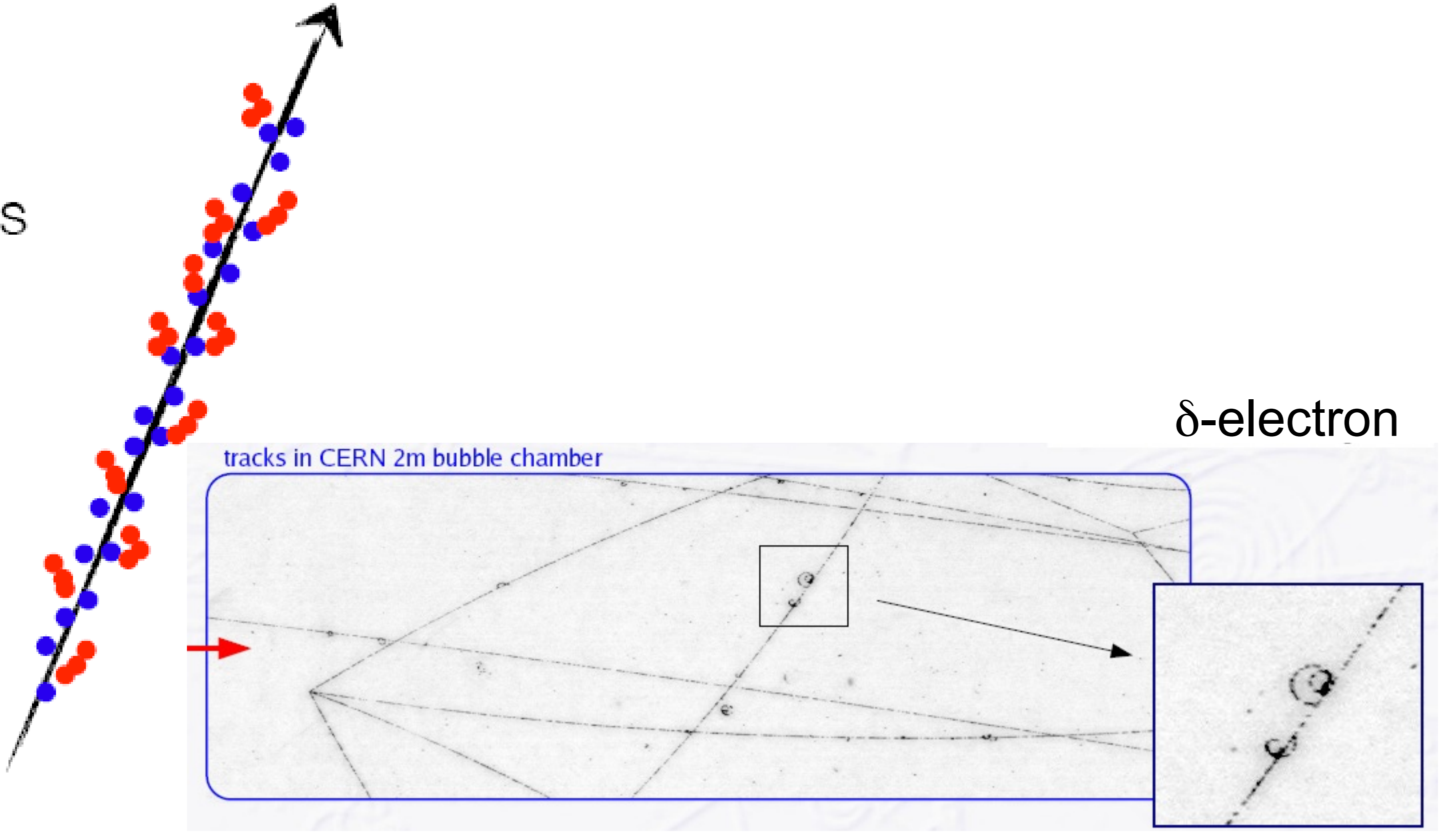
Gaseous detectors

measurement of ionization
position determination

Introduction

Schematic Principle
of gas detectors



- ● Primary Ionization
- ● Secondary Ionization (due to δ-electrons)

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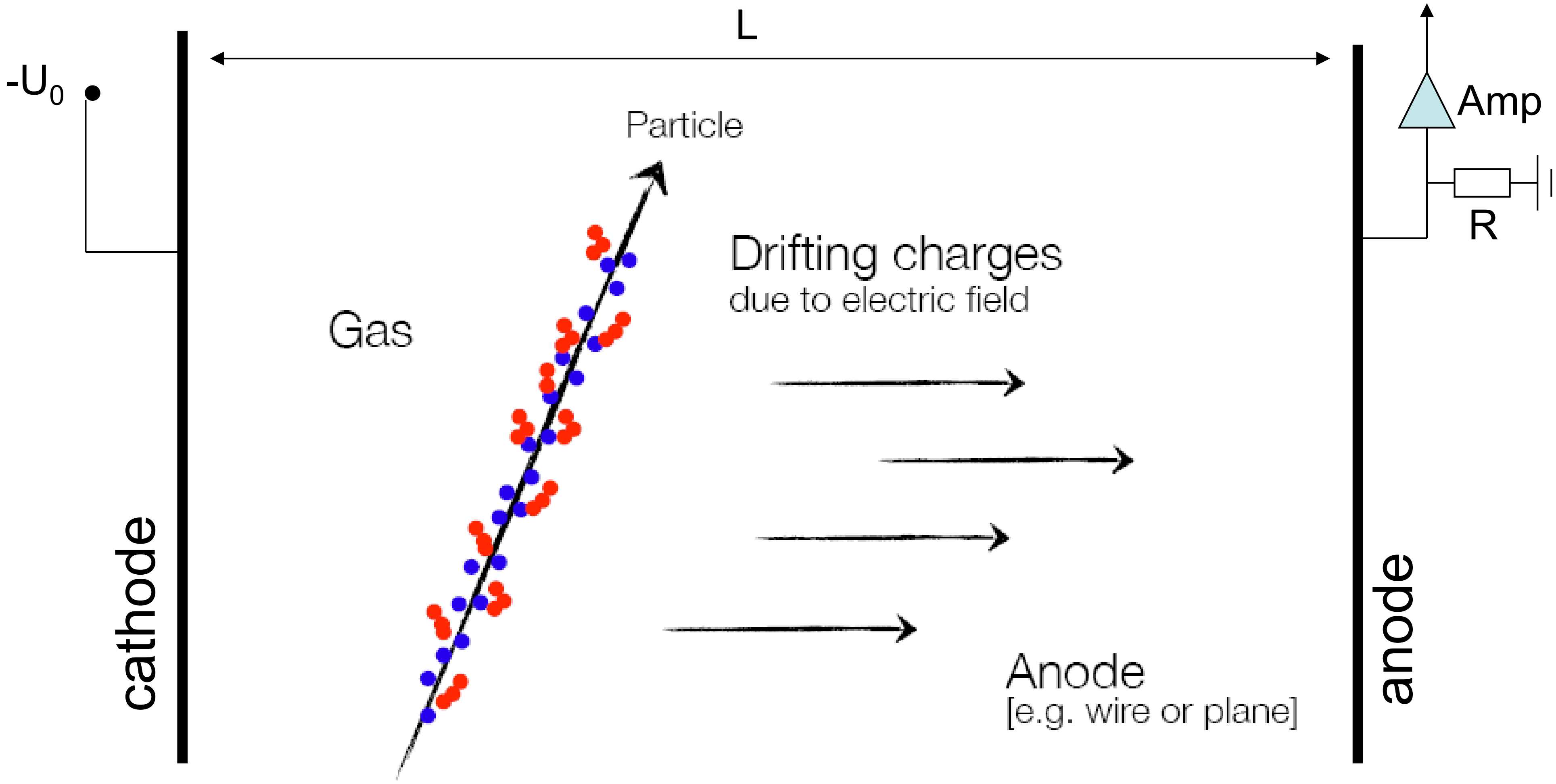

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Ionization

Primary ionization

$$X + p \rightarrow X^+ + p + e^-$$

p = charge particle traversing the gas
X = gas atom
e^- = delta-electron (δ)

Secondary ionization

if E_δ is high enough ($E_\delta > E_i$)

$$X + e^- \rightarrow X^+ + e^- + e^-$$

Relevant Parameters
for gas detectors

Ionization energy : E_i
Average energy/ion pair : W_i
Average number of primary ion pairs [per cm] : n_p
Average number of ion pairs [per cm] : n_T

Differences due to δ-electrons

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

[about 2-6 times n_p]
[L: layer thickness]

Typical values: $E_i \sim 30$ eV
$n_T \sim 100$ pairs / 3 keV incident particle

Table for most common gases

($E_i = I_o$)

Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

Quelle: K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

Ionization statistics

Production of ion/electron pairs is a Poissonian distributed

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

with $\langle n_p \rangle = L/\lambda$ and $\lambda = 1/(n_e \sigma_I)$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

Recombination and electron attachment:

Admixture of electronegative gases (O_2, F, Cl) influences detection efficiency

Diffusion:

Influences the spatial resolution ...

Mobility of charges:

Influences the timing behavior of gas detectors ...

Avalanche process via impact ionization:

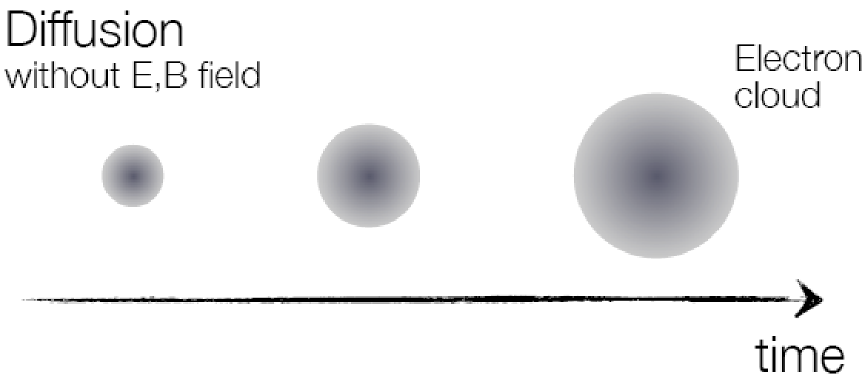
Important for the gain factor of the gas detector ...

Transport of electrons/ions in gas

Diffusion:

classical kinetic theory of gases

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$



after a diffusion time t the electrons/ions are Gaussian distributed with a spread

$$\sigma(r) = \sqrt{6Dt}$$

where D is the diffusion coefficient

$$\boxed{D = \frac{1}{3} v\lambda}$$

the mean free path of electrons/ions in the gas: $\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 P}$

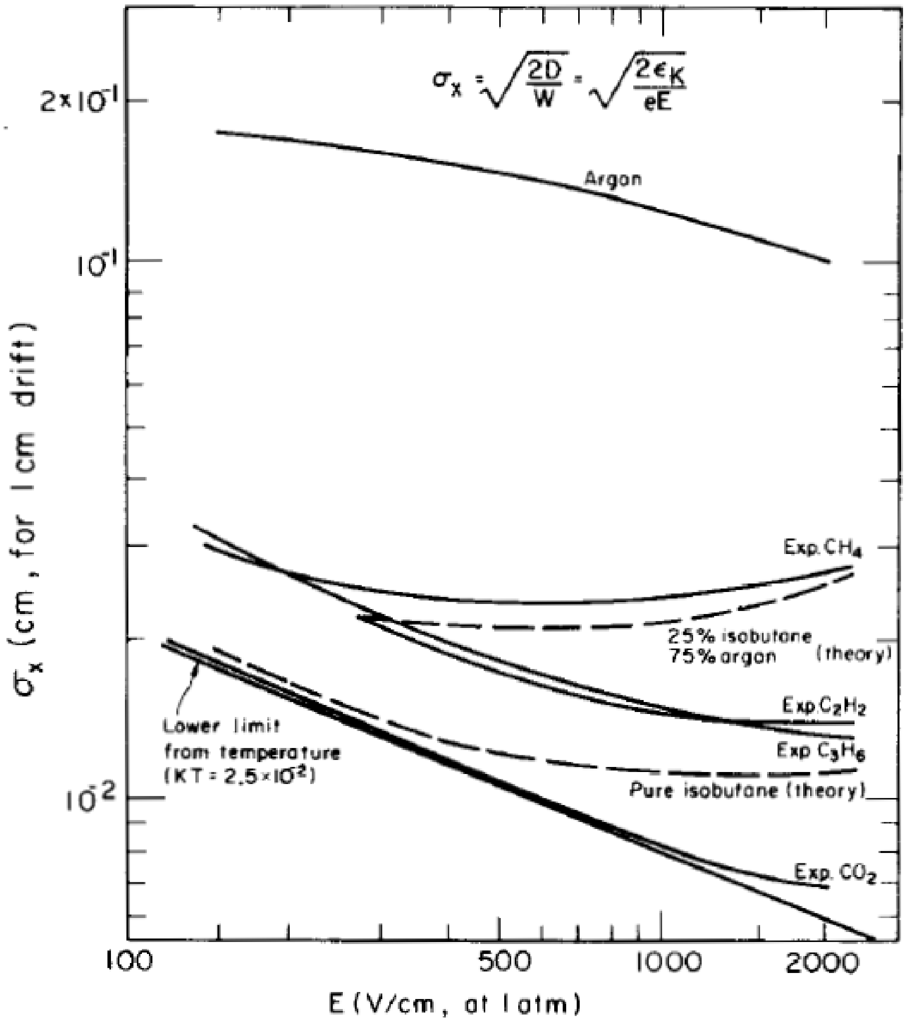
the mean velocity according to Maxwell distribution: $v = \sqrt{\frac{8kT}{\pi m}}$

m=mass of particle

$$\boxed{D = \frac{1}{3} v\lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}}$$

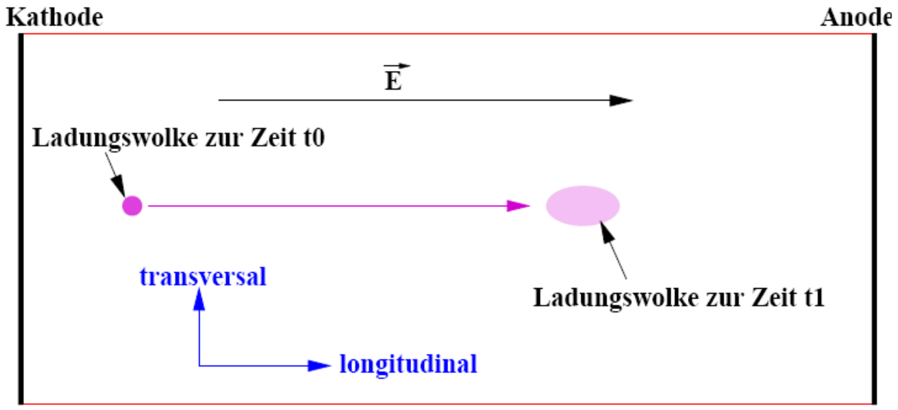
D depends on gas pressure P and temperature T

Diffusion in electric field



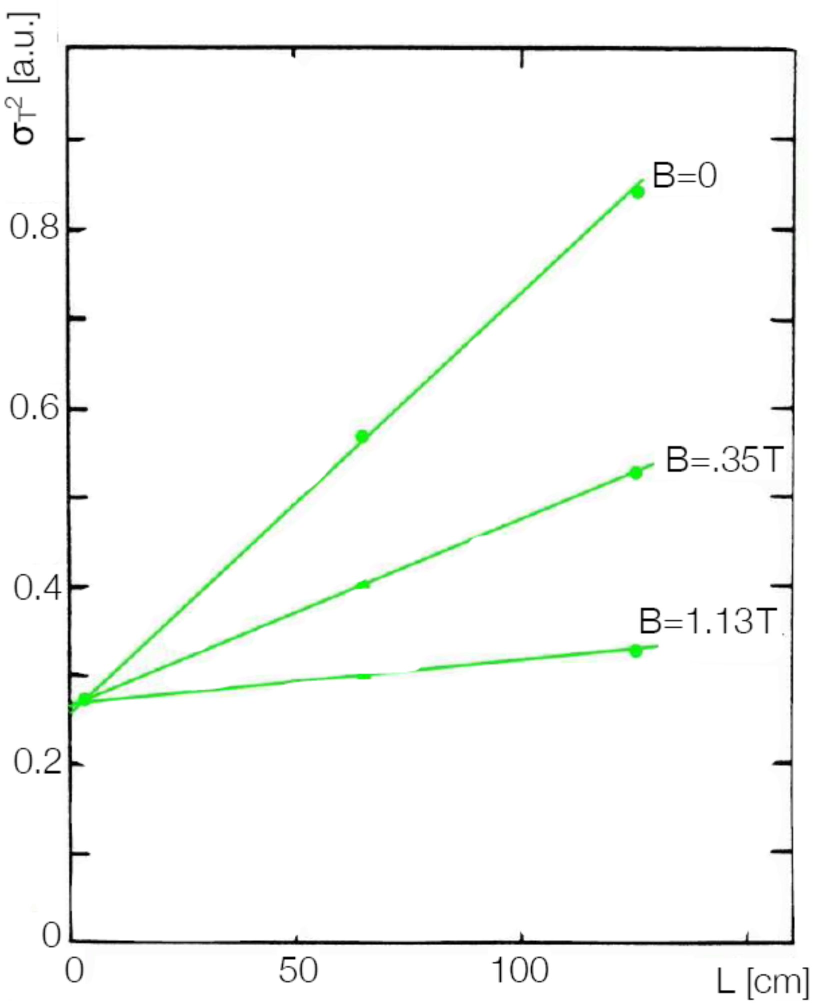
Drift in direction of E-field superimposed to statistical diffusion

Extra velocity influences longitudinal diffusion
Transverse diffusion not affected



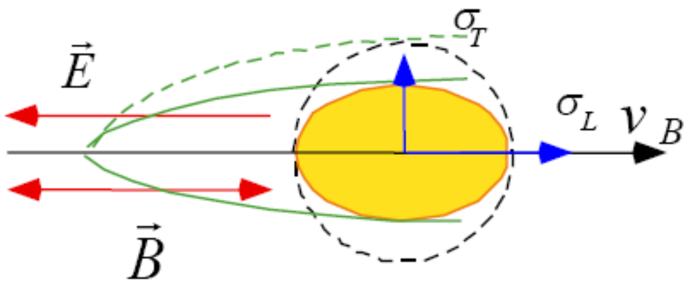
E-field reduced diffusion in longitudinal direction

Diffusion in magnetic field



In the presence of a B-field different effects on longitudinal and transverse diffusion

No Lorentz force along B-field direction



Transverse diffusion as function of drift length for different B fields

B-Field can substantially reduce diffusion in transverse direction

Transport of electrons/ions in gas

Drift and Mobility:

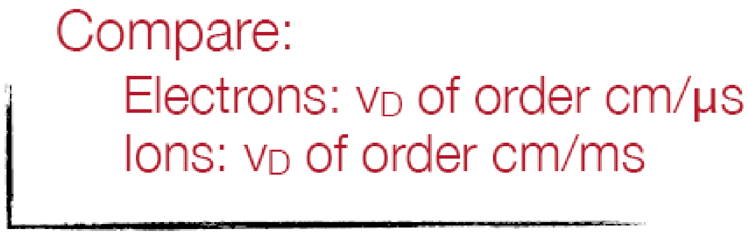
with external E-field: electrons/ions obtain velocity v_D in addition to thermal motion; on average electrons/ions move along field lines of electric field E

$$\vec{v}_D = \mu_\pm \,|\vec{E}\,|$$

typical:
E ~ 1 kV / cm-atm`

μ_+ : ion mobility
for ions $v_D \sim E/P$, i.e. for constant pressure constant mobility

μ_- : electron mobility
in cold gas approximation ($T_{kin} \sim kT$) ➔ $v_D \sim E$, μ = const.
in hot gas ($T_{kin} >> kT$) ➔ v_D = const., μ = not const.

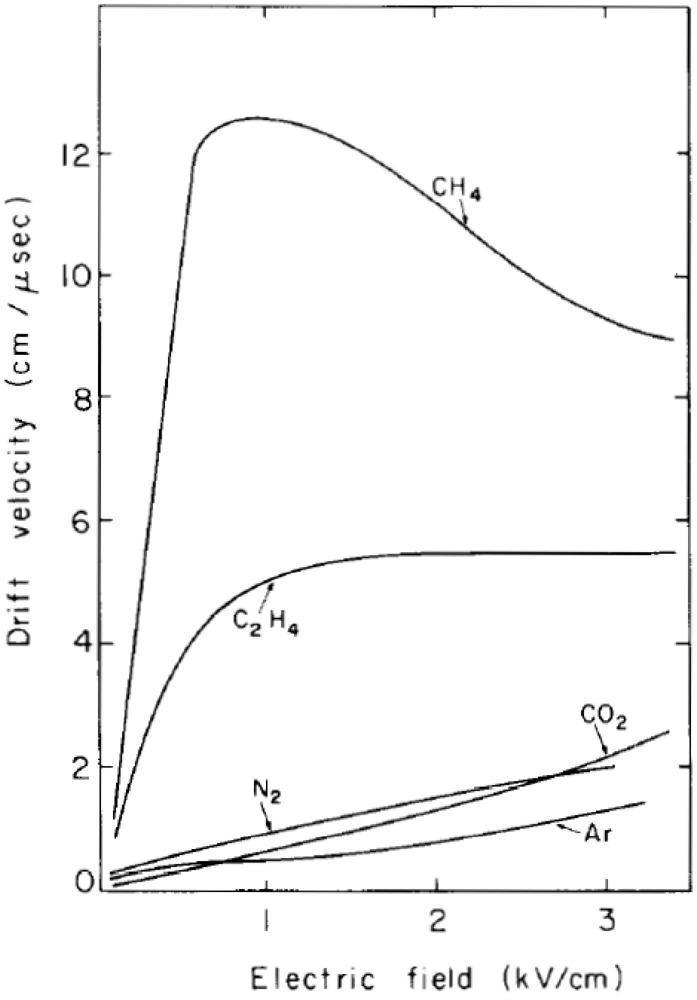


Compare:
Electrons: v_D of order cm/μs
Ions: v_D of order cm/ms

$$\boxed{D/\mu = kT/e}$$

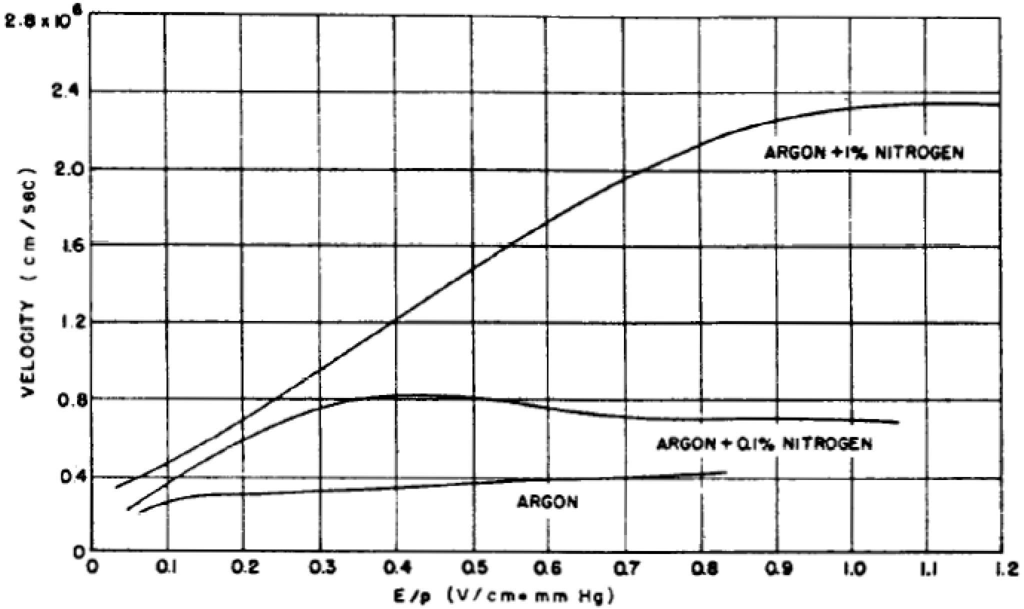
Einstein relation for ideal gases in thermal equilibrium
the gain in velocity may affect the diffusion rate and thereby the time behavior of the detector (e.g. drift chamber)

Drift velocity



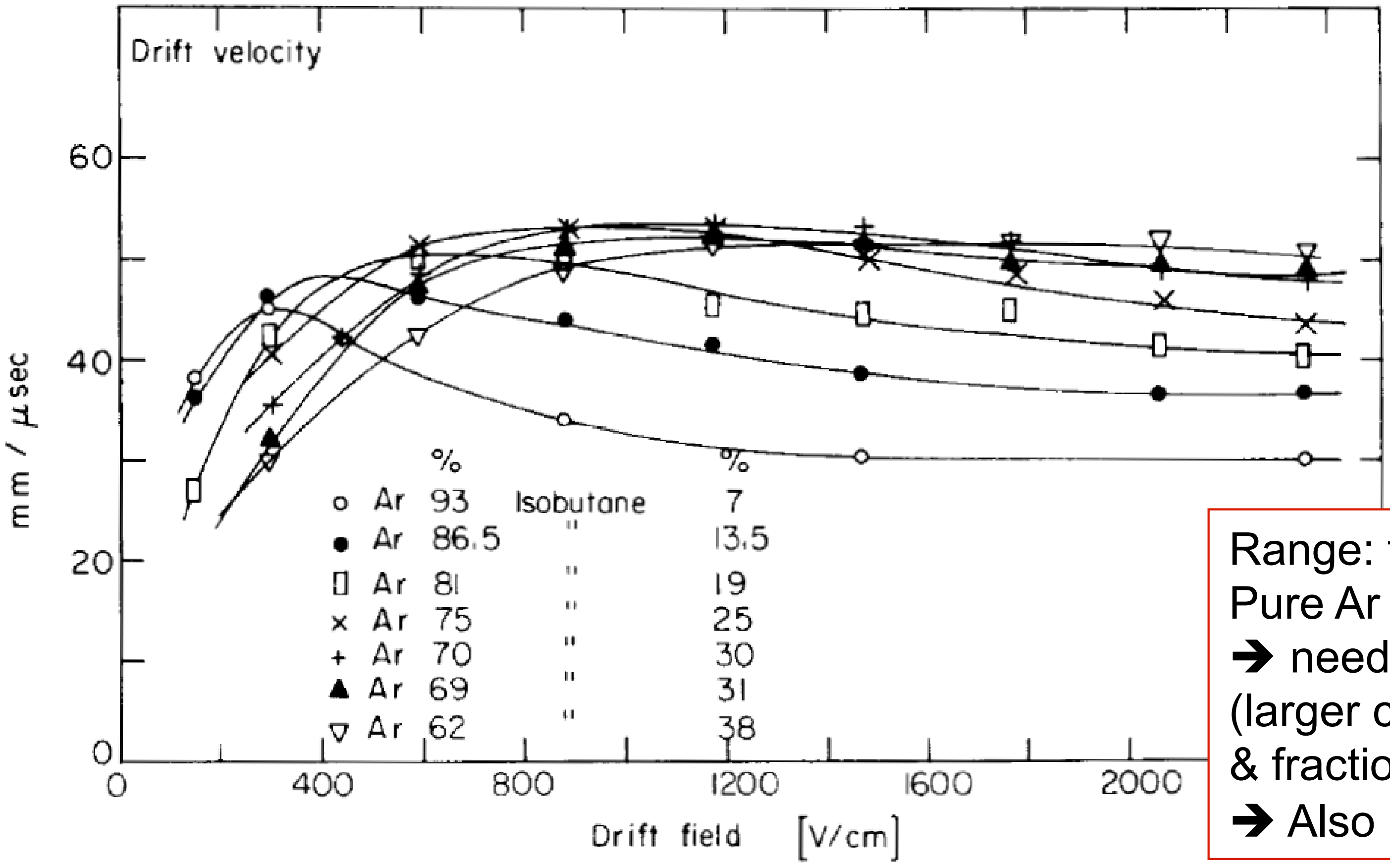
Drift velocity of electrons
in several gases at normal conditions

Use gas mixture to obtain constant v_D
Important for applications using drift time to get
spatial information



E-Field/pressure

Drift velocity



Range: few 10 mm/μs
Pure Ar : ~10 mm/μs
➔ need quenching gas
(larger cross-sections
& fractional energy loss)
➔ Also less diffusion

Drift velocity in several argon-isobutane (C_4H_{10}) mixtures

Avalanche multiplication

Large electric field yields
large kinetic energy of electrons ...

➛ Avalanche formation

Larger mobility of electrons results in liquid
drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

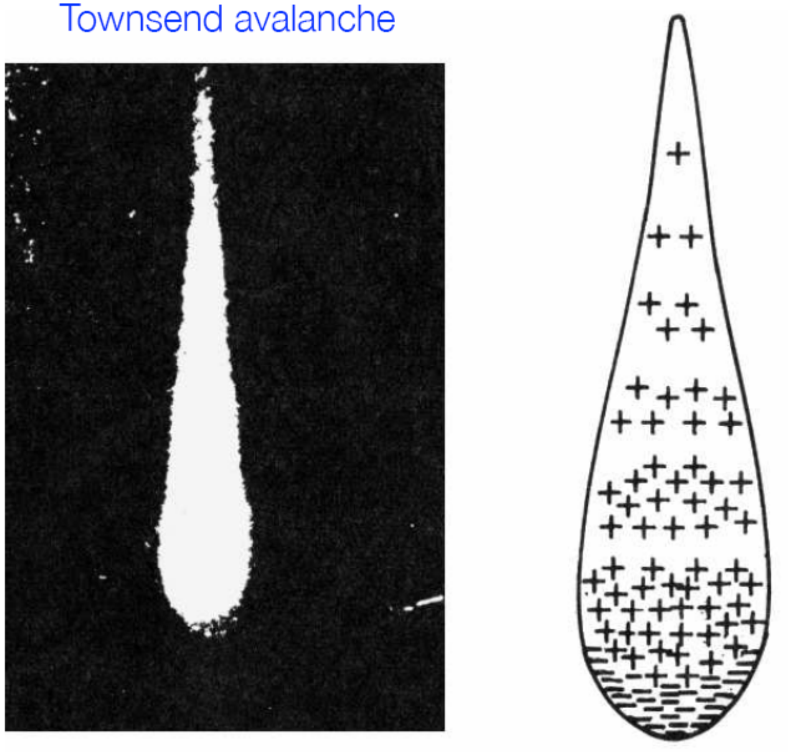
Probability of an ionization per
unit path length: $\alpha = 1/\lambda_{ion}$ [1st Townsend coefficient]

$$dn = n \cdot \alpha\, dx$$

$$n = n_0 e^{\alpha x}$$

n(x) = electrons at location x

Townsend avalanche



Drop-like shape of an avalanche

Left: cloud champer picture
Right: schematic view

Gain:

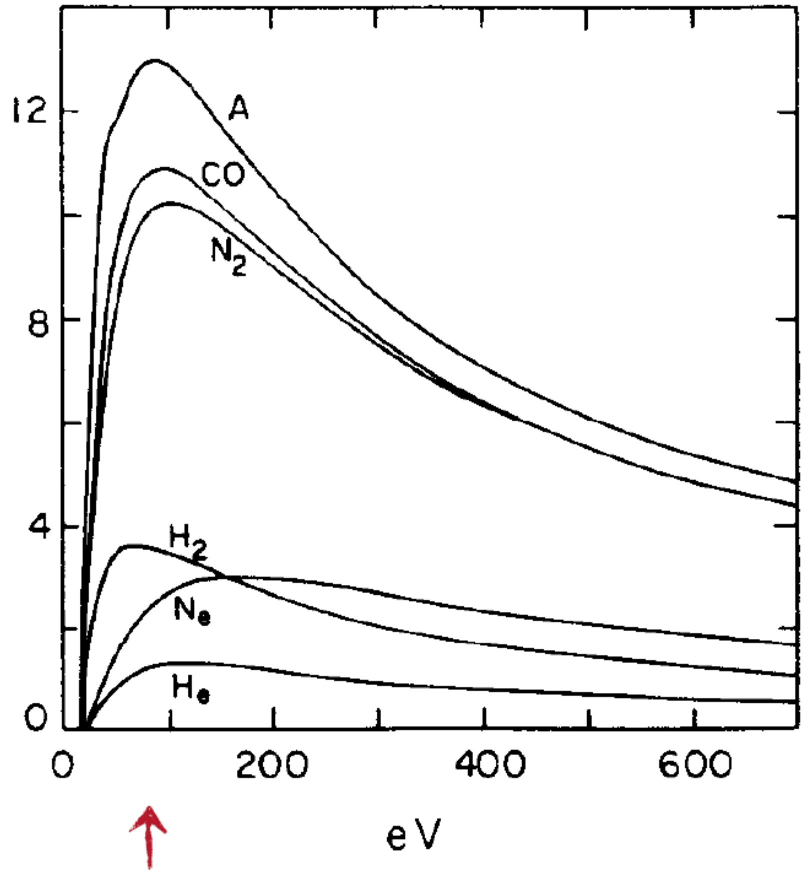
$$G = \frac{n}{n_0} = e^{\alpha x}$$

and more general for $\alpha = \alpha(x)$: $$G = \frac{n}{n_0} = \exp\left[\int_{x_1}^{x_2} \alpha(x) dx\right]$$

[Raether limit: $G \approx 10^8$; $\alpha x = 20$; then sparking sets in ...]

Avalanche multiplication

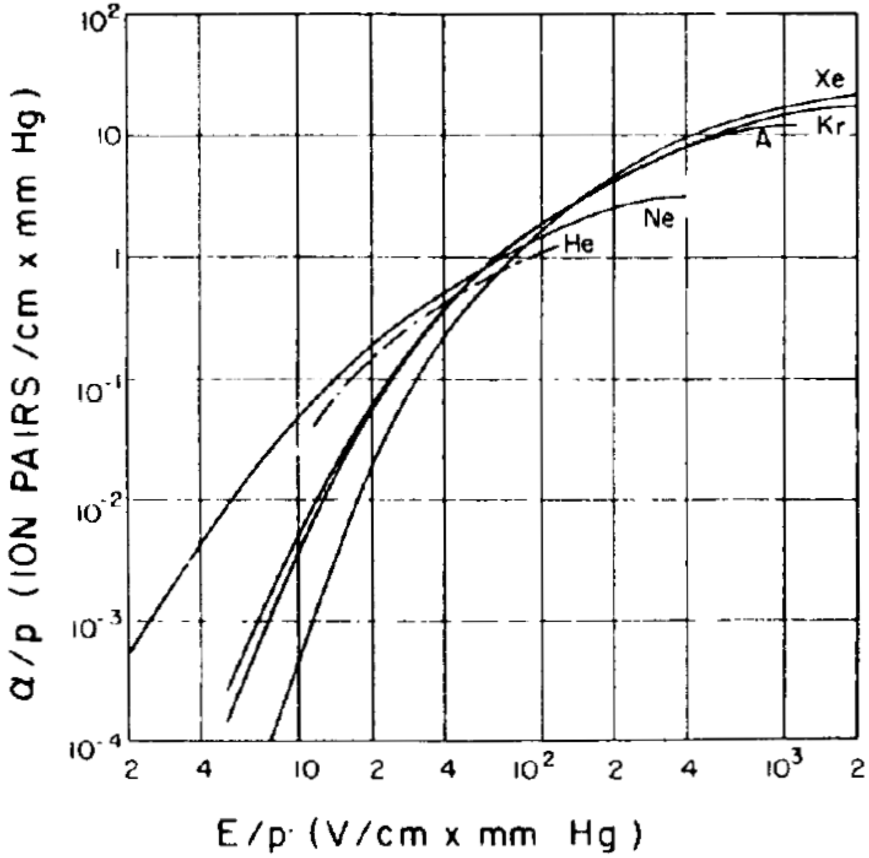
Ionization Probability



Need about 75-100 eV
for high ionization probability

[need to gain this energy within few microns]

Townsend Coefficient



E ≈ 75 kV/cm
needed to reach $\alpha = 1$

Gas amplification factor

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

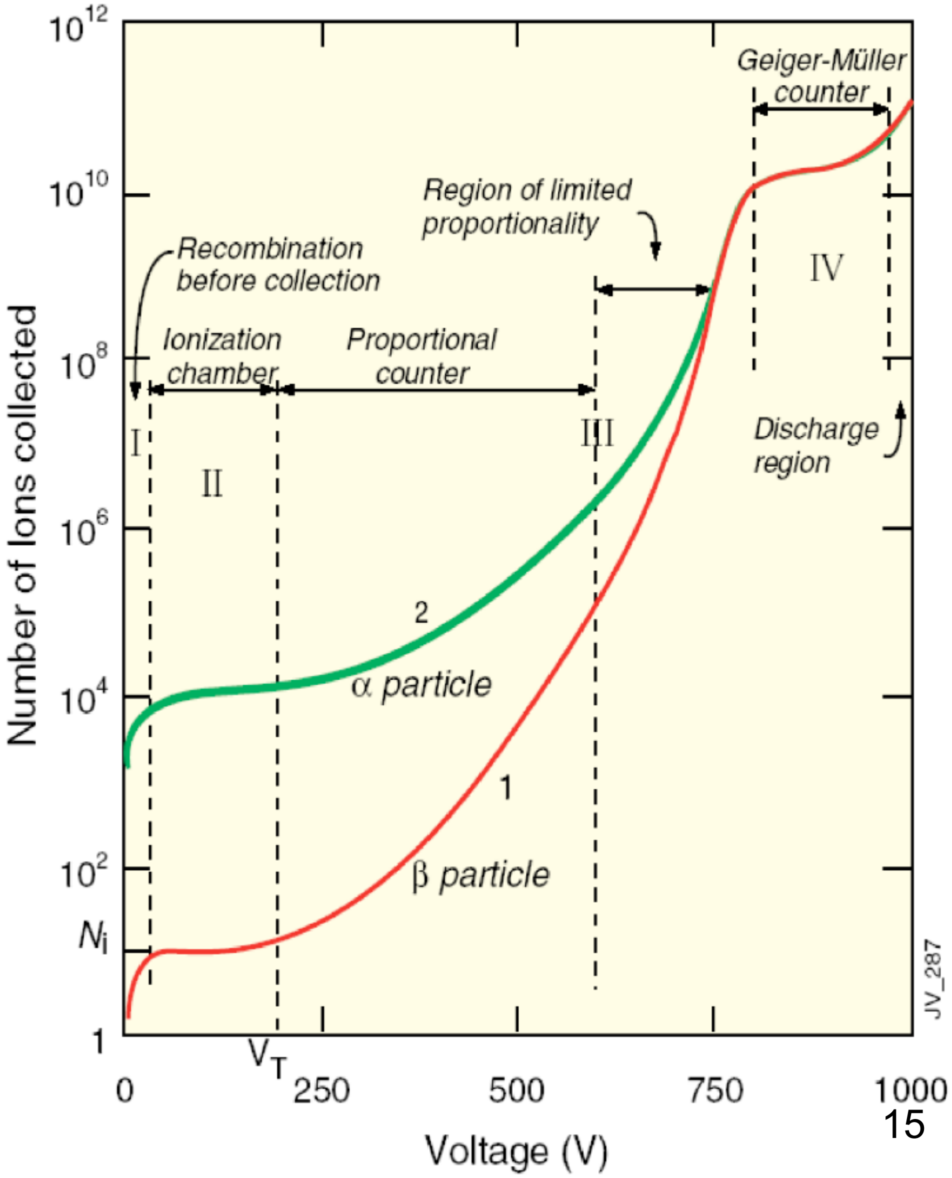
Limited proportional mode:

[saturated, streamer]

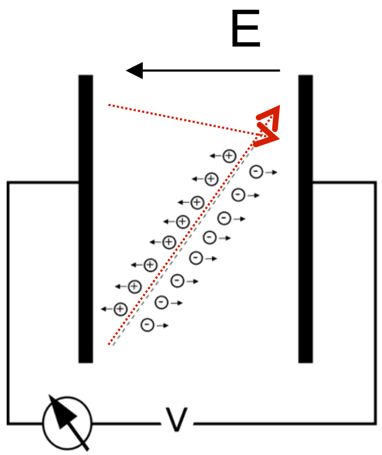
strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



Proportional counter

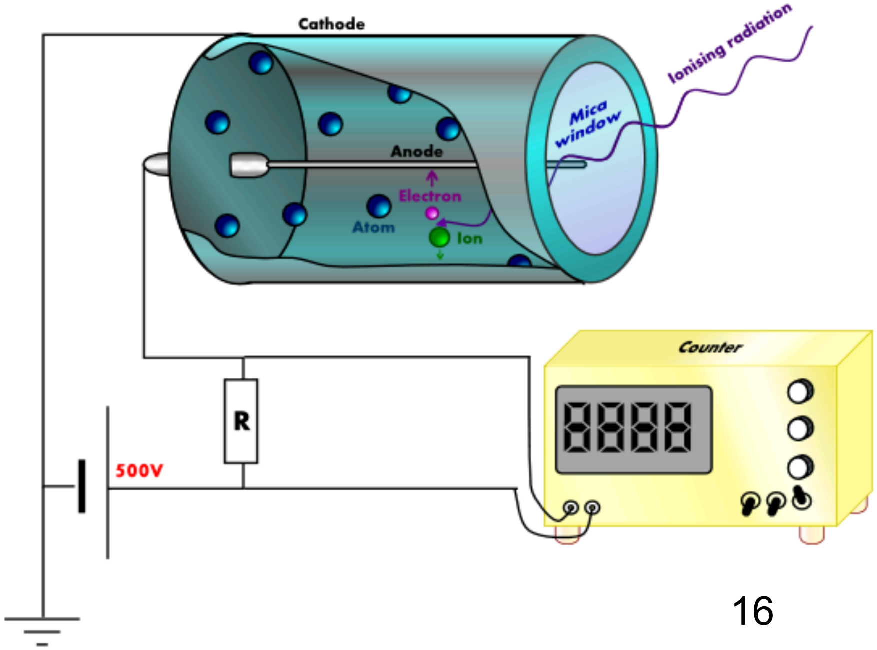


Planar design disadvantage:

E uniform and ⊥ to the electrodes
amount of ionization produced proportional to path length and to position where the ionization occurs
➔ not proportional to energy

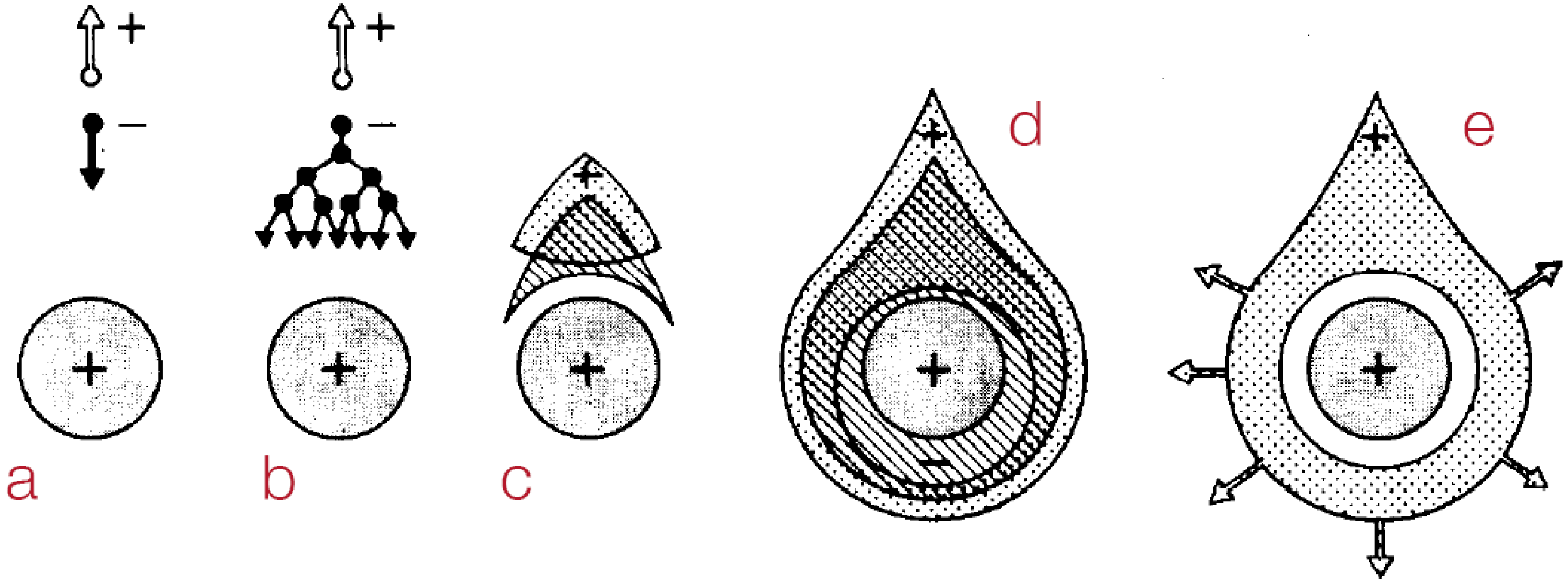
Problem solved using Cylindrical proportional counter:

Single anode wire in a cylindrical cathode
E~1/r: weak field far from the wire
electrons/ions drift in the volume
multiplication occurs only near the anode



Avalanche development

Time development of an avalanche near the wire of a proportional counter



a) a single primary electron proceeds towards the wire anode,
b) in the region of increasingly high field the electron experiences ionizing collisions (avalanche multiplication),
c) electrons and ions are subject to lateral diffusion,
d) a drop-like avalanche develops which surrounds the anode wire,
e) the electrons are quickly collected (~1ns) while the ions begin drifting towards the cathode generating the signal at the electrodes.