Modern Particle Detectors

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Summary of First Lecture

- Overview: old and new detectors
- Detection principles
- Interaction of charged particles with matter
  - Inelastic collisions with atomic electrons ⇨ ionization energy loss
  - Emission of Cherenkov radiation
  - Emission of Transition radiation
    - ⇨ unified treatment in **PAI model**
  - Emission of Bremsstrahlung
- Mean energy loss: Bethe formula and friends
- Energy loss distributions (straggling functions): Landau et al.

Plan of the Lecture

1. Introduction
2. Interaction of charged particles with matter
3. Ionization detectors
4. Position measurement and tracking
5. Photon detection
6. Calorimetry
7. Detector systems

3 Ionization Detectors

3.1 Detection of Ionization

Principle: collection of electrons and ions (holes) produced in detector medium by ionizing radiation

Detector material:

- gas ⇨ fast collection of e^- and ions, e.g. Ne, Ar
- liquid ⇨ higher density, e.g. liquid Ar
- solid ⇨ higher density, self-supporting, e.g. semiconductor

Setup:

- vessel with two electrodes and thin entrance window
- filled with active medium ⇨ creation of electron-ion (hole) pairs
- electric field between anode and cathode
  - separation of e^- and ions (holes), drift and diffusion
  - signal induction
  - collection at anode/cathode

3.2 Diffusion of Charge Carriers

Field-free gas: quick thermalization of charge carriers in collisions

⇨ Maxwell distribution of velocities (thermal equilibrium):

$$F(c)\mathrm{d}c = 4\pi n\left(\frac{m}{2\pi kT}\right)^{3/2} c\, e^{-mc^2/(2kT)}\mathrm{d}c \qquad \bar{c} = \sqrt{\frac{8kT}{\pi m}}$$

$$\overline{E}_{\mathrm{kin}} \equiv \varepsilon = \frac{m}{2}\overline{c^2} = \frac{3}{2}kT$$

Definition of temperature

Point-like charge cloud at t=0 ⇨ Distribution at time t?

Ansatz: $\mathbf{J} = -D\,\nabla n$

$\mathbf{J}$ = flux density
∇n = gradient of particle density
D = diffusion coefficient

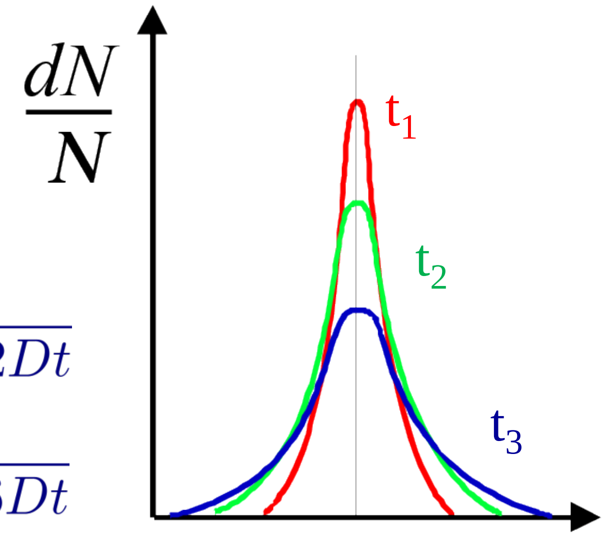
⇨ diffusion equation $\displaystyle \frac{\partial n}{\partial t} = D\,\Delta n$

Solution: Gaussian law

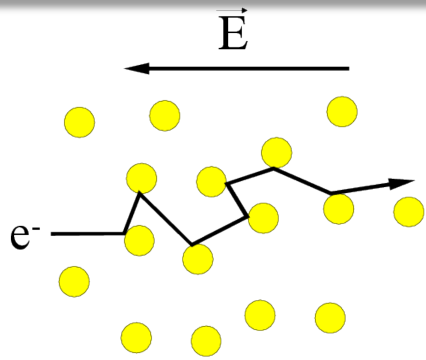
$$\frac{\mathrm{d}N}{N} = \frac{n\mathrm{d}z}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-z^2/4Dt}\mathrm{d}z$$

$$\sqrt{\langle z^2\rangle} \equiv \sigma_z = \sqrt{2Dt}$$

$$\sqrt{\langle r^2\rangle} \equiv \sigma_r = \sqrt{6Dt}$$



Drift of Charge Carriers



Microscopically:

External electric field ➪ acceleration

Collisions ➪ slowing down

Macroscopically: drift motion with drift velocity $\boldsymbol{u}$

Ansatz: Langevin equation

$$m\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = e\boldsymbol{E} + e(\boldsymbol{u} \times \boldsymbol{B}) - K\boldsymbol{u}$$

Ku = frictional force
$\tau = \frac{m}{K}$ = characteristic time

Solution for $t \gg \tau$: steady state for which $\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = 0$

$$\boldsymbol{u} = \frac{e}{m}\tau\,|\boldsymbol{E}|\,\frac{1}{1+\omega^2\tau^2}\left[\hat{\boldsymbol{E}} + \omega\tau\left(\hat{\boldsymbol{E}} \times \hat{\boldsymbol{B}}\right) + \omega^2\tau^2\left(\hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{B}}\right)\hat{\boldsymbol{B}}\right]$$

$\omega = \frac{eB}{m}$ = cyclotron frequency

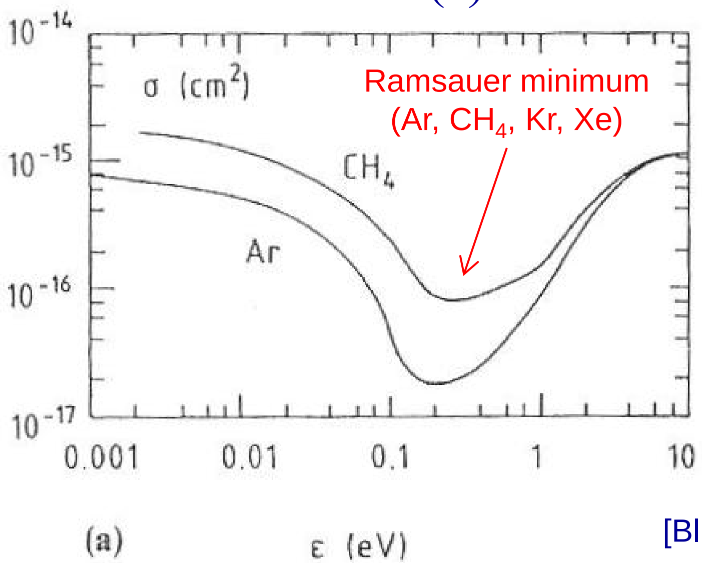
➪ Drift velocity $\boldsymbol{u}$ dominated by dimensionless parameter $\omega\tau$

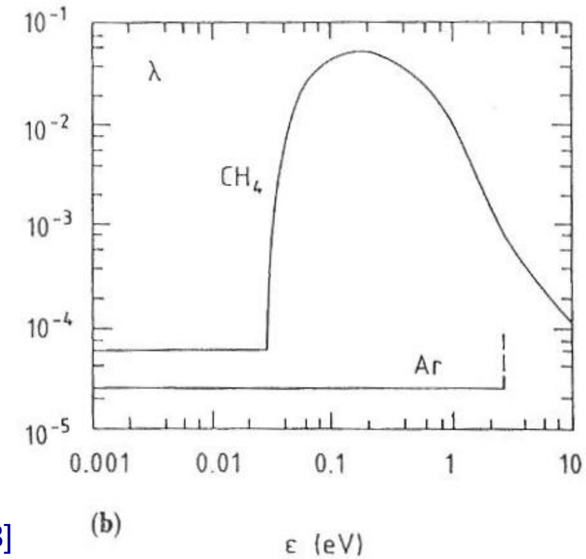
Drift of Electrons

- rapid acceleration in electric field
- small energy loss in elastic collisions with atoms
- e⁻ momentum randomized in collisions
- energy gain in electric field is mainly in random motion >> thermal energy

⇨ drift velocity $$u^2 = \frac{eE}{mn\sigma}\sqrt{\frac{\Lambda}{2}} \ll c^2 = \frac{eE}{mn\sigma}\sqrt{\frac{2}{\Lambda}}$$ average velocity

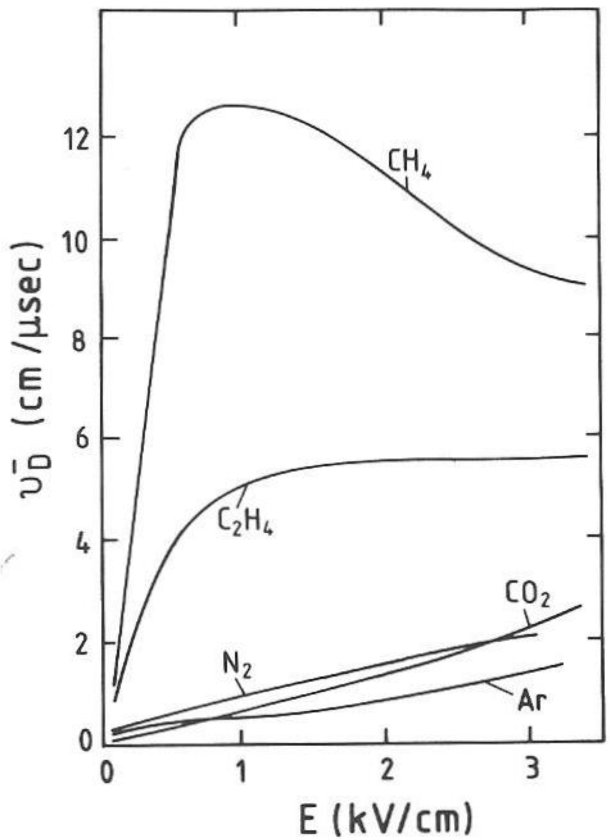
$\Lambda = \Lambda(\varepsilon)$ average fractional energy loss per collision
$\sigma = \sigma(\varepsilon)$ collision cross section

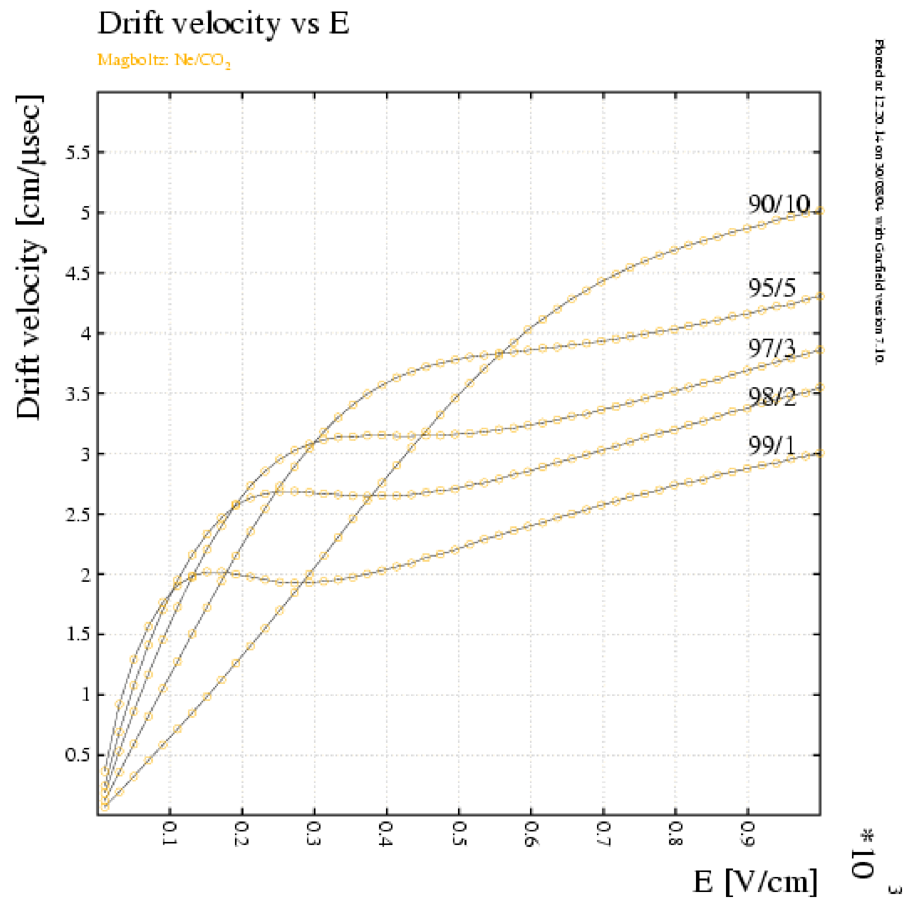




[Blum,Rolandi, Springer, 1993]

Drift Velocity of Electrons





Ne/CO_2 Mixtures

3.3 Gas Amplification

Increase electric field in gaseous detector up to several kV/cm

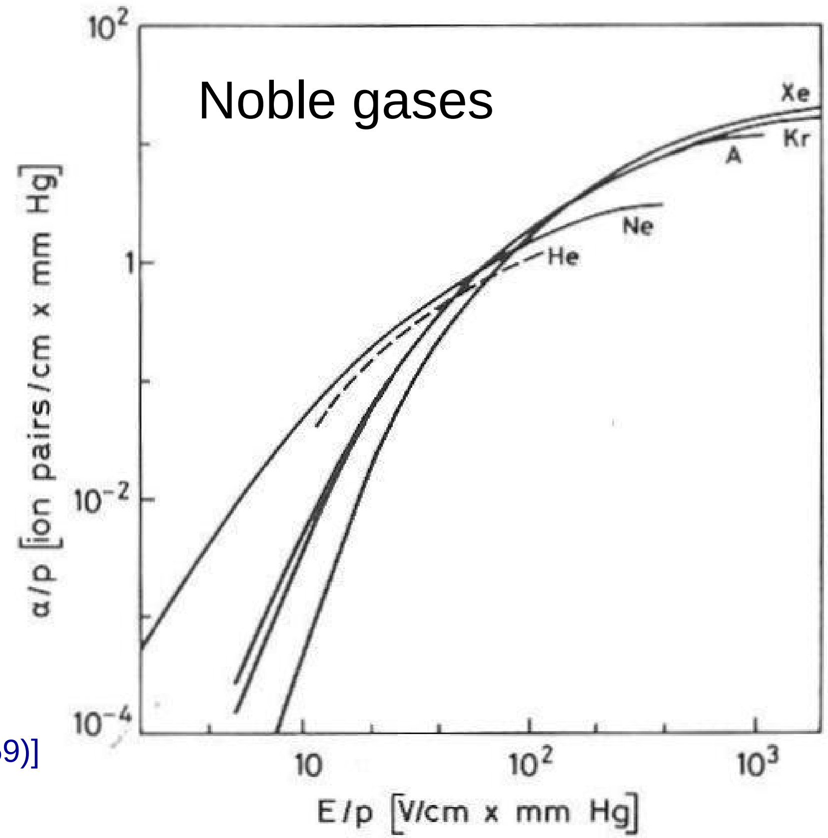
⇨electrons gain sufficient energy between collisions to ionize gas molecules

⇨avalanche generation

Probability of ionization per unit path length: 1. Townsend coefficient

$$\alpha = \frac{1}{\lambda_{\mathrm{ion}}} = n\sigma_{\mathrm{ion}}$$

λ_{ion} = mean free path for sec. ionizing collision
σ_{ion} = cross section for ionizing collision
n = density of gas molecules



Homogeneous electric field:

$$\mathrm{d}N = N\alpha\,\mathrm{d}x \Rightarrow N = N_0 e^{\alpha x}$$

Gain: $$G = \frac{N}{N_0} = e^{\alpha x}$$

[S.C. Brown, Basic Data of Plasma Physics, MIT Press (1959)]

Fluctuations of Gain

Proportional counter: average number of electrons ∝ initial electrons N_i

Random nature of multiplication process ⇨ fluctuations

Assumption: each initiating electron develops its own small avalanche, independent of presence of other electrons nearby

$$N = n_1 + n_2 + n_3 + \cdots + n_k$$

Probability distribution of number N of total electrons
$=$ sum over probability distributions $P(n)$ of number of electrons n in individual small avalanches (mean $\bar{n}$, variance σ^2)

If number k of initiating electrons large ⇨ central limit theorem

$$F(N) = \frac{1}{S\sqrt{2\pi}} \exp[(N - \bar{N})^2/2S^2] \quad \text{with} \quad \bar{N} = k\bar{n} \quad \text{and} \quad S^2 = k\sigma^2$$

Fluctuations of Gain

- Exact shape of $P(n)$ not needed if k large
- Often: detection of single electrons important, e.g. drift chambers, PMT

  ⇨ $P(n)$ particularly interesting

Avalanche distribution in weak fields: Yule-Furry law

$$P(n,s) = \frac{1}{\bar{n}(s)} \, e^{-\frac{n}{\bar{n}(s)}} \qquad \text{and} \qquad \sigma(s) = \bar{n}(s) \qquad \text{(s = drift coordinate)}$$

- i.e. a purely exponential distribution with small signals being most probable!
- R.m.s. width is equal to the mean

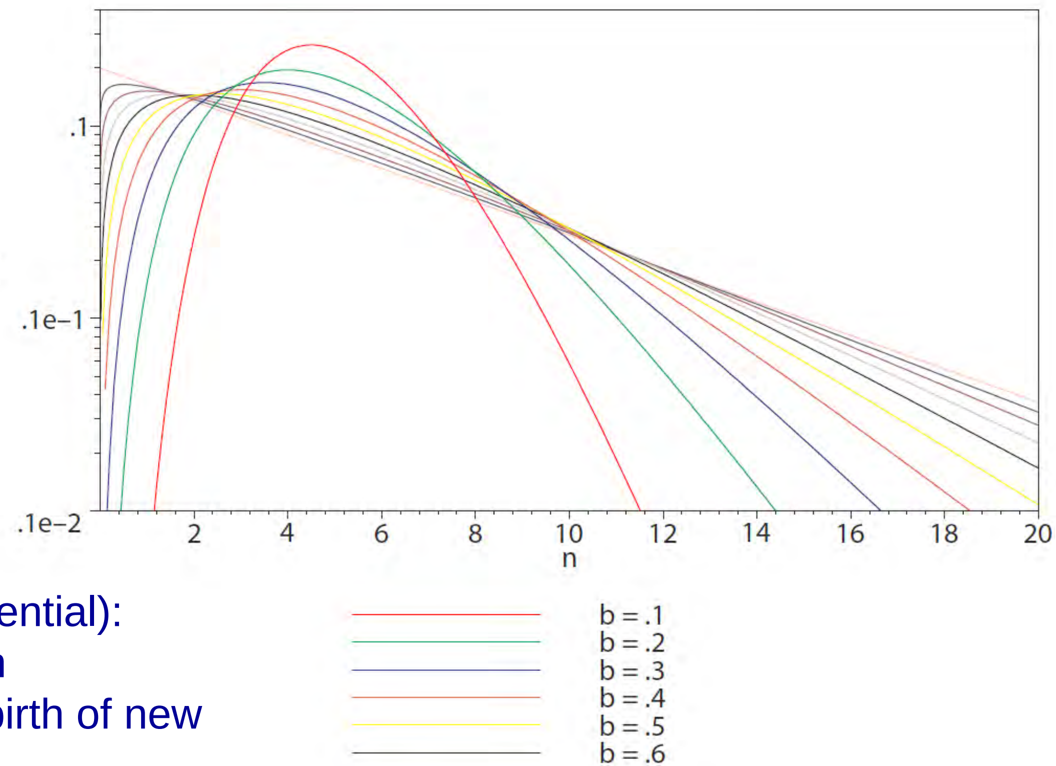
Fluctuations of Gain

Avalanche distribution in strong fields:

- Different distributions in literature: Legler et al., …
- Often used as good approximation: Polya distribution

$$P(n) = \frac{1}{b\bar{n}} \frac{1}{k!} \left(\frac{n}{b\bar{n}} \right)^{k} e^{-n/b\bar{n}}$$

$$k = \frac{1}{b} - 1$$



- b=1 ⇨ Furry distribution (single exponential): Probability for birth of new e^- prop. to n
- b=0 ⇨ Poisson distribution: Prob. for birth of new e^- indep. of n

Energy Resolution

Assume statistically independent sources of fluctuations:

- k ionization electrons, $\langle k \rangle = N_i$, $\sigma_i = \sqrt{F \cdot N_i}$ (F Fano factor)
- each ionization electron creates an avalanche of size n_j,

$$\langle n \rangle = \frac{1}{N_i} \sum_{j=1}^{N_i} n_j \ , \qquad \sigma_{\bar{n}}^2 = \frac{1}{N_i} \sigma_n^2$$

⇨ signal amplitude

$$S = \sum_{j=1}^{N_i} n_j = N_i \cdot \bar{n}$$

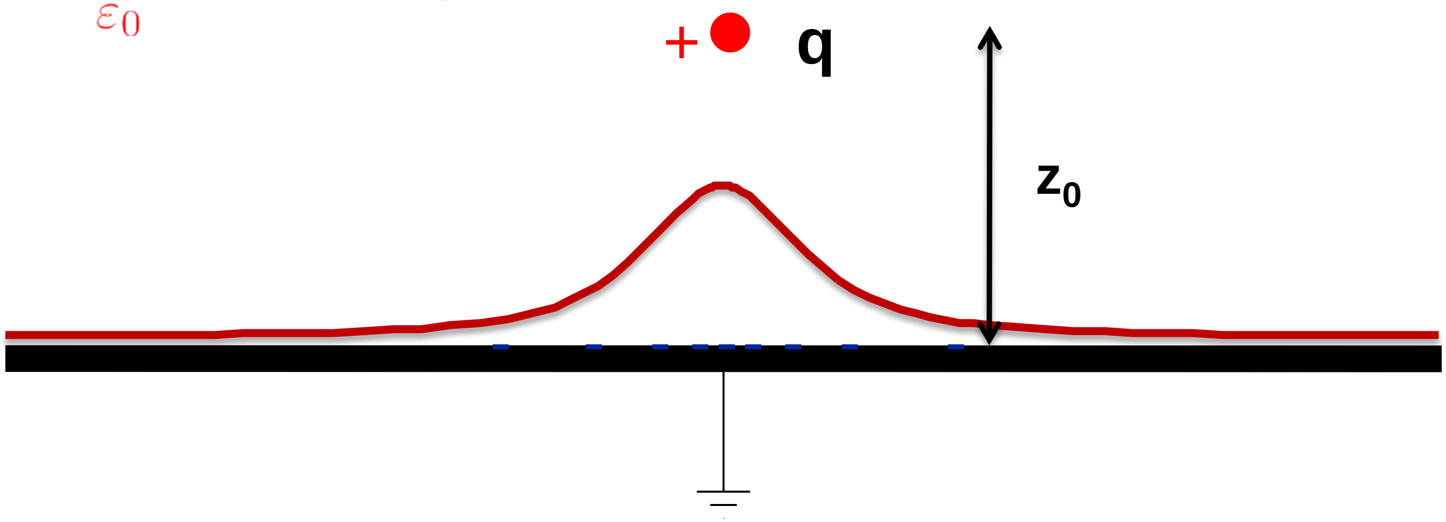
signal fluctuations

$$\left(\frac{\sigma_S}{S}\right)^2 = \left(\frac{\sigma_i}{N_i}\right)^2 + \left(\frac{\sigma_{\overline{n}}}{\overline{n}}\right)^2 = \left(\frac{\sigma_i}{N_i}\right)^2 + \frac{1}{N_i}\left(\frac{\sigma_n}{\overline{n}}\right)^2$$

Consider charge q above a grounded electrode

- electric field is perpendicular to conductor at the surface
- changes take place only on surface
- surface charge density σ and electric field E on the surface are related by Gauss' law

$$EA = \frac{1}{\varepsilon_0}\sigma A \Rightarrow \sigma = \varepsilon_0 E$$



Signal Formation

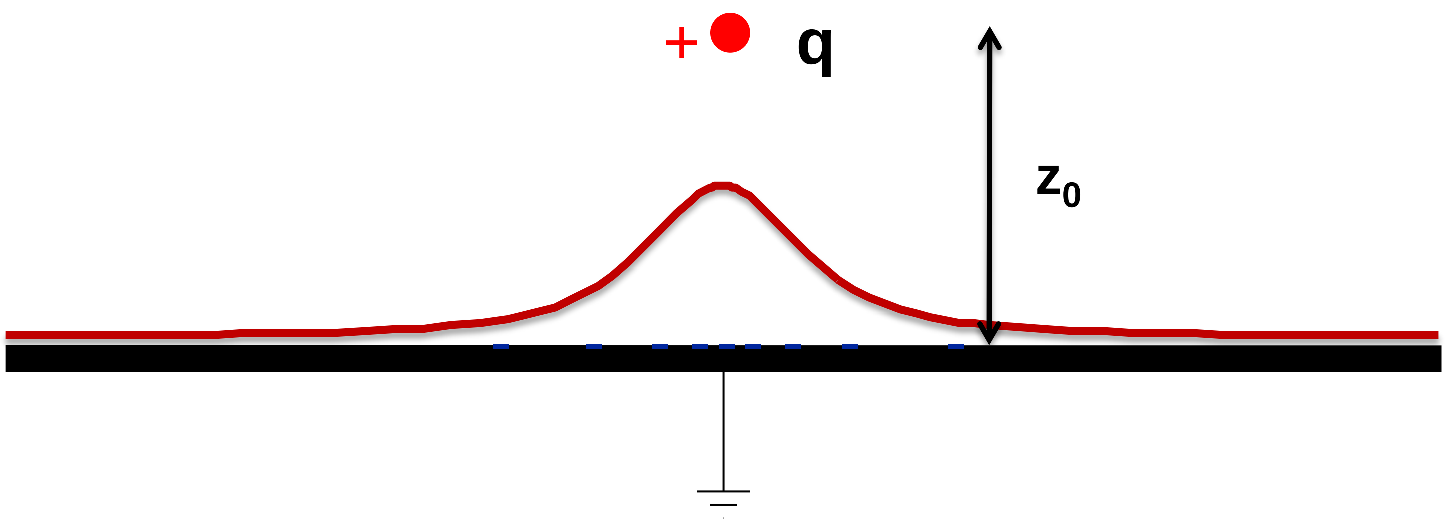
In order to find the charge induced on an electrode, we have to

a) solve the Poisson equation with boundary condition $\phi = 0$ on the conductor surface

$$\Delta\varphi = -\frac{\rho}{\varepsilon_0}, \quad \mathbf{E} = -\boldsymbol{\nabla}\varphi$$

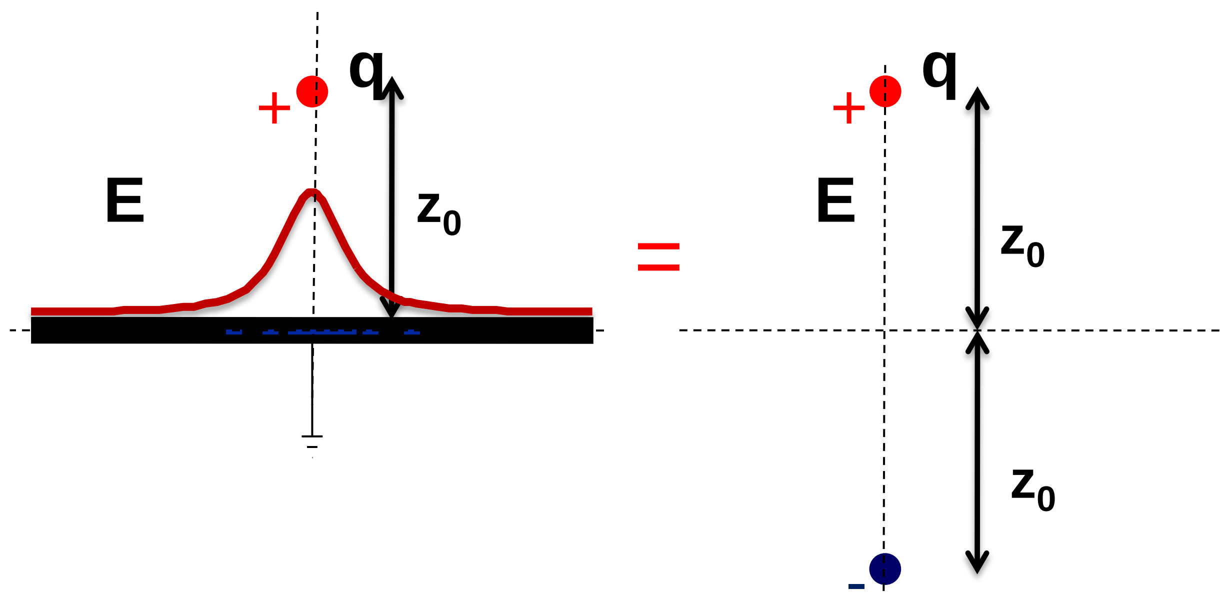
b) calculate the electric field E on the surface of the conductor

c) integrate $\varepsilon_0 E$ over the surface of the electrode



For this particularly simple setup with one electrode

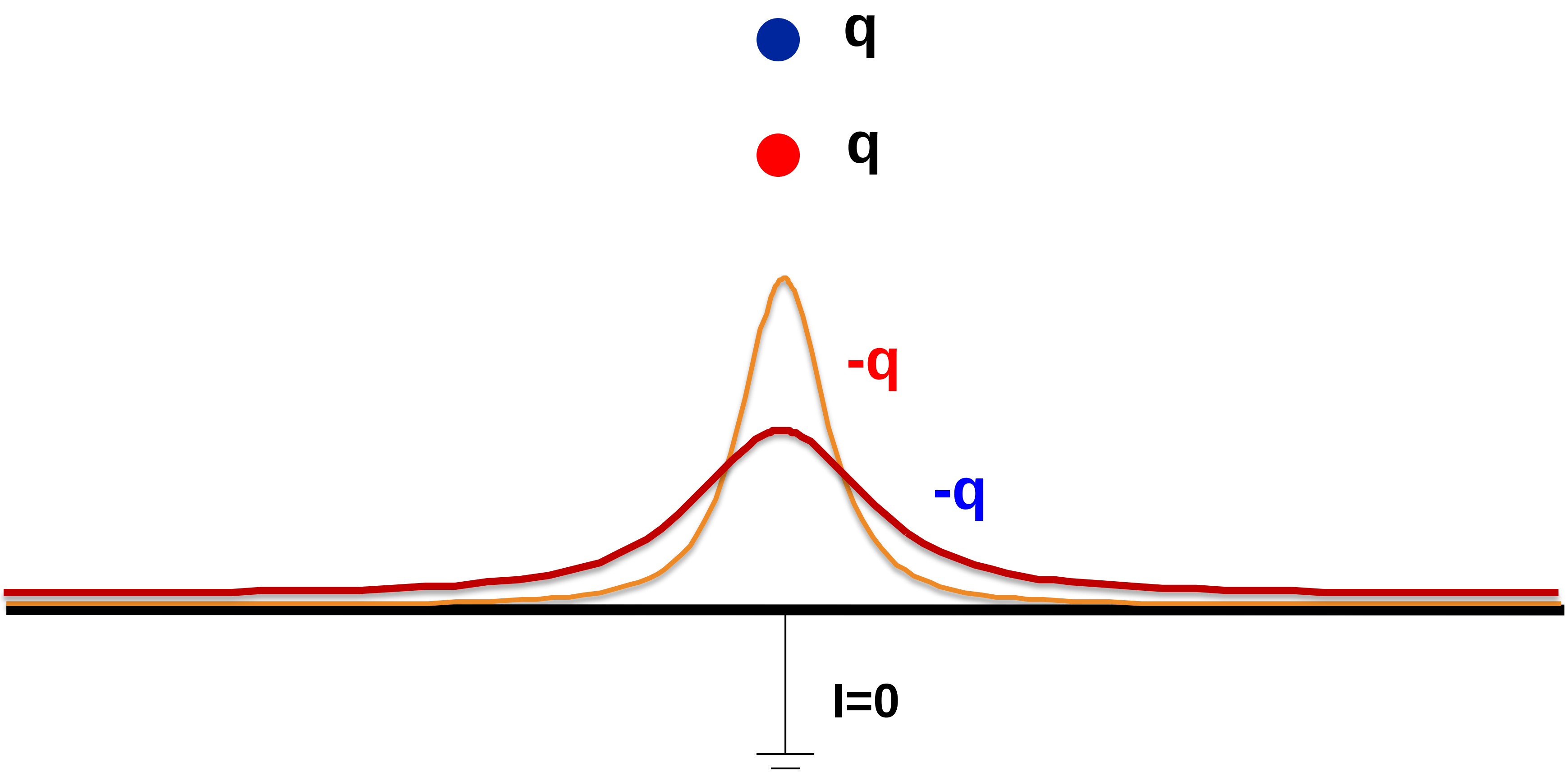
⇨ use mirror charge



Signal Formation

Movement of charge q (no external field needed!)

⇨ change of induced surface charge on electrode

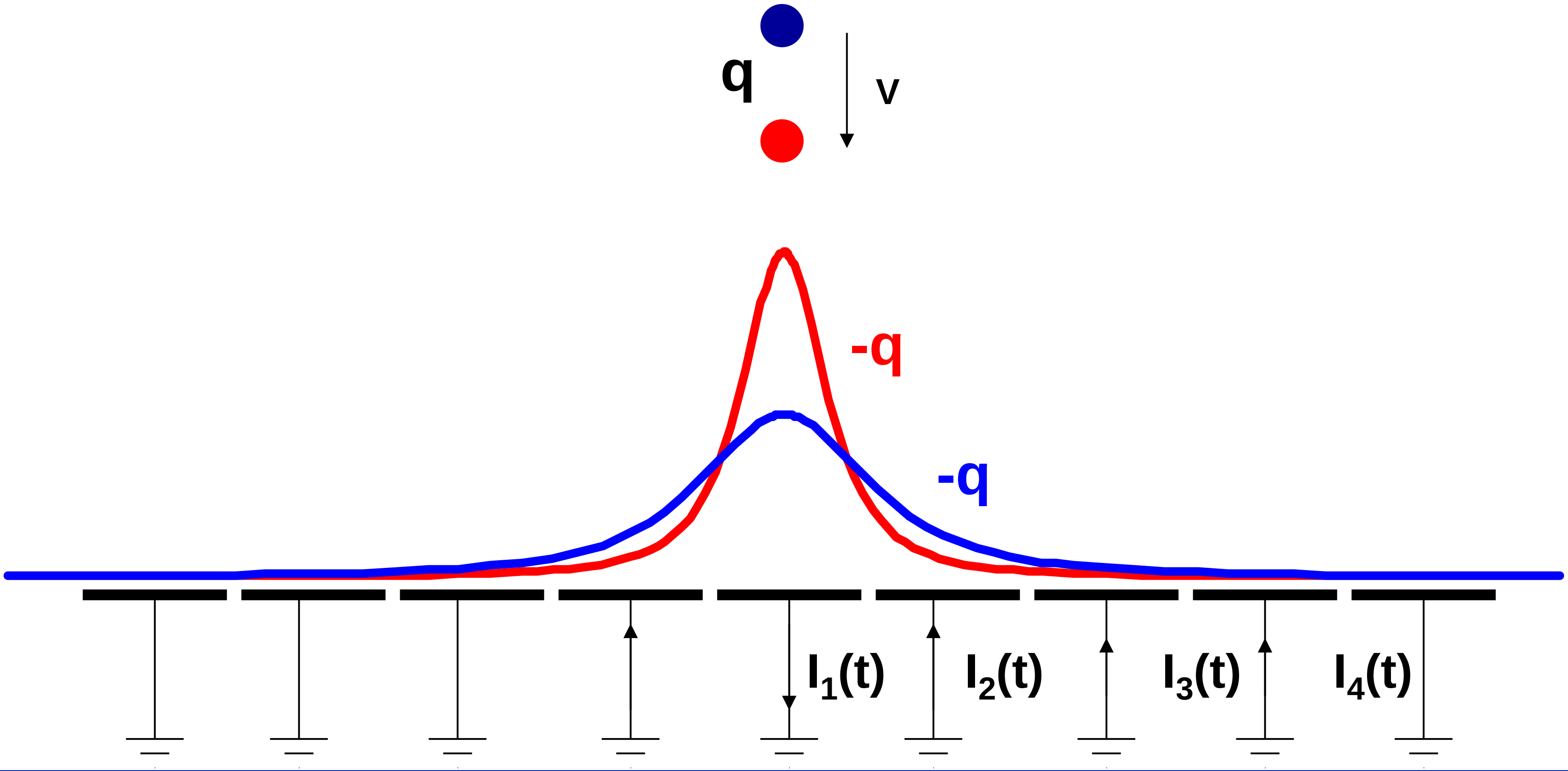


Signal Formation

Movement of charge q (no external field needed!)

⇨ change of induced surface charge on electrode

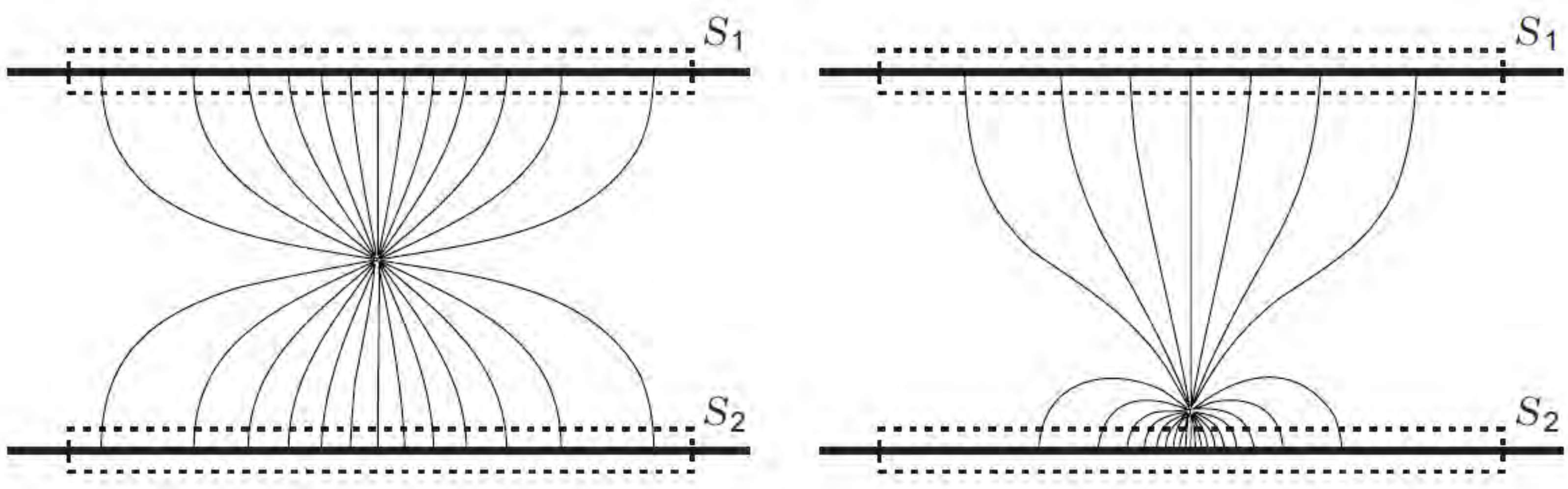
⇨ current on segmented electrodes



Signal Formation

How to calculate the induced signal?

- solve Poisson equation with moving charge
- use mirror charges to get rid of electrodes
- use Ramo-Shockley theorem



[H. Spieler, Semiconductor detector systems, Oxford, 2005]

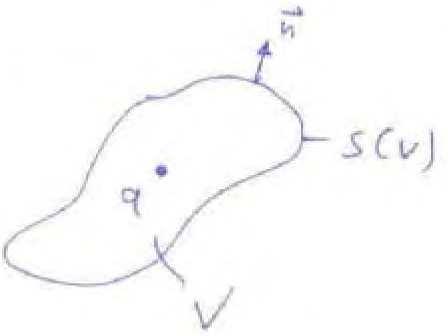
Ramo-Shockley Theorem

[W. Shockley, J. Appl. Phys. 9, 635 (1938), S. Ramo, Proc. IRE 27, 584 (1939)]

Calculation of signals induced on grounded electrodes:

- Gauss' Law: point charge inside closed surface

$$\oint \mathbf{E}\cdot\mathbf{n}\,\mathrm{d}a = \frac{1}{\varepsilon_0}\int_V \rho(\mathbf{x})\,\mathrm{d}^3x$$



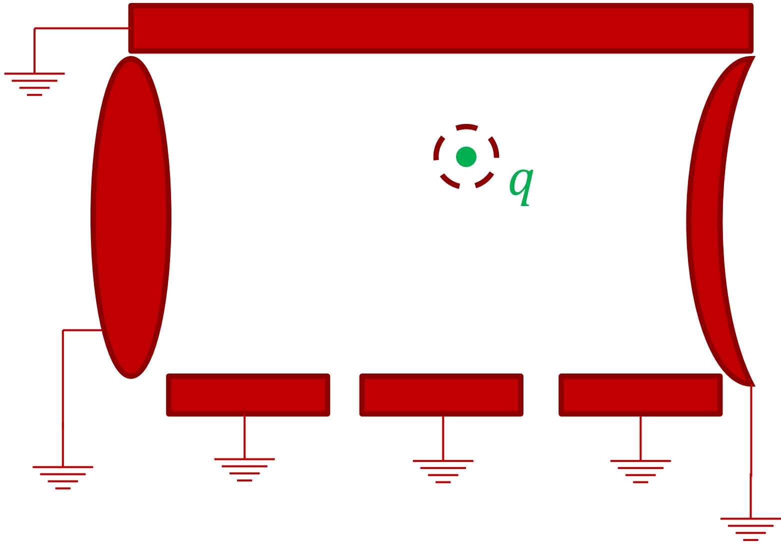
- Green's 2nd theorem:

$$\int_V \left(\phi\Delta\psi - \psi\Delta\phi\right)\mathrm{d}^3x = \oint_S \left(\phi\frac{\partial\psi}{\partial n} - \psi\frac{\partial\phi}{\partial n}\right)\mathrm{d}a$$

with $\dfrac{\partial\phi}{\partial n} \equiv \boldsymbol{\nabla}\phi\cdot\mathbf{n}\,[= -\mathbf{E}\cdot\mathbf{n}]$

Consider detector volume delimited by grounded electrodes:

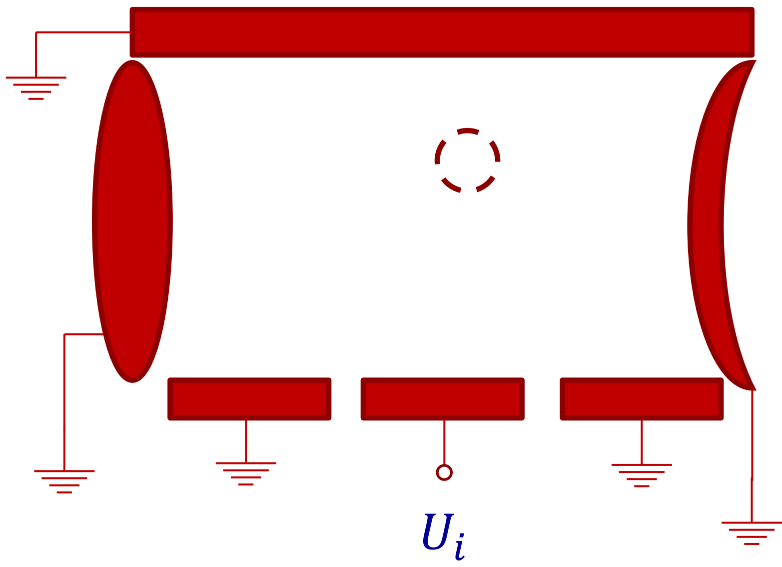
- Real situation: charge q at position $\boldsymbol{x}_0$, all electrodes grounded, i.e. $U_i = 0, i = 1,2, \ldots$ ⇨ solution $\phi(\boldsymbol{x})$



Consider detector volume delimited by grounded electrodes:

- Real situation: charge q at position $\boldsymbol{x}_0$, all electrodes grounded, i.e. $U_i = 0, i = 1,2, \ldots$ ⇨ solution $\phi(\boldsymbol{x})$
- Auxiliary situations: charge q removed, all electrodes grounded except electrode i, i.e.

  $U_j = 0, j \neq i$ ⇨ solutions $\phi_i(\boldsymbol{x})$ with
  $\phi_i(\boldsymbol{x}) = U_i$ at surface of electrode i

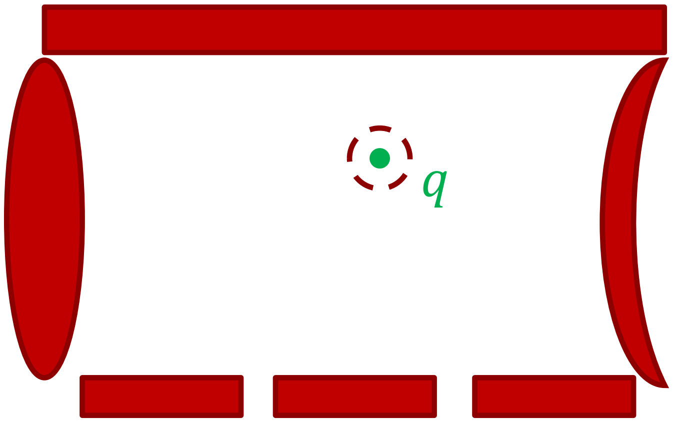


Space between electrodes and charge q free of charges

$$\Rightarrow \Delta\phi(\mathbf{x}) = 0$$
$$\Delta\phi_i(\mathbf{x}) = 0$$

Ramo-Shockley Theorem

Apply Green's 2nd theorem to volume V delimited by $S(V)$:



$$\underbrace{\int_V \left(\phi \Delta \phi_i - \phi_i \Delta \phi\right) \mathrm{d}^3 x}_{=0} = \oint_{S(V)} \left(\phi \frac{\partial \phi_i}{\partial n} - \phi_i \frac{\partial \phi}{\partial n}\right) \mathrm{d}a$$

for every i

Solve surface integral by splitting it up into 3 parts

Ramo-Shockley Theorem

$$\Rightarrow Q_i = -q\frac{\phi_i(\mathbf{x}_0)}{U_i}$$

induced charge on electrode i by charge q at position x_0 when all electrodes are grounded

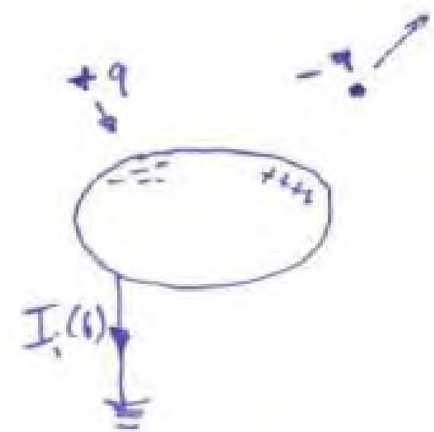
$\phi_i(x_0) =$ potential at point x_0 when point charge q is removed, electrode i is put to potential U_i and all other electrodes are grounded

weighting potential of electrode i

Point charge moving along trajectory $x_0(t)$

⇨ time-dependent induced charge on electrode i

⇨ current $$I_i(t) = -\frac{\mathrm{d}Q_i(t)}{\mathrm{d}t}$$



Sign convention: positive current points away from electrode

Ramo-Shockley Theorem

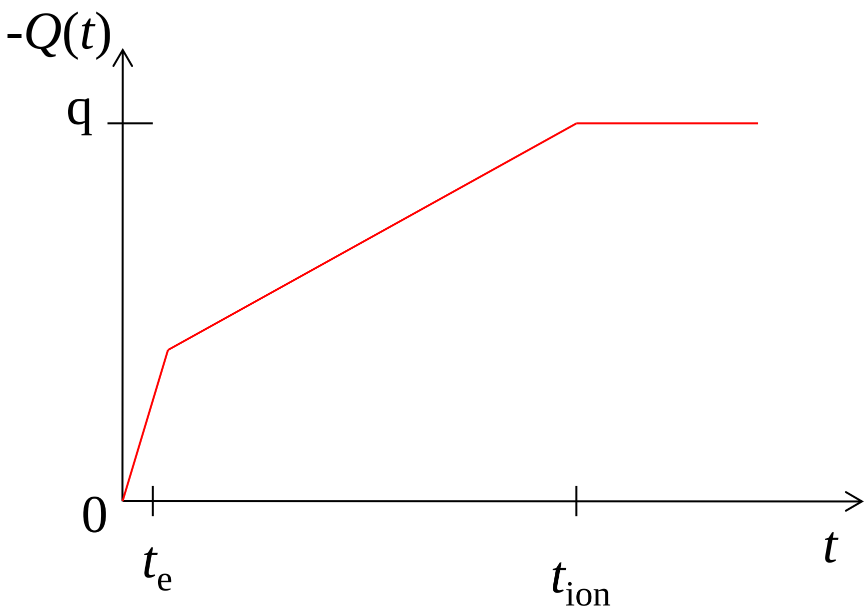
$$I_i(t) = -\frac{\mathrm{d}Q_i(t)}{\mathrm{d}t} = \frac{q}{U_i}\frac{\mathrm{d}}{\mathrm{d}t}\phi\left[\mathbf{x}_0(t)\right]$$

$$I_i(t) = \frac{q}{U_i}\boldsymbol{\nabla}\phi_i\left[\boldsymbol{x}_0(t)\right]\cdot\frac{\mathrm{d}\boldsymbol{x}_0(t)}{\mathrm{d}t} = -\frac{q}{U_i}\boldsymbol{E}_i\left[\boldsymbol{x}_0(t)\right]\cdot\boldsymbol{v}(t)$$

Ramo-Shockley Theorem

The current induced on a grounded electrode by a point charge q moving along a trajectory $\boldsymbol{x}_0(t)$ is $I_i(t)$, where $\boldsymbol{E}_i(\boldsymbol{x}_0)$ is the electric field in the case where the charge q is removed, electrode i is set to voltage U_i, and all other electrodes are grounded.

Plane Ionization Chamber



- Steep linear rise until e- reach anode
- Slow linear rise until ions reach cathode, contribution from e- constant
- Constant for $t > t_{\mathrm{ion}}$

Example: Ar at NTP

$$\left.\begin{aligned} d &= 5\,\mathrm{cm} \\ E &= 500\,\mathrm{V/cm} \end{aligned}\right\} \Rightarrow \begin{aligned} t_e &= 12.5\,\mu s \\ t_{\mathrm{ion}} &= 6\,\mathrm{ms} \end{aligned}$$

Planar Strip Detector

How do the real field and the weighting field look like?

Planar Strip Detector

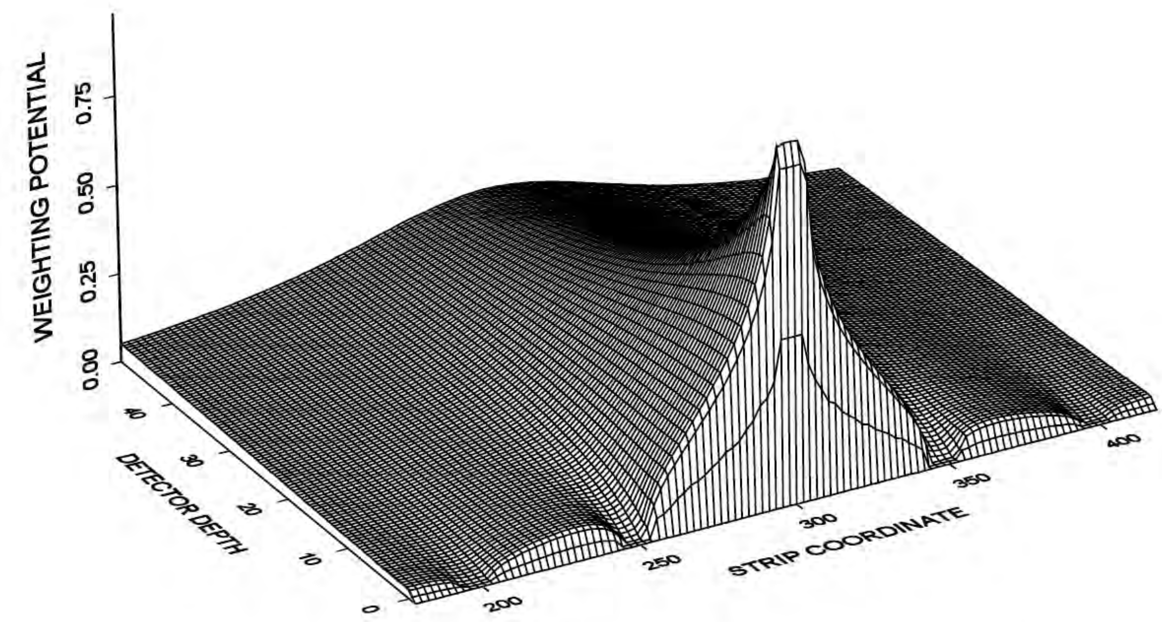
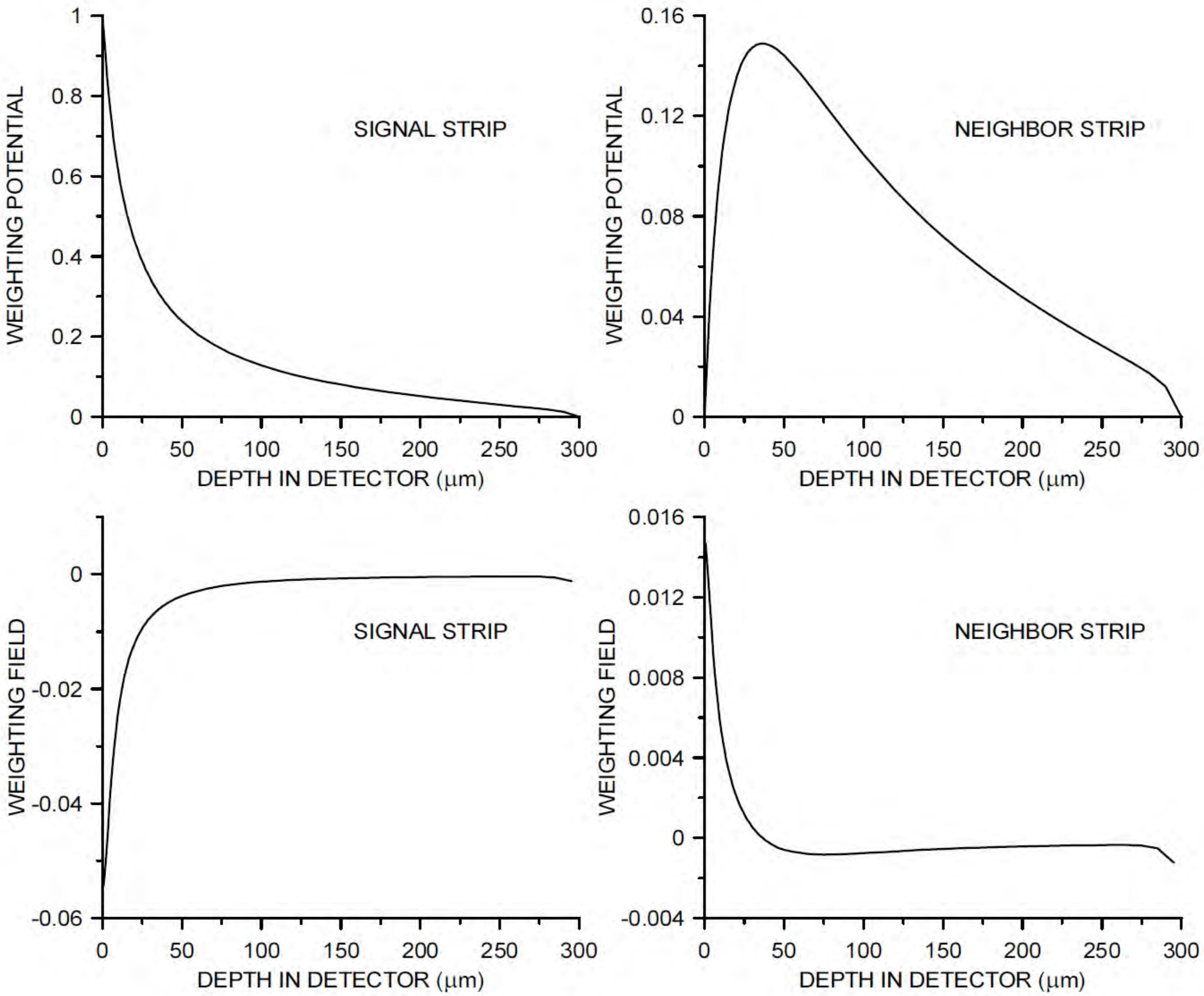


FIG. 2.29. Weighting potential for a 300 μm thick strip detector with strips on a pitch of 50 μm. The central strip is at unit potential and the others at zero. Only 50 μm of depth are shown.

[H. Spieler, Semiconductor detector systems, Oxford, 2005]

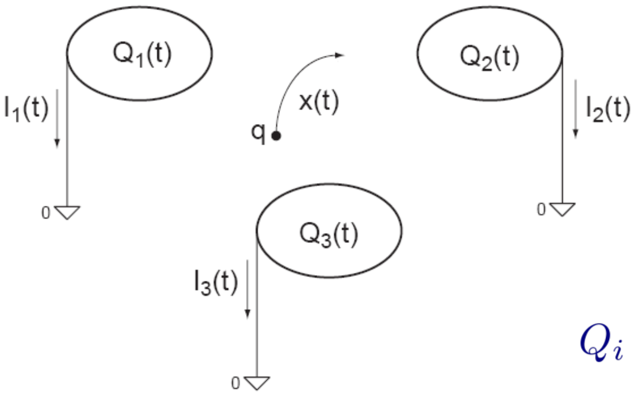
Planar Strip Detector



[H. Spieler, Semiconductor detector systems, Oxford, 2005]

Ramo-Shockley Theorem

universitätbonn

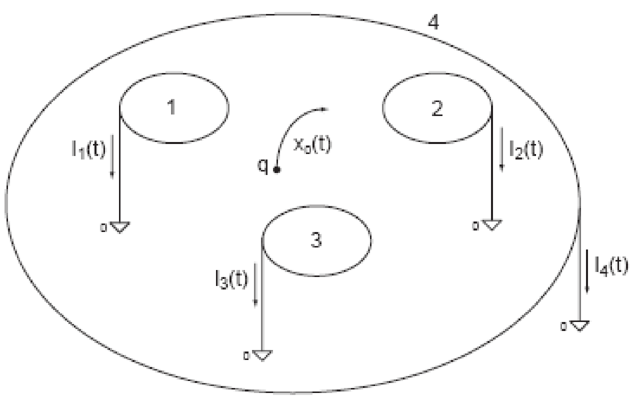


Consequences:

1. Charge induced on electrode i by a charge q moving from point 1 to 2 is

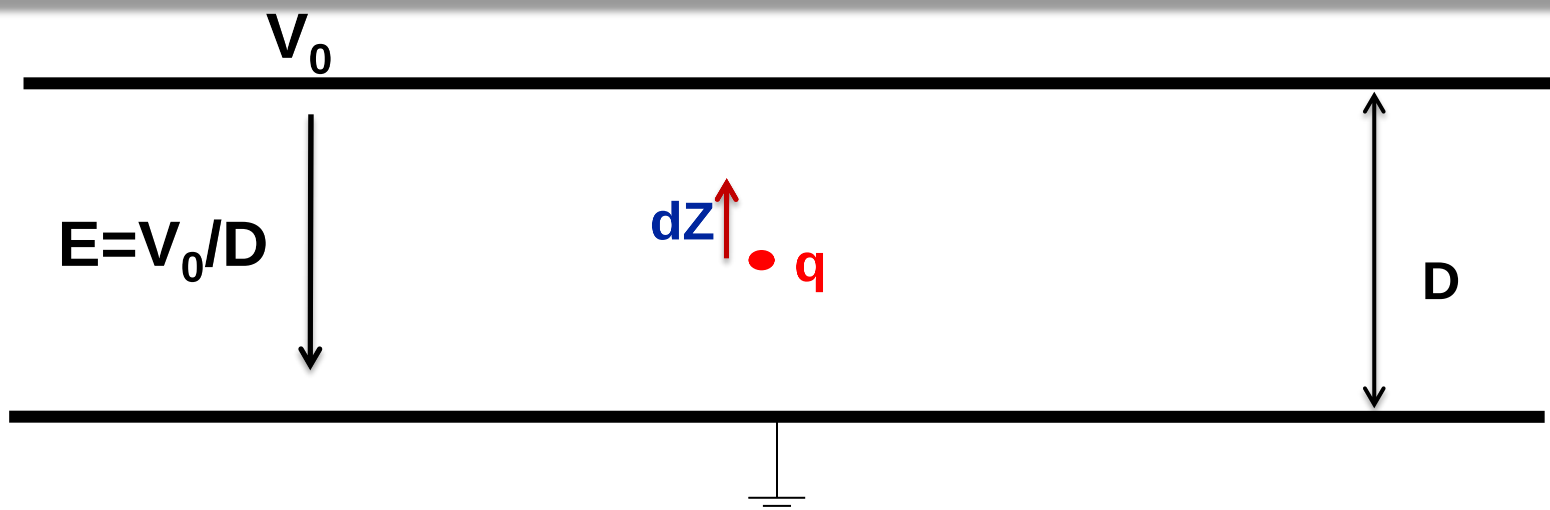
$$Q_i = \int_{t_1}^{t_2} I_i(t)\mathrm{d}t = -\frac{q}{U_i}\int_{t_1}^{t_2} \boldsymbol{E}_i[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)\mathrm{d}t = \frac{q}{U_i}\left[\phi_i(\boldsymbol{x}_1) - \phi_i(\boldsymbol{x}_2)\right]$$

   and is independent of the actual path



2. Once all charges have arrived at the electrodes, the total induced charge in a given electrode is equal to the charge that has arrived at this electrode
3. In case there is one electrode enclosing all others, the sum of all induced currents is zero at any time

Arguing with Energy



$$Energy = \frac{1}{2}CV_0^2 = \frac{1}{2}\frac{Q^2}{C} \qquad dW = qEdz = \frac{qV_0}{D}dz$$

$$d(Energy) = dW \qquad d\frac{1}{2}\frac{Q^2}{C} = \frac{qV_0}{D}dz$$

$$\frac{1}{2}\frac{1}{C}QdQ = \frac{qV_0}{D}dz \qquad dQ = \frac{q}{D}dz$$

Gives correct result!

Arguing with Energy?

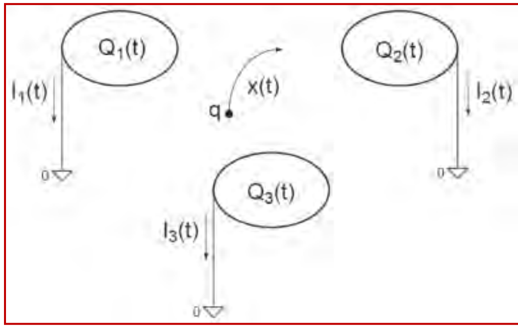
see e.g. [W.R. Leo, Techniques for Nuclear and Particle Physics, Springer, 1987]

- Signal is calculated using energy balance:

  Energy gained by charge in electric field =

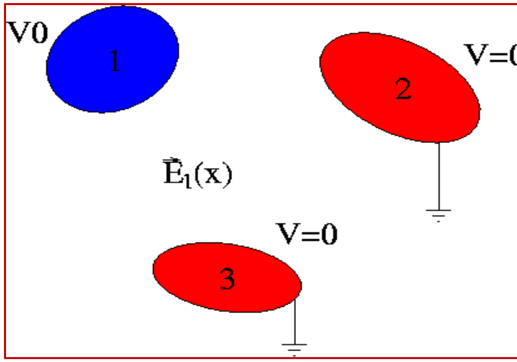
  change of energy stored in capacitor
- In some special cases, this argument gives the correct result, e.g. for a 2-electrode system because there the weighting field and the real field are equal.
- But the argument is very misleading:
  - An induced current signal has nothing to do with energy. In a gas detector the electrons are moving at constant speed in a constant electric field, so the energy gained by the electron in the electric field is lost into collisions with the gas, i.e. heating of the gas.
  - In absence of an electric field, the charge can be moved across the gap without using any force and currents are flowing.

1. Calculate particle trajectory $x_0(t)$ in the „real“ electric field



2. Remove all impedance elements, ground the electrodes and calculate currents induced by moving charge on grounded electrodes

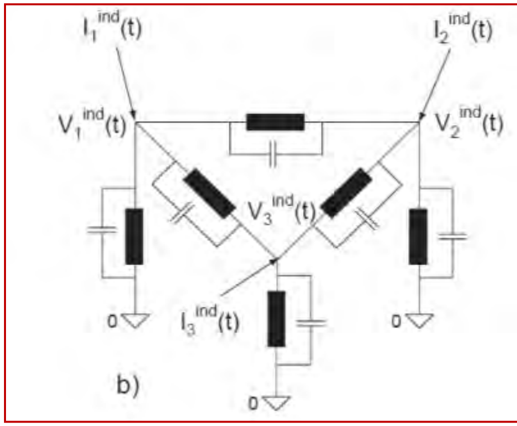
$$I_i(t) = \frac{q}{U_i}\nabla\phi_i\left[\boldsymbol{x}_0(t)\right]\cdot\frac{\mathrm{d}\boldsymbol{x}_0(t)}{\mathrm{d}t} = -\frac{q}{U_i}\boldsymbol{E}_i\left[\boldsymbol{x}_0(t)\right]\cdot\boldsymbol{v}(t)$$



3. Place these currents as ideal current sources on a circuit where the electrodes are simple nodes and the mutual electrode capacitances are added between the nodes. They are calculated from the weighting field by

$$c_{nm} = \frac{\varepsilon_0}{V_w}\oint_{\boldsymbol{A}_n}\boldsymbol{E}_m(\boldsymbol{x})d\boldsymbol{A}$$

$$C_{nn} = \sum_m c_{nm} \qquad C_{nm} = -c_{nm} \quad n \neq m$$



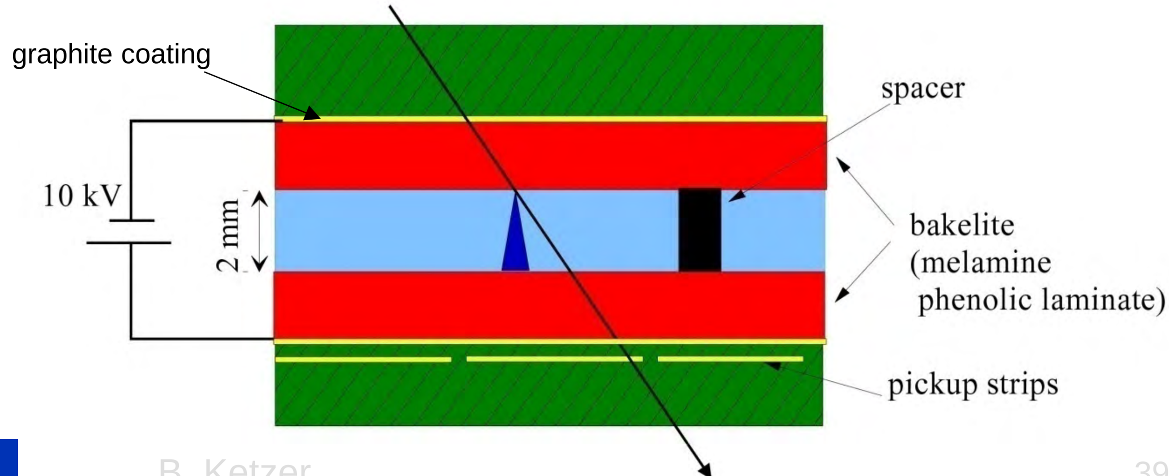
4 Position Measurement

4.1 Resistive Plate Chamber

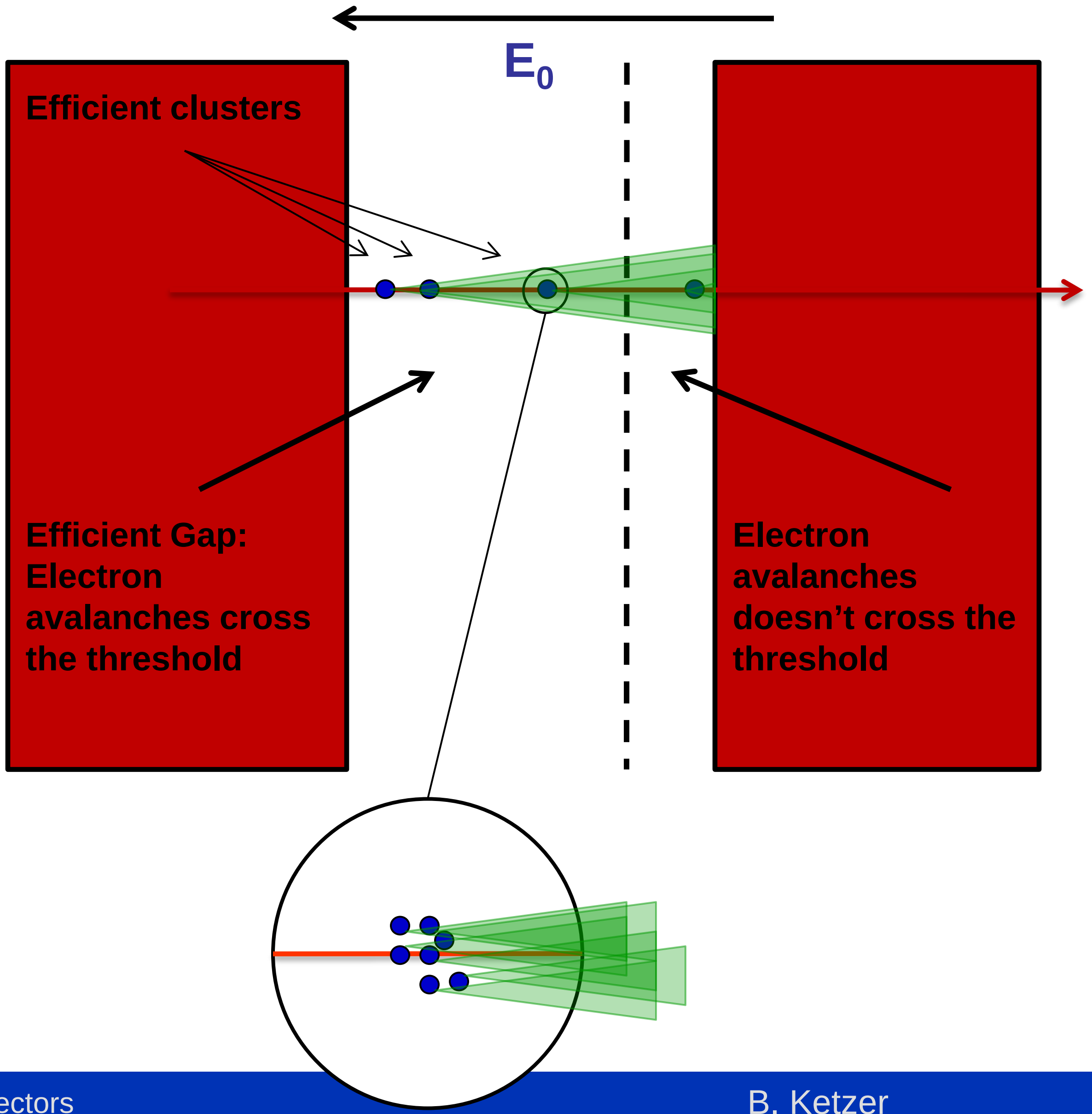
Principle:

[R. Santonico et al., NIM 187, 377 (1981)]

- Parallel plate counter with strong uniform electric field: ~50 kV/cm, 2 mm gap
  - ⇨ very good time resolution: $\sigma_t < 1$ ns
    - – instant avalanche multiplication for all primary clusters
    - – dominated by avalanche statistics, not primary ionization statistics
- High-ohmic electrode material (glass: $\rho = 10^{12}\ \Omega\mathrm{cm}$, Bakelite: 10^{10}-$10^{11}\ \Omega\mathrm{cm}$)
  - ⇨ local decrease of electric field at position of avalanche
  - ⇨ blind spot for time $\tau \sim \rho\varepsilon_0\varepsilon_r$ (relaxation time, 10 ms – 1 s)
- Pickup strips for position information



Resistive Plate Chamber



Number of clusters per unit length follows strictly a Poisson distribution.

Number of efficient clusters follows to a good approximation the same Poisson distribution.

The number of electrons per cluster follows approximately a $1/n^2$ distribution.

→Number of efficient electrons follows approximately a "Landau" distribution.

Each individual electron starts an avalanche, inducing a signal which will cross a given threshold of the readout electronics → time.

Resistive Plate Chamber

Operation:

- **Streamer mode**: L3, BaBar, BELLE
    - large signals (up to ~nC) ➪ no amplifier needed
    - low rate capability: a few 100 Hz/cm^2
- **Proportional mode**: ATLAS, CMS μ trigger
    - suppression of streamers by addition of small amounts of SF_6
    - higher rate capability: a few kHz/cm^2
    - signal ~10× smaller ➪ low-noise amplifier
    - less aging

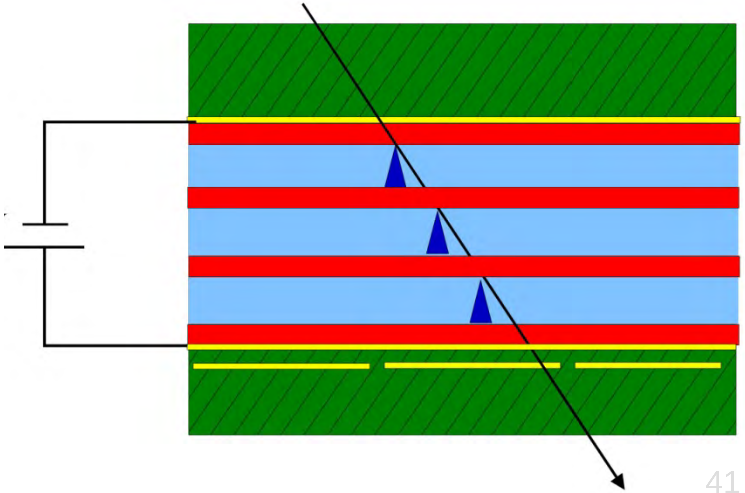
Multi-gap RPC: ALICE TOF barrel, FOPI

- 0.2 – 0.3 mm gaps

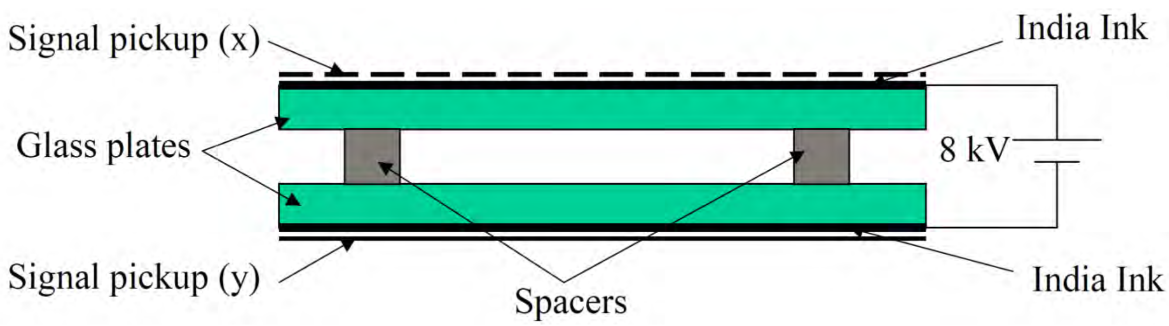
➪ improved efficiency

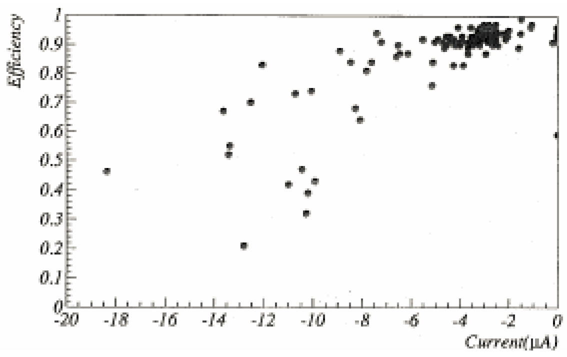
➪ improved time resolution (smaller gaps)

$\sigma_t = 50 - 100$ ps



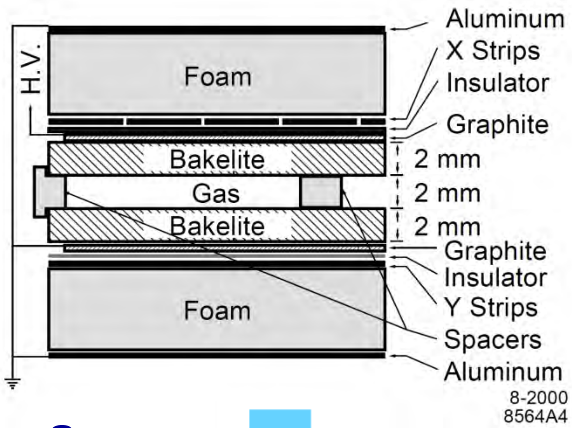
Belle RPC



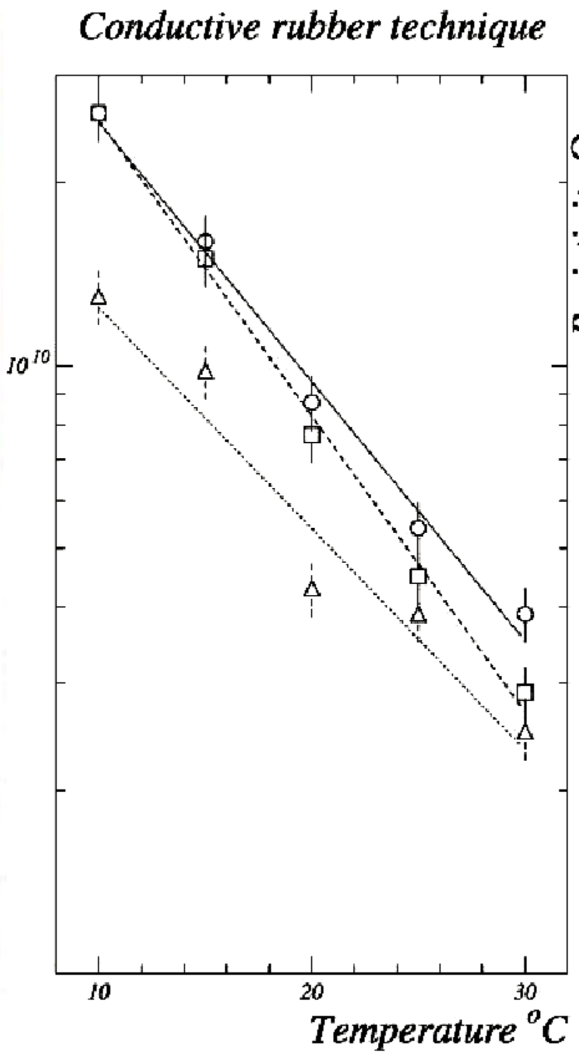


- Operation mode: streamer
- Material: float glass
- Observation: high dark currents, deterioration of efficiency
- Increase of voltage increases dark current ⇨”RPC death spiral”
- Cause: water content > 2000 ppm due to polyethylene tubing
- $C_2H_2F_4$ + water ⇨ HF acid, etched glass surface
- Solution: replace polyethylene by copper tubing

BaBar RPC

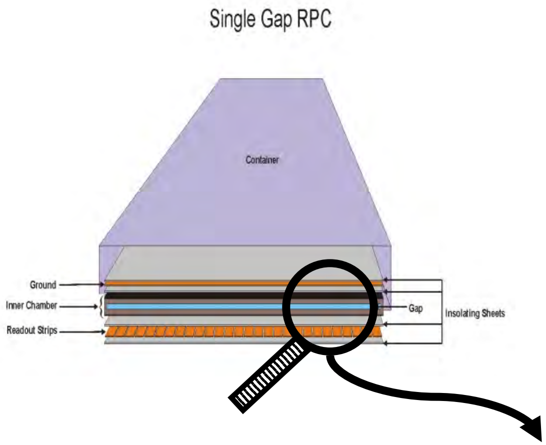


Spacer: 

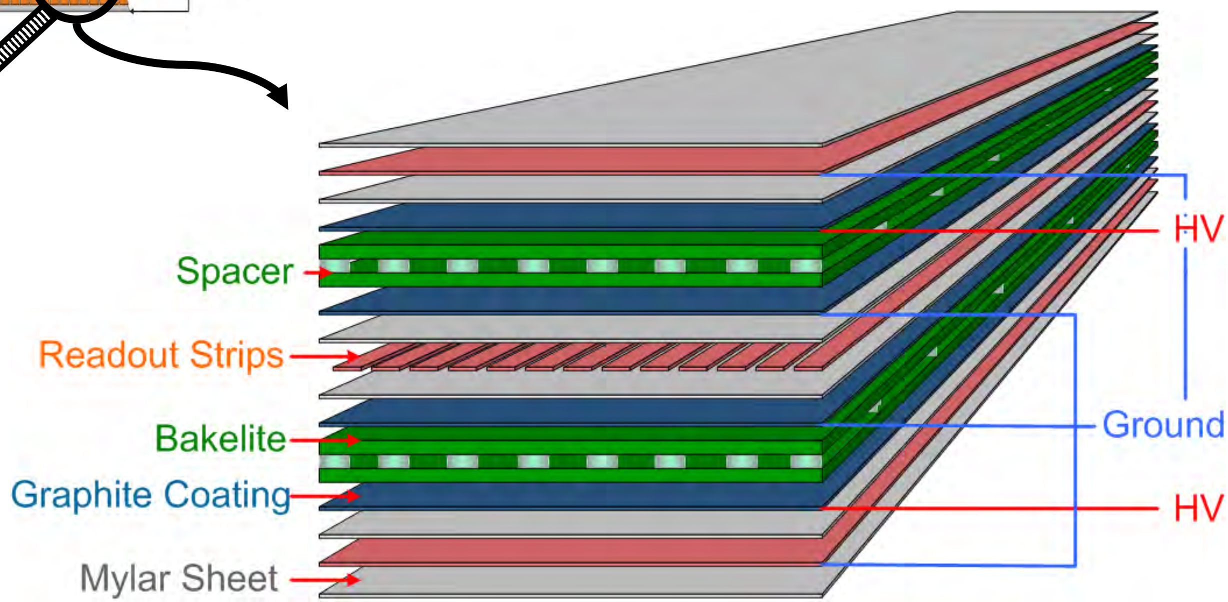


RPC aging	Remediation
Uncured Linseed oil formed droplets and stalagmites in the gap.	Use thinner Linseed oil coating and thoroughly polymerize the oil film before apply HV; Better surface Bakelite, completely abandon the use of Linseed oil coating.
Vanished graphite coating on the bakelite electrodes after accumulated certain amount of charge through the Bakelite.	Better technology for making the graphite coating; Switch to the avalanche mode operation.
Resistivity increase of the Bakelite electrode with the total accumulated charge.	Add water vapor into the gas mix; Switch to the avalanche mode operation.

CMS (CERN LHC): barrel/endcap trigger

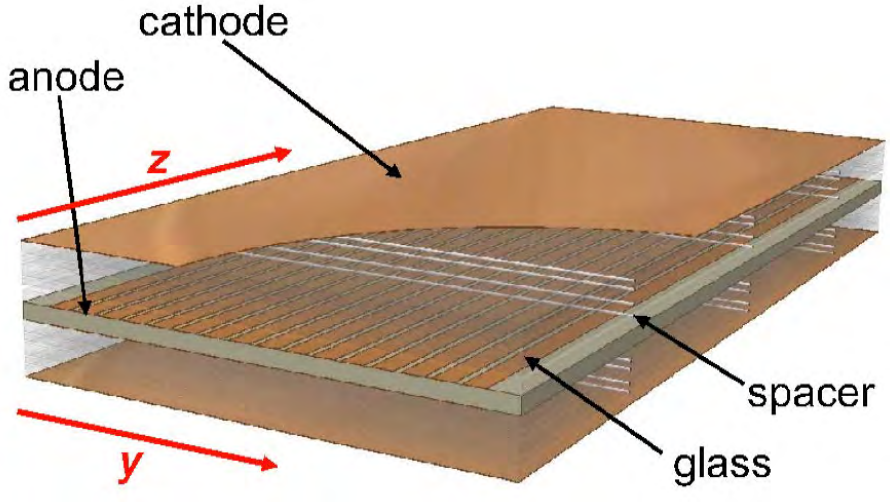


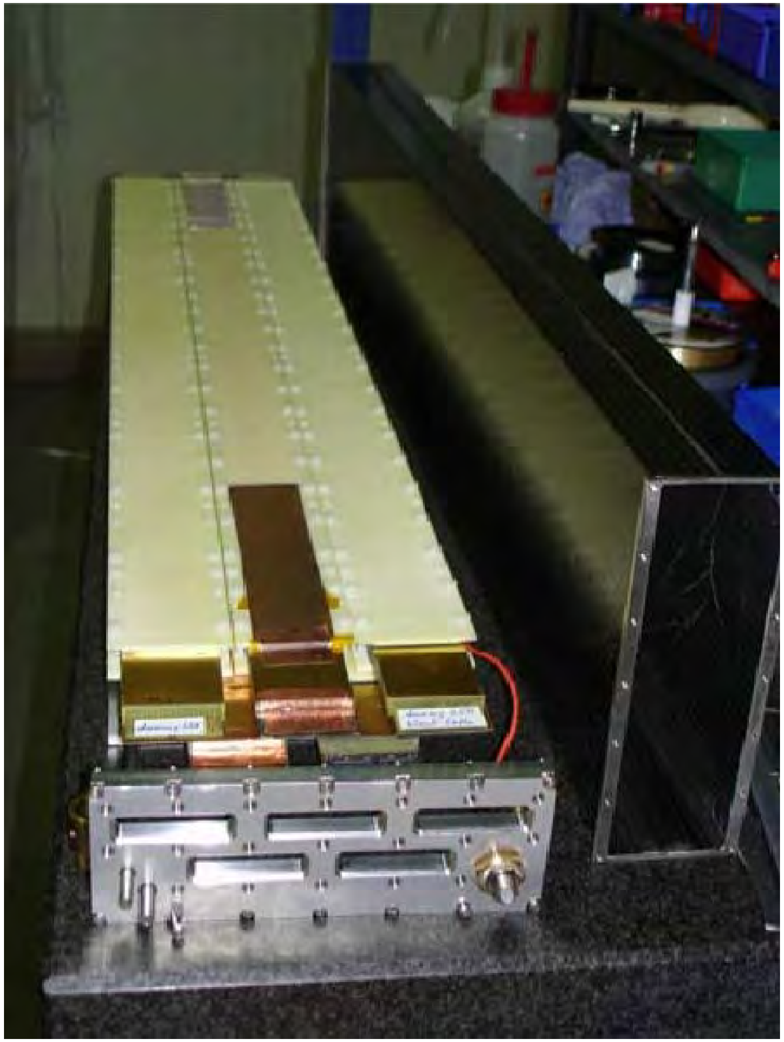
- Freon ($C_2H_2F_4$)/i-C_4H_{10}/SF_6 (95.5/3.5/0.3) + 5000 ppm H_2O
- *Gap: 2* mm
- *U=9000* V
- Total area: 2700 m^2, 105000 channels
- Time resolution <3 ns



Multi-strip Multi-gap RPC:

- Active area: $90 \times 4.6\ \mathrm{cm}^2$
- Gaps: $8 \times 220\ \mu\mathrm{m}$
- Strips: 16, 2-sided readout
- HV: 9.6 kV
- Gas: $C_2H_2F_4$ / i-C_4H_{10} / SF_6 (80/5/15)
- Resolution: $\sigma_{RPC} < 65$ ps

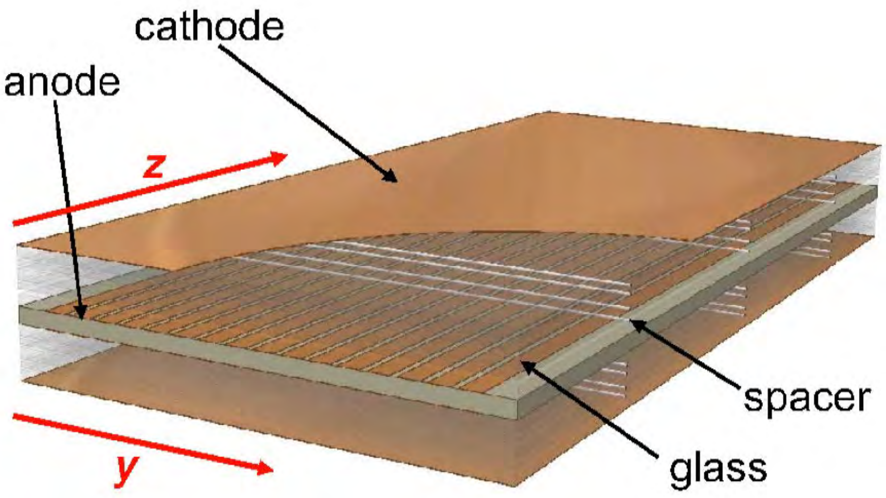


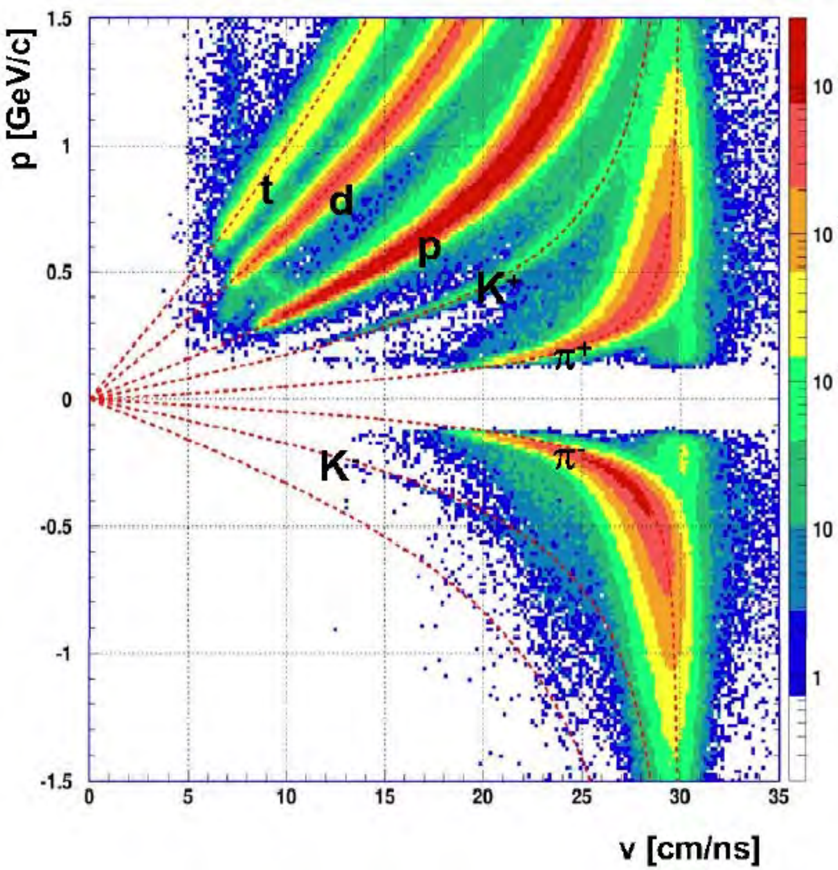


FOPI RPC

Multi-strip Multi-gap RPC:

- Active area: 90 × 4.6 cm^2
- Gaps: 8 × 220 μm
- Strips: 16, 2-sided readout
- HV: 9.6 kV
- Gas: $C_2H_2F_4$ / i-C_4H_{10} / SF_6 (80/5/15)
- Resolution: σ_{RPC} < 65 ps





4 Position Measurement

4.1 Resistive Plate Chambers

4.2 Micropattern Gaseous Detectors

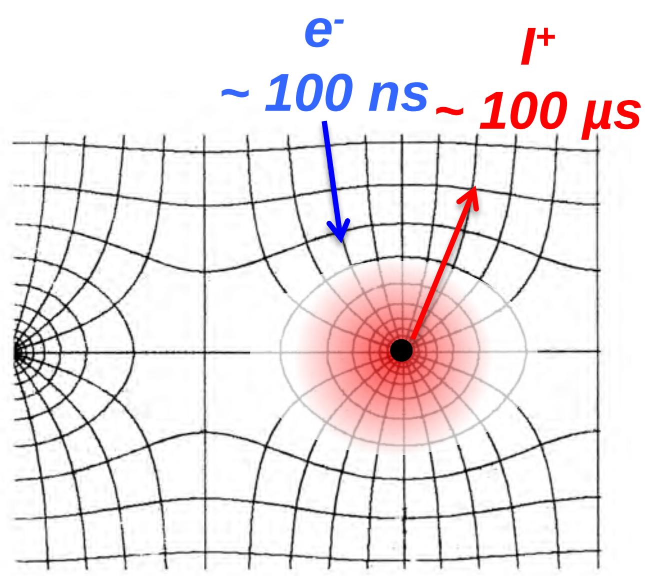
4.3 Semiconductor Detectors

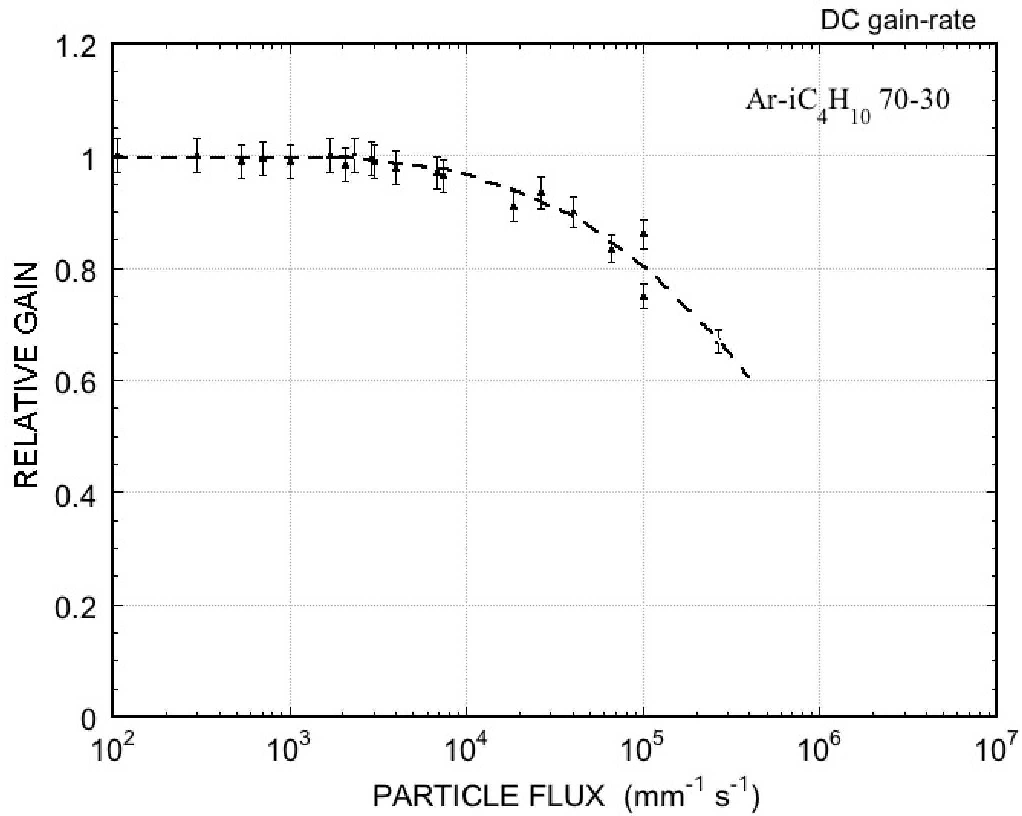
4.4 Track Reconstruction

Wire Chambers

Limitations of Wire-based Detectors

- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm³ (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode





[A. Breskin et al., NIM 124, 189 (1974)]

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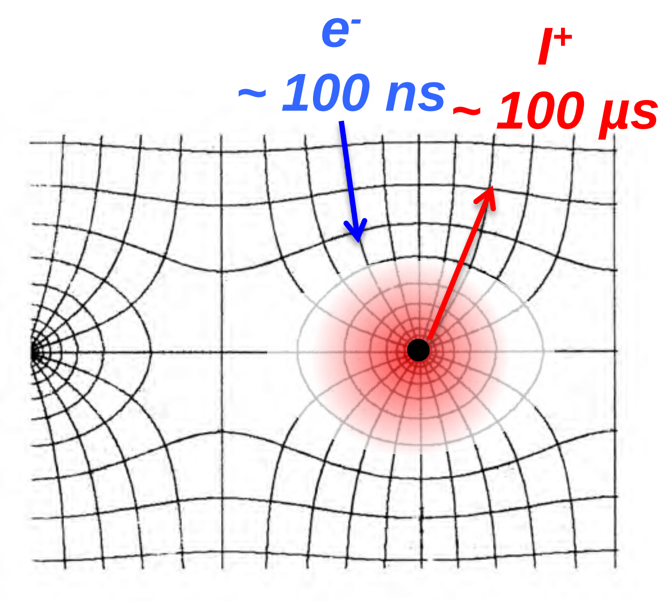

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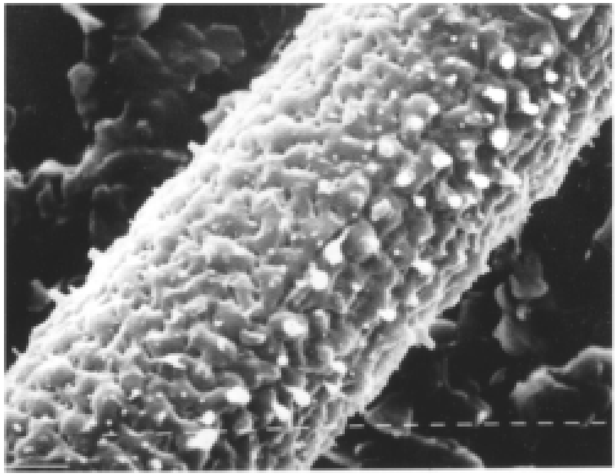
- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm^3 (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode
- Ion backflow: IB = $I_{cathode}$ / I_{anode} ~ 30% for TPC with MWPC
- Aging and discharge damage: polymerization of organic compounds



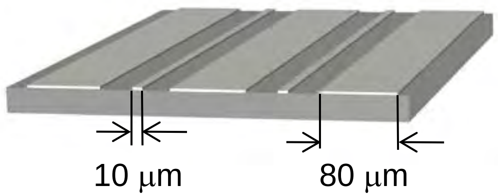
[O. Ullaland, LBL-21170, 107 (1986)]

⇨ Reduction of cell size by a factor of 10

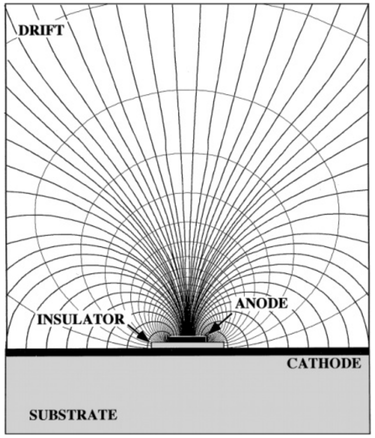
- Photolithography
- Etching
- Coating
- Wafer post-processing

The MPGD Zoo

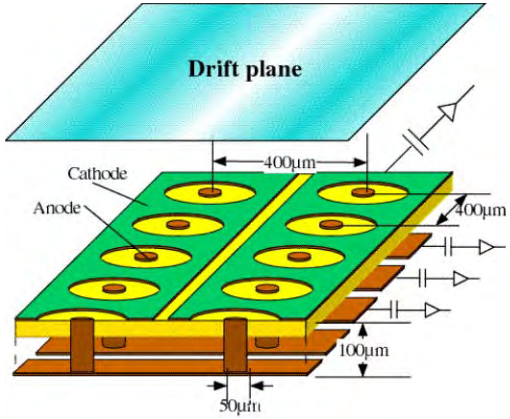
Microstrip Gas Chamber
[A. Oed, NIM A263, 351 (1988)]



Microgap Chamber (MGC)
[F. Angelini et al., NIM A335, 69 (1993)]

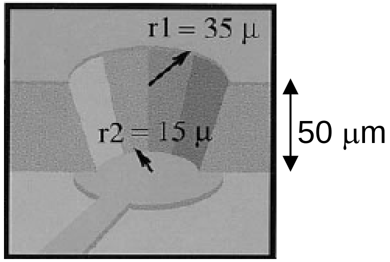


Microdot Chamber
[S.F. Biagi et al., NIM A361, 72 (1995)]

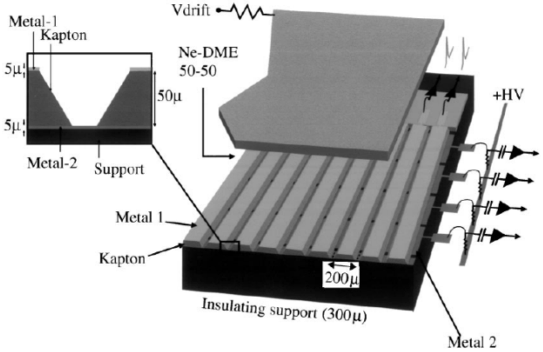


Compteur à Trous (CAT)
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

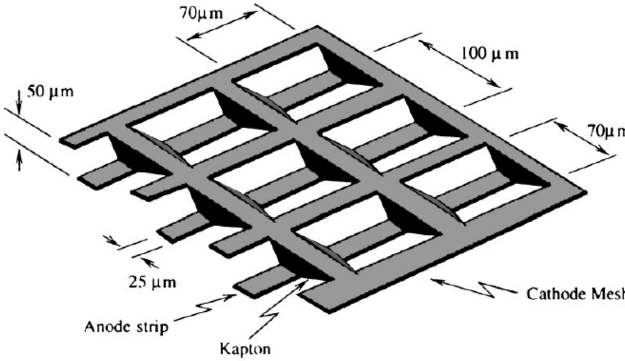
WELL Detector (μCAT)
[R. Bellazzini et al., NIM A423, 125 (1999)]



Micro Groove Counter
[Bellazzini et al., NIM A424, 444 (1999)]

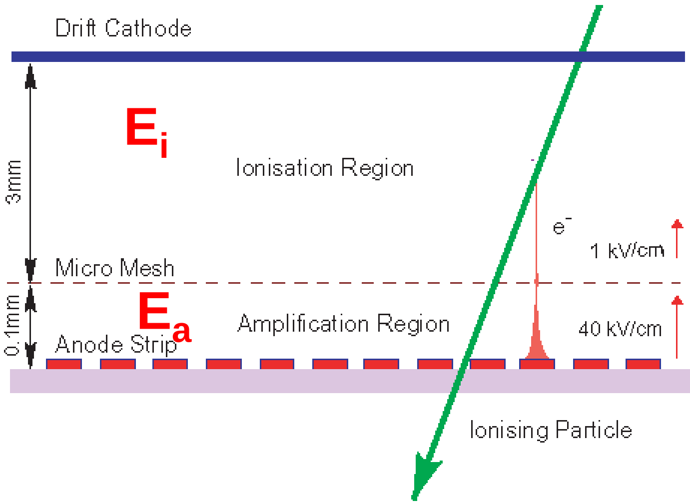


Micro Wire Detector
[B. Adeva et al., NIM A435, 402 (1999)]



and many more...

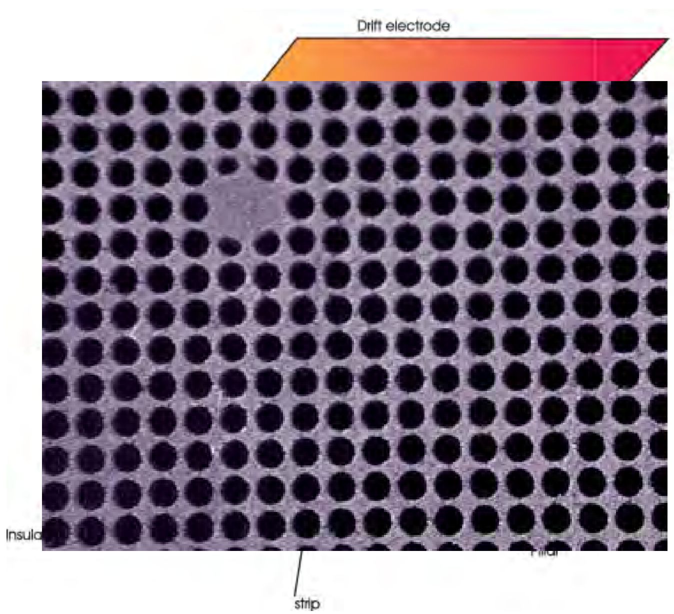
Micromegas

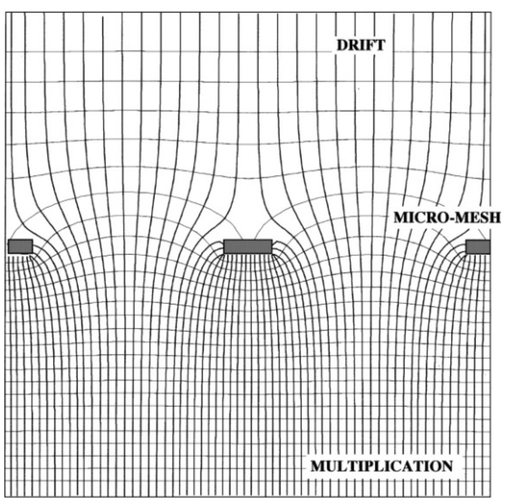


Micromesh Gaseous Structure

[I. Giomataris et al., NIM A376, 29 (1996)]

- Thin gap parallel plate structure
- Fine metal grid (Ni, Cu) separates conversion (~ 3 mm) and amplification gap (50-100 μm)
- Very asymmetric field configuration: 1 kV/cm vs. 50 kV/cm





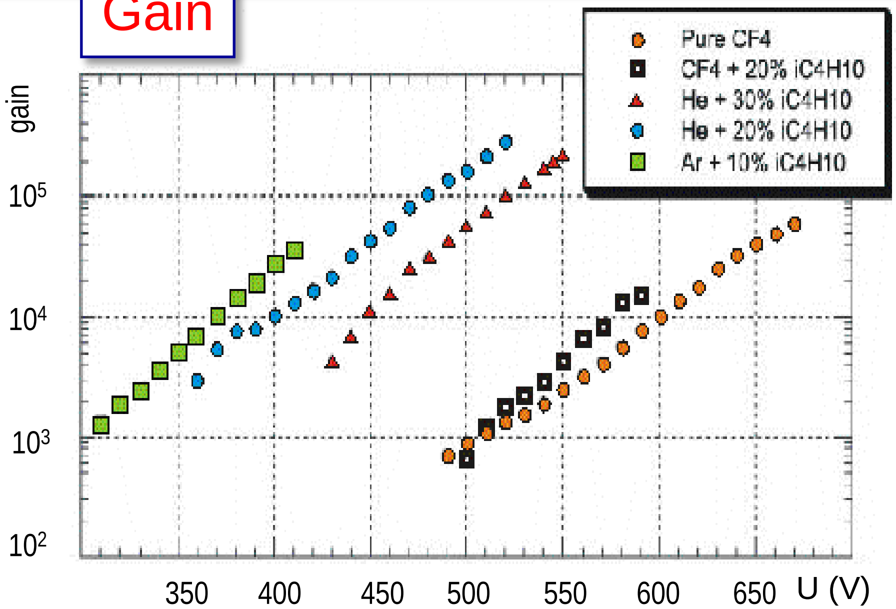
➡ Fast collection of ions (~ 100 ns)

➡ Saturation of Townsend coefficient (mechanical tolerances)

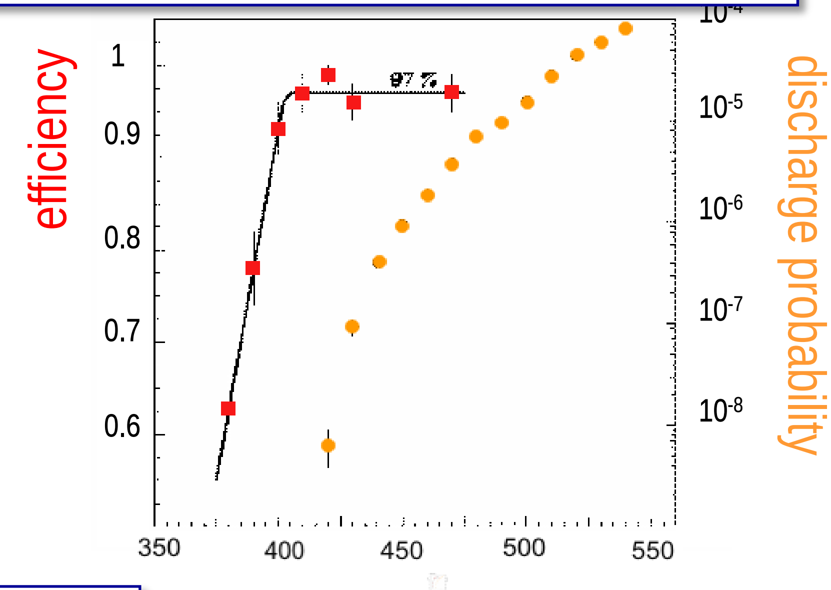
➡ good energy resolution

Micromegas Performance

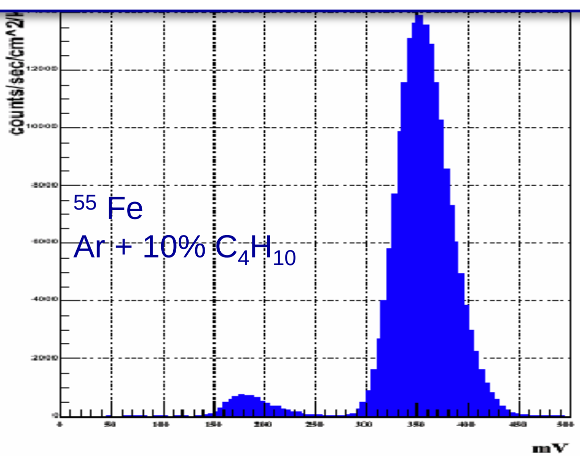
Gain



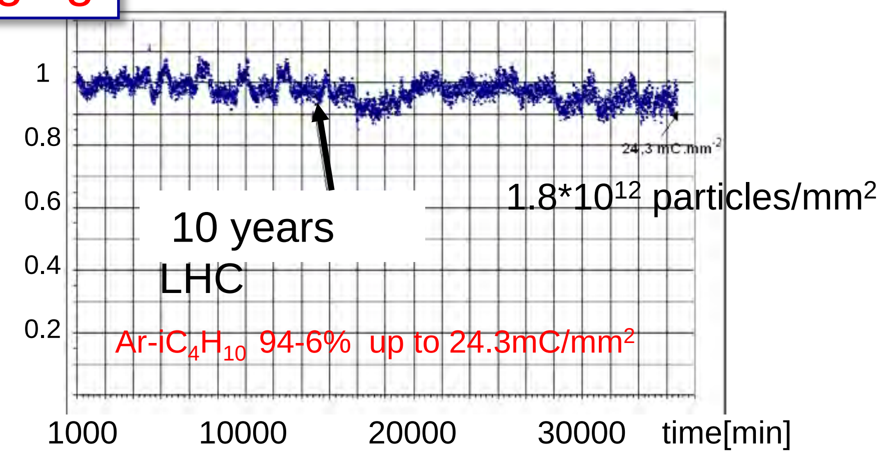
Efficiency & discharge probability



Energy resolution ~ 10%

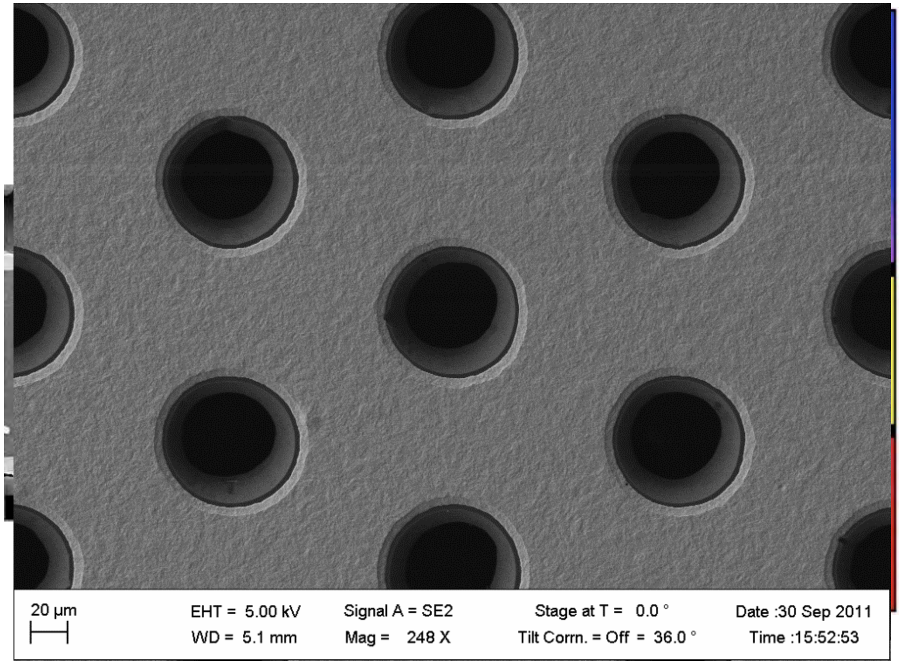


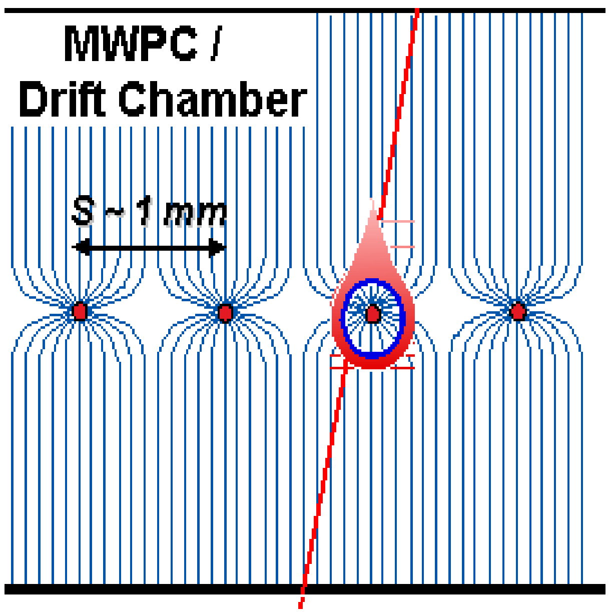
Aging



[D.Thers et al NIM A 469,133 (2001)]

GEM

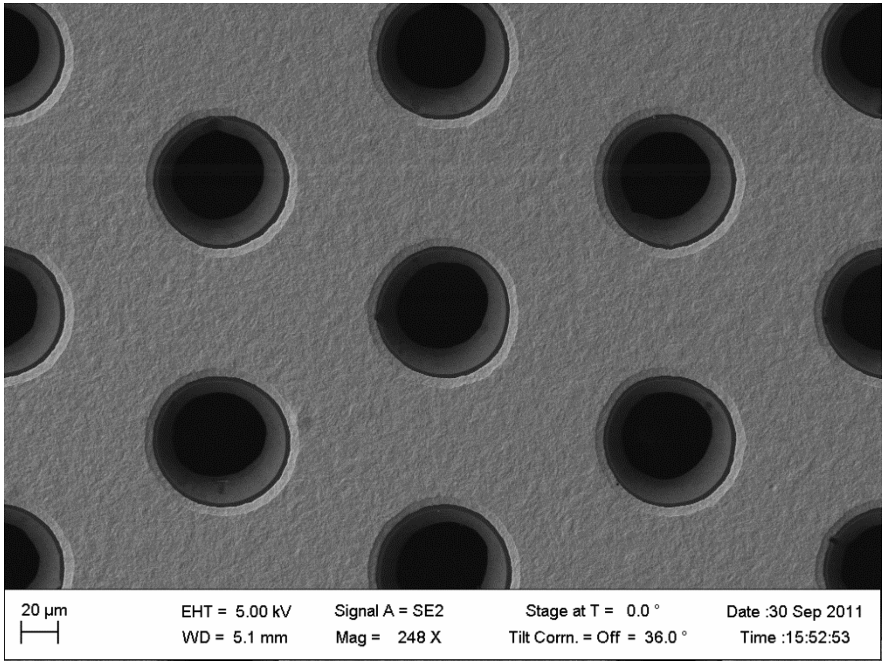




- GEM: **G**as **E**lectron **M**ultiplier

  [F. Sauli, NIM A386, 531 (1997)]
- Thin polyimide foil, typ. 50 μm
- Cu-clad on both sides, typ. 5 μm
- Photolithography: ~ 10^4 holes/cm^2
- Granularity 10×higher than MWPC

- ΔU=300-500 V
  - ⇨ high E-field: ~50 kV/cm
  - ⇨ avalanche multiplication



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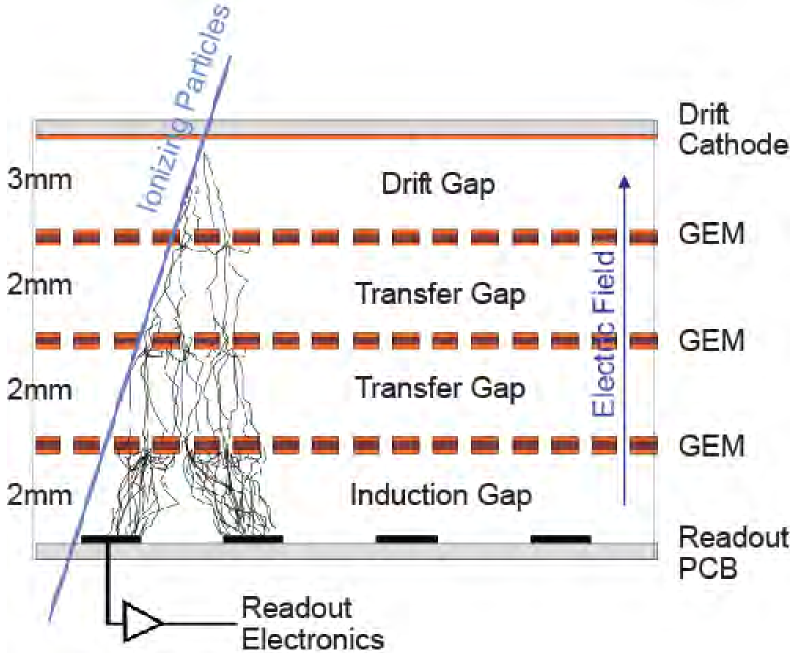
- Granularity 10×higher than MWPC

Triple GEM amplification

➡ higher gain at lower GEM voltages
[S. Bachmann, B. Ketzer et al., NIM A479, 294 (2001)]

➡ discharge prevention
[B. Ketzer et al., IEEE Trans. Nucl. Sci. 48, 1065 (2001)]

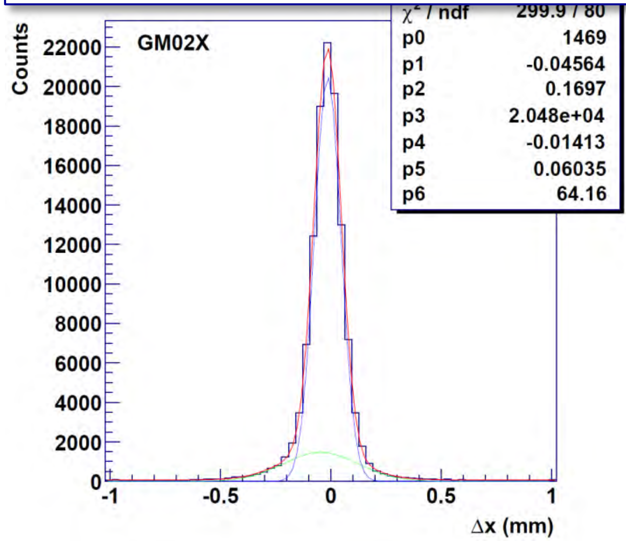
➡ no aging up to 7 mC/mm^2
[C. Altunbas, B. Ketzer et al., NIM A515, 249 (2003)]

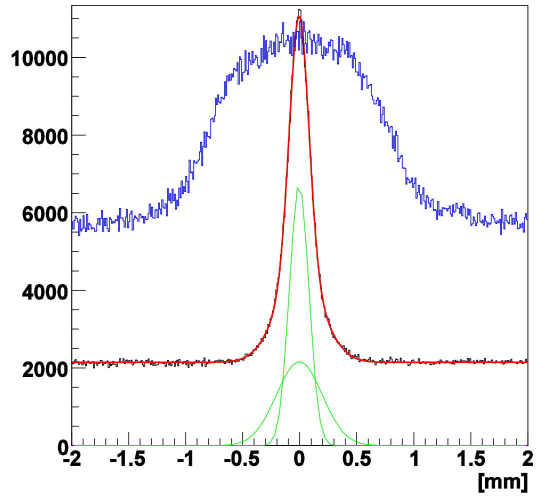


GEM Performance

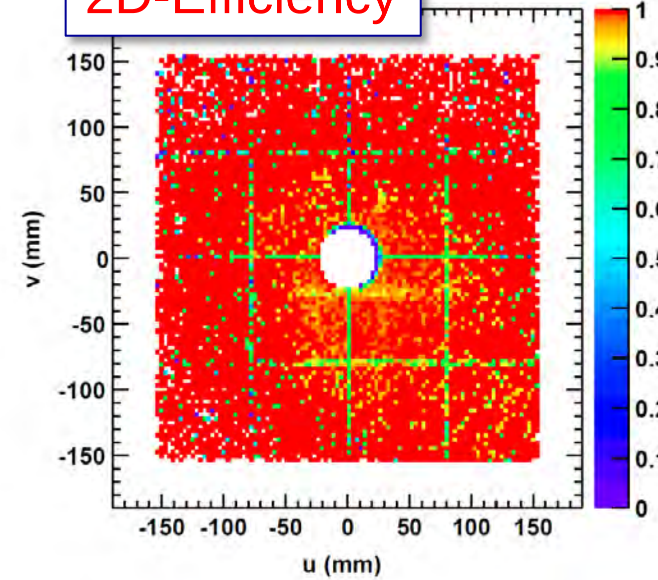
Spatial resolution: [B. Ketzer et al., NIM A535, 314 (2004)]

- low intensity: 50 μm (400 μm strips)
- $4 \cdot 10^7 s^{-1}$ μ: 70 μm
- $2 \cdot 10^8 s^{-1}$ μ: 135 μm ($1 mm^2$ pixels)





2D-Efficiency



Aging: [M Alfonsi.et al., NIM A518, 106 (2004)]

- Ok up to200 mC/mm2