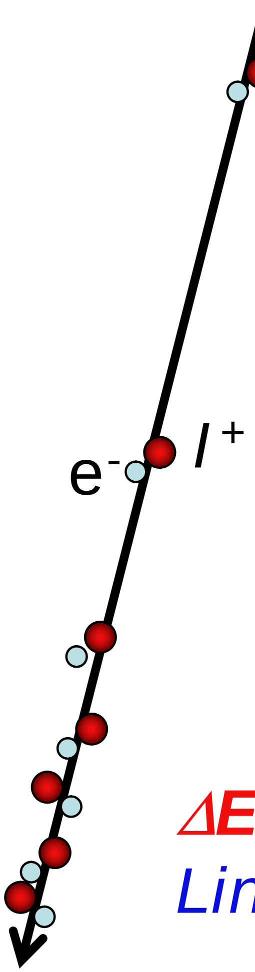
Detection of Ionizing Radiation

Primary Ionization Track (Gases)

incoming particle
ionization track
→ ion/e⁻ pairs



$\Delta E \propto n$

Linear

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

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

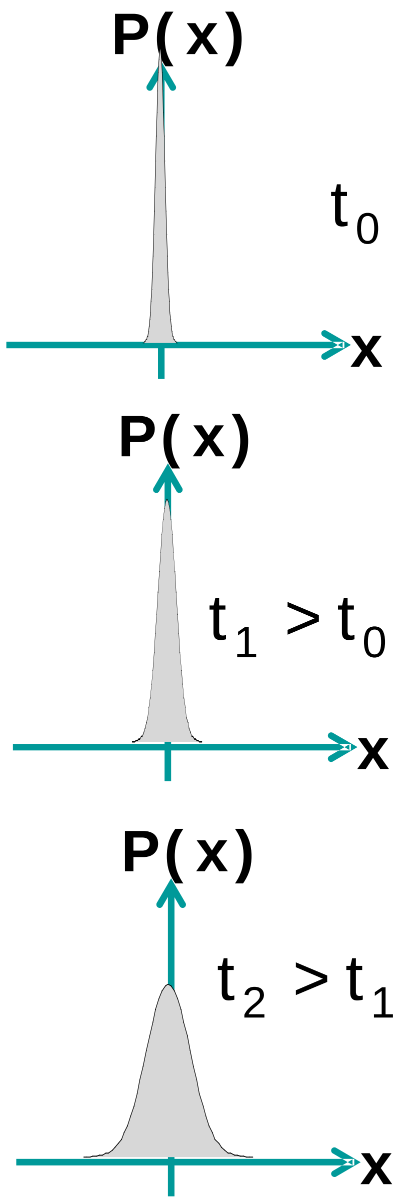
Statistical ionization process: Poisson statistics
Detection efficiency ε depends on average number <n> of ion pairs

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

GAS (STP)	thickness	ε (%)
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

Higher ε for slower particles

Free Charge Transport in Gases



1D Diffusion equation → $P(x) = (1/N_0)\, dN/dx$

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4Dt}} \cdot \exp\left\{-\frac{x^2}{4D \cdot t}\right\}$$

$$\langle x \rangle_{rms} := \sqrt{\langle x^2 \rangle} = \sigma_x = 2Dt$$

$$D = \frac{1}{3} \cdot \langle v \rangle \cdot \lambda$$

D diffusion coefficient,
<***v***> mean speed
λ mean free path

Thermal velocities :

$$\langle v \rangle = \sqrt{\frac{8kT}{\pi m}} = \sqrt{\frac{8}{3\pi}} \sqrt{\langle v^2 \rangle}$$

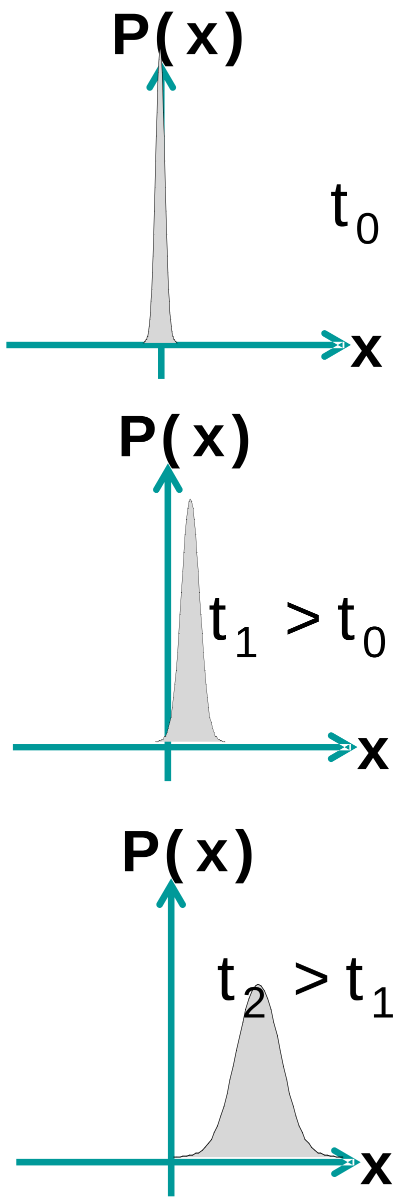
Maxwell+Boltzmann velocity distribution

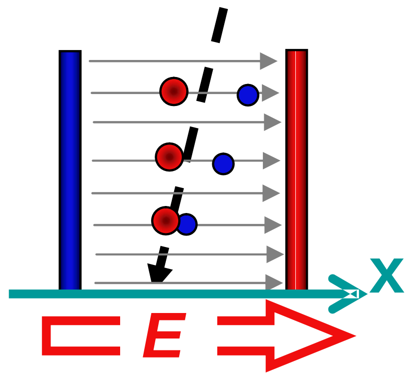
$$D(ion) \ll D(e^-)$$

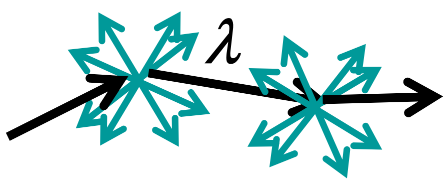
Small ion mobility

Driven Charge Transport in Gases

Electric field $E = \Delta U/\Delta x$ separates +/- charges







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

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

$$\tau = \lambda / \langle v \rangle \quad \textit{mean collision time}$$

$$\bar{D} = \mu \cdot \frac{kT}{e} \qquad \mu := \frac{w}{E} \quad \textit{mobility}$$

Cycle: acceleration – scattering
Drift and diffusion depend on field strength and gas pressure p (or ρ).

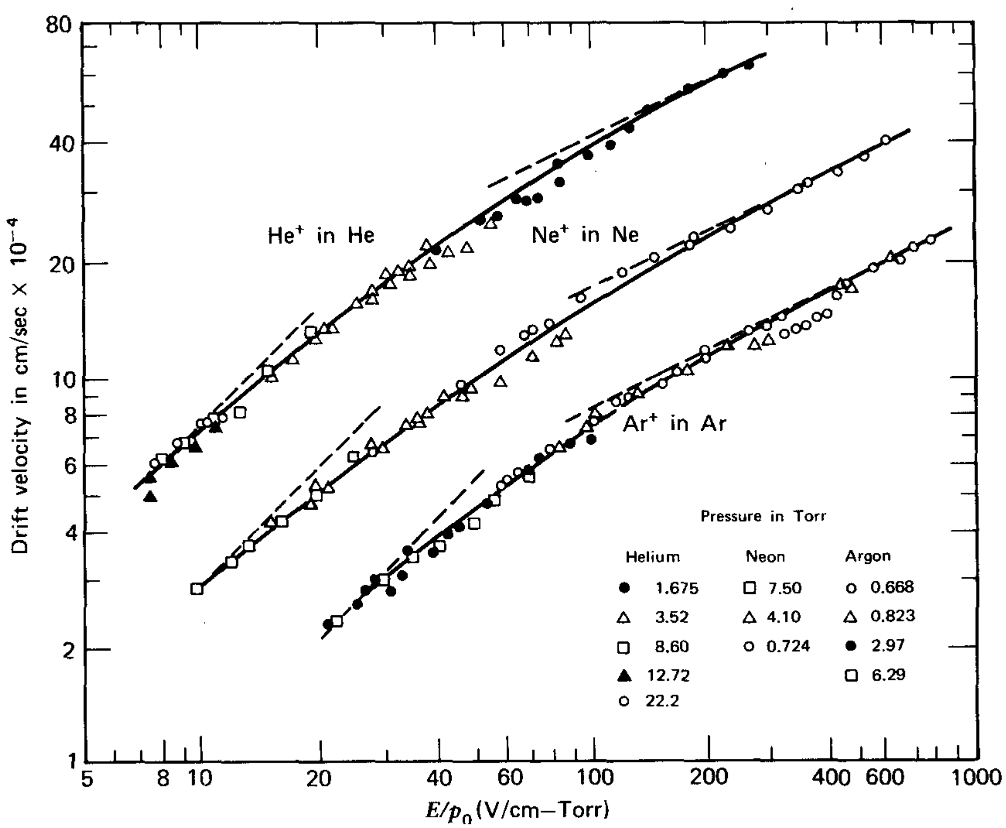
$$w = w(E/p); \quad \bar{D} = \bar{D}(E/p)$$

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 $\mu^+ = \boldsymbol{w^+ / E}$

Independent of field,
for given gas at $p, T = const$.



Typical ion drift velocities ($Ar+CH_4$ counters):

$w^+ \sim (10^{-2} - 10^{-5})\ cm/\mu s$

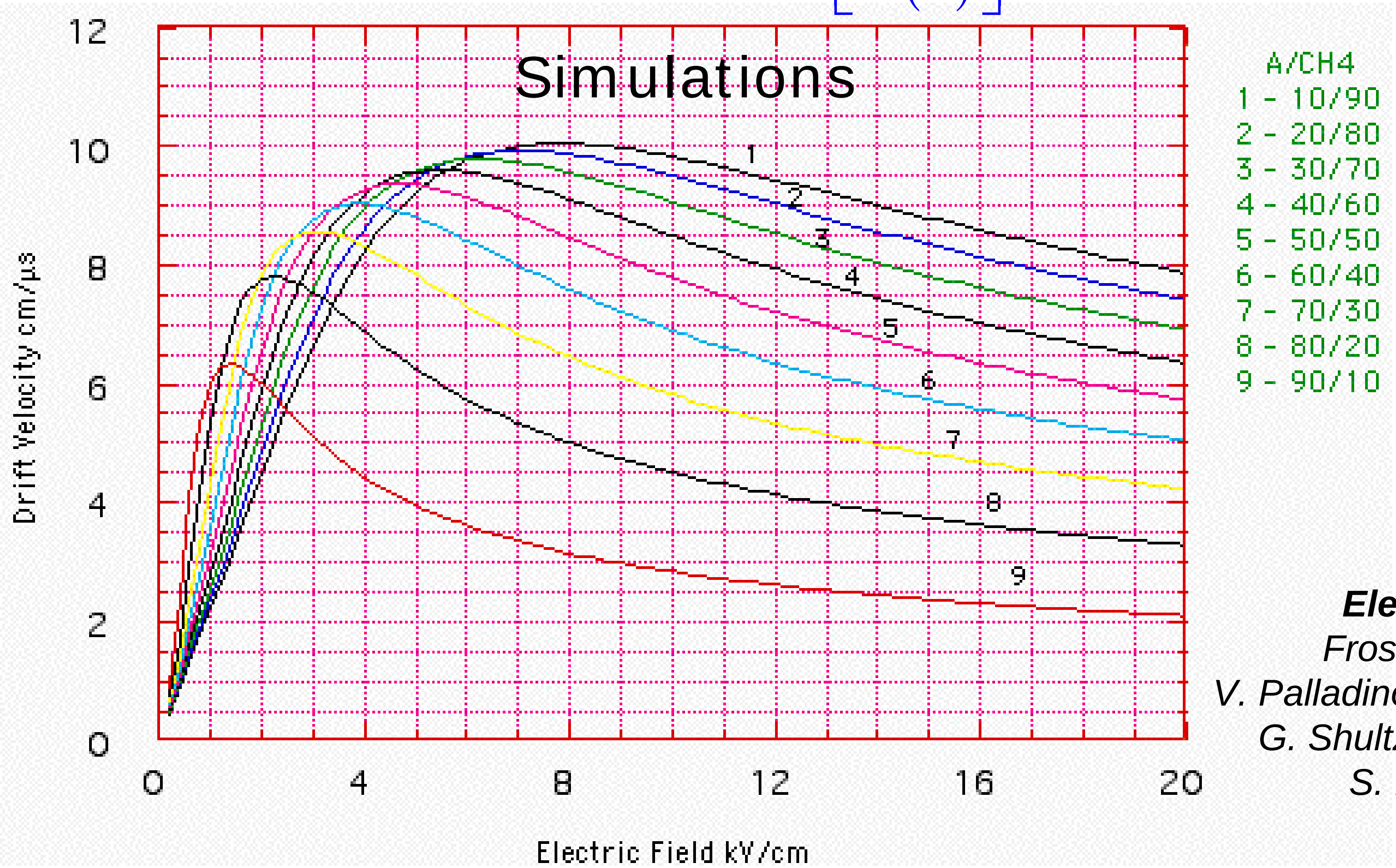
slow!

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

Electron Transport

Multiple scattering/acceleration produces effective spectrum P(ε)
→ calculate effective λ and τ.

$$w^{-} = \frac{2}{3}\frac{e}{m}E\int \varepsilon \cdot \frac{\partial}{\partial \varepsilon}\left[\frac{P(\varepsilon)}{v(\varepsilon)}\right]d\varepsilon \qquad \bar{D} = \frac{1}{3}\int \lambda(\varepsilon)\cdot v(\varepsilon)\cdot P(\varepsilon)\,d\varepsilon$$



$$v(\varepsilon) = \sqrt{2\varepsilon/m}$$

$w^{-} \sim 10^{3}\ w^{+}$

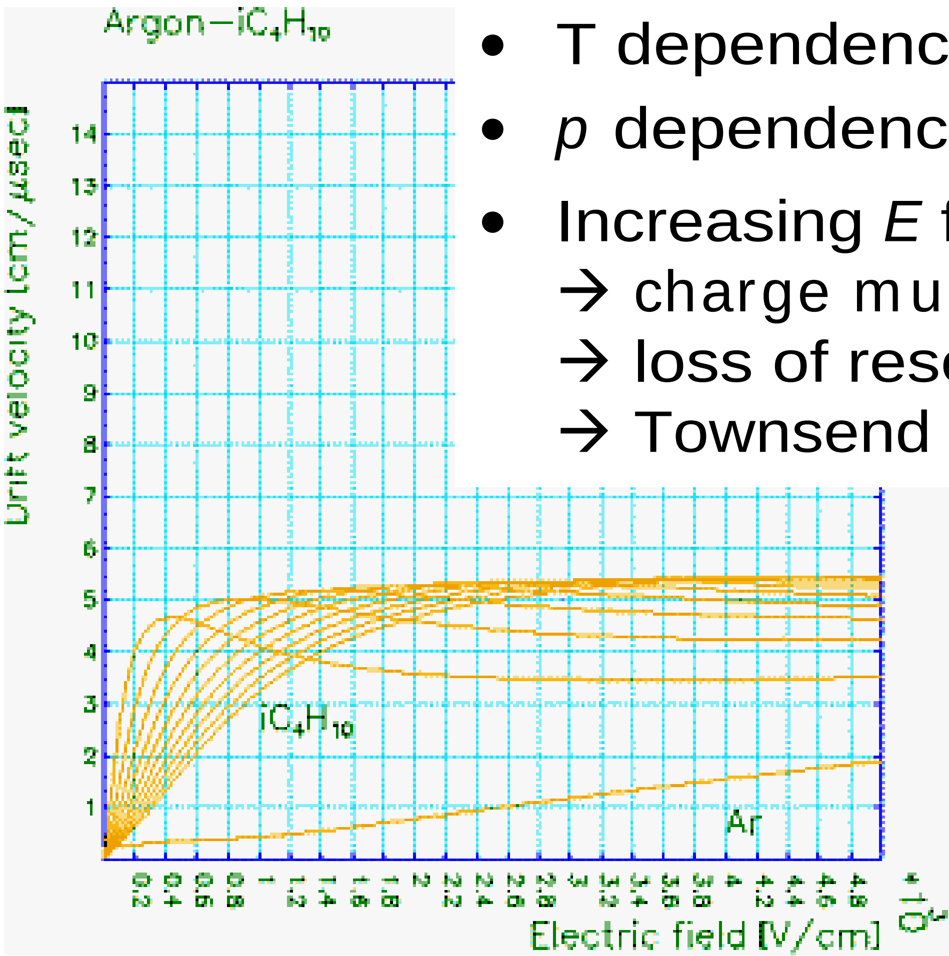
Electron Transport:

Frost et al., PR 127(1962)1621
V. Palladino et al., NIM 128(1975)323
G. Shultz et al., NIM 151(1978)413
S. Biagi, NIM A283(1989)716

http://consult.cern.ch/writeup/garfield/examples/gas/trans2000.html#elec

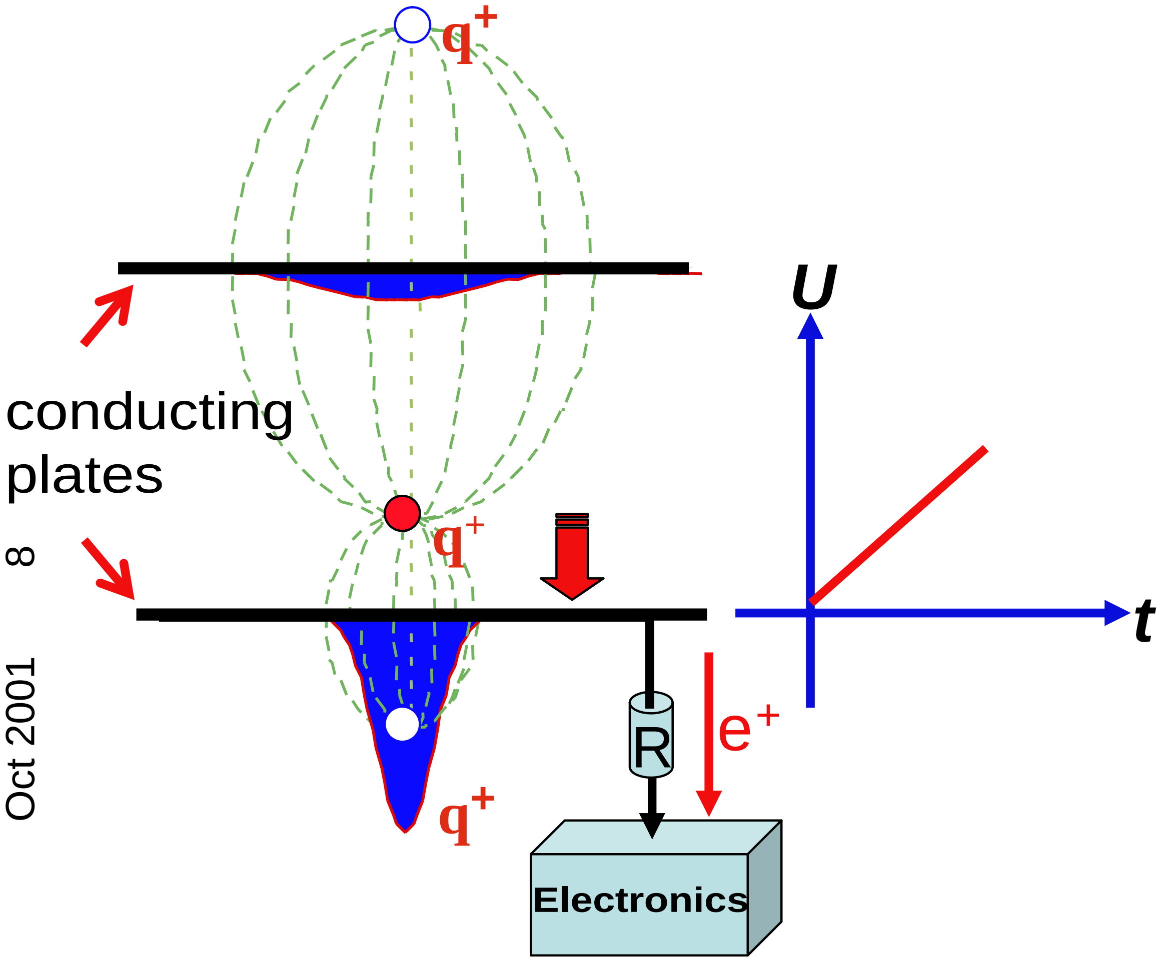
Stability and Resolution

- Anisotropic diffusion in electric field ($D_{perp} > D_{par}$).
- Electron capture by electro+negative gases, reduces energy resolution
- T dependence of drift: $\Delta w/w \approx \Delta T/T \sim 10^{-3}$
- *p* dependence of drift: $\Delta w/w \approx \Delta p/p \sim 10^{-3}\text{-}10^{-2}$
- Increasing *E* fields
  → charge multiplication/secondary+ ionization
  → loss of resolution and linearity
  → Townsend avalanches



W. Udo Schröder

Electronics: Charge Transport in Capacitors



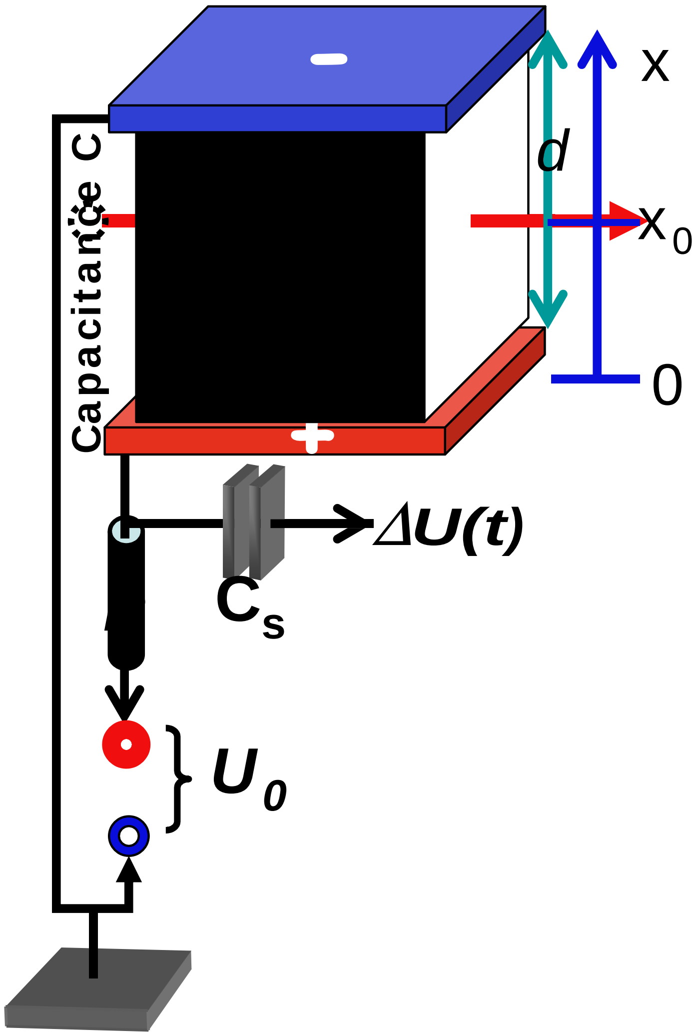
Charges q^+ moving between parallel conducting plates of a capacitor influence t-dependent negative images q^+ on each plate.

If connected to circuitry, current of e^- would emerge from plate, in total proportionally to charge q^+.

W. Udo Schröder

Signal Generation in Ionization Counters

Primary ionization: Gases I ≈ 20-30 eV/IP, **Si**: I ≈ 3.6 eV/IP **Ge**: I ≈ 3.0 eV/IP



Energy loss Δε: $n = n_I = n_e = \Delta\varepsilon / I$

number of primary ion pairs ***n*** *at* x_0, t_0

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

Energy content of capacitor C:

$$1)\ W(t) = \frac{C}{2}\left[U_0^2 - U^2(t)\right] \approx CU_0 \Delta U(t)$$

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

$$= + \frac{neU_0}{d}\left[x_I(t) - x_e(t)\right]$$

$$1) + 2) \searrow \qquad \nwarrow\!\!\searrow\ w^+(t)(t - t_0)$$

$$\Delta U(t) = \frac{W(t)}{CU_0} = \frac{ne}{Cd}\left[w^+(t) - w^-(t)\right](t - t_0)$$

W. Udo Schröder

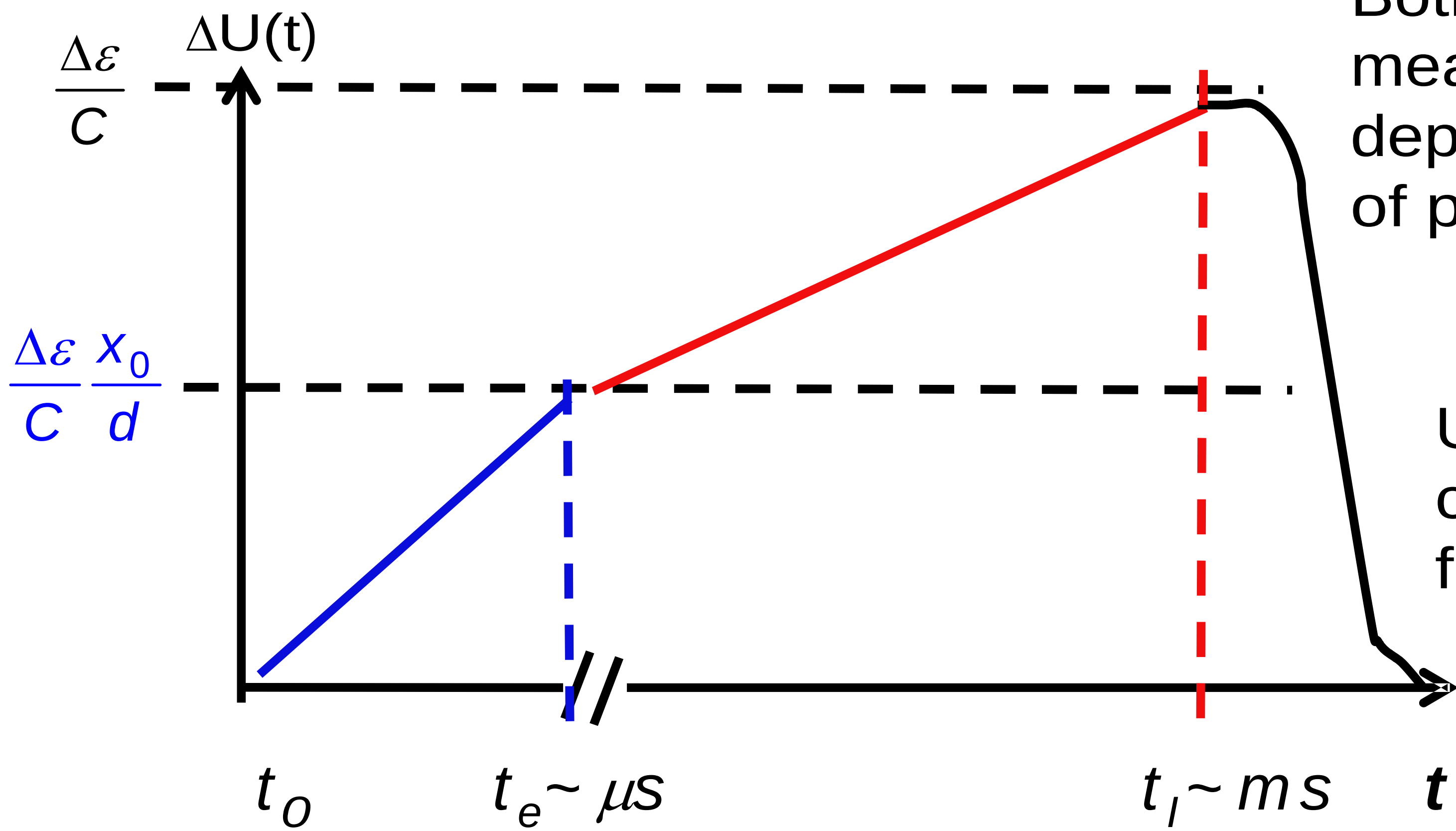
Time-Dependent Signal Shape

$$\Delta U(t) = \frac{\Delta\varepsilon}{Cd}\left[w^{+}(t) - w^{-}(t)\right](t - t_0)$$

Total signal:
e & I components

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

Drift velocities ($w^{+} > 0$, $w^{-} < 0$)



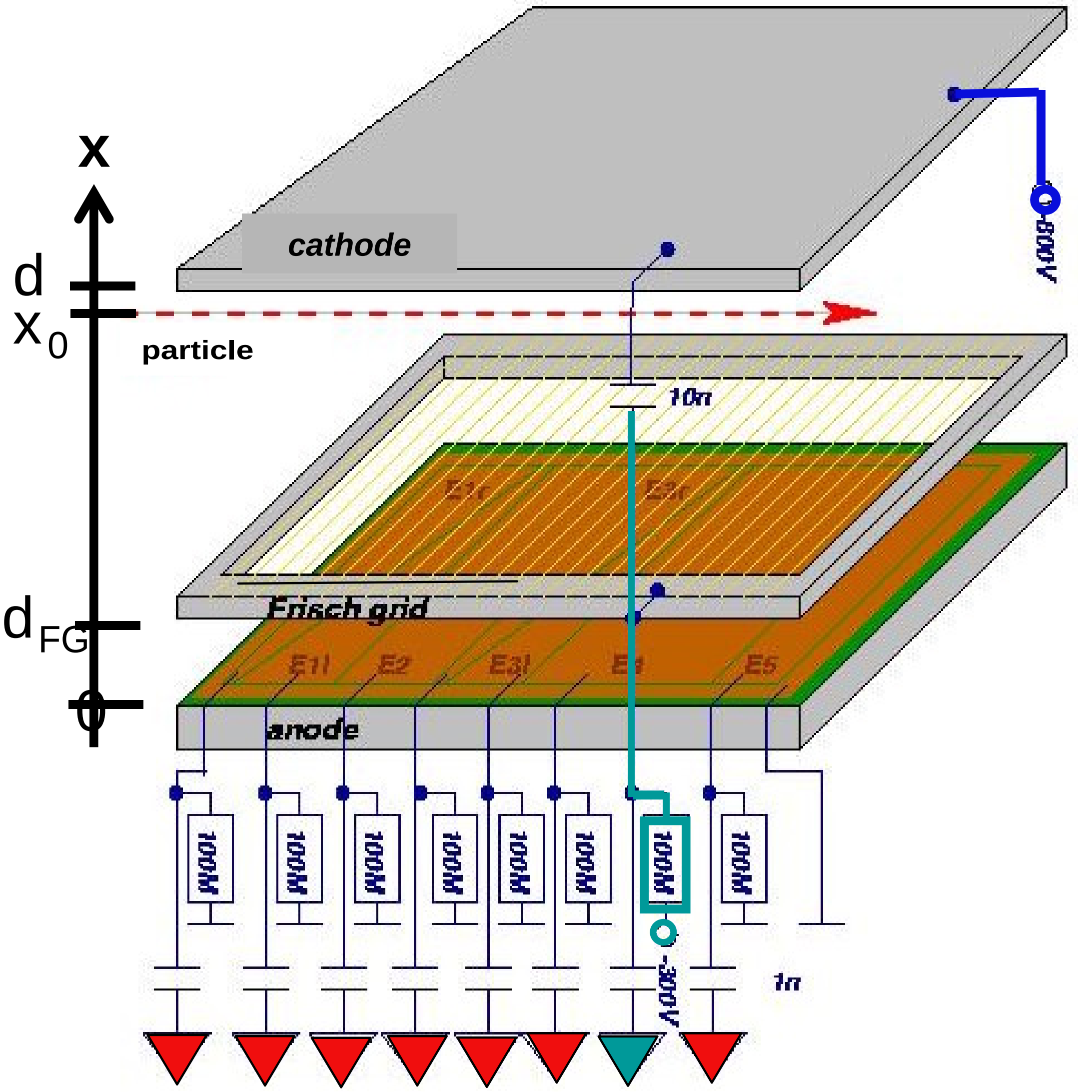
Both components measure Δε and depend on position of primary ion pairs

$$x_0 = w^{-}(t_e - t_0)$$

Use electron component only for fast counting.

W. Udo Schröder

Frisch Grid Ion Chambers



Anode/FG signals out

Suppress position dependence of signal amplitude by shielding charge-collecting electrode from primary ionization track.

Insert wire mesh (Frisch grid) at position x_{FG} held constant potential U_{FG}.
e^- produce signal only when inside sensitive anode-FG volume, ions are not "seen".
→

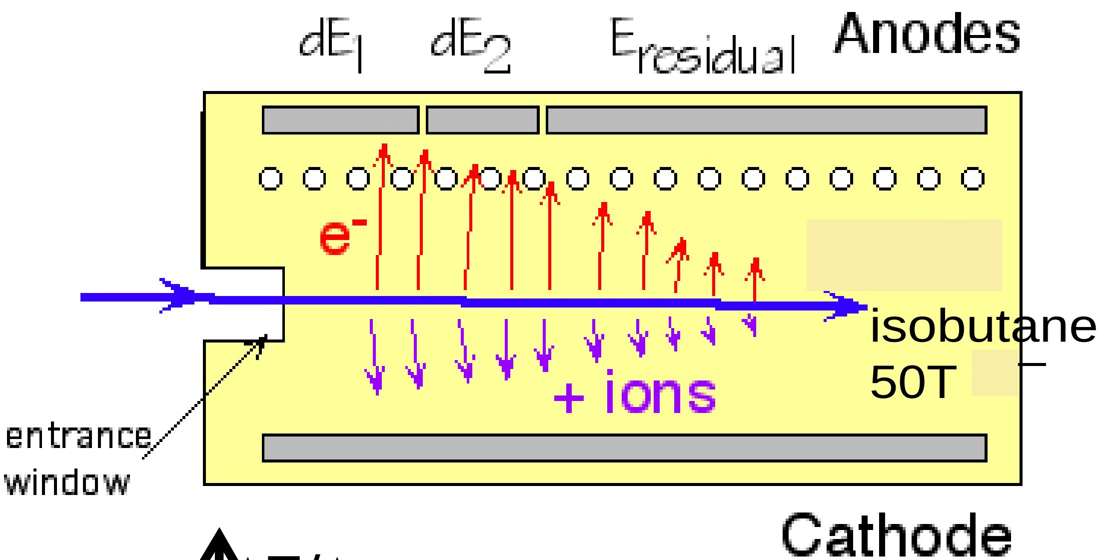
$$\Delta U(t) = \frac{\Delta\varepsilon}{Cd_{FG}} w^{-}(t)(t - t_{FG})$$

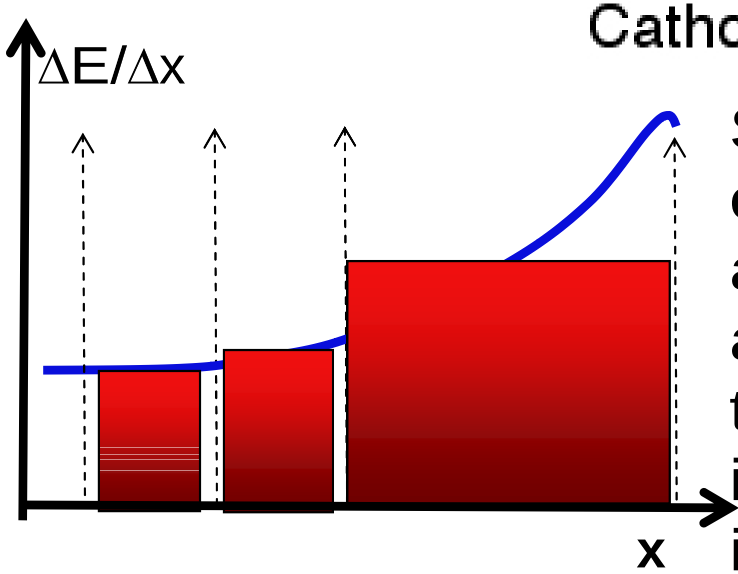
not x dependent.

x-dependence used in "*drift chambers*".

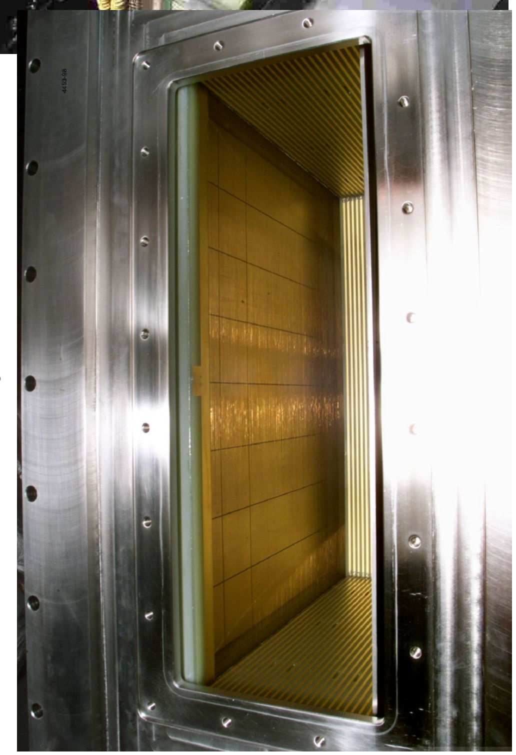
Bragg-Curve Sampling Counters

Sampling Ion chamber with divided anodes

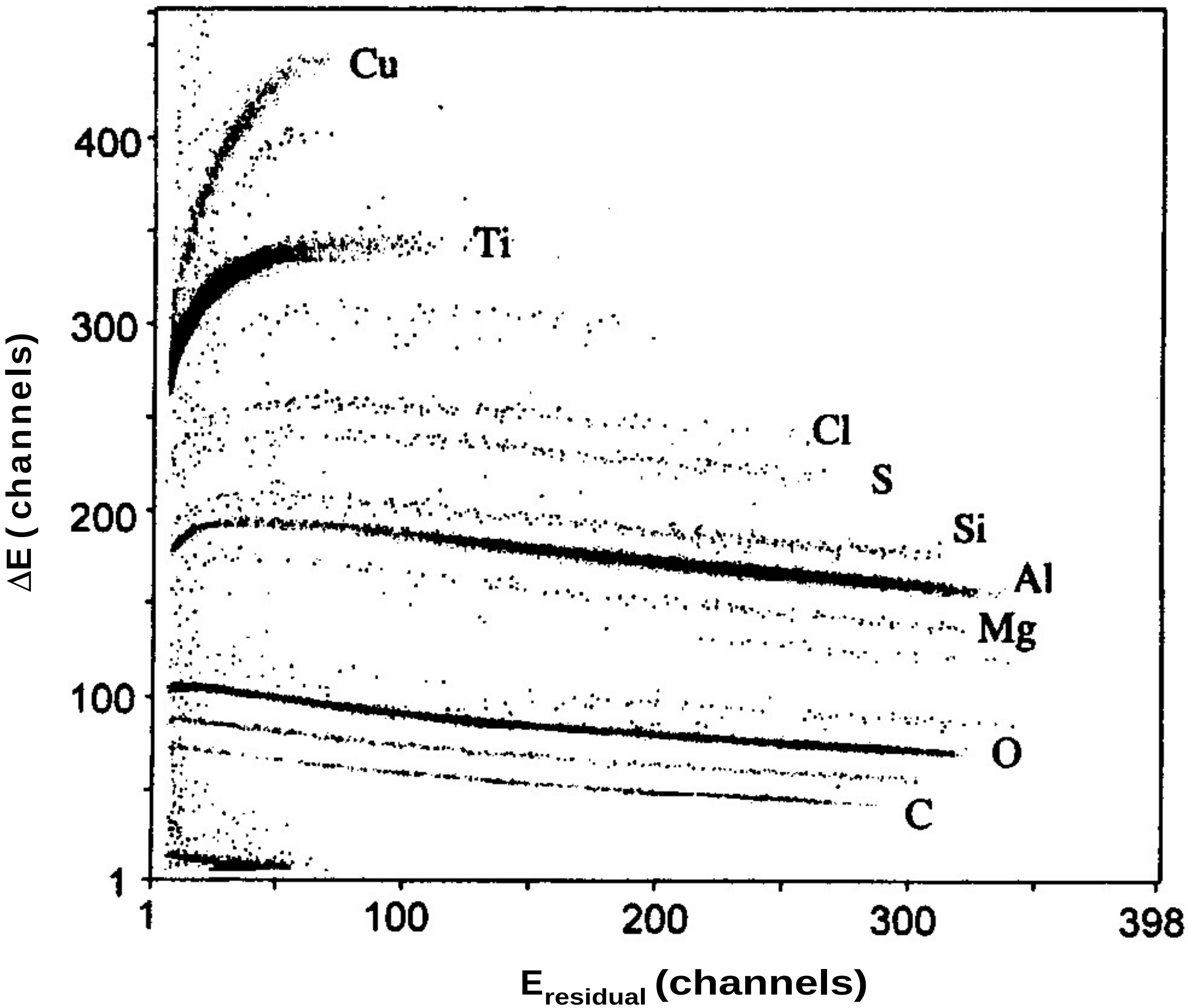




Sample Bragg energy-loss curve at different points along the particle trajectory improves particle identification.



IC Performance



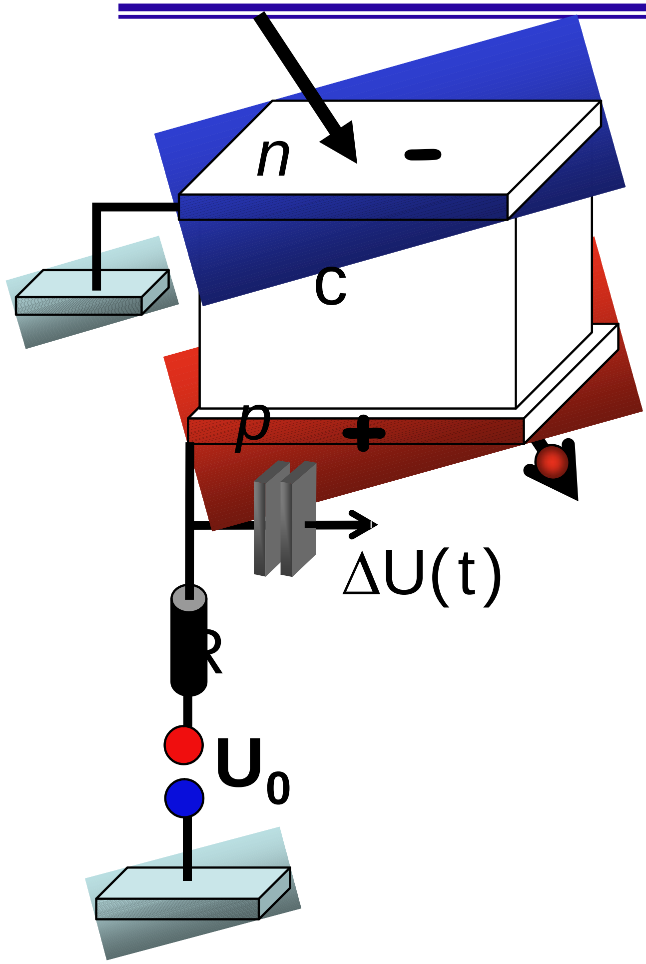
ICs have excellent resolution in E, Z, A of charged particles but are slow detectors. Gas IC need very stable HV and gas handling systems.

Energy resolution

$$\sigma_{\varepsilon}^{2} = F\left\langle n_{ip}\right\rangle = F\frac{\Delta\varepsilon}{I}$$

F<1 Fano factor

Solid-State IC

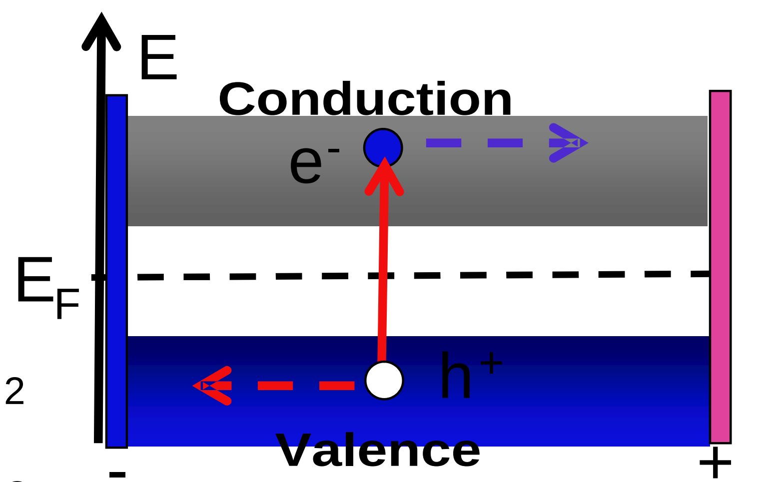


Solids have larger density → higher stopping power dE/dx → more ion pairs, better resolution, smaller detectors (also more damage, max dose ~ 10^7 particles

Semiconductor *n-, p-, i- types*

Si, Ge, GaAs,.. (for e^-, lcp, γ, HI)

Band structure of solids:



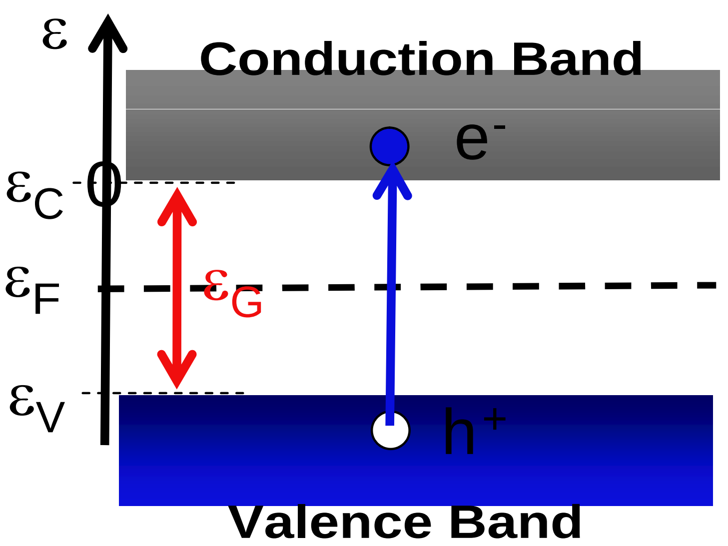
Ionization lifts e^- up to conduction band → free charge carriers, produce $\Delta \boldsymbol{U(t)}$.

Bias voltage U_0 creates charge-depleted zone

Capacitance Si :

$$C = \begin{cases} 2.2 \big/ \sqrt{\rho_n U_0} \;\; pF/mm^2 \\ 3.7 \big/ \sqrt{\rho_p U_0} \;\; pF/mm^2 \end{cases}$$

Particles and Holes in Semi-Conductors



Fermion statistics:

$$n_e(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2 \hbar^3} \sqrt{\varepsilon} \cdot f_e(\varepsilon) \qquad V = volume$$

$$n_h(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2 \hbar^3} \sqrt{|\varepsilon|} \cdot f_h(\varepsilon) \qquad n_e = n_h \,!!$$

$$\varepsilon_F = \varepsilon_C - \varepsilon_G/2 = -\varepsilon_G/2 \quad for \;\; \varepsilon_C := 0$$

$$e^- : \; f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

$$h^+ : \; f_h(\varepsilon) = \left[1 + \exp\left(\frac{-\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

$$f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon - \varepsilon_F}{kT}\right)\right]^{-1}$$

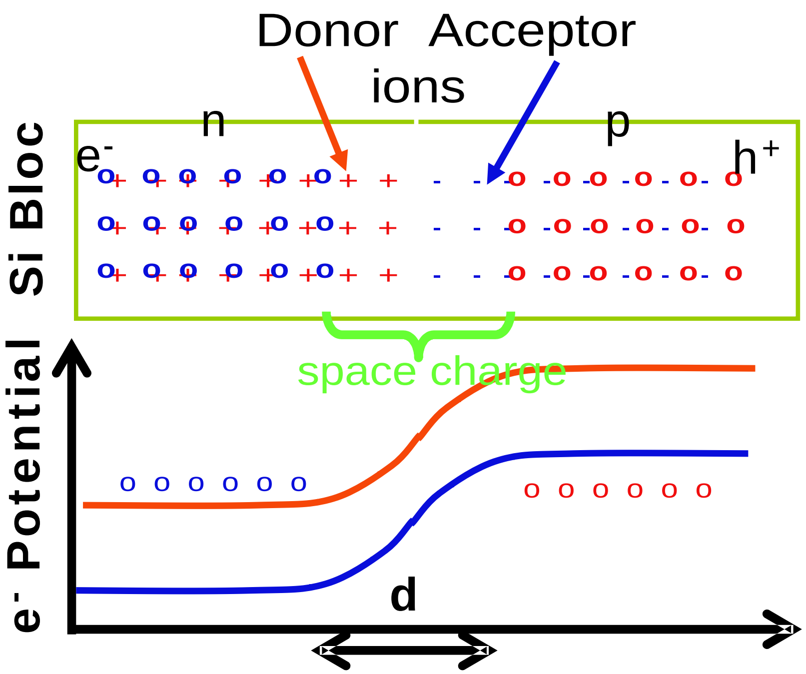
$$\xrightarrow[kT \approx 25meV \ll \varepsilon_G]{} \exp\left(-\frac{\varepsilon + \varepsilon_G/2}{kT}\right)$$

$$\langle n_e^2 \rangle = n_e n_h = \left(\frac{(2m)^{2/3} V}{2\pi^2 \hbar^3}\right)^2 \langle \varepsilon \rangle \exp\left(-\frac{\varepsilon_G}{kT}\right)$$

Small gaps ε_G (Ge) → large thermal currents. Reduce by cooling.

$$\boxed{\langle n_e \rangle_{rms} \sim \exp\left(-\frac{\varepsilon_G}{2kT}\right)} \quad \propto conductivity \;\; at \;\; T$$

Semiconductor Junctions and Barriers



Similar: Homogeneous *n(p)-type* Si with reverse bias U_0 also creates carrier-free space $d_{n,p}$: up to 1mm possible.

Need detector with no free carriers. Si: *i*-type (intrinsic),*n-type, p-type* by diffusing *Li*, e^- donor (P, Sb, As), or acceptor ions into Si.

Trick: Increase effective gap → Junctions diffuse donors and acceptors into Si bloc from different ends.

Diffusion at interface → e^-/h^+ annihilation → space charge

→*Contact Potential and zone depleted of free charge carriers*

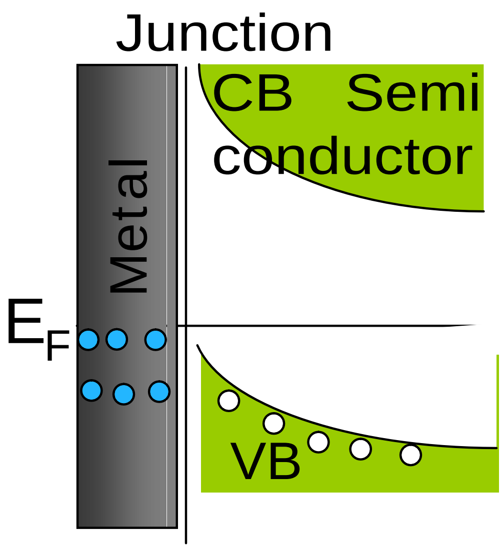
→Depletion zone can be increased by applying "reverse bias" potential

$$d_{n,p} \approx 3.3 \cdot 10^{-5} \sqrt{\rho_{n,p} U_0}\ \mu m$$

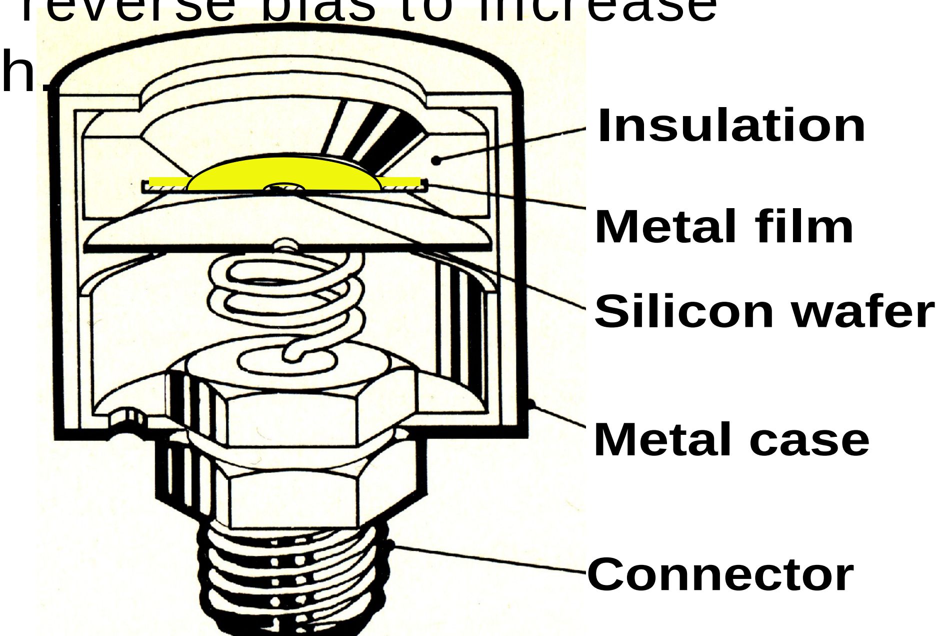
$$\rho_{n,p} \sim 20\, k\Omega cm,\ U_0 = 500V \quad \rightarrow d \approx 70\ \mu m$$

W. Udo Schröder

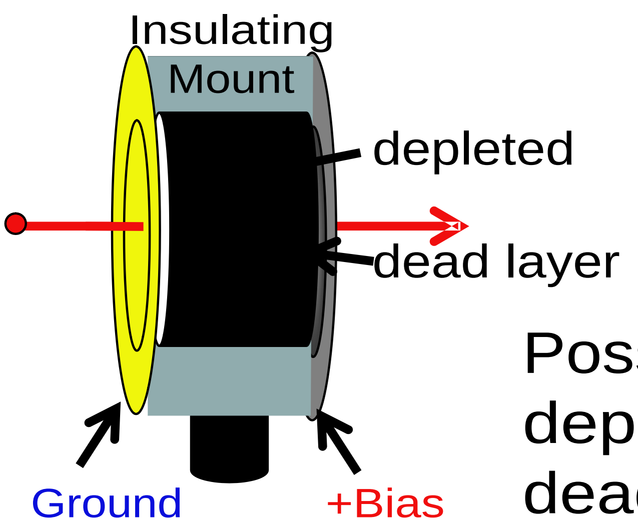
Surface Barrier Detectors



Different Fermi energies adjust to on contact. Thin metal film on Si surface produces space charge, an effective barrier (contact potential) and depleted zone free of carriers. Apply reverse bias to increase depletion depth.



ORTEC
HI detector



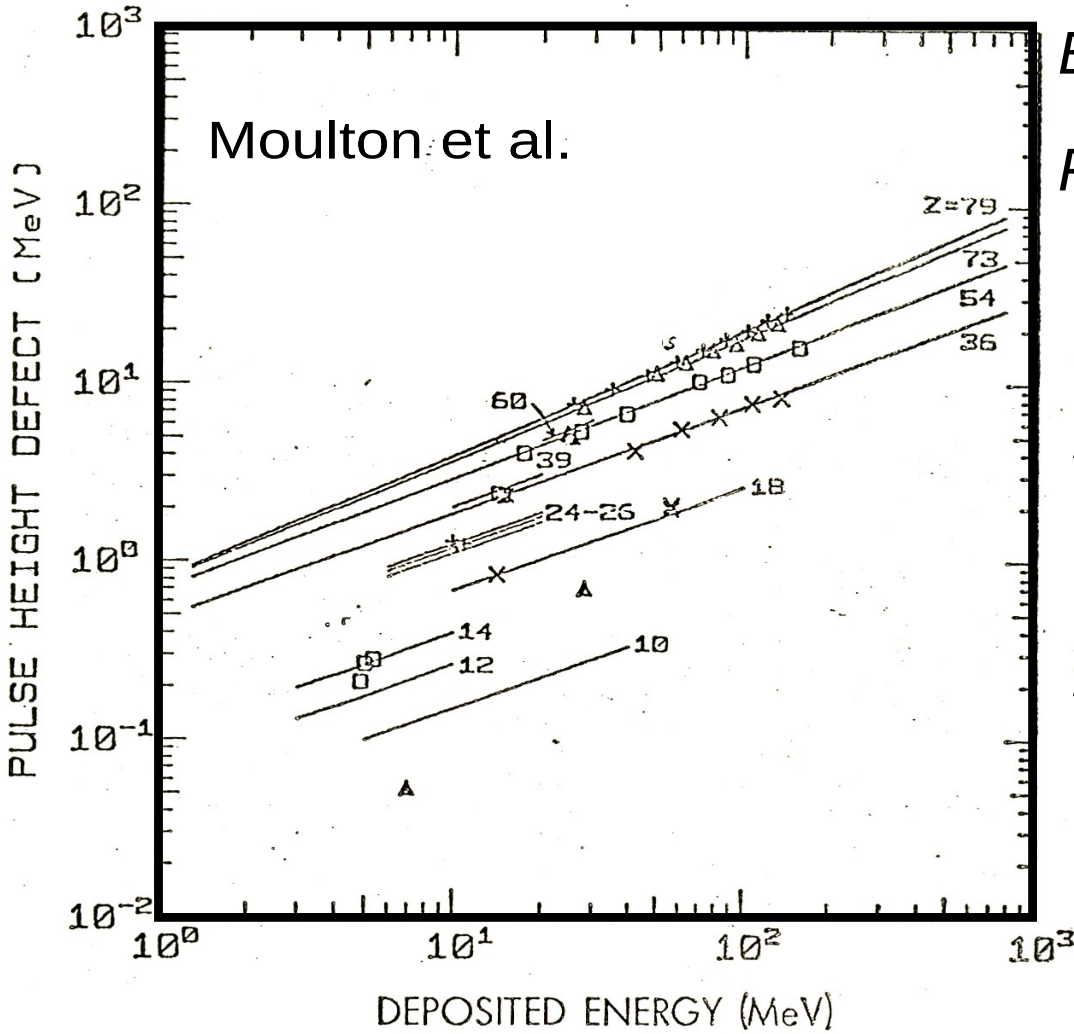
Front: Au Back: Al
evaporated electrodes

Possible:
depletion depth ~ 100μ
dead layer $d_d \lesssim 1\mu$
V ~ 0.5V/μ
Over-bias reduces d_d

Charge Collection Efficiency

Heavy ions: $E_{deposit} > E_{app}$ = apparent energy due to charge recombination, trapping. Light ions $E_{deposit} \approx E_{app}$

Typical charge collection times: t~ (10-30)ns



$$E_{PhD} := E_{deposit} - E_{app}$$

$$Fit: \ E_{PhD}\left(E_{deposit}\right) = 10^{b(Z,A)} E_{deposit}^{a(Z,A)}$$

$$a(Z) = 2.230 \cdot 10^{-5} Z^2 + 0.5682$$

$$b(Z) = -14.25 / Z + 0.0825$$

$$a(A) = 3.486 \cdot 10^{-6} A^2 + 0.5728$$

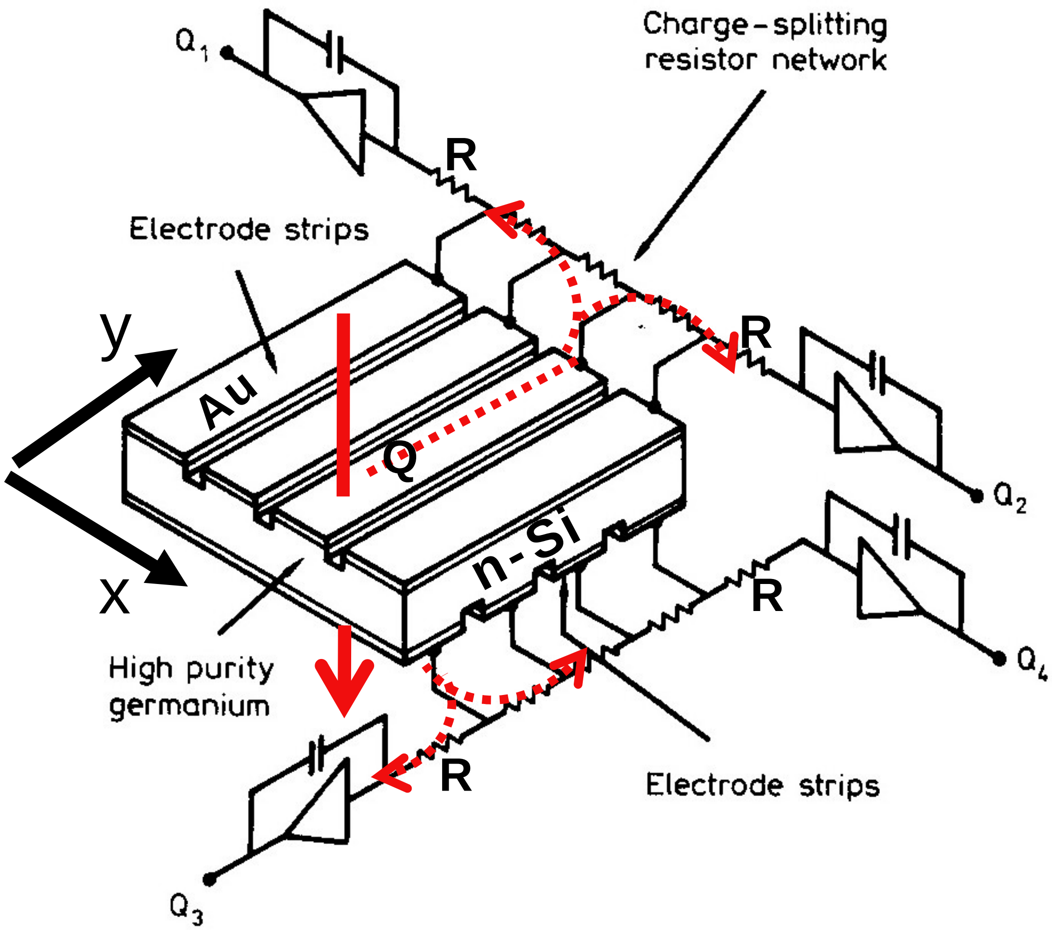
$$b(A) = -28.40 / A + 0.0381$$

Affect also collection time
→ lower signal rise time.

W. Ûdo Schröder

Position-Sensitive Semiconductor Detectors

Gerber et al., IEEE TNS-24,182(1977)



Double-sided x/y matrix detector, resistive readout.

$$Q_1 = Q \cdot \frac{x_n}{L_x} \quad Q_2 = Q \cdot \frac{(L_x - x_n)}{L_x}$$

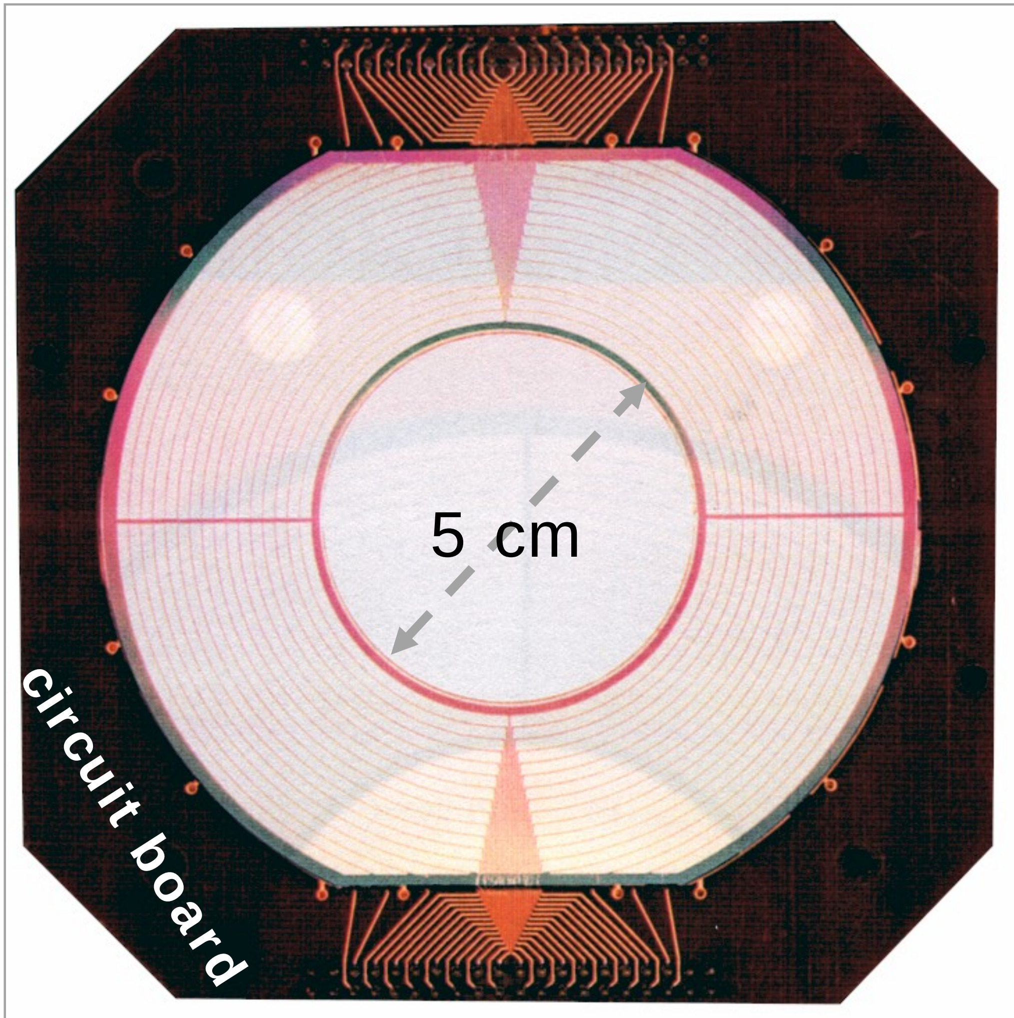
$$Q_3 = Q \cdot \frac{y_m}{L_y} \quad Q_4 = Q \cdot \frac{(L_y - y_m)}{L_y}$$

$$Q_1 + Q_2 = Q_3 + Q_4 = Q \propto \Delta E$$

~2000 Ωcm, 300μ → $U_0 \approx 160$V

W. Udo Schröder

Si-Strip Detectors



Typically (300-500)μ thick. Fully depleted, thin dead layer.

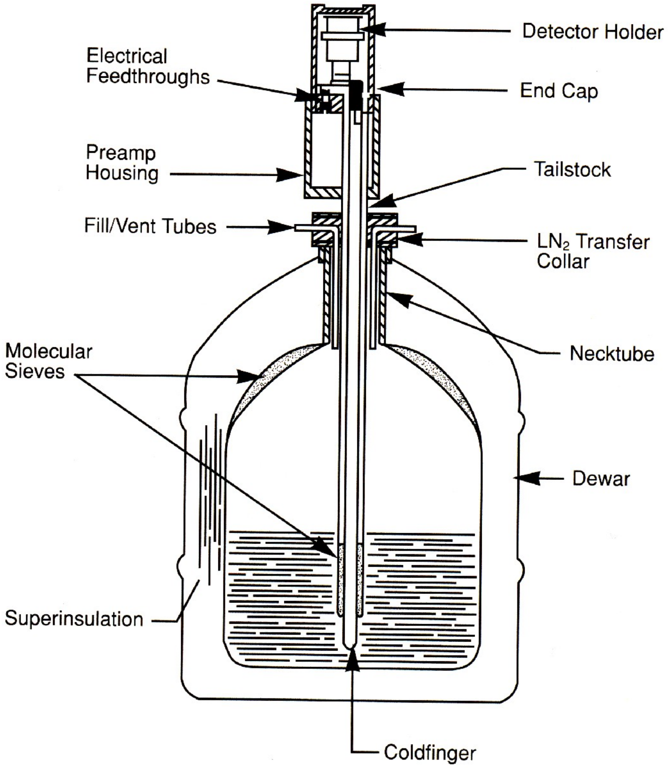
Annular: 16 θ bins, 4 ϕ (Micron Ltd.)

Rectangular with 7 strips

Ge γ–ray Detectors

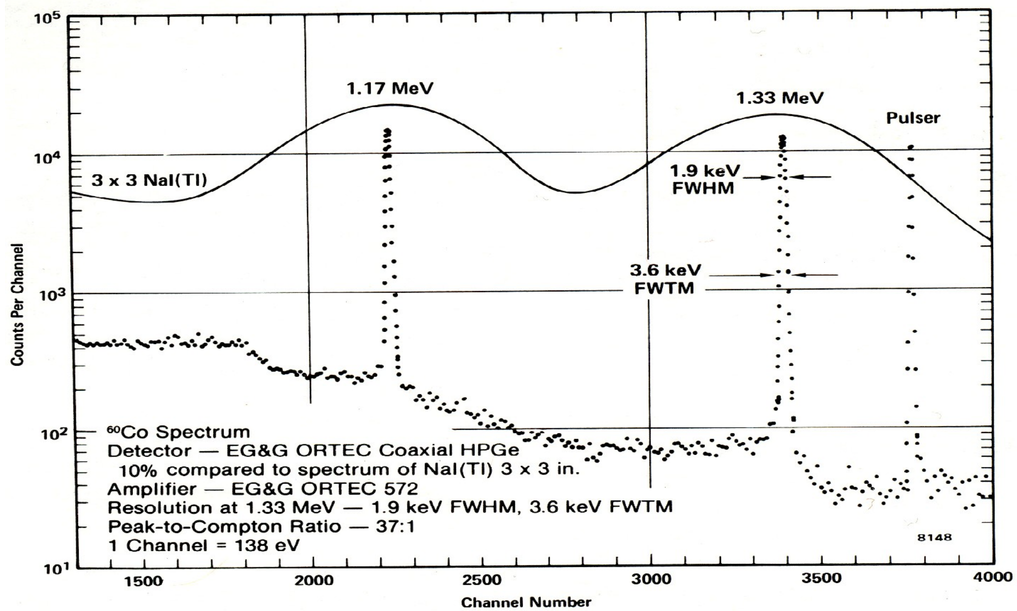
Ge detectors for γ-rays use *p-i-n* Ge junctions.
Because of small gap E_G, cool to -77°C (LN_2)

Ge Cryostate (Canberra)



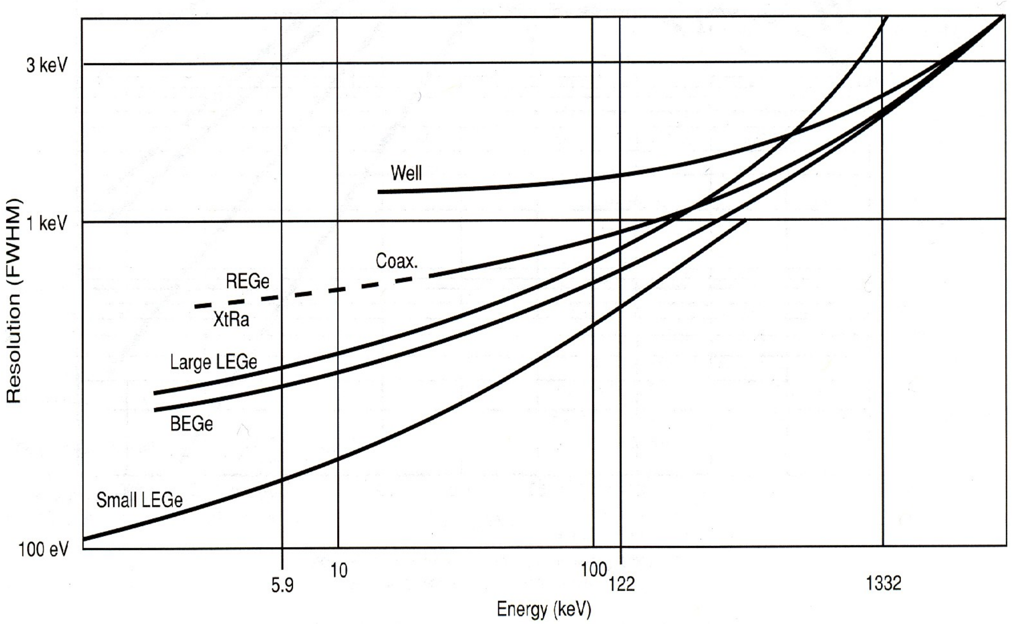
Ge cryostate geometries (Canberra)

Properties of Ge Detectors: Energy Resolution



Superior energy resolution, compared to NaI

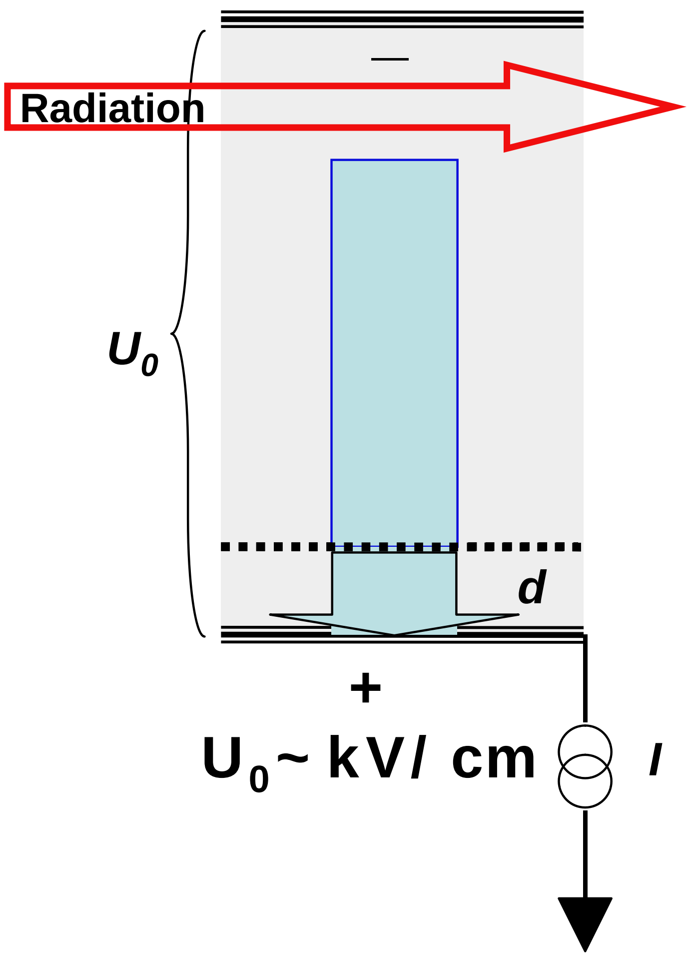
$\Delta E_\gamma \sim 0.5\text{keV} @ E_\gamma = 100\text{keV}$

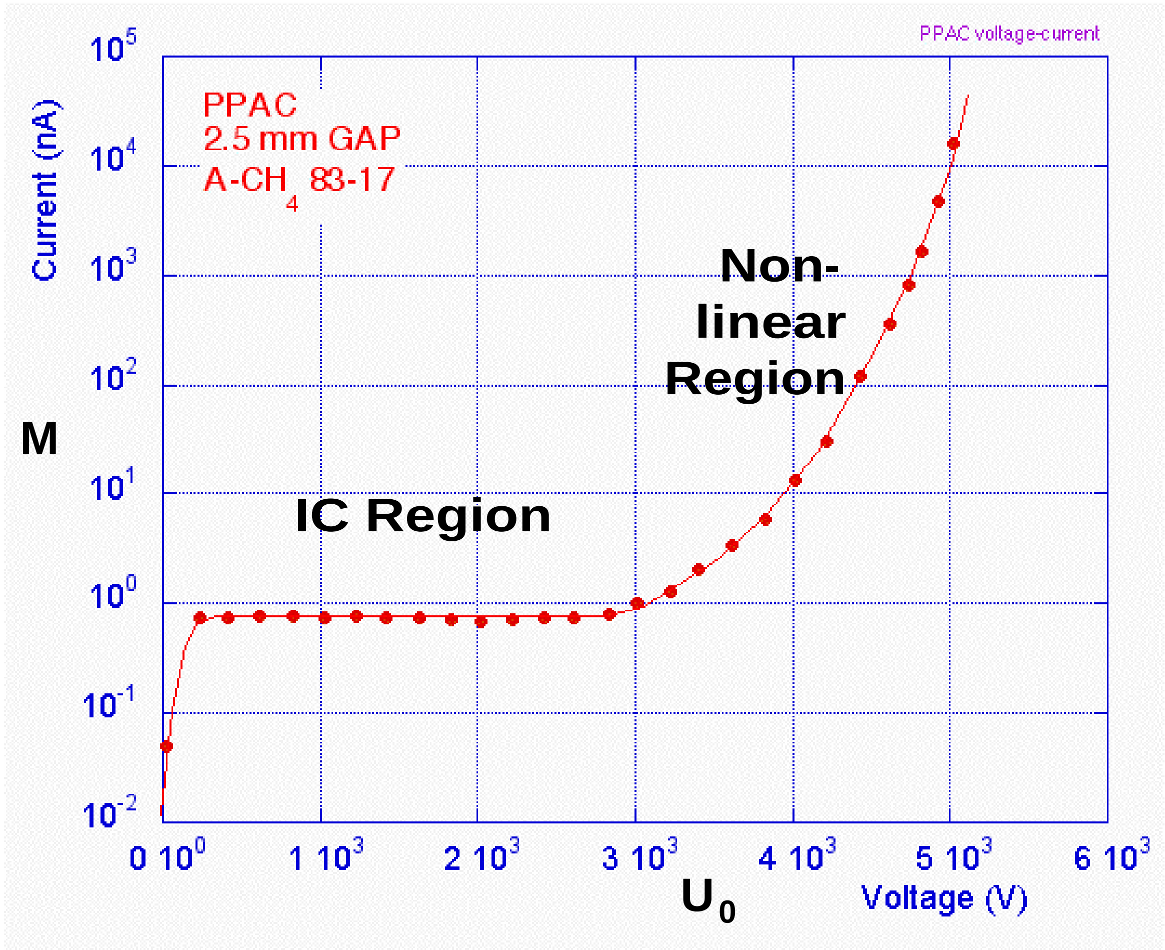


Size=dependent mall detection efficiencies of Ge detectors ≲ 10% →solution: bundle in 4π-arrays *GammaSphere, EuroBall, Tessa,...*

W. Udo Schröder

Townsend Gas Avalanche Amplification



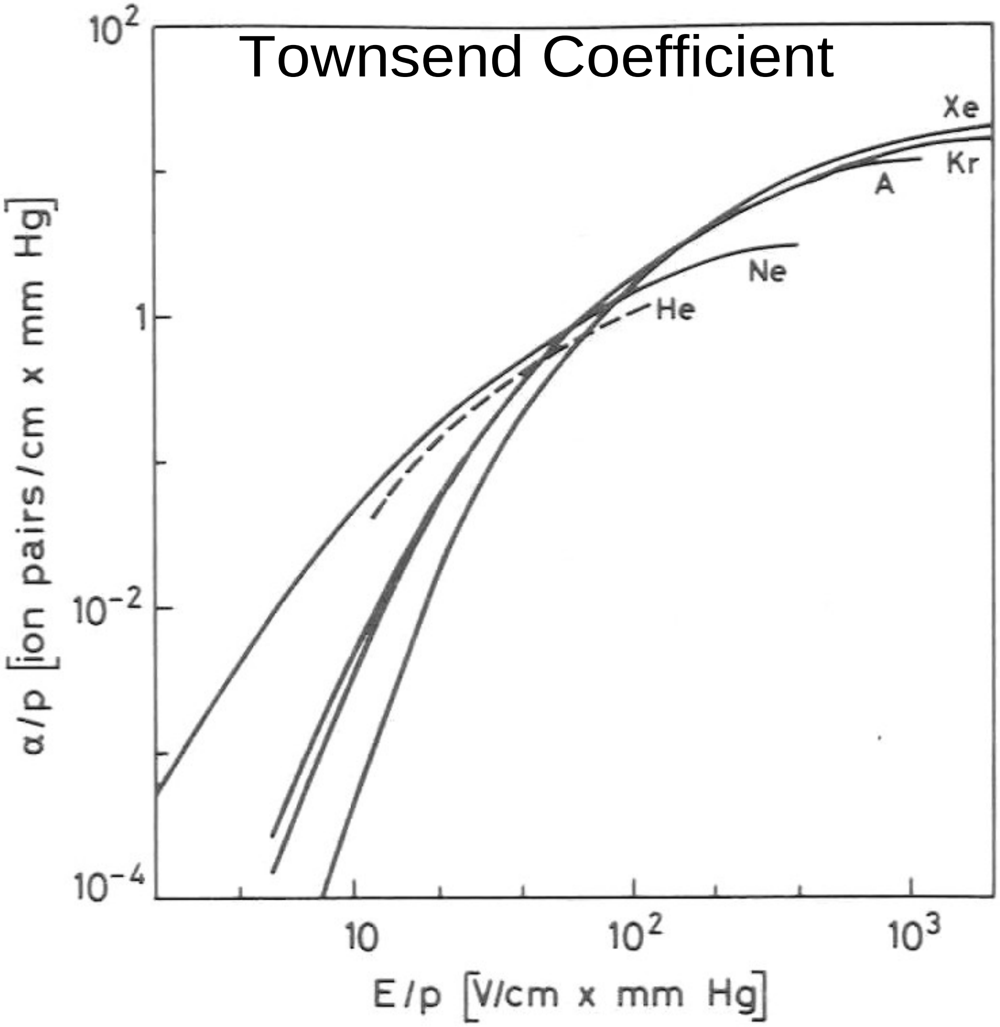


Amplification M

$$M = \frac{n}{n_{ip}} \propto \frac{1}{n_{ip}} \int i(t)dt \; ; \quad n_{ip} = primary\ IP$$

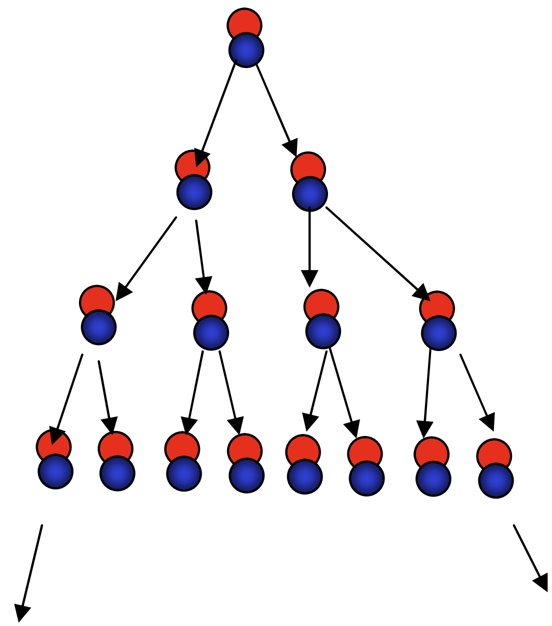
$$\alpha := (\ell n M)/d \quad 1. Townsend\ coefficient$$

Avalanche Formation



Electrons in outer shells are more readily removed, ionization energies are smaller for heavier elements.

Electron-ion pairs through gas ionization

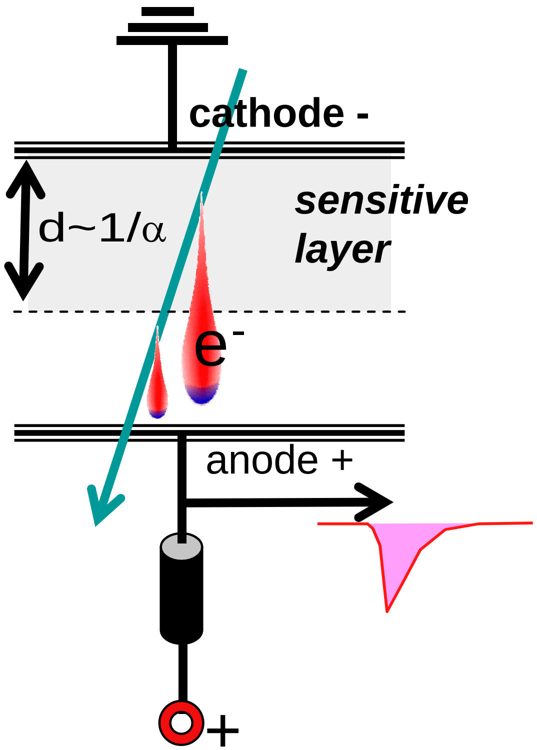


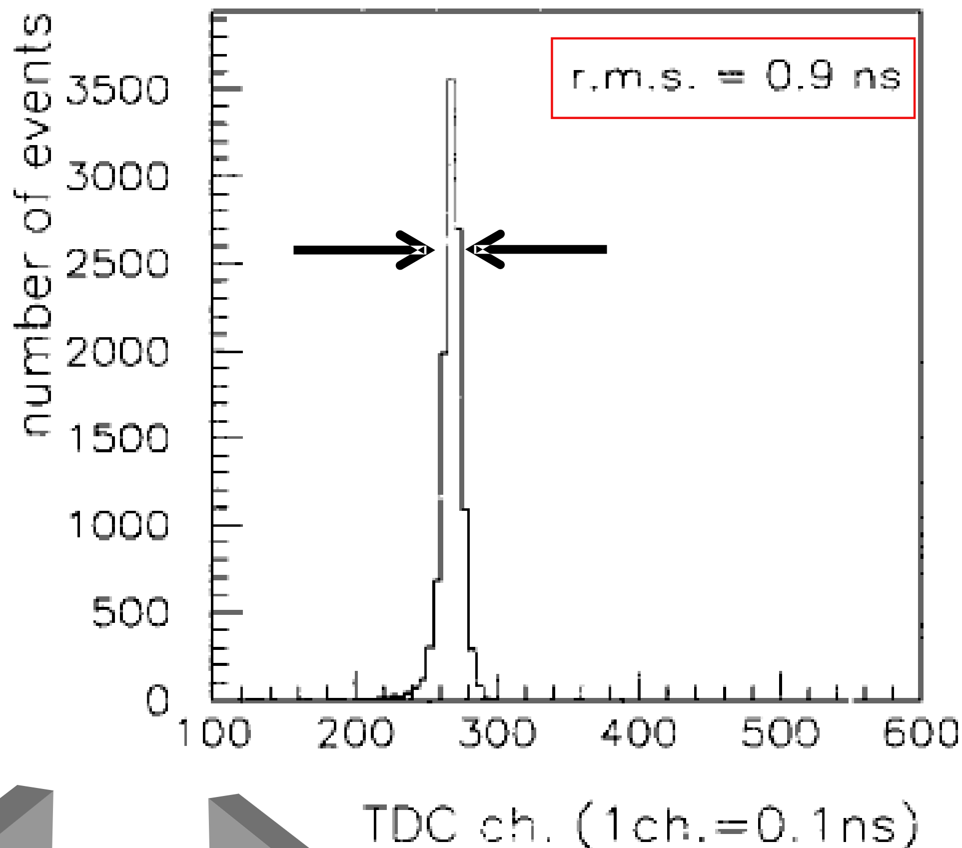
$$dn = \alpha \cdot n \cdot dx$$

$$n(x) = n_0 \cdot e^{\alpha \cdot x} \quad for \ \alpha = const$$

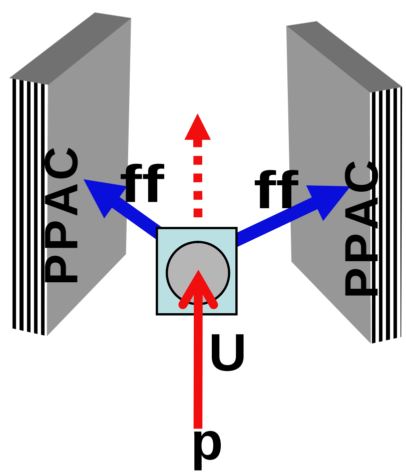
$$n(x) = n_0 \cdot \exp\left\{ \int_0^x \alpha(x')dx' \right\}$$

Parallel Plate Counters: t-Resolution





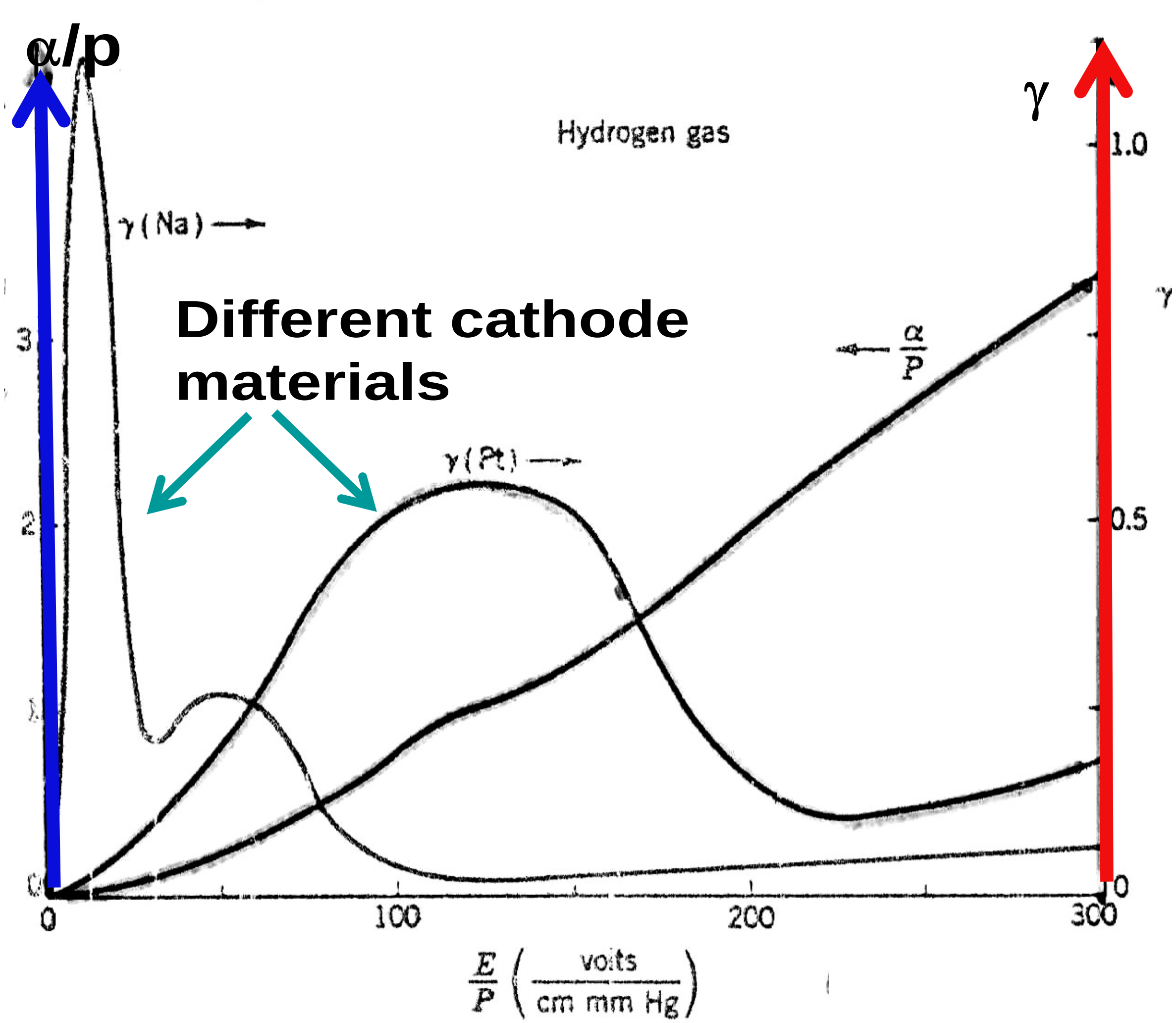
Charges produced at different positions along the particle track are differently amplified.
→ non-linearity $n_{ip}(\Delta E)$



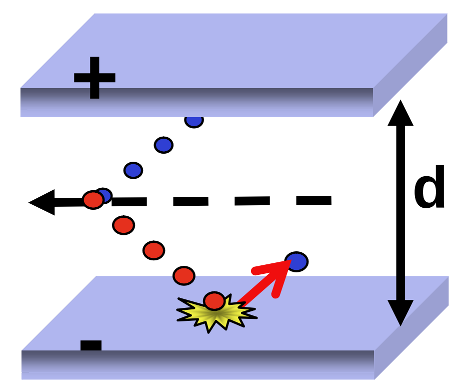
PPACs used where time resolution important, U(p,f)f

W. Udo Schröder

Sparking and Spark Counters



Impact ionization Probability γ



Amplification by impact ionization

$$M = \frac{n}{n_0} = \frac{e^{\alpha \cdot d}}{1 - \gamma \cdot \left[e^{\alpha \cdot d} - 1 \right]}$$

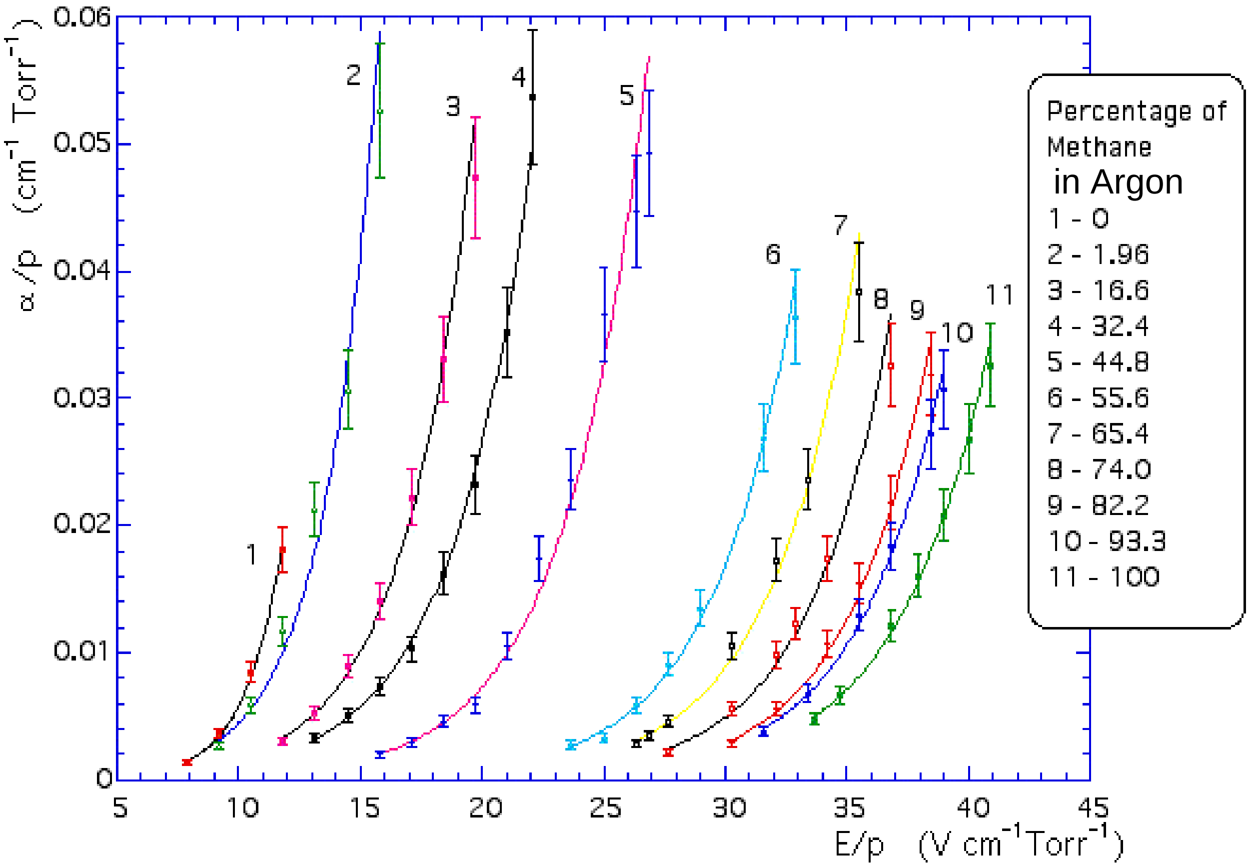
$$Sparking: \gamma \cdot e^{\alpha \cdot d} \approx 1$$

$$p \sim (10^{-1} - 10^{-3})\, Torr$$

Prevent spark by reducing λ for ions: collisions with large organic molecules
→ **quenching**

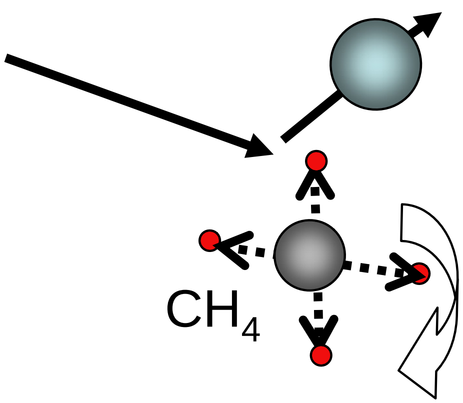
Avalanche Quenching

A. Sharma and F. Sauli, Nucl. Instr. and Meth. A334(1993)420



Reduce λ and energy of ions by collisions with complex organic molecules (CH4, ...).

Excitation of rotations and vibrations already at low ion energies



Organic vapors = “self quenching”

W. Udo Schröder

Effective Ionization Energies

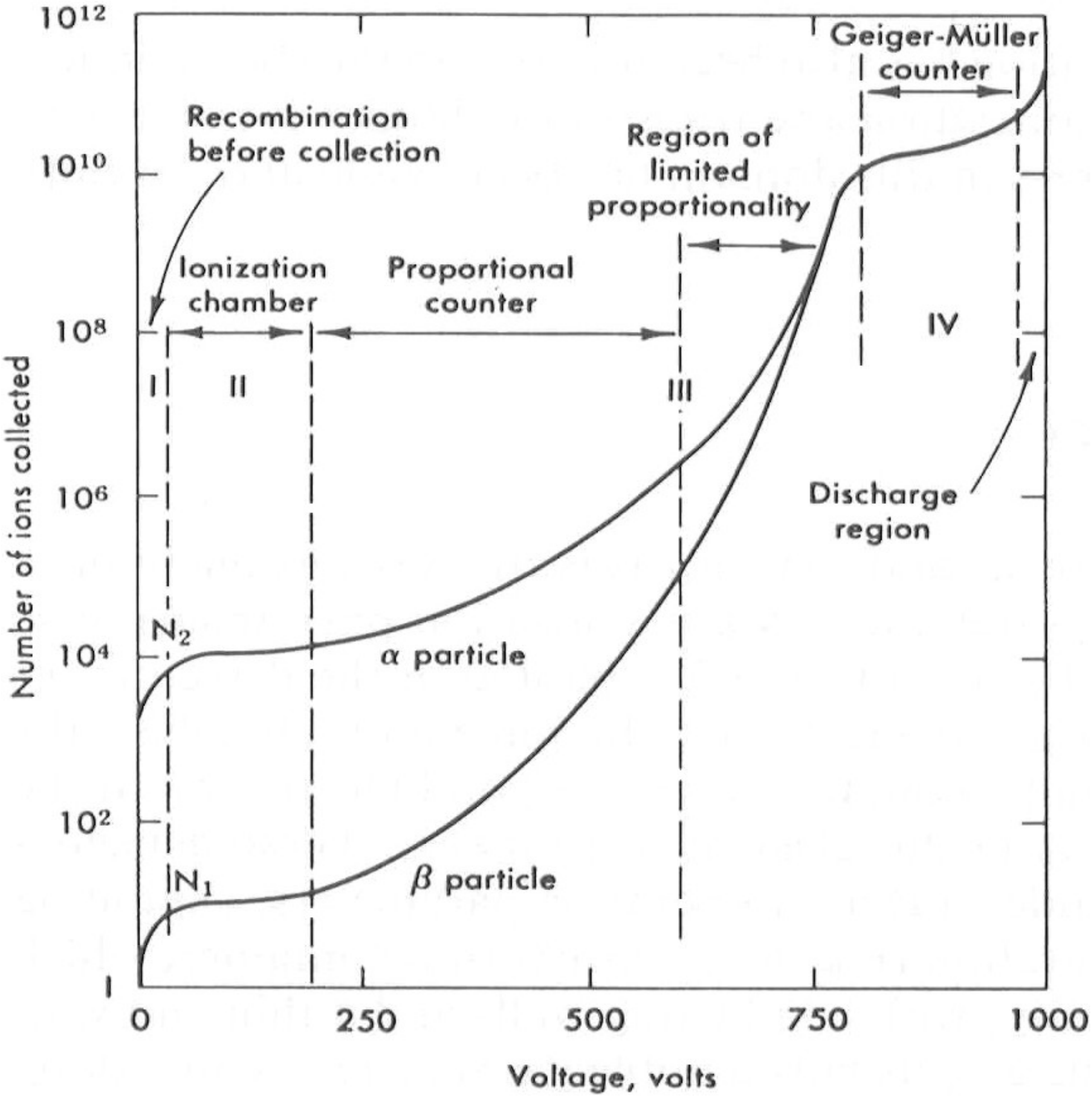
Excitation and ionization characteristics of various gases

	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

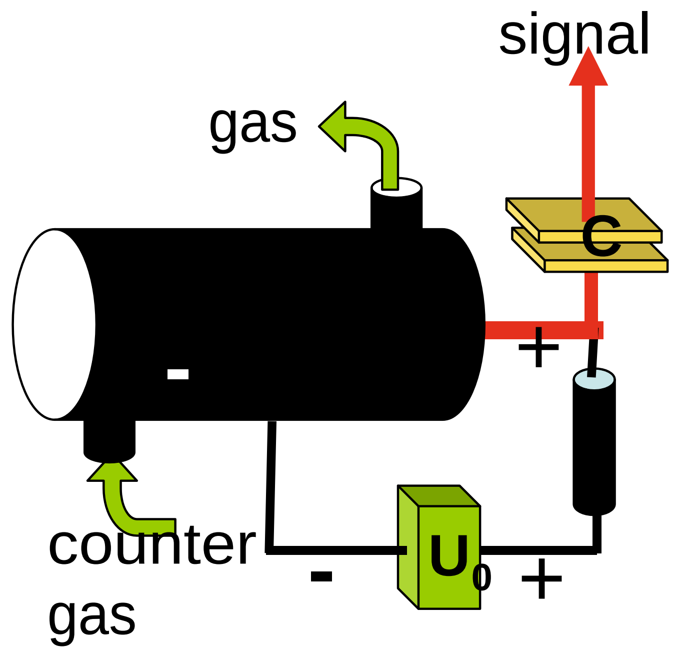
Mean energy per ion pair larger than IP because of excitations

Large organic molecules have low-lying excited rotational states → excitation without ionization through collisions → quenching additives

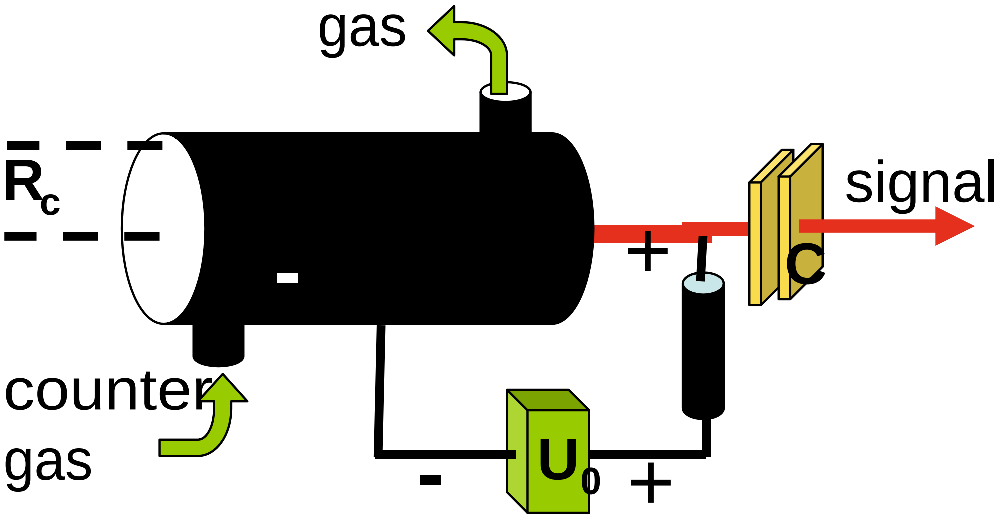
Amplification Counters



Single-wire gas counter



Proportional Counter

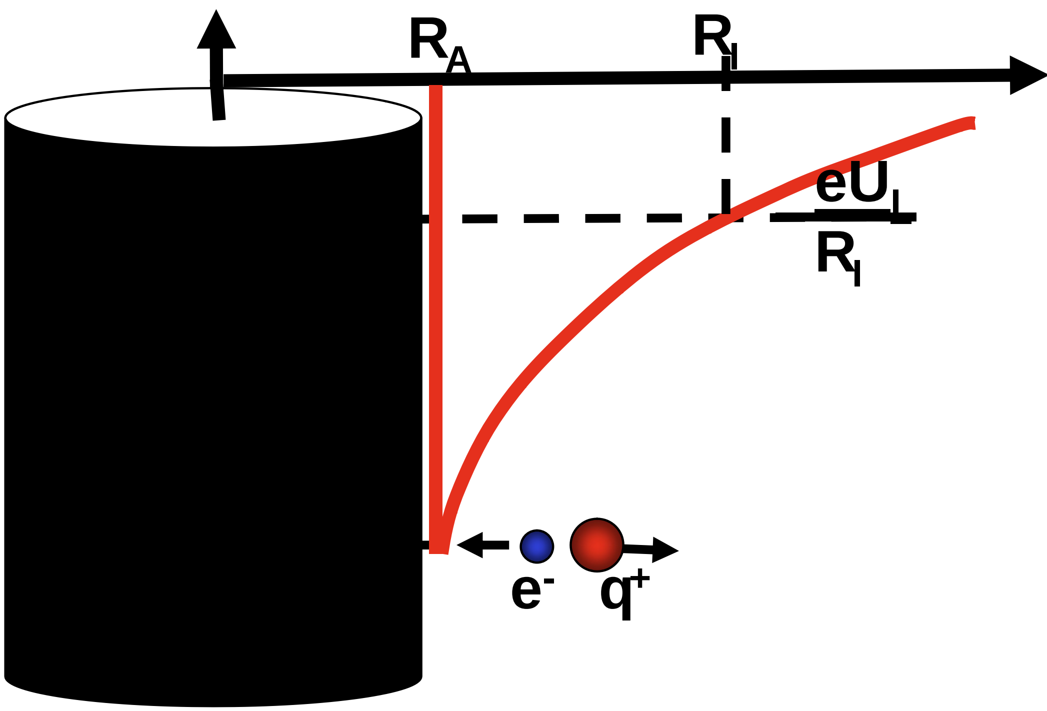


Anode wire: small radius
$R_A \approx 50\ \mu m$ or less

Voltage $U_0 \approx (300\text{-}500)$ V

Field at r from wire

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

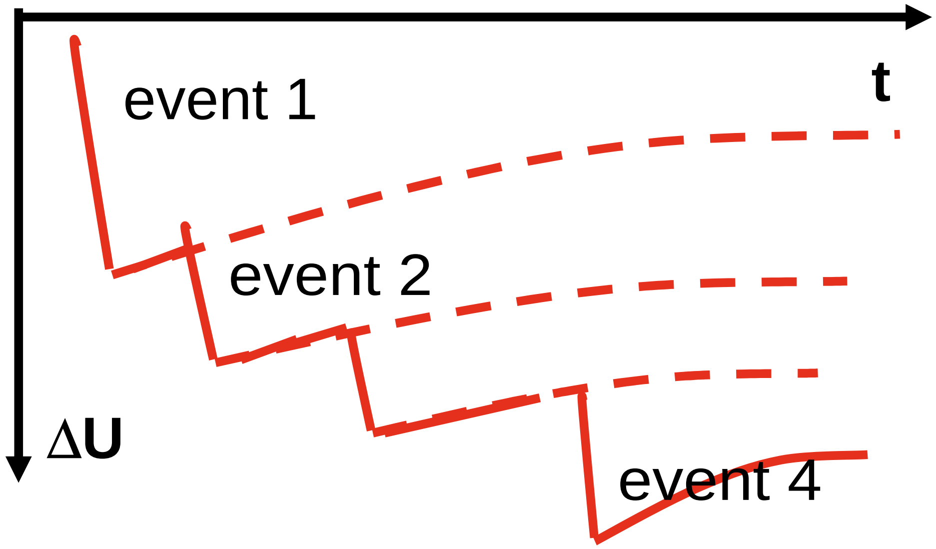


Avalanche $R_I \rightarrow R_A$, several mean free paths needed

Pulse height mainly due to positive ions (q^+)

W. Udo Schröder

Pulse Shape

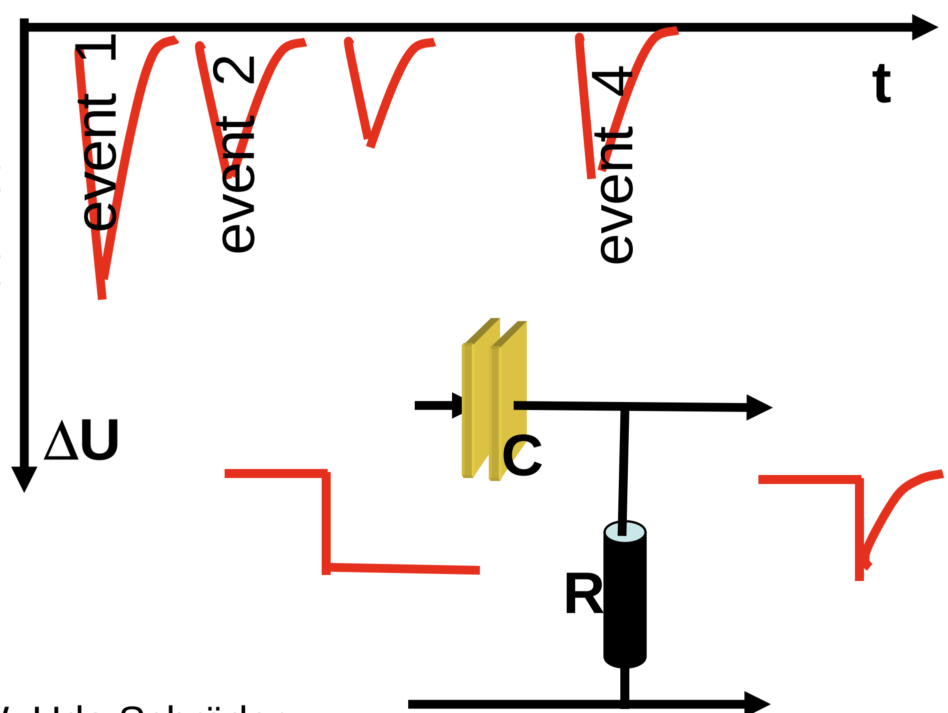


$$Pulse\ shape: time\ t,\ \ wire\,length\ L$$

$$\Delta U(t) \propto \frac{-q}{4\pi\varepsilon L} \cdot \ln(1+\frac{t}{t_0})$$

$$t_0 = \pi\varepsilon / \mu C U_0,\ \ mobility\ \ \mu = w_{drift} / E$$

$$\varepsilon = dielectric\ constant$$



long decay time of pulse → pulse pile up, summary information

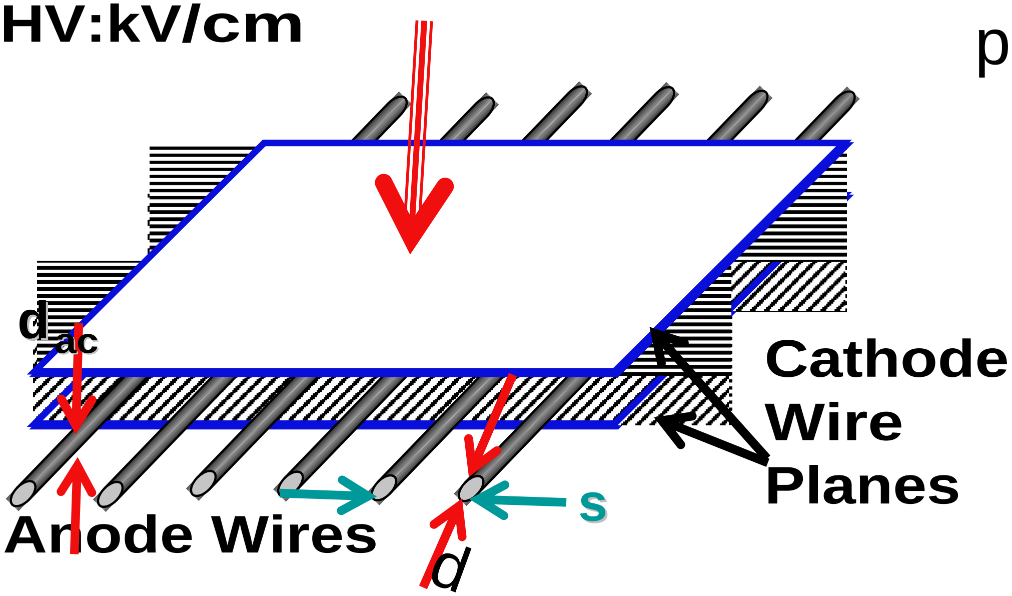
differentiate electronically, RC-circuitry in shaping amplifier, individual information for each event (=incoming particle)

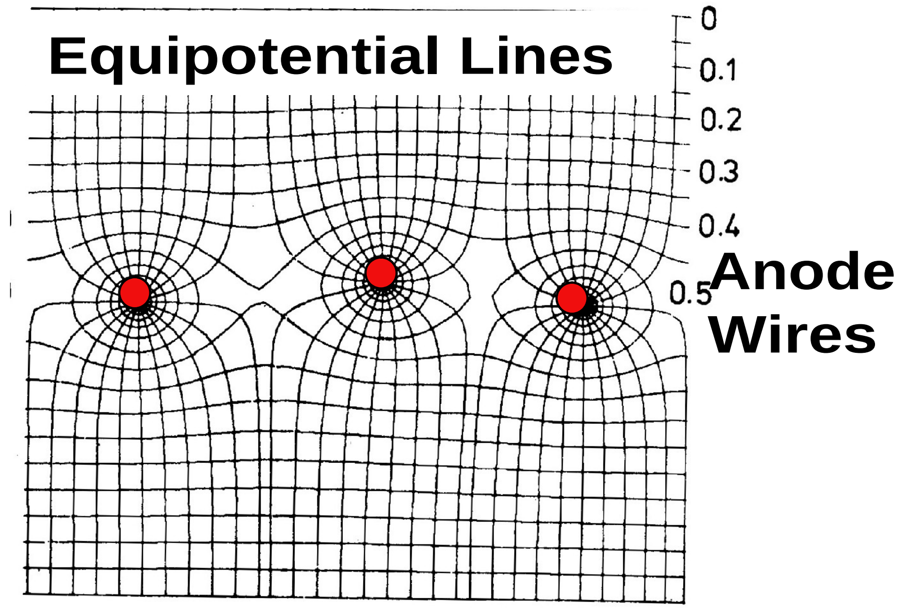
W. Udo Schröder

Multi-Wire Proportional Counters

Magic Gas: Ar(75%), iso-butane (24.5%), freon (0.5%) HV:kV/cm

(**Charpak 1968-80**) Important for detection of high-energy particles, beam profile,..





$$Field\ \ at\ (x,y) \succ (0,0)$$

$$V(x,y) = -U_0 \frac{C}{4\pi\varepsilon} \ln\left[4\left(\sin^2\frac{\pi}{s}x + \sinh^2\frac{\pi}{s}y\right)\right]$$

$$Capacitance\ C = \frac{2\pi\varepsilon}{\pi d_{ac}/s - \ln(\pi d/s)} \quad ;\ d_{ac} \gg s \gg d$$

Field strength close to anode wires:
$V(x,y) \propto 1/r$

The End