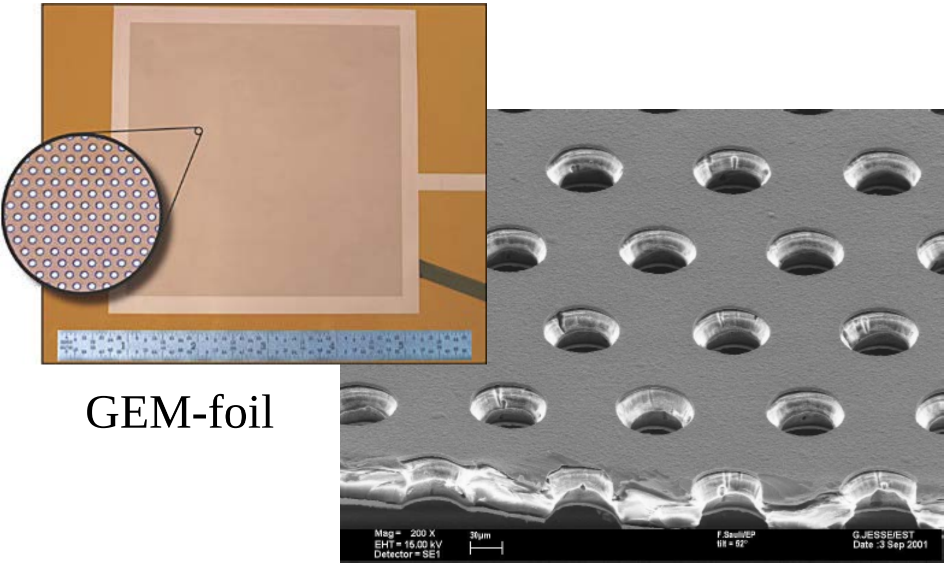




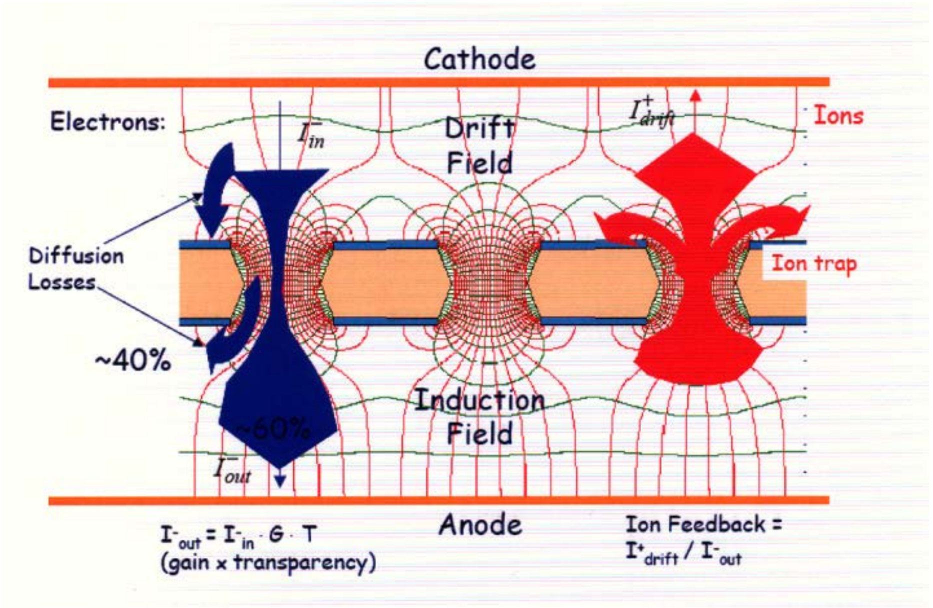




Gas Electron Multipliers Technology

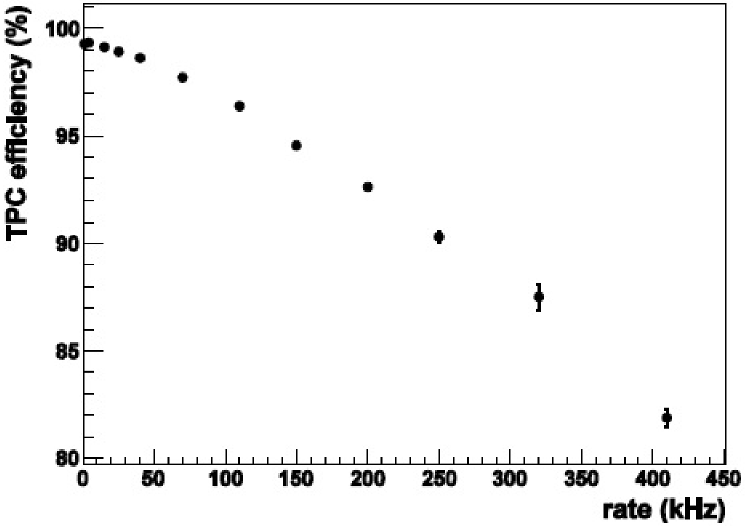


GEM-foil



50 µm insulator, 5 µm Cu on both sides, 500 V

^{238}U at 1 GeV/u



TPC with C-pads: 100 kHz

GEM-TPCs: 10 MHz

Geiger-Müller counter

- The discharge is not any more localized
- The number of charge carriers is not any more related to the primary ionization
- The gas amplification amounts to 10^8-10^{10}