Introduction to Gas Detectors

P. Vitulo

Dipartimento di Fisica Nucleare e Teorica

Università di Pavia & INFN Pavia

PV Primorsko 20-26 June 2010

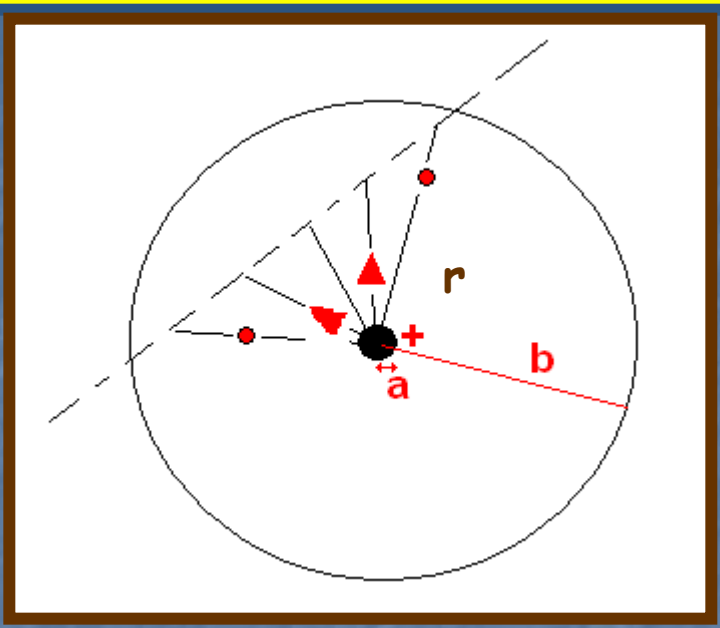
Outlook

- Basics (statistics of the ionization processes)
- Monte Carlo simulation of the basic processes
- Drift of electrons in gas; diffusion and attachment
- Avalanche formation
- Secondary effects on the development of the avalanche
- Signal generation: the Ramo's Theorem
- (Ionization, Proportional and Geiger-Muller counters)
- Resistive Plate Counters

Gas Detectors

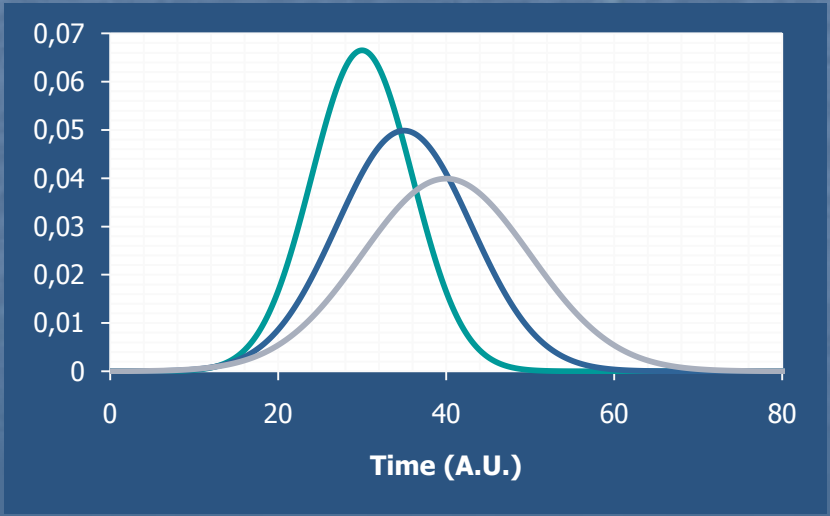
1) The gas mixture represents the sensitive medium
2) The moving of the charge developed inside the detector starting from the primary ionization represents the signal
3) We need to increase this charge to "see" the signal
4) This can be done with 2 geometrical configurations (and an electric field..)

Gas Detectors.....cylindrical geometry



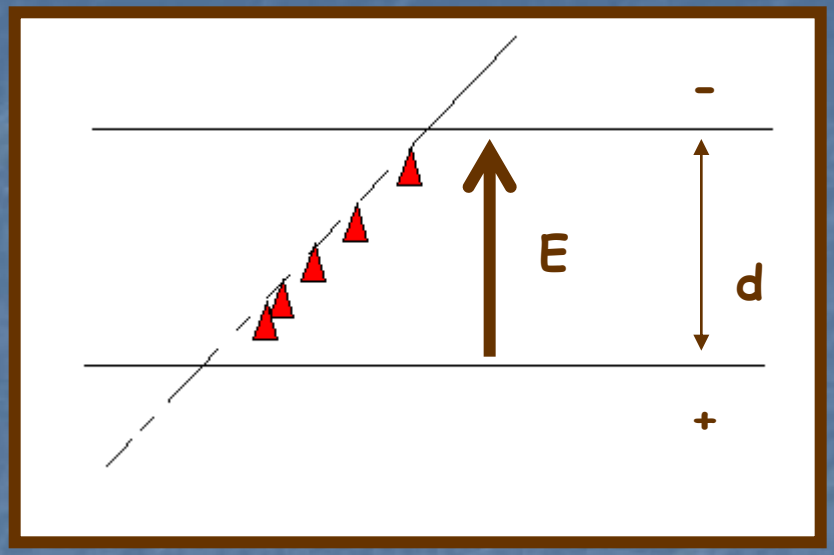
Electron clusters produced at different radii "see" a different electric field

$$E = \frac{V}{r \ln \frac{b}{a}}$$



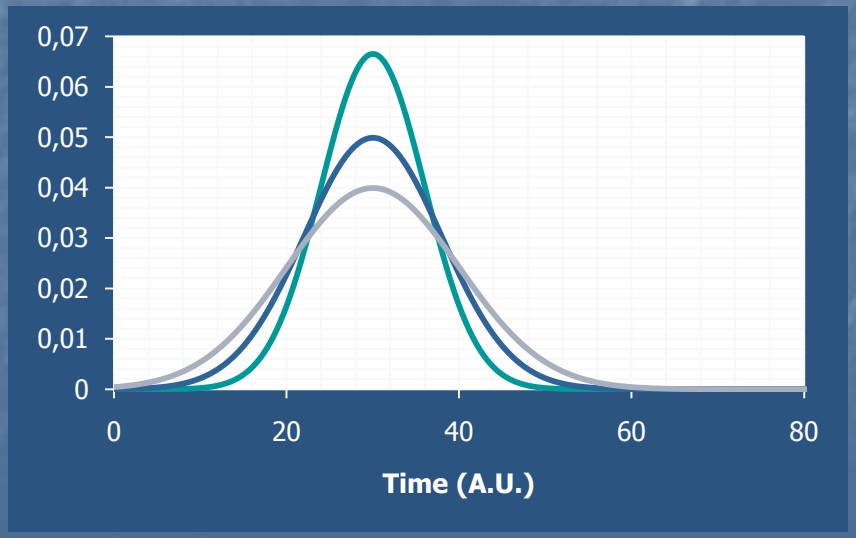
The signal is the contribution of subsequent avalanches (i.e. at different time)

Gas Detectors.....parallel geometry



All the clusters "see" the same electric field !

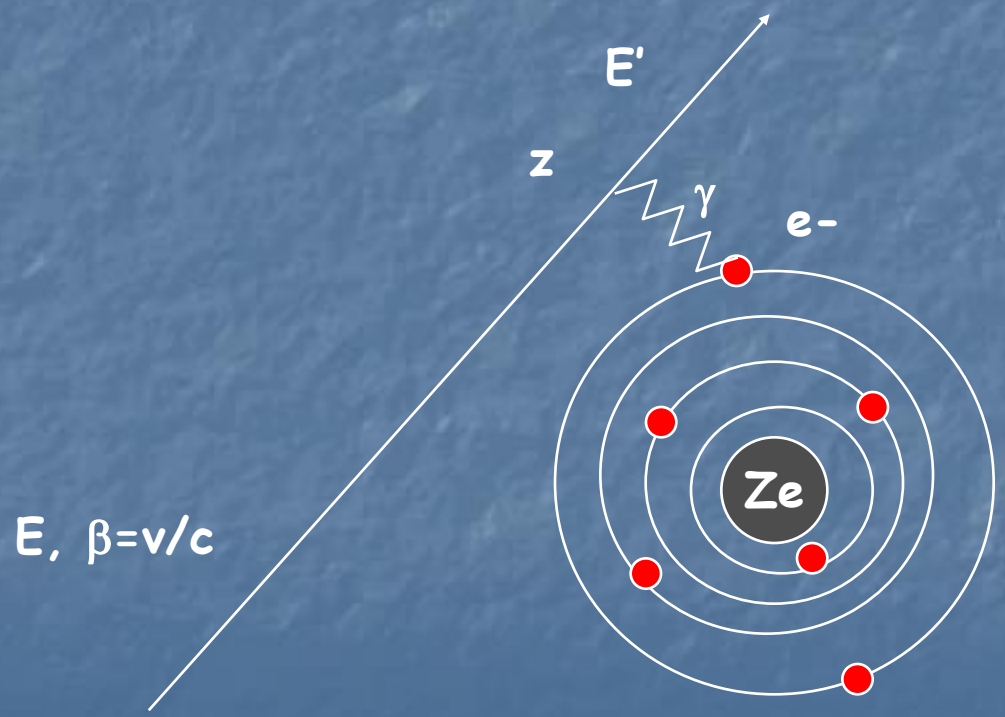
$$E = \frac{V}{d}$$



The signal is the simultaneous contribution of every avalanche (that can reach the right dimension inside the gap)

In any case they are based on the work done by an electric field on the free e- (-ve and +ve ions) inside the gas after the primary ionization due to the passage of a charged particle.

So the story begins with .. a) the interaction of a charged particle within the gas where it ionizes the gas molecules by losing energy through successive collisions



Probability of releasing an electron with energy E

$$P(E)dE \approx \frac{dE}{E^2}$$

- Energy loss:

  E-E' = ΔE

- Specific energy loss (or Stopping power):

  ΔE/Δx

Primary Ionization

The ionization process is a statistic process. The collisions with the gas atoms are randomly distributed and characterized by a *mean free path*

$$\lambda_I = \frac{A}{N_A \rho \sigma_I}$$

N_A Avogadro number ($moli^{-1}$)

ρ gas density ($gr\,cm^{-3}$)

A gas mass number ($gr\,moli^{-1}$)

σ_I ionization cross section (cm^2)

So the "average number of collisions" along a path L will be $\mu = \frac{L}{\lambda_I}$

This is the average value but it "fluctuates" around a distribution (Poisson)

$$P(\mu, k) = \frac{\mu^k}{k!} e^{-\mu}$$

That gives the probability of having k collisions when the average is μ so this is the probability distribution of the primary ionization.
It is interesting to calculate the figure → that is an estimate of the inefficiency of a detector!

$$P(\frac{L}{\lambda},0) = e^{-\frac{L}{\lambda}} = 1 - \varepsilon$$

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

$$\lambda = \frac{1}{n} = \frac{1}{25} = 0.04 \text{ cm}$$

$$L = 1 \text{ cm}$$

$$\mu = \frac{L}{\lambda} = Ln = 25 \Rightarrow$$

average number of collisions in L

..ok good ..can we reduce the thickness? →

….not too much!!

An Ar detector 1 cm wide will have an inefficiency →

$$1 - \varepsilon = P(\frac{L}{\lambda}, 0) = 1.5 \times 10^{-11}$$

$$L = 1 \text{ mm}, \ \mu = \frac{L}{\lambda} = \frac{0.1}{0.04} = 2.5$$

$$1 - \varepsilon = P(\frac{L}{\lambda}, 0) = e^{-\mu} = 0.08 = 8\% \text{ !!}$$

How is the distribution between subsequent ionizations ?

Particle track

$$f(l)dl = P(\frac{l}{\lambda},0)\times\frac{dl}{\lambda} = e^{-\frac{l}{\lambda}}\times\frac{dl}{\lambda}$$

The probability of having an ionization after a path l centered in dl

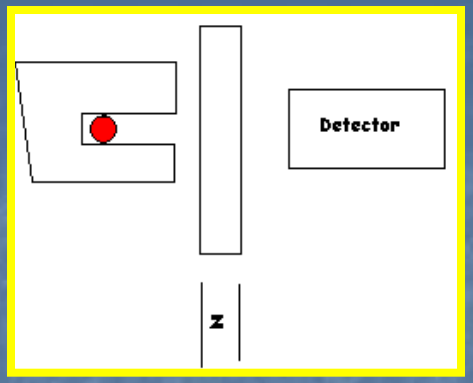
$$f_N(l) = \frac{1}{\lambda}e^{-\frac{l}{\lambda}}$$

Exponentially distributed

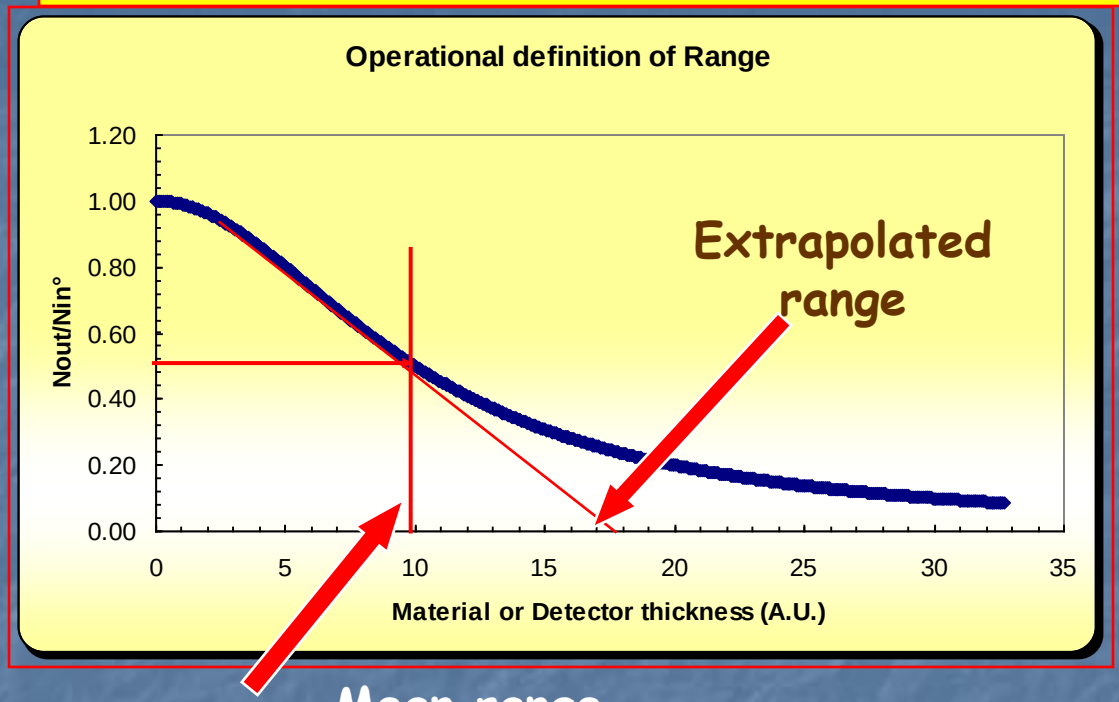
MCarlo simulation

$$l = -\lambda\ln(1-RND)$$

Particle's Range



Measure Nout/Nin after a thickness z of material and take the thickness at 50% of the output



Or Numerically (for electrons):

$$R_B = \int_{E_{in}}^{0} \frac{1}{(dE/dx)} dE$$

$$-\frac{dE}{dx}(keV/cm) = 7.85\times10^4 \frac{Z}{A}\frac{\rho}{E}\ln(1.165\frac{E}{I_{av}})$$

$$\rho(g/cm^{-3}) \quad , \quad \frac{Z}{A}, I_{av}$$ target density, $\frac{\text{atomic num}}{\text{atomic weight}}$, average ion. potential of target atoms

$$I_{av} = 9.76Z + 58.5Z^{-0.19}\times10^{-3} \cong 0.0115Z(keV)$$

Stopping Power via Montecarlo

$$w\langle N_p \rangle = L\left\langle \frac{dE}{dx} \right\rangle$$

Based on this formula, ie. the total average energy loss is equal to the stopping power time the track length

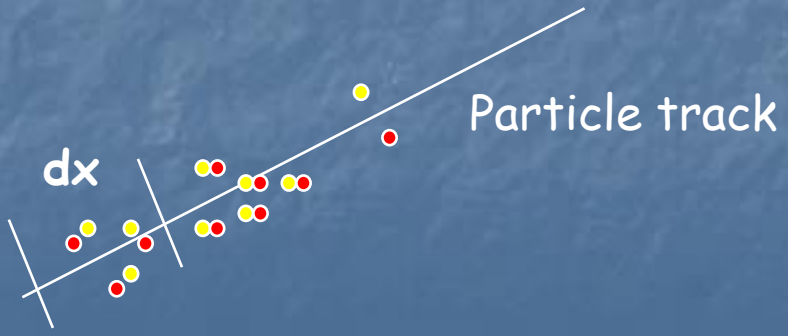
W = *average energy needed to produce an ions pair*

N_p = number of primary electrons

L = track length

$\frac{dE}{dx}$ = stopping power

The recipe:



1) $dx = -\frac{\ln(1-Rnd)}{prim}$

2) $E_{\text{int}} = Rnd \times (\frac{1}{E_{ion}} - \frac{1}{E_{end}})$

3) $E_{prim} = \frac{1}{(\frac{1}{E_{ion}} - E_{\text{int}})} - E_{ion}$

4) $N_{\text{sec}} = \frac{E_{prim}}{w}$

Primary Ionization exponentially distributed (see before…)

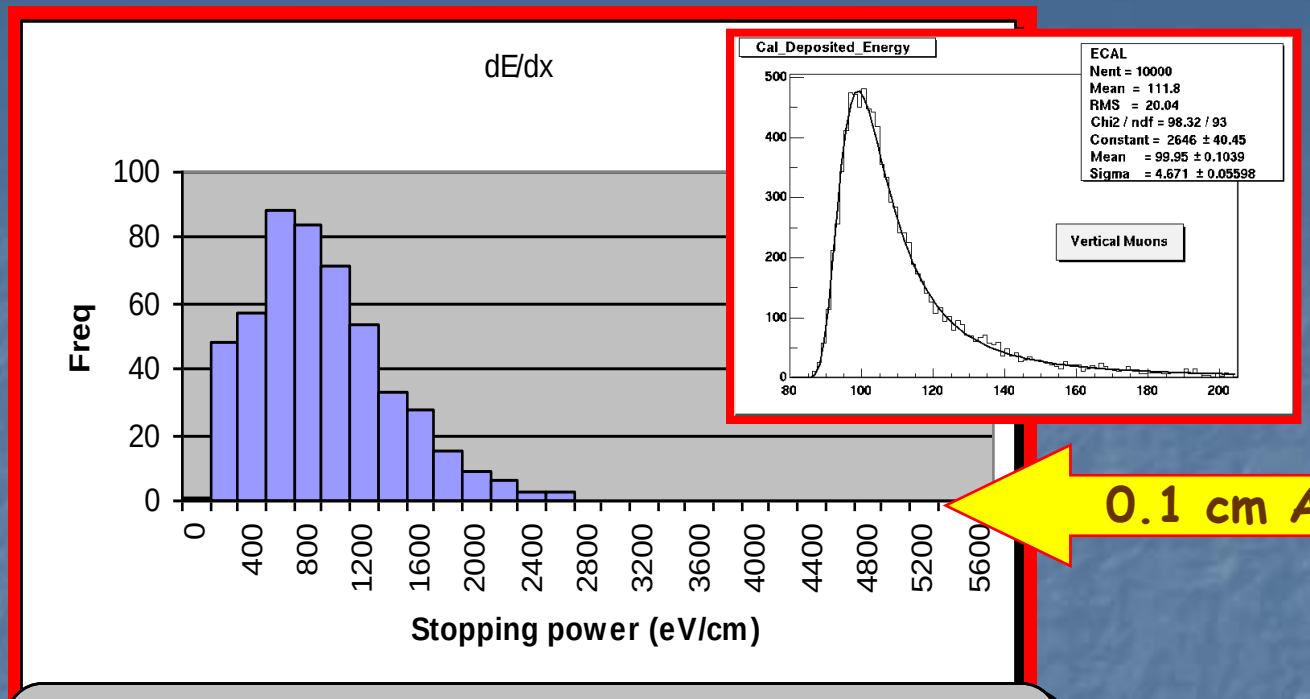
Interaction follows $1/E^2$ distribution and

energy loss is at max $E_{end}-E_{ion}$ →

If Rnd=O(1) $E_{prim}=O(E_{end}-E_{ion})$

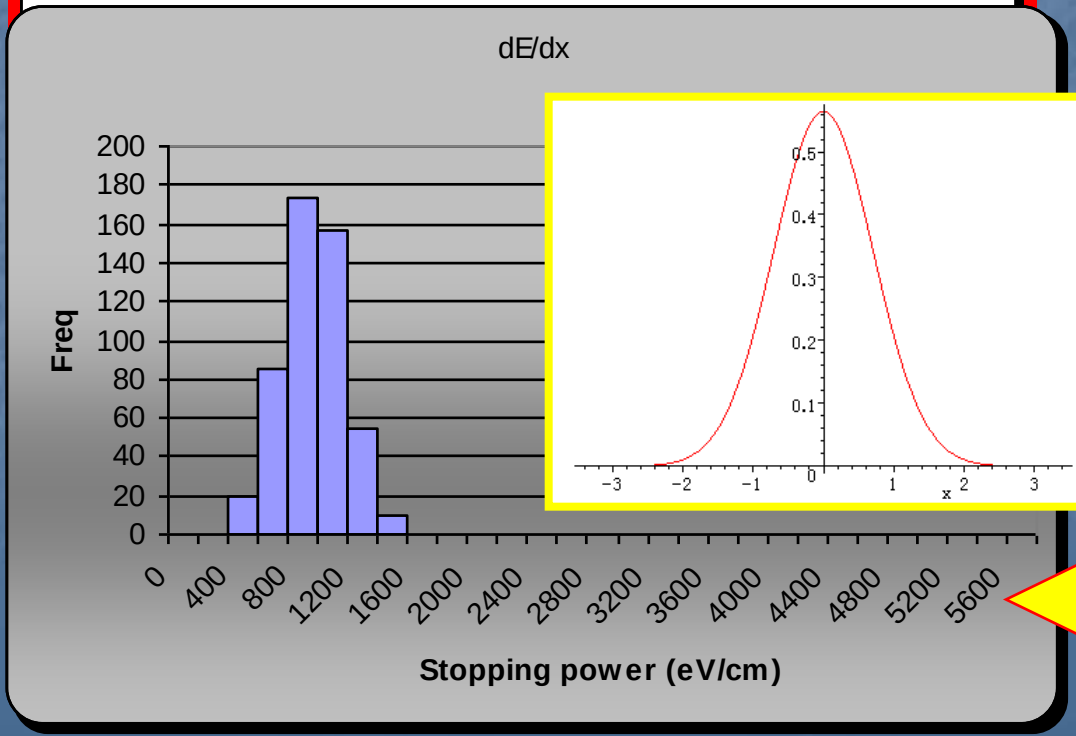
Also secondary electrons can be created

Montecarlo results: stopping power of a charged particle in Argon gas. Comparison between small and large thickness



Landau distribution → rare large energy loss collisions

0.1 cm Ar

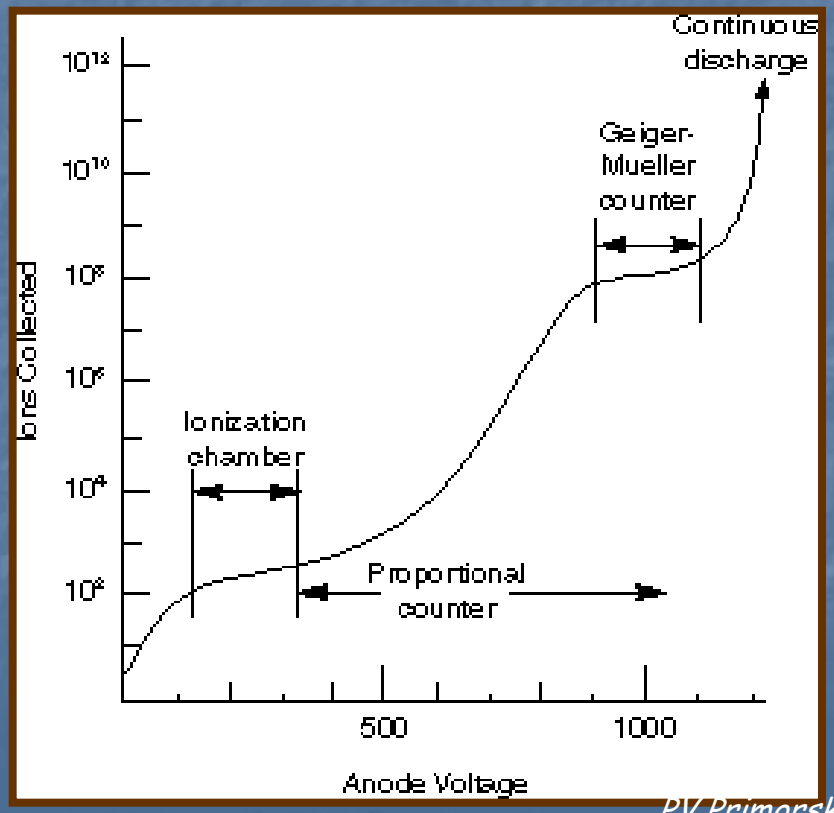


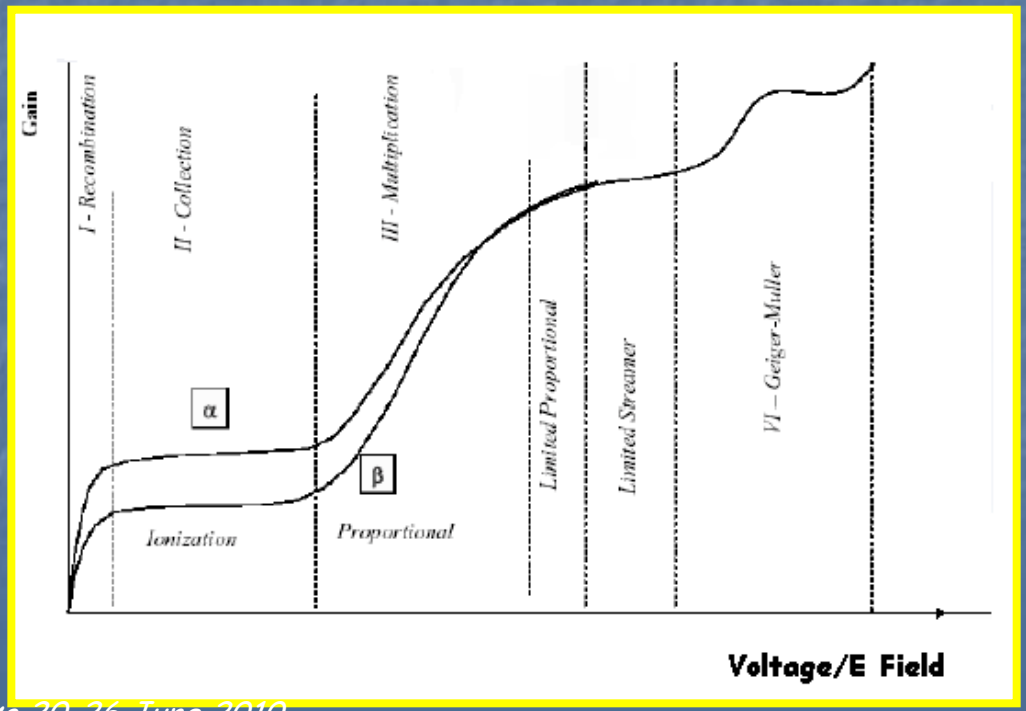
Gaussian distribution→ frequent collisions with small energy loss

1 cm Ar

Drift of electrons in gas

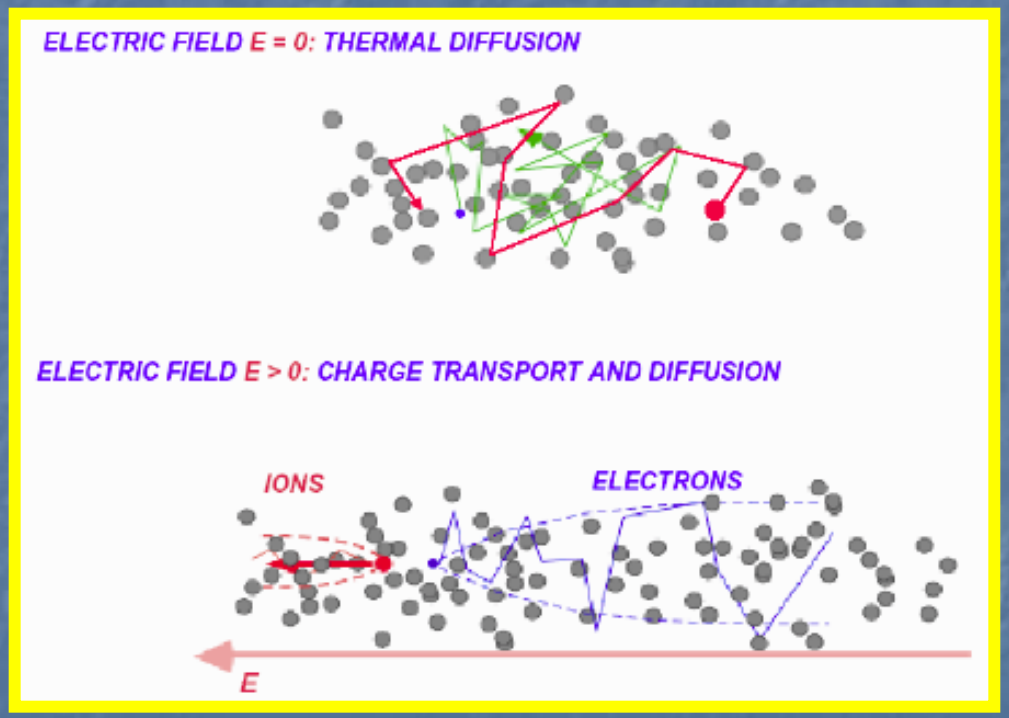
Once the primary ionization is created by a crossing particle into the active volume the created electrons and positive ions start to recombine each other if they are not subjected to a driven force that separate them and possibly initiate the multiplication process. That's why an electric field is always used. The intensity of the field (i.e. the applied voltage) rules the various amplification mechanisms in the gas.





Drift…

If E=0 thermal diffusion makes the electrons and ions to recombine. If an electric field is applied electrons and ions have a net displacement in the direction of the applied field (superimposed to the always present random-directional movement)



Let's complicate this…in experiments a B field is also present (to measure the particles momenta) .

In any case this is the case of an object (electron) moving in a frictional medium (the gas) with external forces (E and B).

The Langevin Equation gives us the response:

$$m\frac{d\vec{u}}{dt} = e\vec{E} + e\vec{u} \wedge \vec{B} - k\vec{u}$$

Drift…

$$m\frac{d\vec{u}}{dt} = e\vec{E} + e\vec{u}\wedge\vec{B} - k\vec{u}$$

m, e →mass and charge of the particle

Ku → friction force (due to the collisions)

Dividing by m and considering the system at equilibrium (du/dt = 0) we end up with:

$$\frac{\vec{u}}{\tau} = \frac{e}{m}\left[\vec{E} + \vec{u}\wedge\vec{B}\right]$$

where we put τ = m/k (which is a characteristic time) . By letting

ω_x=e/m B_x $\quad$ ε_x=e/m E_x

ω_y=e/m B_y $\quad$ ε_y=e/m E_y

ω_z=e/m B_z $\quad$ ε_z=e/m E_z

$$M\vec{u} = \varepsilon$$

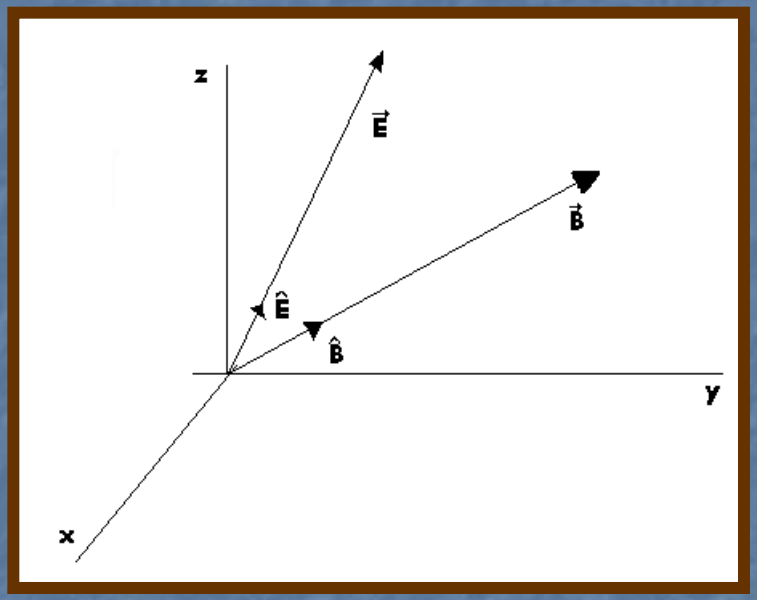
$$M = \begin{pmatrix} \frac{1}{\tau} & -\omega_z & \omega_y \\ \omega_z & \frac{1}{\tau} & -\omega_x \\ -\omega_y & \omega_x & \frac{1}{\tau} \end{pmatrix}$$

$$\vec{u} = M^{-1}\varepsilon$$

$$a_x = 1 + \omega_x^2 \tau^2 \qquad b = \omega_z \tau + \omega_x \omega_y \tau^2$$
$$a_y = 1 + \omega_y^2 \tau^2 \qquad c = \omega_x \tau + \omega_y \omega_z \tau^2$$
$$a_z = 1 + \omega_z^2 \tau^2 \qquad d = \omega_y \tau + \omega_z \omega_x \tau^2$$

$$\omega^2 = \omega_x^2 + \omega_y^2 + \omega_z^2 = (\frac{e}{m})^2 B^2$$

$$M^{-1} = \frac{\tau}{1 + \omega^2 \tau^2} \begin{pmatrix} a_x & b & -d \\ -b & a_y & c \\ d & -c & a_z \end{pmatrix}$$



By letting $\overline{E} = |\overline{E}|\hat{E}, \quad \overline{B} = |\overline{B}|\hat{B}$

$$\vec{u} = \frac{e}{m}\tau |\vec{E}| \frac{1}{1 + \omega^2 \tau^2} \left[\hat{E} + \omega\tau \left(\hat{E} \wedge \hat{B} \right) + \omega^2 \tau^2 \left(\hat{E} \bullet \hat{B} \right) \hat{B} \right]$$

$$\vec{u} = \frac{e}{m}\tau |\vec{E}| \frac{1}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\left(\hat{E}\wedge\hat{B}\right) + \omega^2\tau^2\left(\hat{E}\bullet\hat{B}\right)\hat{B}\right]$$

$\omega\tau$ is a parameter that rules the drift :

1) $\omega\tau$ = 0 (B=0) → u is parallel to E

$$\vec{u} = \frac{e}{m}\tau\vec{E} = \mu\vec{E} \Rightarrow \mu = \frac{e}{m}\tau$$

$$\omega^2 = \omega_x^2 + \omega_y^2 + \omega_z^2 = \left(\frac{e}{m}\right)^2 B^2$$

μ is the mobility of the electron (ion) and can then be defined as the ratio between the drift velocity and the electric field when B is absent.

2) For $\omega\tau$ large compared to 1

The drift velocity is parallel to B

3) If E*B=0 (i.e. B and E are orthogonal) and for large $\omega\tau$ the drift velocity is parallel to the vector product of B and E

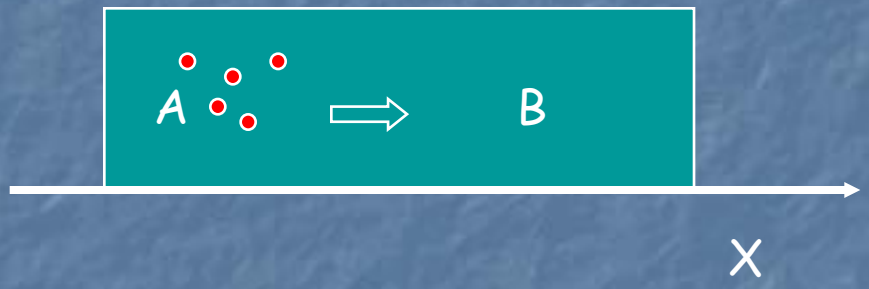
AND …..MORE…DIFFUSION

Diffusion = the random drift of the particles from a high concentration region to a lower one.

If the diluent is steady the only mechanism of transport is the diffusion.

If it is in motion also a drag force adds.

Suppose to have a cloud of electrons created in A : if the gradient of concentration along x is different from 0, there exists a net flux from A to B



$$\frac{\partial C}{\partial x} \neq 0$$

1st Fick Law

If the gradient of concentration is small the flux density is proportional to it →

Otherwise it is only the first term of a series

Expansion →

$$J_x = -D\frac{\partial C}{\partial x}$$

$$J_x = -D\frac{\partial C}{\partial x} + E\frac{\partial^2 C}{\partial x^2} + \ldots$$

The diffusion equation is one of the numerous form of the transport equation:

Particles → $J_P = -D\frac{\partial C}{\partial x}$ $m^{-2}s^{-1}$

Mass → $J_m = -D\frac{\partial C}{\partial x}$ kg/m^2s

Heat → $J_H = -\lambda\frac{\partial C}{\partial x}$ $Joule/m^2s$

El. Charge → $J_e = -\sigma\frac{\partial C}{\partial x}$ C/m^2s

($\frac{\partial something}{\partial x}$ is called driving force:

the gradient of something creates the movement of something else)

More important for our goals is the 2nd Fick's law on diffusion

$$J_x = -D\frac{\partial C}{\partial x} \Rightarrow \frac{\partial J_x}{\partial x} = -D\frac{\partial^2 C}{\partial x^2}$$

$$div\bar{J} = -\frac{\partial C}{\partial t}$$ Continuity equation

$$\Rightarrow \frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) = D\nabla^2 C$$

$$\frac{\partial C}{\partial t} = D\nabla^2 C$$

A Gaussian concentration that spreads out with time is the solution of this differential equation

$$C(x,t) = \frac{C_0}{\sigma(t)\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2(t)}} \qquad \sigma^2(t) = \sigma^2(0) + 2Dt$$

1D

If at a starting time the concentration is Gaussian, after some time t it remains Gaussian-like but with a bigger variance.

Lets go back to drift velocity→

$$v = \mu E = \frac{L}{t} \rightarrow 2Dt = \frac{2DL}{\mu E}$$

so we have

$$\sigma_x{}^2(t) = 2Dt = \frac{2DL}{\mu E}$$

If you want to have lower diffusion go to higher electric field (not always possible…)

$$C(r,t) = \left(\frac{1}{\sqrt{4\pi Dt}}\right)^3 e^{-\frac{r^2}{4Dt}} \qquad r^2 = x^2 + y^2 + (z-ut)^2$$

3D

AND …..MORE…ELECTRON ATTACHMENT

The presence of an electronegative gas (or impurities) reduces the pulse height because it removes electrons.

Be λ = the mean free path (= $A/N_a\sigma\rho$)

v = the instantaneous velocity of the electron

u = the drift velocity

p = fraction of electronegative gas (%)

h= attachment probability

→(v/λ) = collision rate with molecules

→$(v/\lambda)p$ = collision rate with the electronegative gas

→$h\,(v/\lambda)p$ = attachment rate

We can so define a characteristic length related to the attachment:

attachment length = drift velocity times $(\text{attachment rate})^{-1}$

$$\lambda_c = \frac{u}{\left(h(\frac{v}{\lambda})p\right)}$$

→ Mean free path between attachment

$\beta = 1/\lambda_c$ is the attachment coefficient

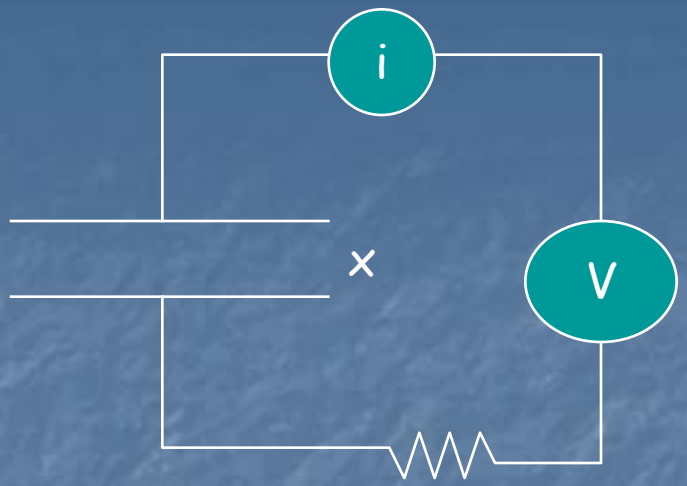
$$\lambda = \frac{A}{N_a \sigma \rho}, \quad \nu = \sqrt{\frac{2\varepsilon}{m}} \Rightarrow$$

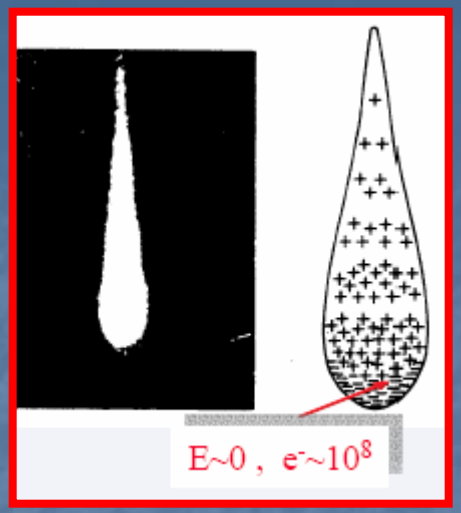
$$\frac{1}{\beta} = \lambda_c = \sqrt{\frac{m}{2\varepsilon}} \frac{uA}{N_a h \rho \sigma p}$$

$$\frac{dn}{dx} = \beta n \Rightarrow n(x) = n(0) e^{\int_0^x \beta dx'}$$

→ Attached electrons. This has to be taken into account when calculating the avalanche formation (see later)

Avalanche development





Electron discharges in gas were studied by J.S. Townsend (Nature 62 (1900) 340) who started a collection of experiments that have been the basis of following studies.

Experimental facts:

- the current in a parallel plane chamber rises (at fixed p) with the electric field E=V/x . But critical behaviors (breakdown) were also known

$$i = i_0 e^{\alpha x}, \alpha = f(\frac{E}{p})$$

Up to know we have studied the problems related to the presence of diffusion and attachment… Let's now see the good things…suppose to have an electron drifting in a gas under the effect of an electric field..

→ by drifting **1 cm** into the gas it creates α new electrons (and +ve ions). So we can write that **αdx** is the number of new electrons creates by the first one in **dx**.
→The variation **dn** for **n** electrons drifting by **dx** is **dn=nαdx** from which we have

$$n(x) = n(0)e^{\int \alpha dx}$$

[α]= cm^{-1} = average number of ionizing collisions in 1 cm;

→λ = 1/ α = average distance between two ionizing collisions. Usually α is considered constant in all the calculations and exits the integral…(but this is not quite true..)

α= First Townsend coefficient

If we have an electronegative gas in the mixture (with β attachment coefficient) not all the electrons can reach the electrode because they are removed from the drifting swarm.

In the same way : **dn**= created electrons in dx – attached electrons in dx → **dn=αndx - βndx = (α–β)ndx** →

$$n(x) = n(0)e^{\int (\alpha-\beta)dx} \qquad M = \frac{n(x)}{n(0)} = e^{\int (\alpha-\beta)dx}$$

Effective first Townsend coefficient

GAS GAIN

Functional dependence of α

A collision produces ionization only if the work done by the electric field in **Δx** is greater than the atom ionization energy.

eE Δx >= e V_{ion} → Δx >= V_{ion}/E If μ = Δx/λ is the average number of collisions in Δx (λ = mean free path) the probability of having , on average, one ionizing collision is $\mu e^{-\mu}$ →

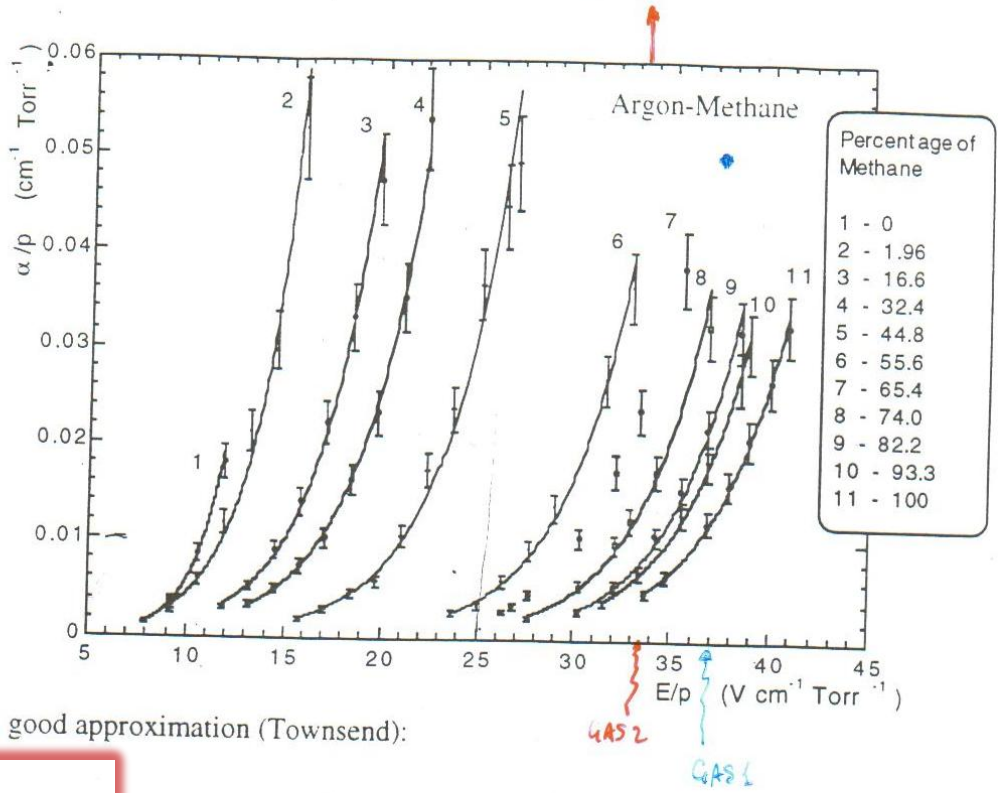
$(\Delta x/\lambda)e^{-(\Delta x/\lambda)}$ in the unity path → $(1/\lambda)e^{-(Vion/\lambda E)}$ but 1/λ = Ap (p= gas pression)

→ $\alpha = Ape^{-ApVion/E}$ or

$$\frac{\alpha}{p} = Ae^{-\frac{B}{E/p}}$$

Korff Relation

FIRST TOWNSEND COEFFICIENT IN MIXTURES



In good approximation (Townsend):

$$\frac{\alpha}{P} = A e^{-B\frac{P}{E}}$$

Argon-Methane mixtures:

Data Set[@]	1	2	3	4	5	6	7	8	9	10	11
Percentage of Methane	0	1.96	16.6	32.4	44.8	55.6	65.4	74.0	82.2	93.3	100
A ($cm^{-1}Torr^{-1}$)	2.8	3.1	2.7	2.3	5.8	38.3	68.0	111.4	237.3	244.7	436.1
B ($Vcm^{-1}Torr^{-1}$)	60.6	65.5	81.7	88.4	130.1	230.1	265.6	298.5	342.5	347.8	388.3
E/p[#] ($Vcm^{-1}Torr^{-1}$)	11.8	15.8	19.7	22.1	26.8	32.8	35.5	36.8	38.4	38.9	40.8

A. Sharma and F. Sauli, Nucl. Instrum. Methods A334 (1993) 420

Secondary effects

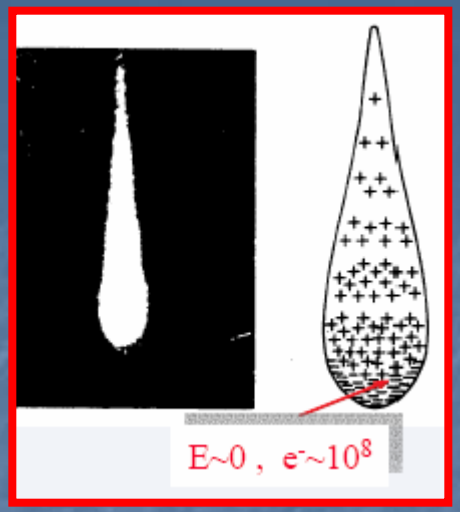
To the primary process of ionizing collisions (controlled by the first Townsend coefficient α) several processes can follow that increase the formation of the avalanche. These effects are regulated by the 2nd Townsend coefficient η such that:

$$i = \frac{i_0 e^{\alpha d}}{1 - \eta(e^{\alpha d} - 1)}$$

For a particular value $d_s = \frac{1}{\alpha}\ln(\frac{1+\eta}{\eta})$ The current diverges and

$V_s = E d_s$ is the sparking potential

We go from the avalanche to the sparking regime: into the middle we can have a streamer regime…



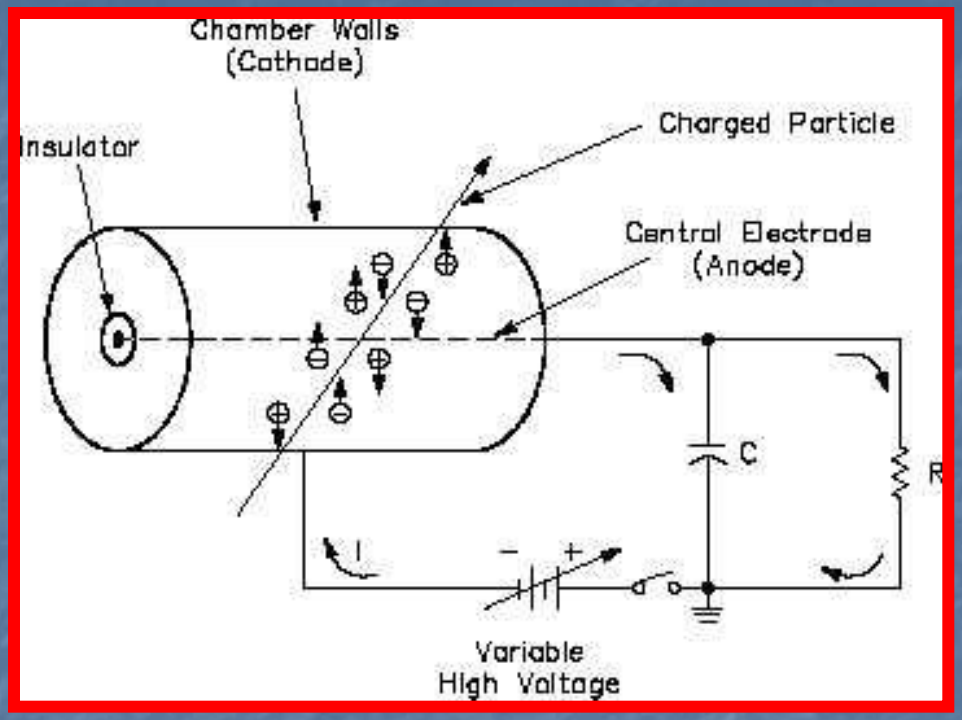
Streamer

when the gain is greater than 10^8 (Reather limit);

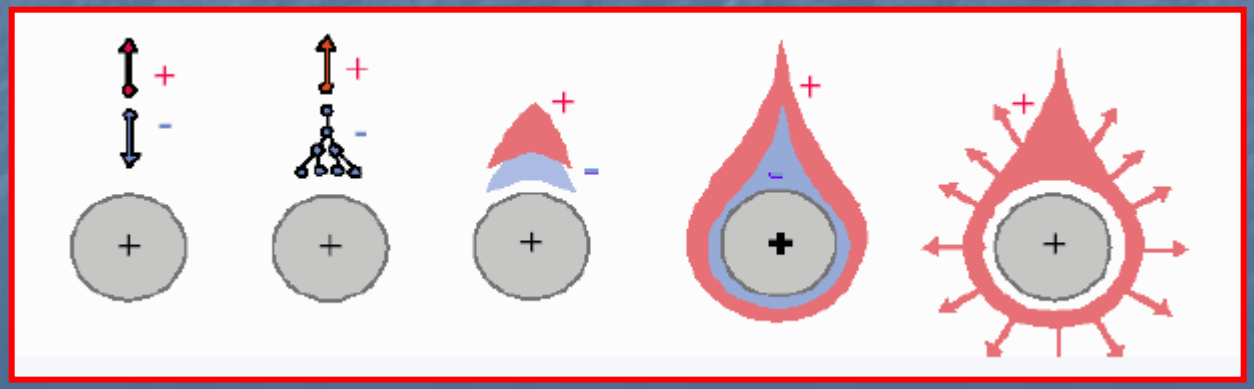
- the spatial charge produces an internal electric field opposite to the one applied and of the same magnitude, this in turn makes
- recombination of electrons and +ve ions which in turn makes
- production of UV photons that
- produce secondary avalanches

$$10^8 = e^{\alpha d} \Rightarrow \alpha d \approx 18 \div 20$$

Signal generation on the wire of a cylindrical detector

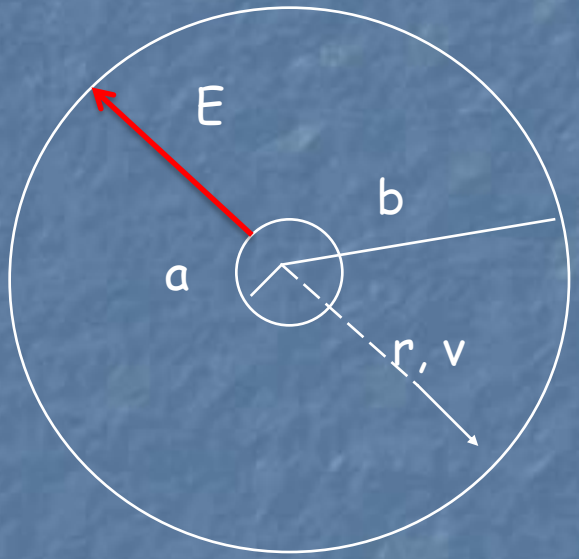


The signal on the anode is generated by induction of the moving charges inside the detector before the actual collection



Ramo's Therorem

Suppose a charge q is drifting with velocity v inside a cylindrical detector to which an electric field E has been applied. The induced current at the anode is $i = -q\vec{E}_w \cdot \vec{v}$ E_w is the *weighting field* i.e. the electric field per unit voltage at the electrode.



We consider the effect of a positive ions that is drifting toward the cathode:

$$E(r) = \frac{V}{r\ln(\frac{b}{a})} = E(a)\frac{a}{r} \Rightarrow E_w = \frac{1}{r\ln(\frac{b}{a})}$$

The positive ion is moving along the field direction so that v and E are parallel.

$$v = \frac{dr}{dt} = \mu_+ E = \mu_+ E(a)\frac{a}{r}$$

$$i(r) = -q\frac{1}{r\ln(\frac{b}{a})}\mu_+ E(a)\frac{a}{r} = -q\mu_+ E(a)\frac{a}{r^2\ln(\frac{b}{a})}$$

To obtain i=i(t) we need to know the dynamic of the ion:

$$\frac{dr}{dt} = \mu_+ E(r) = \mu_+ E(a)\frac{a}{r} \Rightarrow rdr = \mu_+ E(a) a dt$$

$$\int_a^r r' dr' = \int_0^t \mu_+ E(a) a dt' \Rightarrow \frac{r^2}{2} - \frac{a^2}{2} = \mu_+ E(a) a t$$

$$r^2 = a^2 + 2\mu_+ E(a) a t = a^2 (1 + \frac{2\mu_+ E(a)}{a} t) = a^2 (1 + \frac{t}{t_0})$$

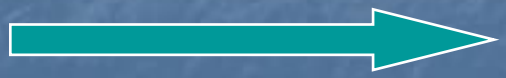
$$with\ t_0 = \frac{a}{2\mu_+ E(a)}$$

Characteristic time of the ion (order of ns)

$$i(r) = -q \frac{1}{r \ln(\frac{b}{a})} \mu_+ E(a) \frac{a}{r} = -q\mu_+ E(a) \frac{a}{r^2 \ln(\frac{b}{a})}$$

$$\Rightarrow i(t) = -q\mu_+ E(a) \frac{1}{a \ln(\frac{b}{a})} \frac{1}{(1 + \frac{t}{t_0})}$$

$$i_m = q\mu_+ E(a) \frac{1}{a \ln(\frac{b}{a})} \Rightarrow \frac{i(t)}{i_m} = -\frac{1}{(1 + \frac{t}{t_0})}$$

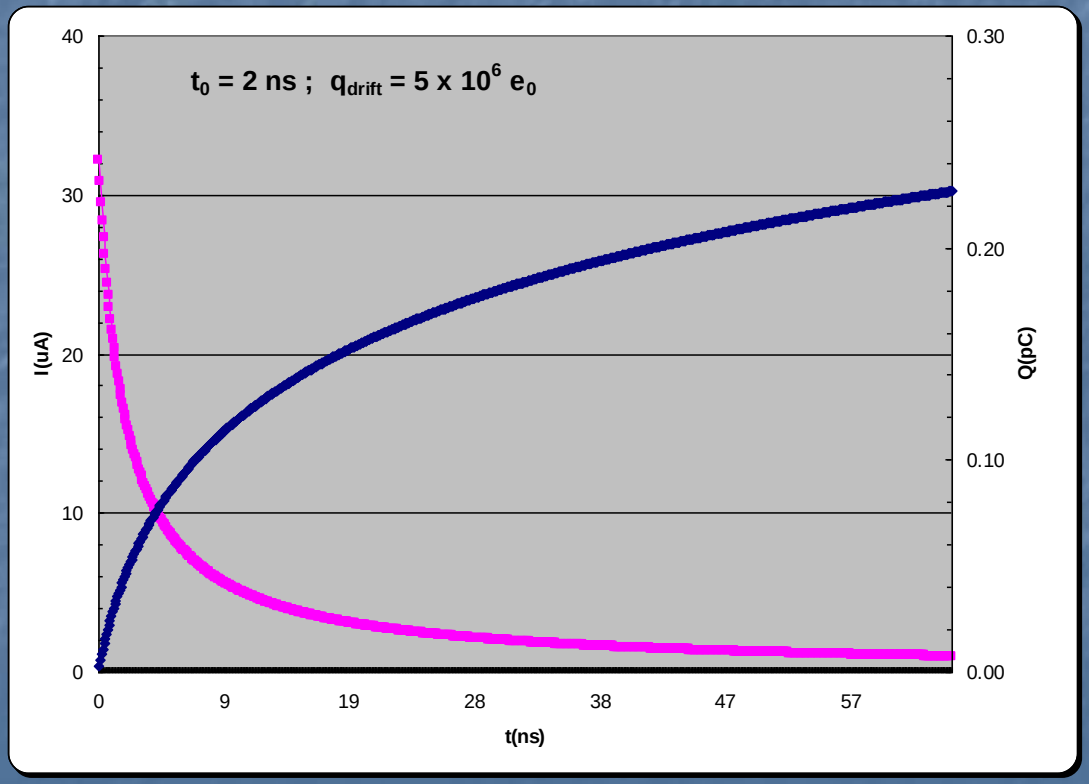


If this current is integrated by a capacitor :

$$V(t) = \frac{1}{C}\int i(t)dt = -\frac{q}{2C\ln(\frac{b}{a})}\ln(1+\frac{t}{t_0})$$

Typical values:

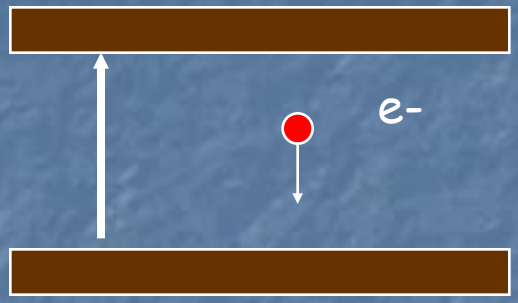
$$q = 10^6 e_0$$
$$\frac{b}{a} = 500$$
$$t_0 = 2ns$$



The induced charge is:

$$\frac{Q_i(t)}{q} = -\frac{1}{2\ln(\frac{b}{a})}\ln(1+\frac{t}{t_0})$$

What happens for a parallel geometry?



$$i = -q\vec{E}_w \cdot \vec{v}$$

Now v and E have opposite versus and

We have also a different $E_w = k/d$, k depending on the geometry and on the material of the electrodes…

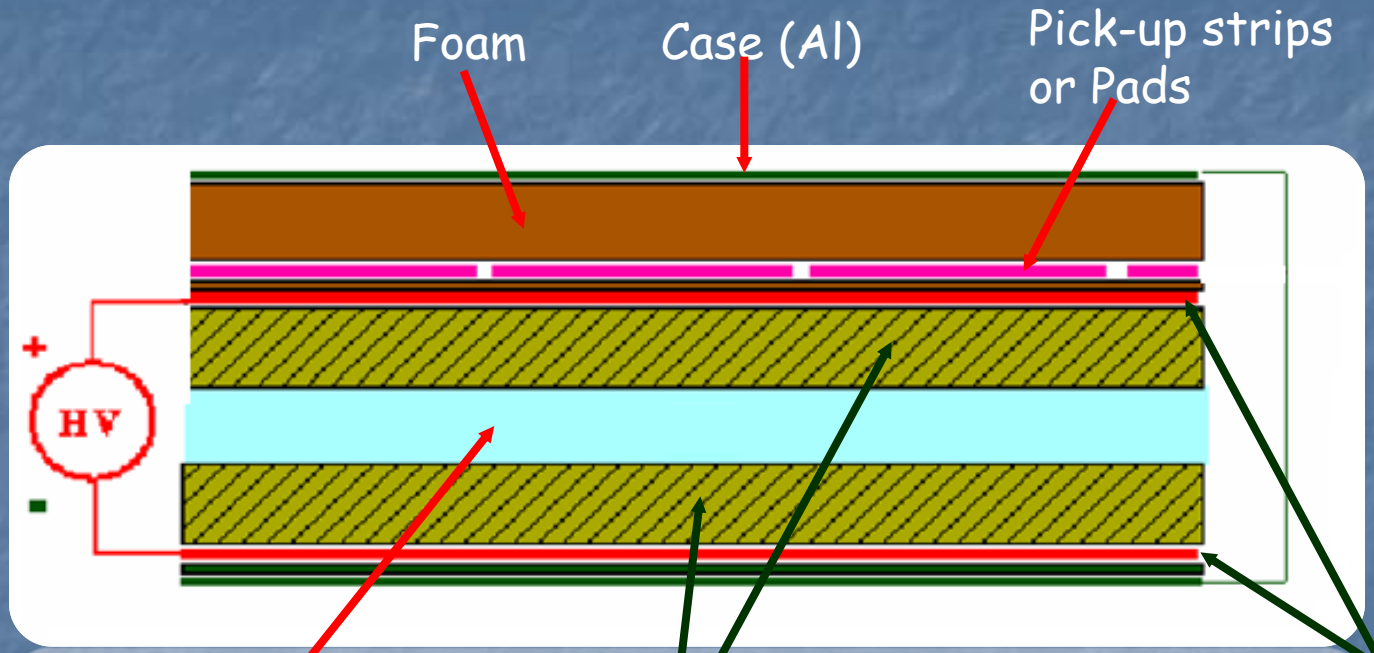
$$i(t) = q(t)\frac{k}{d}v(t) = q_0 e^{\alpha v t}\frac{k}{d}v$$

$$Q_i(t) = \int i(t)dt = q_0\frac{k}{\alpha d}(e^{\alpha v t} - 1) \approx q_0\frac{k}{\alpha d}e^{\alpha v t}$$

It is interesting to note that the ratio of the induced charge and the total charge inside the detector is

$$\frac{Q_i}{Q_{tot}} = \frac{k}{\alpha d}$$

Resistive Plate Counters (RPCs)



Gas volume (2 mm)

Resistive Electrodes with linseed oil film

melamine, phenolic resins → "bakelite" better said HPL (High Pressure Laminates)

HV distribution: semi-conductive layer (graphite …)

P ~ 1 Atm

$\rho \sim 10^{10}$-10^{12} Ωcm

Why we need a semi conductive layer?

We want to see the induced signal into the pick-up strips (signal is affected by the surface resistivity of the semi conductive layer)

Why we need high (volume) resistivity electrodes ?

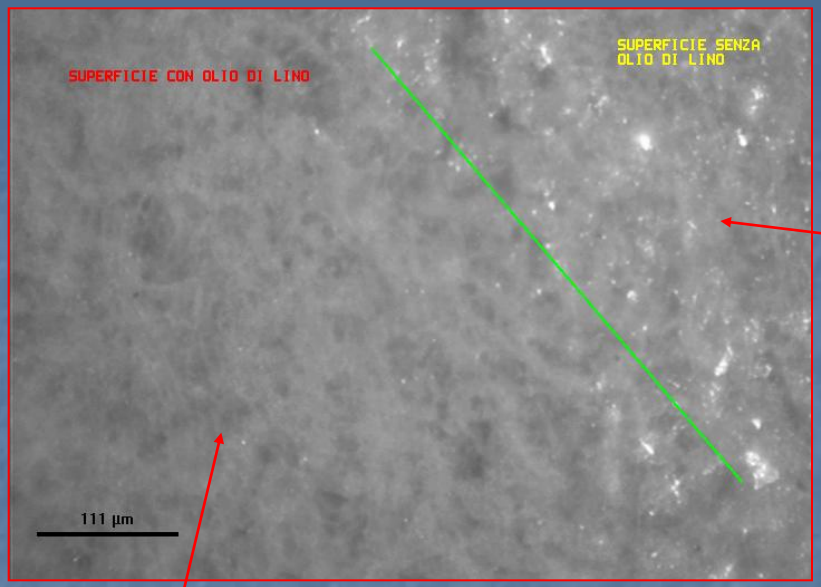
To localize the discharge that takes place inside the detector (better on this later on)

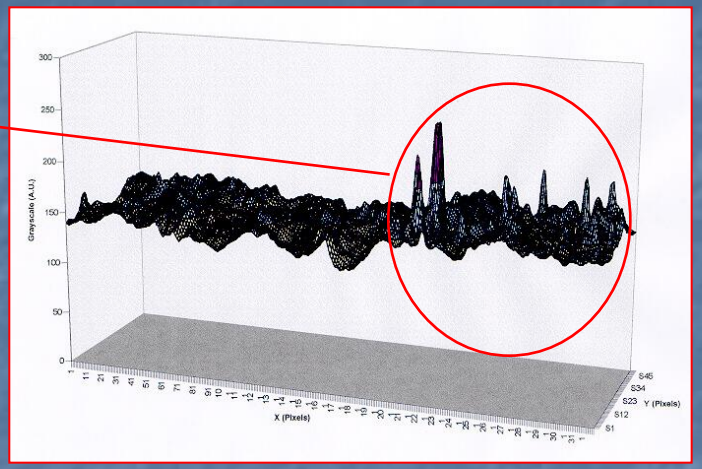
Only a limited area around the discharge remains inefficient to the next event

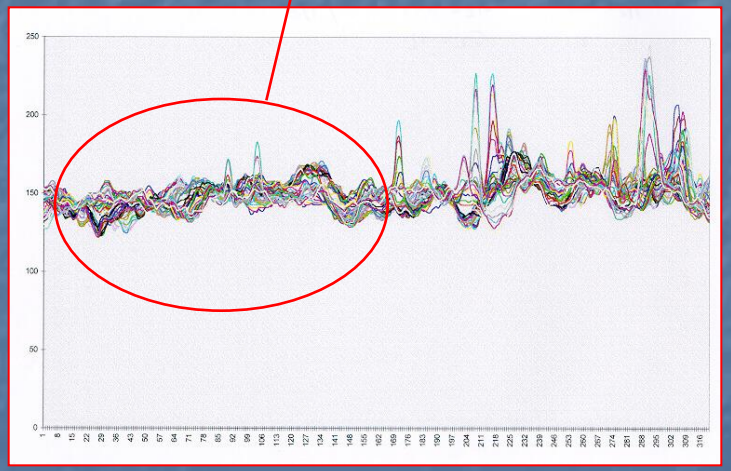
The same mechanism is also done by the gas mixture that contains iC_4H_{10} as a UV qhencher and SF_6 as electron quencher

Why Electrodes are "cured" with linseed oil ?

Linseed oil makes the surface smoother

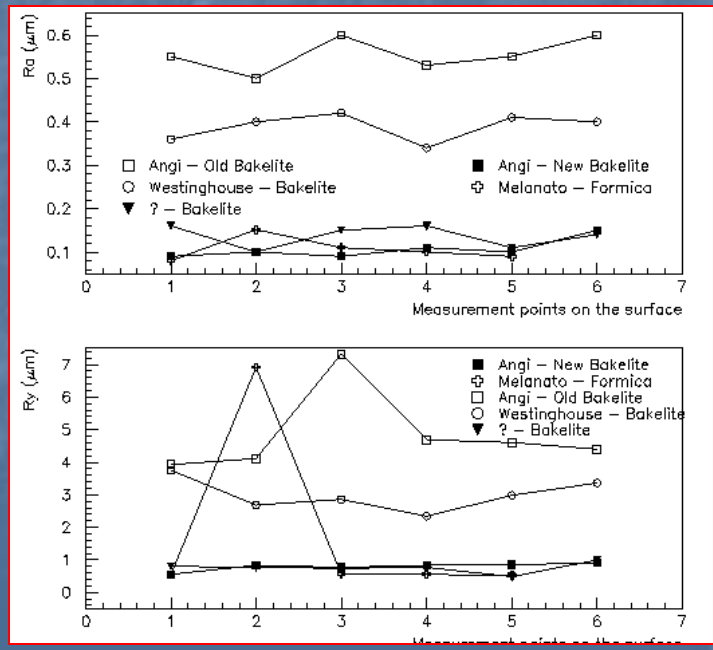




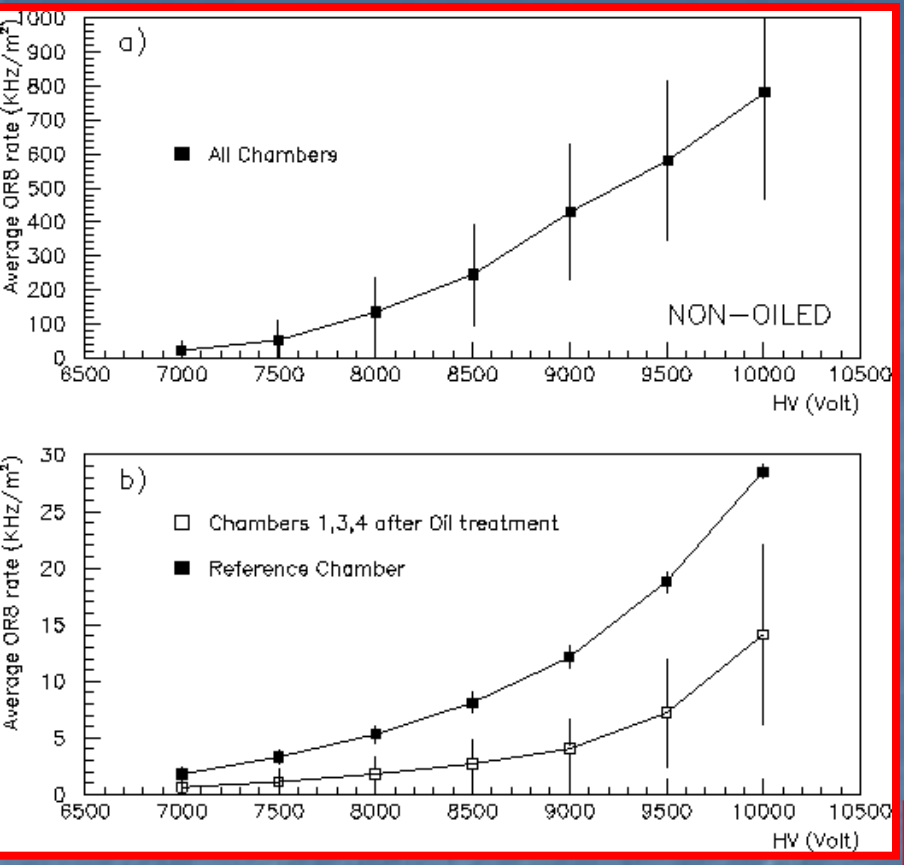


The smoother the surface, the lower the intrinsic noise of the detector

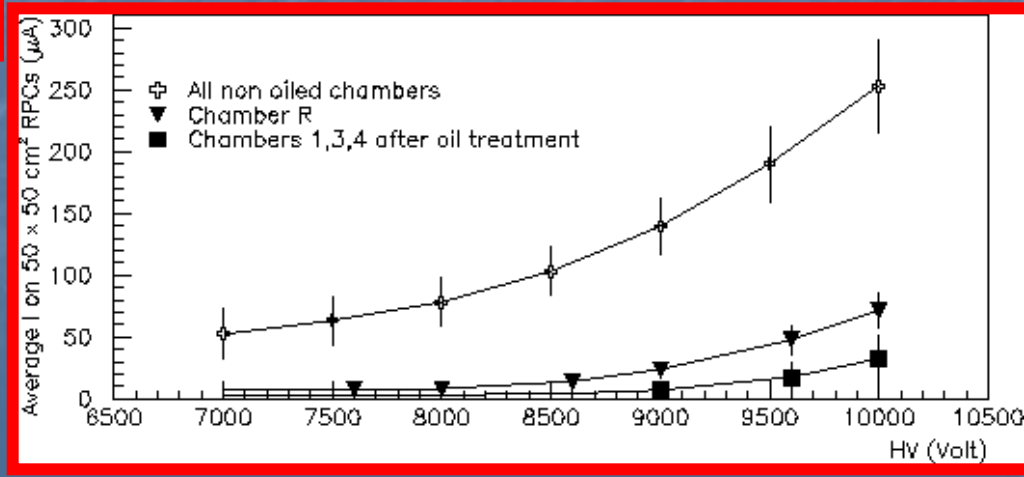
Roughness measurements



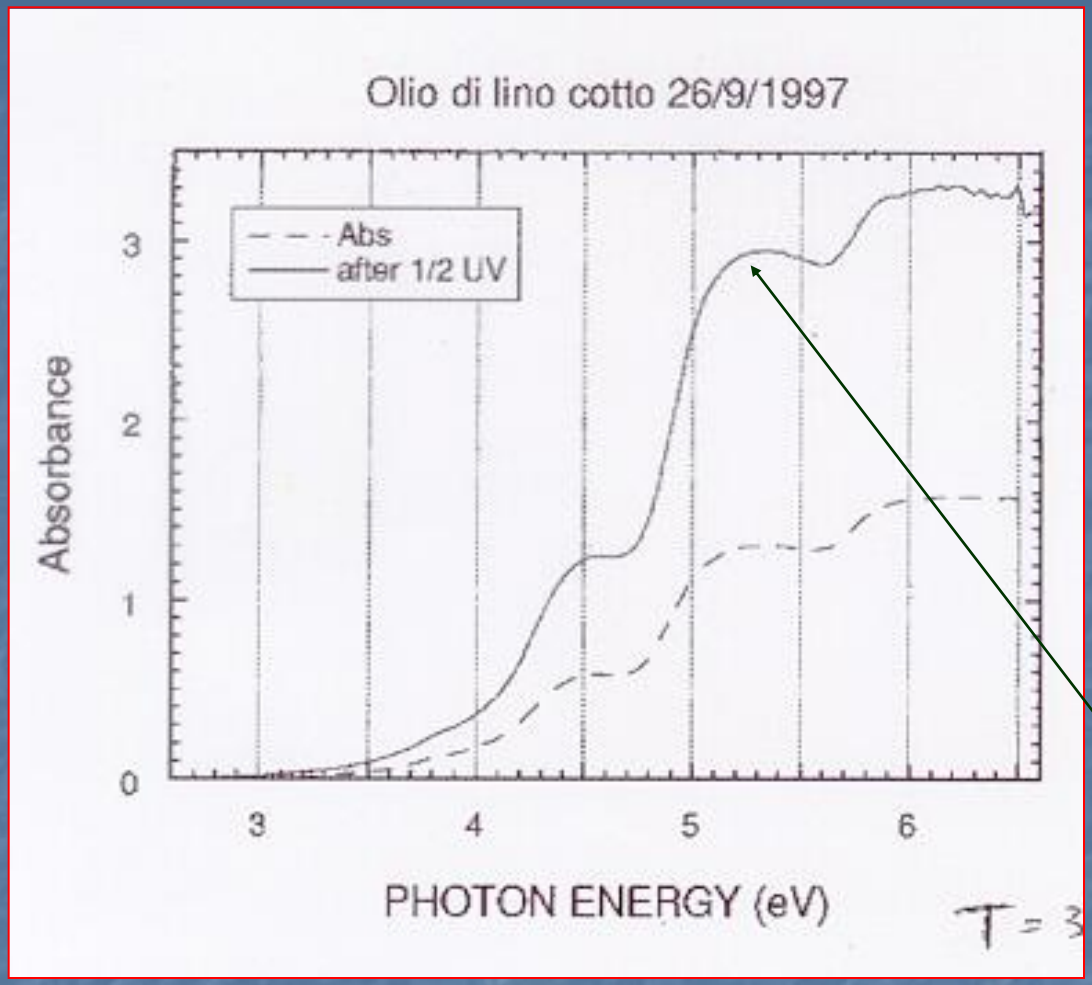
Why Electrodes are "cured" with linseed oil ? (cntd)



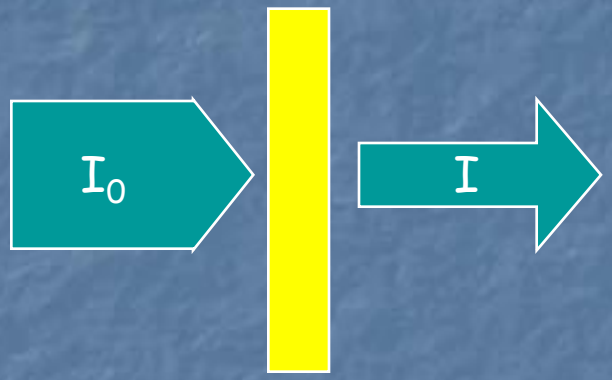
Reduced Currents and Noise rate



Linseed oil as a UV quencher?



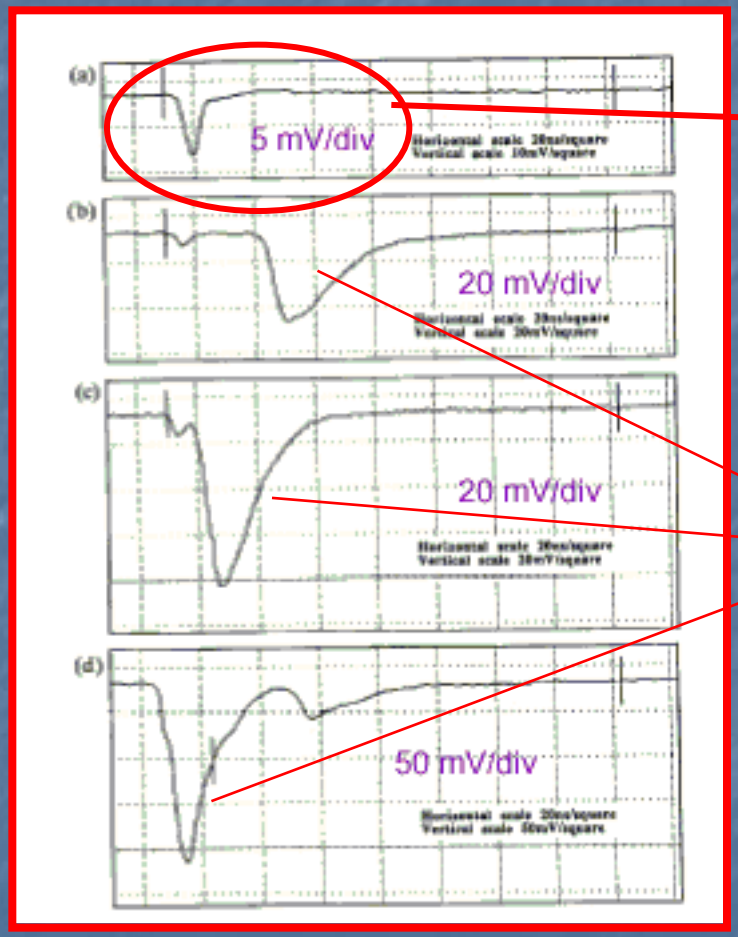
$$A = \log_{10}\left(\frac{I_0}{I}\right)$$

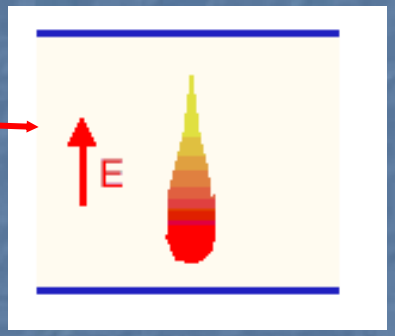


After aging with intense UV lamp

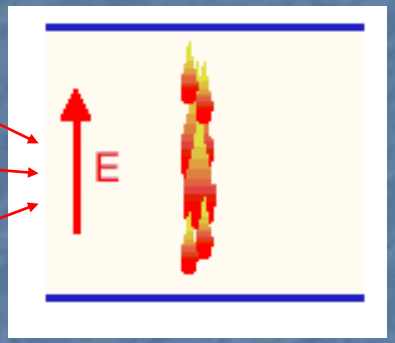
Working Regime

RPC work with a uniform E (4-5 kV/mm) in avalanche or streamer mode depending on the gas mixture and on the applications needs

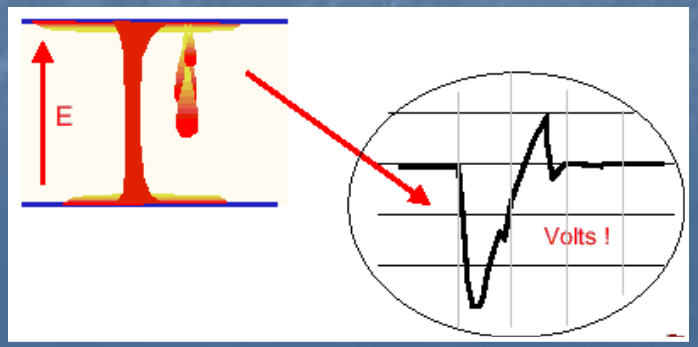




Avalanche:

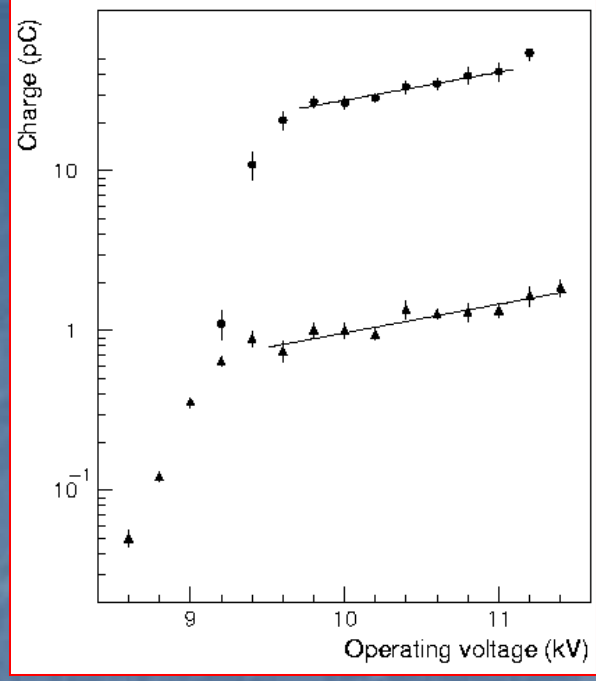


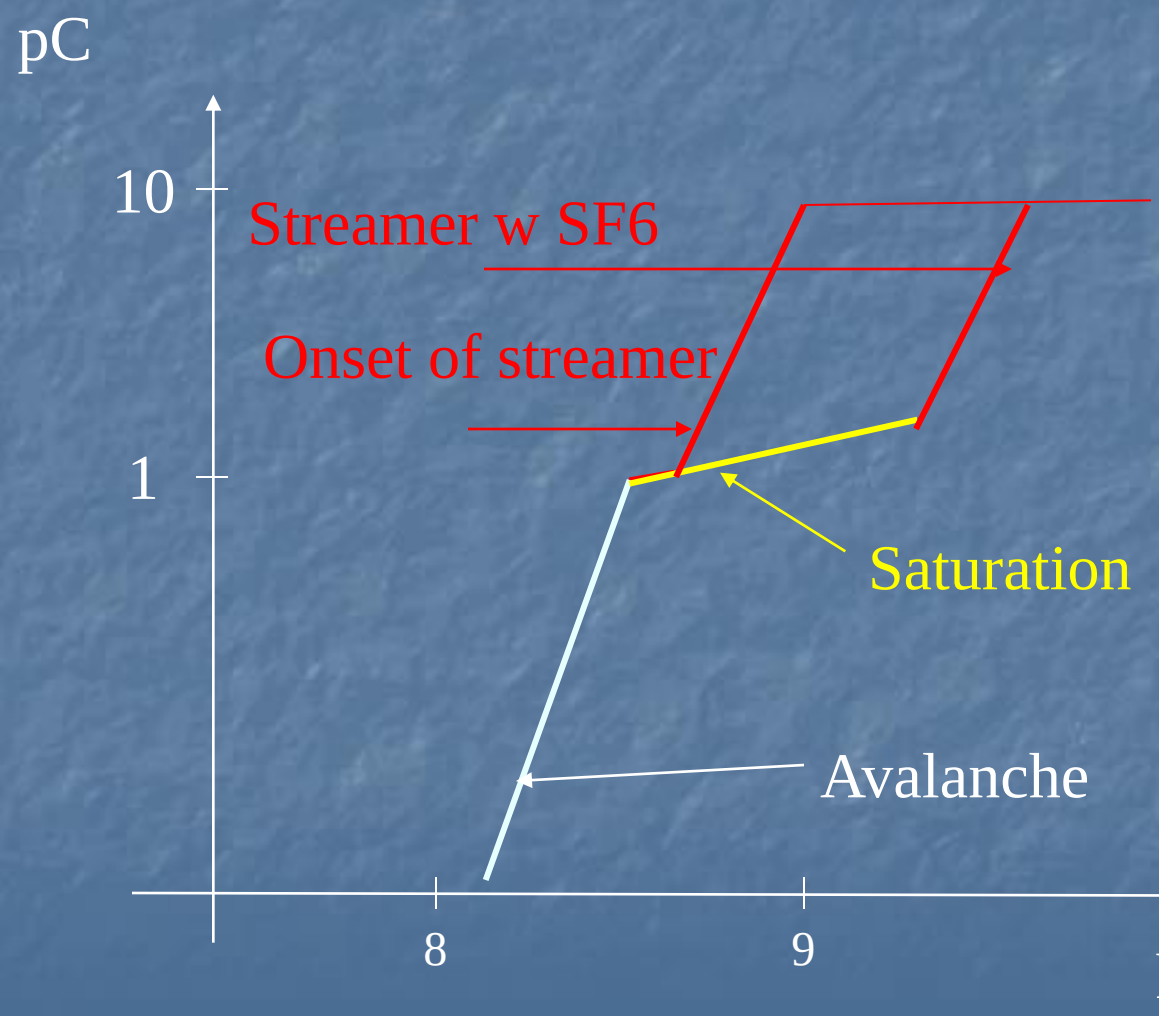
Stramer:



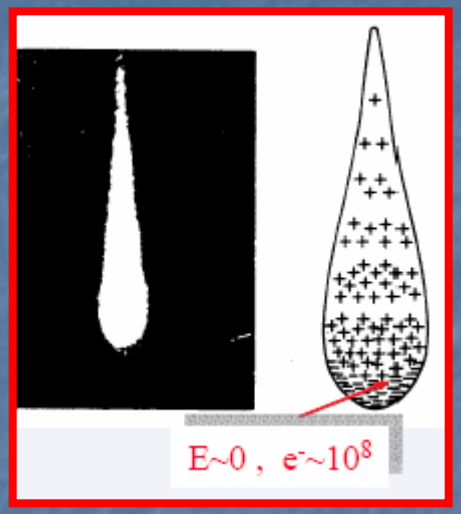
Spark:

Charge saturation





A reminder from before…



Streamer

when the gain is greater than 10^8 (Raether limit);

- the spatial charge produces an internal electric field opposite to the one applied and of the same magnitude, this in turn make
- recombination of electron and +ve ions which in turn makes
- production of UV photons that
- produce secondary avalanches

$$10^8 = e^{\alpha d} \Rightarrow \alpha d \approx 18 \div 20$$

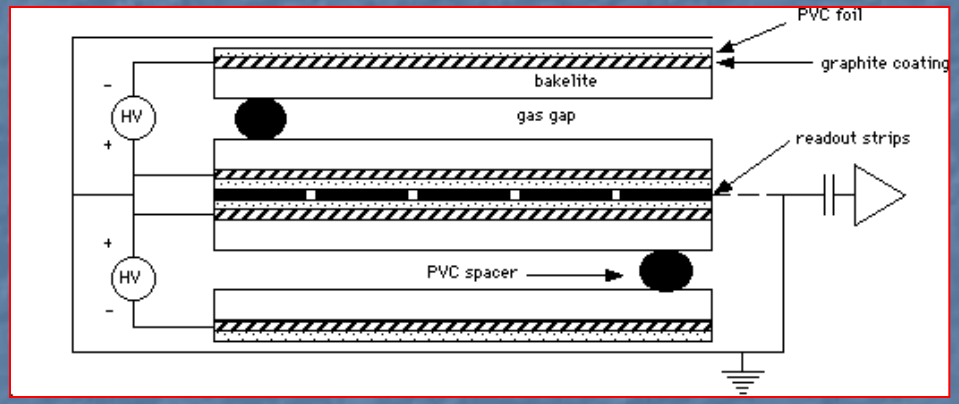
Induced signal:

$$i = -q\vec{E}_w \cdot \vec{v}$$

$$\frac{Q_i}{Q_{tot}} = \frac{k}{\alpha d}$$

$$i(t) = q(t)\frac{k}{d}v(t) = q_0 e^{\alpha v t}\frac{k}{d}v(t)$$

$$Q_i(t) = \int i(t)dt = q_0 \frac{k}{\alpha d}(e^{\alpha v t} - 1) \approx q_0 \frac{k}{\alpha d}e^{\alpha v t}$$



$$k = \frac{\varepsilon_r d}{n_g \varepsilon_r d + (n_g + 1)s}$$

d = gap width

ε_r = dielectric permettivity

s = electrode width

n_g = number of gaps

These are average values→ we have to consider also fluctuation on the avalanche development due to:

-the number of cluster/event (Poissonian fluctuation)

-the number of primary electrons/cluster

-gain fluctuation (Polya or Furry distribution)

Avalanche development and fluctuation

$$P_{cl}(n_{cl}=k)=\frac{(g\lambda)^k}{k!}e^{-g\lambda}$$

$$P_P(n_{av}=n)=\left[\frac{n}{N}(1+\vartheta)\right]^{\vartheta}e^{\left[-\frac{n}{N}(1+\vartheta)\right]}$$

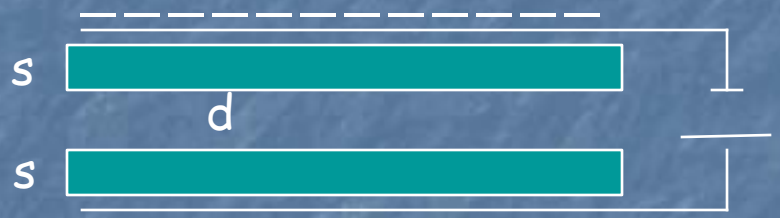
$$P_F(n_{av}=n)=\frac{1}{N}e^{-\frac{n}{N}}$$

$$q(x)=\sum_{j=1}^{n_{cl}} q_{el}n_j^0 M_j e^{\eta\left(x-x_j^0\right)}$$

$$P_P^j(x_0^j=x)=\frac{\lambda}{(j-1)!}(x\lambda)^{j-1}e^{-x\lambda}$$

How do we calculate the factor ?

$$k = \frac{\varepsilon_r d}{n_g \varepsilon_r d + (n_g + 1)s} = \frac{\varepsilon_r d / s}{n_g \varepsilon_r d / s + (n_g + 1)}$$



V_0 = 1 V

Following Ramo's theorem prescriptions we set to 1 V the potential of the electrode where we want to calculate the induced current (and ground the others)

$$V_0 = 2V_s + V_d = 2V_s + Ed \quad (V_0 = 1 \Rightarrow E = E_W)$$

$$1 = 2V_s + E_W d \qquad \varepsilon_r^g (\approx 1) E_g = \varepsilon_r E_b$$

$$E_s = \frac{E_W}{\varepsilon_r} = \frac{V_s}{s} \Rightarrow V_s = \frac{E_W}{\varepsilon_r} s$$

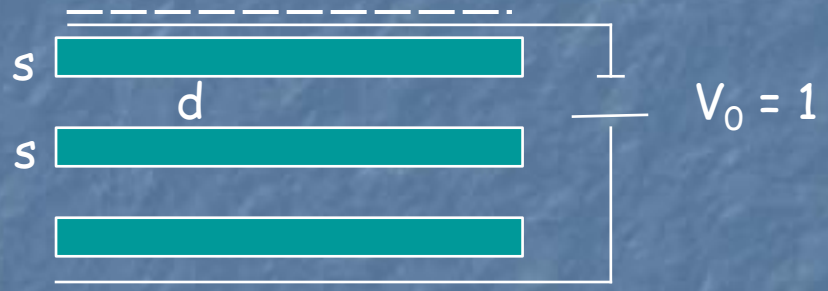
$$1 = 2\frac{E_W}{\varepsilon_r} s + E_W d \qquad 1 = E_W d \left(\frac{\varepsilon_r d + 2s}{\varepsilon_r d}\right)$$

$$E_W = \frac{1}{d} \times \left(\frac{\varepsilon_r d / s}{2 + \varepsilon_r d / s}\right) = \frac{k}{d} \qquad (n_g = 1)$$

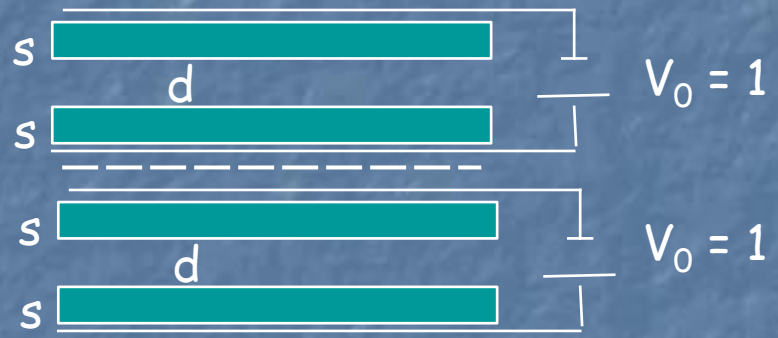
Continuity of the normal component of the electrical flux density D

k= signal attenuation factor = f(ε_r, geometry)

Read-out geometry



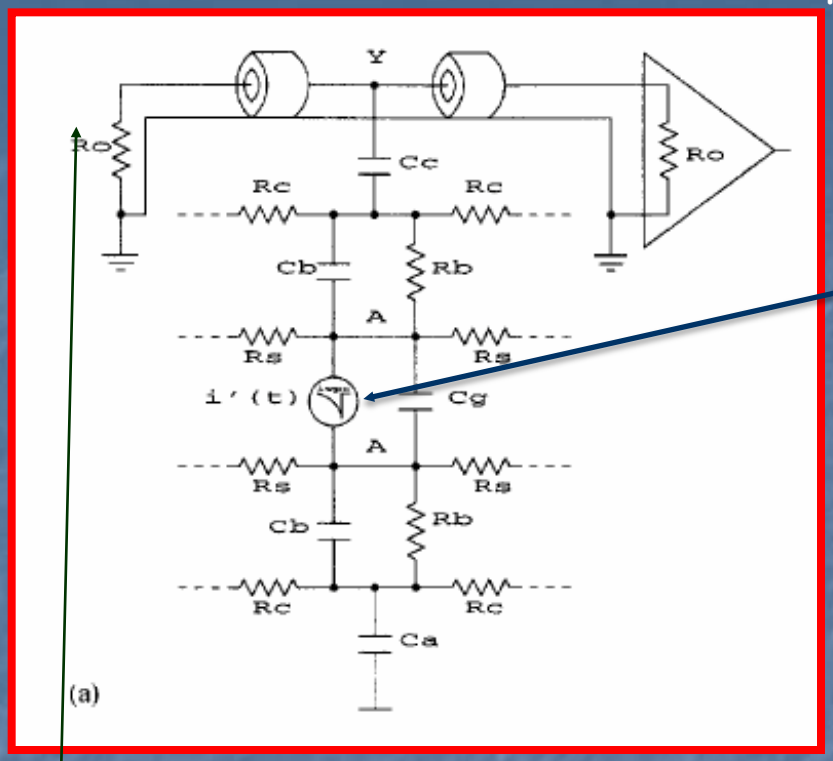
"Common Read-out"

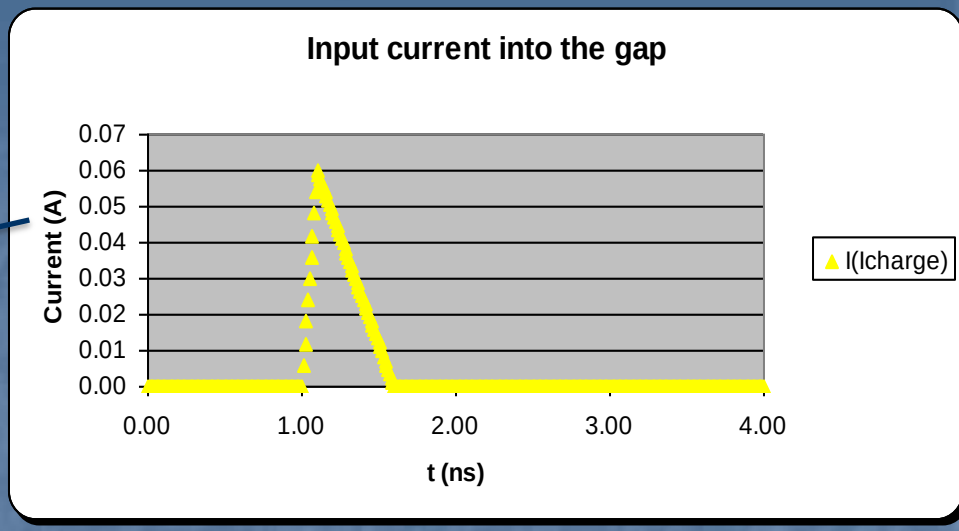


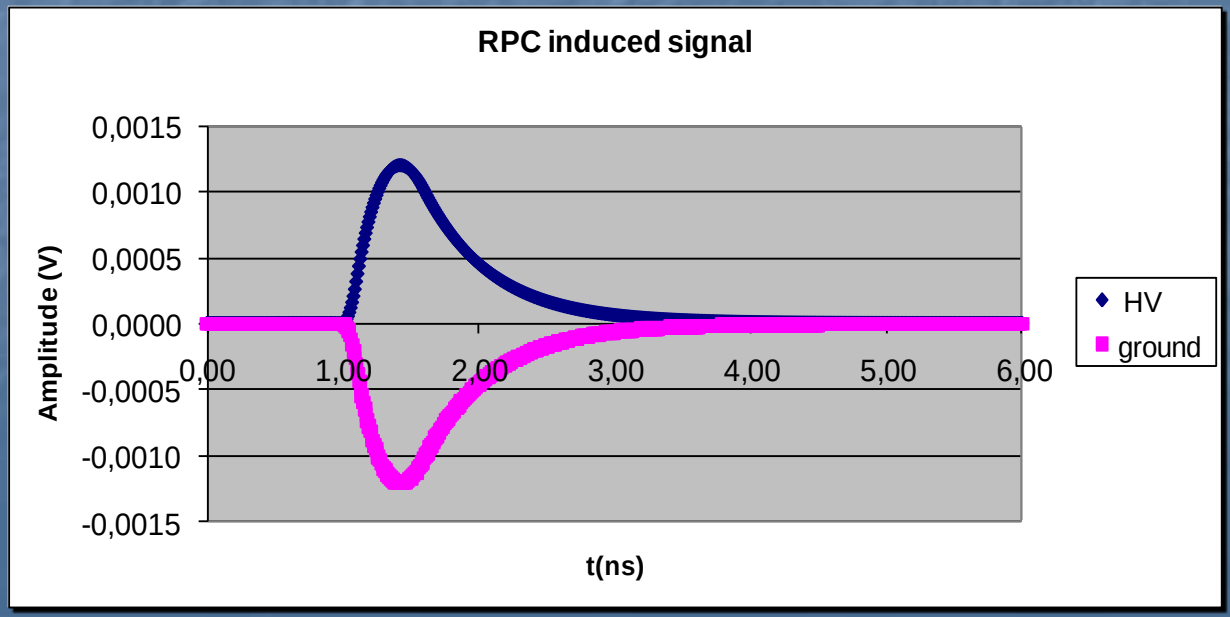
$$k = \frac{\varepsilon_r d / s}{2\varepsilon_r d / s + 3}$$

$$k = 2 \times \frac{\varepsilon_r d / s}{\varepsilon_r d / s + 2}$$

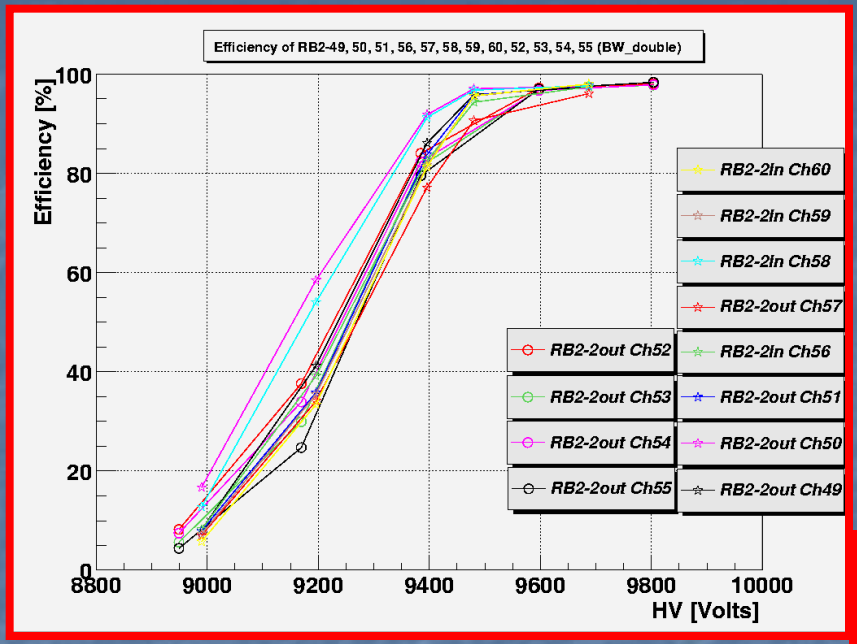
Pspice simulation





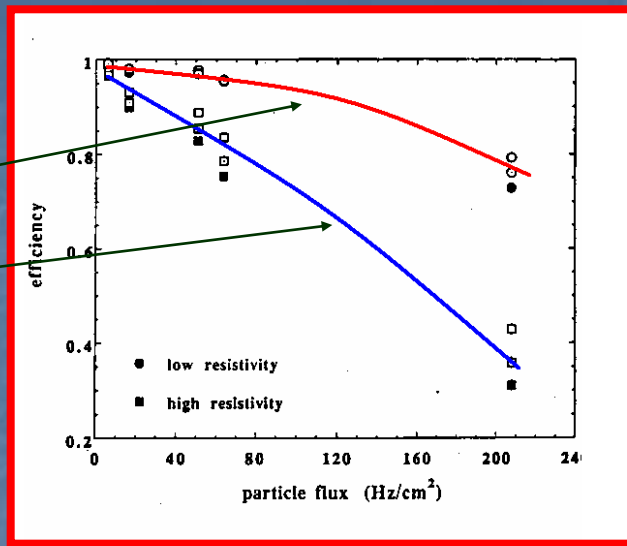


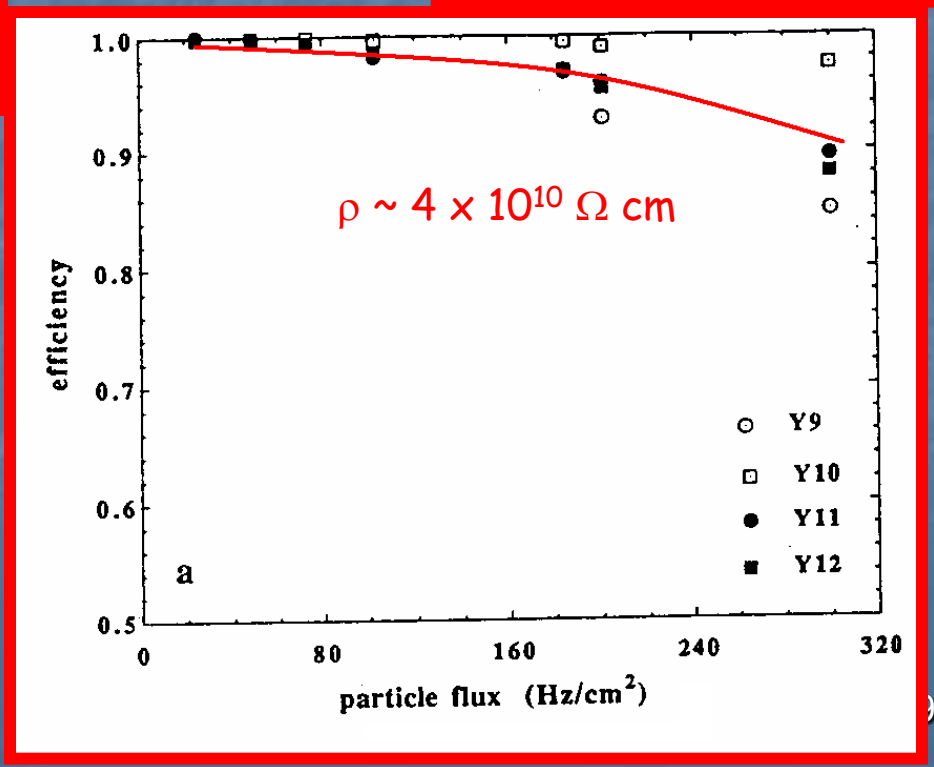
Double gap RPC efficiency to charged particles



Low ρ

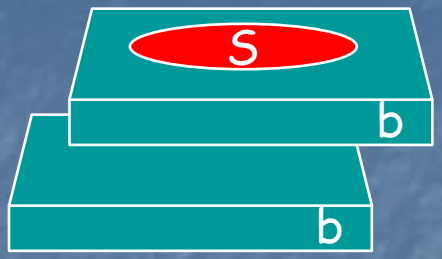
High ρ





Rate Capability

How particle rate affects RPCs operation



$$F = flux(\frac{part}{cm^2 s}),\ \mathrm{R} = \rho\frac{b}{\mathrm{S}}(\Omega),\ \mathrm{q} = \frac{\mathrm{charge}}{\mathrm{part}}(\frac{C}{part})$$

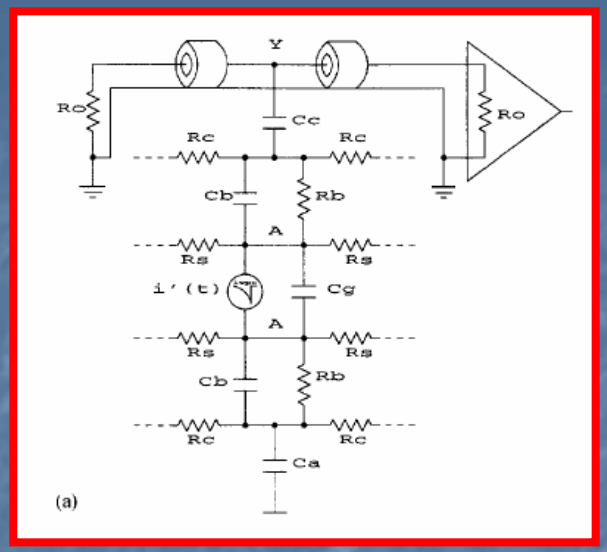
$$\frac{part}{cm^2 s}\times\frac{\mathrm{charge}}{\mathrm{part}} = J = \frac{curr}{cm^2} = \frac{I}{S} = \frac{\Delta V}{RS} = \frac{\Delta V}{\rho b}$$

$$\Delta V = F\times q\times\rho\times 2b$$

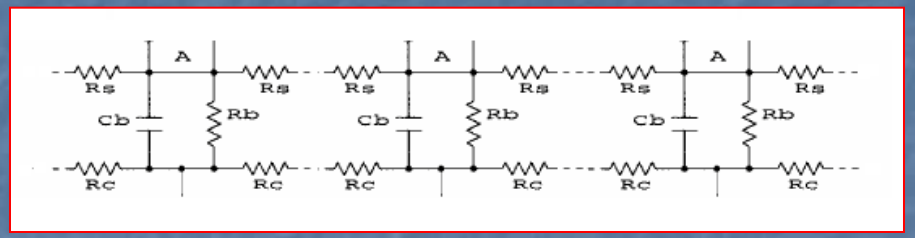
ΔV is the voltage drop across the RPC (gap + electrodes)

Es: RPCs@LHC :
F=10 Hz/cm^2 (Barrel) ρ = 5 10^{10} Ω cm b=0.2 cm q=25 pC → ΔV = 5 V OK!

Why we need high volume resistivity electrodes ?



Lumped circuit made of elementary small cells



$$R_b = \rho \frac{d}{S}\,;\, C_b = \frac{\varepsilon_0 \varepsilon_r S}{d}$$

Discharging time linked to drift velocity and multiplication factor

$$\tau_{dis} = \frac{1}{\eta v_d} \approx 10ns$$

Recovery time of one cell = R_bC_b:

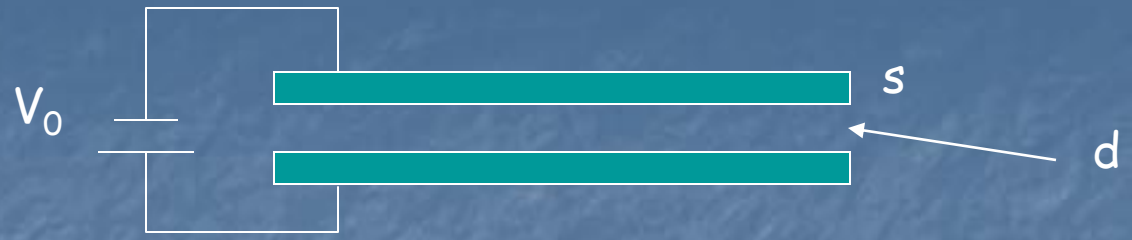
$$\tau_{rec} = \rho\varepsilon_0(\varepsilon_r + \frac{2b}{g}) \approx 10ms$$

$\tau_{dis} << \tau_{rec}$

Since the recovery time is much higher than the discharge one once the electrons are collected at the anode they neutralize the corresponding +ve charges, the electric field goes to 0 and the discharge is locally quenched.

→ During the discharge electrodes behave like a dielectric

How does the dielectric permittivity ε_r enter the physics of RPCs ?



A) First example (static): which is the voltage drop V_b on the bakelite plates ?

$$V_0 = 2V_b + V_g \qquad \varepsilon_r^g E_g = \varepsilon_r E_b$$

Continuity of the normal component of the electrical flux density D

$$V_0 = 2s\frac{\varepsilon_r^g(\approx 1)E_g}{\varepsilon_r} + V_g$$

$$V_0 = 2s\frac{V_g}{\varepsilon_r d} + V_g = \frac{2s+\varepsilon_r d}{\varepsilon_r d}V_g$$

$$V_g = \frac{\varepsilon_r d}{2s+\varepsilon_r d}V_0$$

s=d=2mm @ ε_r usually chosen as 4 to 7 for bakelite (see textbooks)

V_g = (67% to 77%) V_0

Inverting the relation and allowing V_g > 95% V_0

ε_r must be greater (when DC coupled)

ε_r > 40 !! (and even greater)

B) Second example (dynamic): which is the induced charge on a pick-up strip?

$$q_{ind} = \frac{q_e}{\eta d} k(\varepsilon_r) n_0 M \left[e^{\eta (d - x_0)} - 1 \right]$$

single cluster

q_e	Electron charge
n_0	Nuber of initial electrons
M	Gain fluctuations
x_0	Initial coordinate of the cluster
η	Effective townsend coefficient
d	Gap width

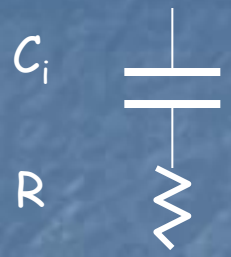
This ε_r has a different value wrt that of the previous example

$$k(\varepsilon_r) = \frac{\varepsilon_r d}{2s + \varepsilon_r d}$$

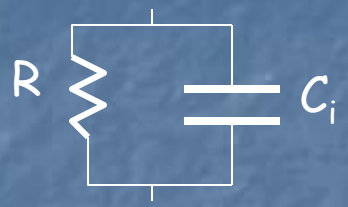
Case A) $\varepsilon_r = \varepsilon_r (\omega \sim 0)$

B) $\varepsilon_r = \varepsilon_r (\omega \sim$ optical limit) signal transient

Usual representation of dielectrics by lumped circuits equivalents



The Simplest:



$$k' = \frac{\varepsilon'}{\varepsilon_0} = \frac{C_i}{C_0}\frac{1}{(1+\omega^2\tau^2)}$$ permittivity

$$k'' = \frac{\varepsilon''}{\varepsilon_0} = \frac{C_i}{C_0}\frac{\omega\tau}{(1+\omega^2\tau^2)}$$ loss factor

$$tg\,\delta = \frac{k''}{k'} = \omega\tau$$ loss tangent

$$k' = \frac{\varepsilon'}{\varepsilon_0} = \frac{C_i}{C_0}$$

$$k'' = \frac{\varepsilon''}{\varepsilon_0} = \frac{1}{\omega\tau_0}$$

$$tg\,\delta = \frac{k''}{k'} = \frac{1}{\omega\tau}$$

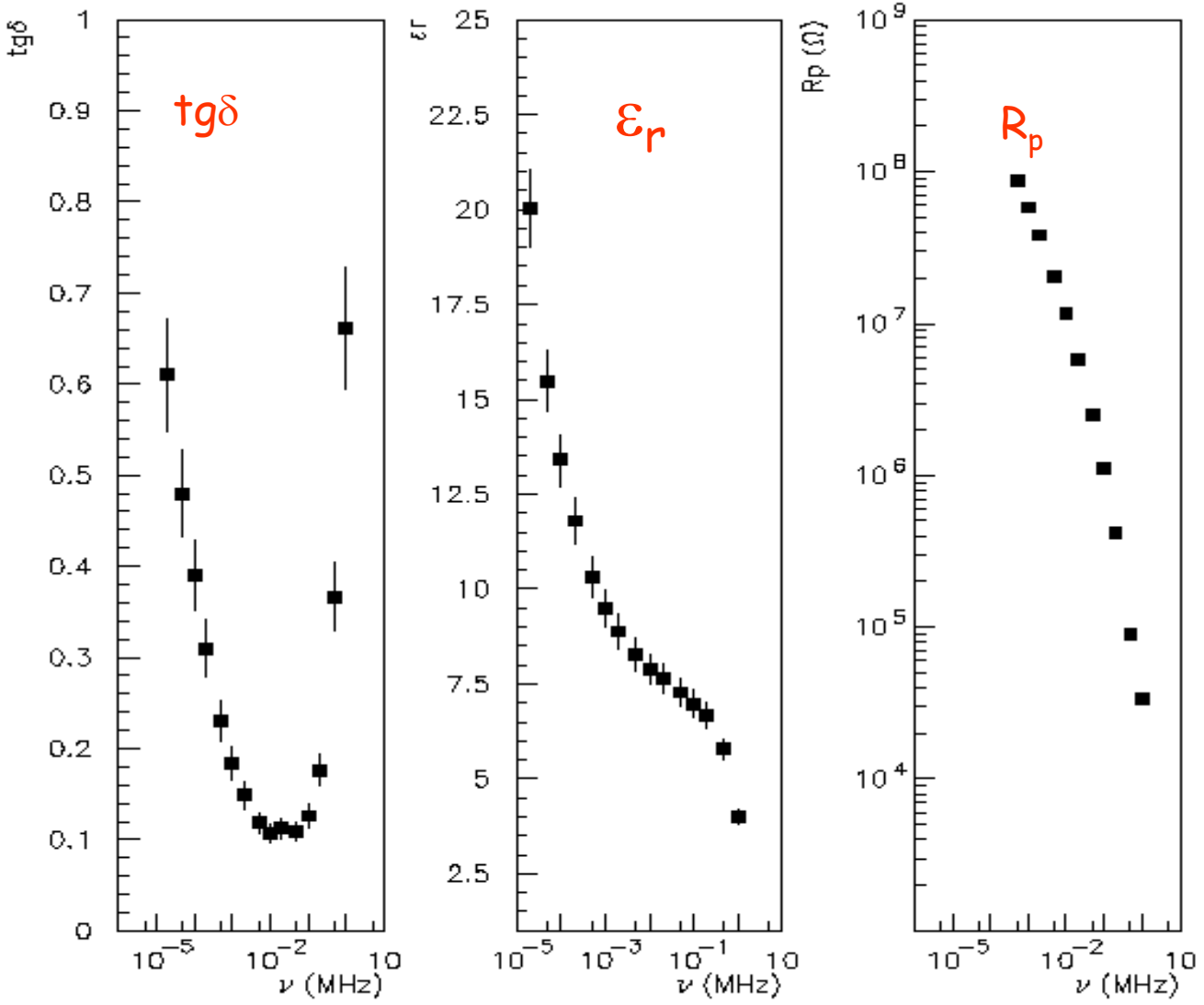
or combination

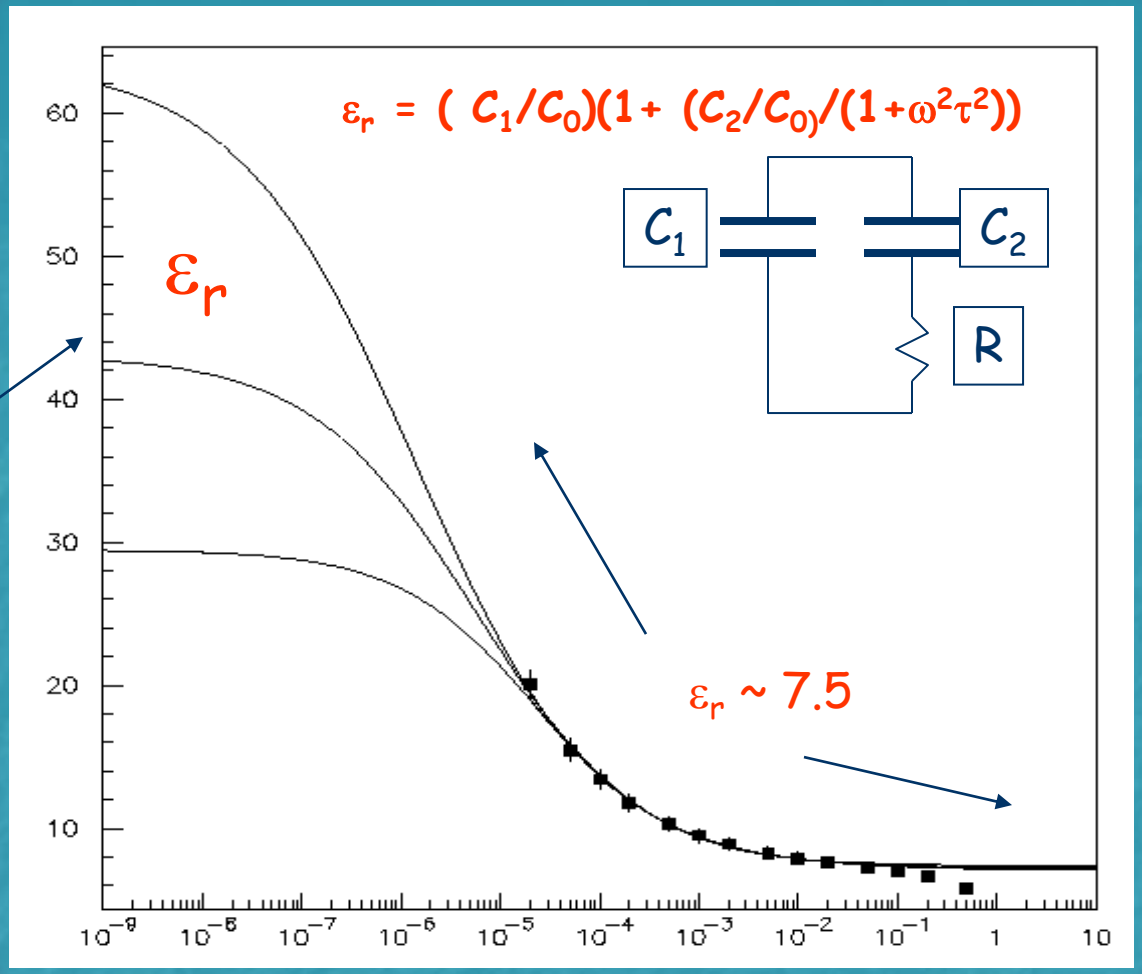
$$\varepsilon^* = \frac{\varepsilon'}{\varepsilon_0} - j\frac{\varepsilon''}{\varepsilon_0} = \frac{1}{j\omega C_0}\frac{1}{Z}$$

RELAXATION SPECTRA

Melaminic sample T = 25 ^{0}C

"Melaminic" refers to the used resin for the electrodes production.
Usually the exterior surfaces of a plate



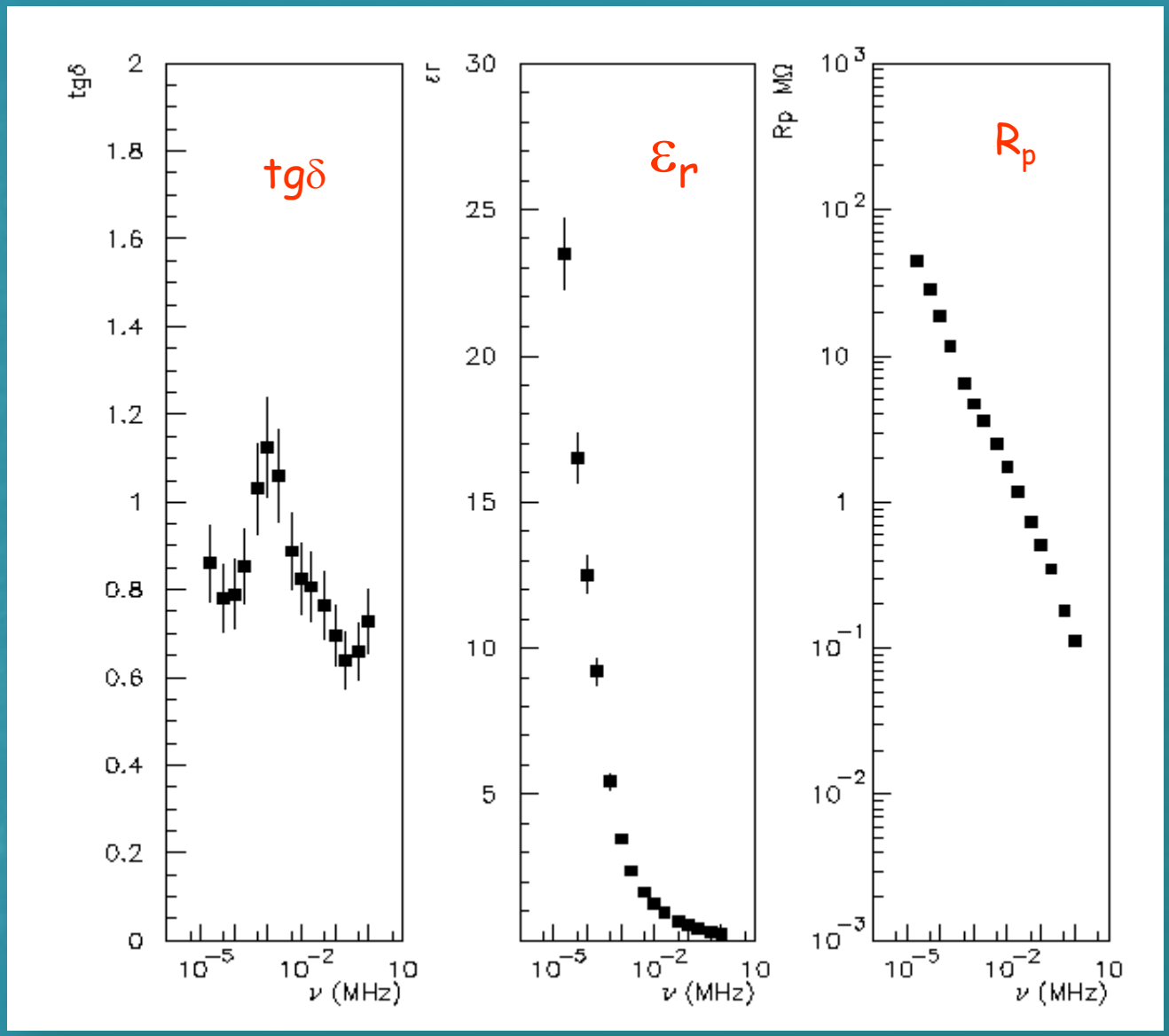


Difficult to measure but ε_r @ 0 Hz
(DC coupled) could be well fitted from 30 to 60 and even more

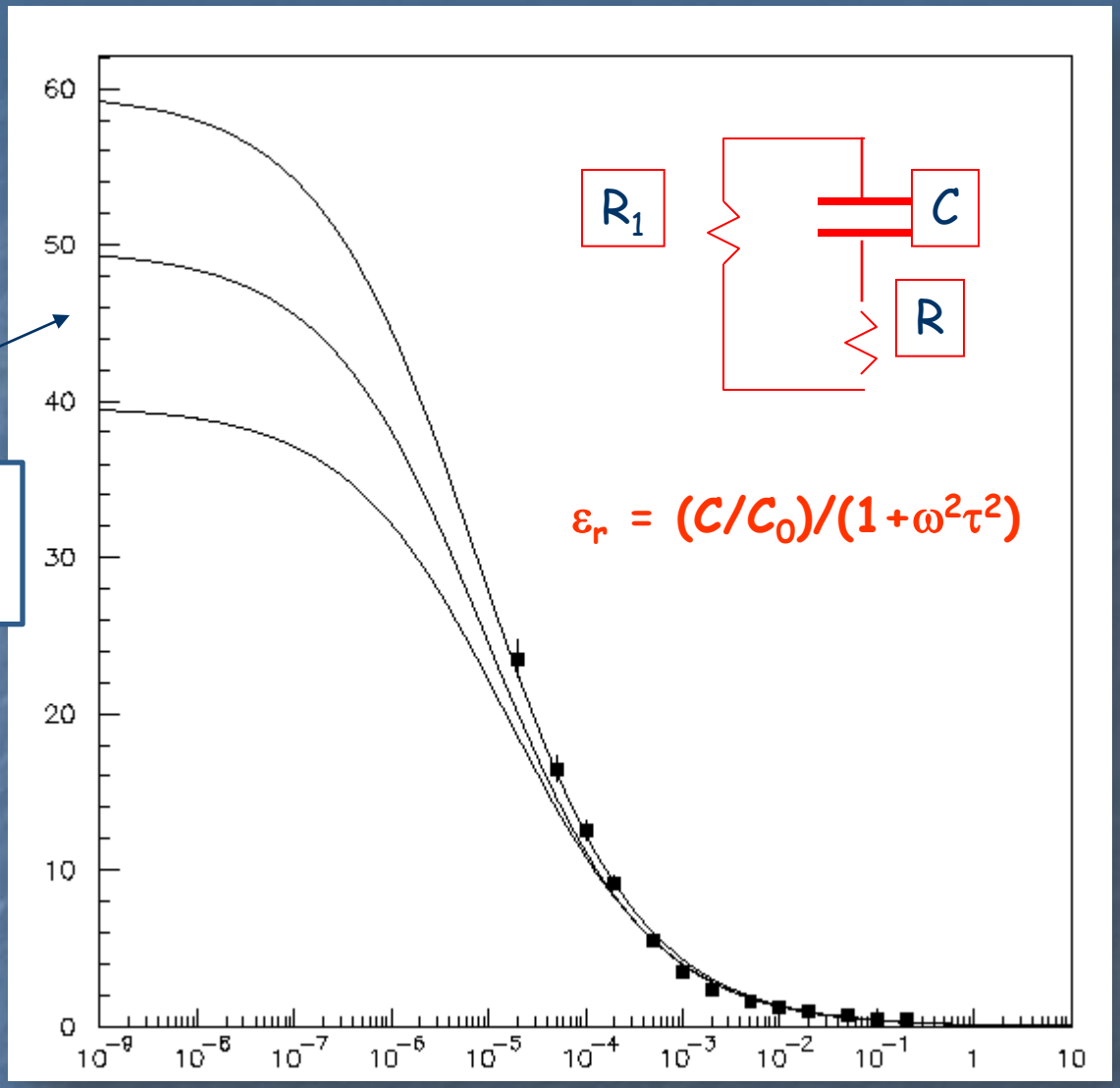
Simple lumped circuit model

Phenolic sample T = 23 °C

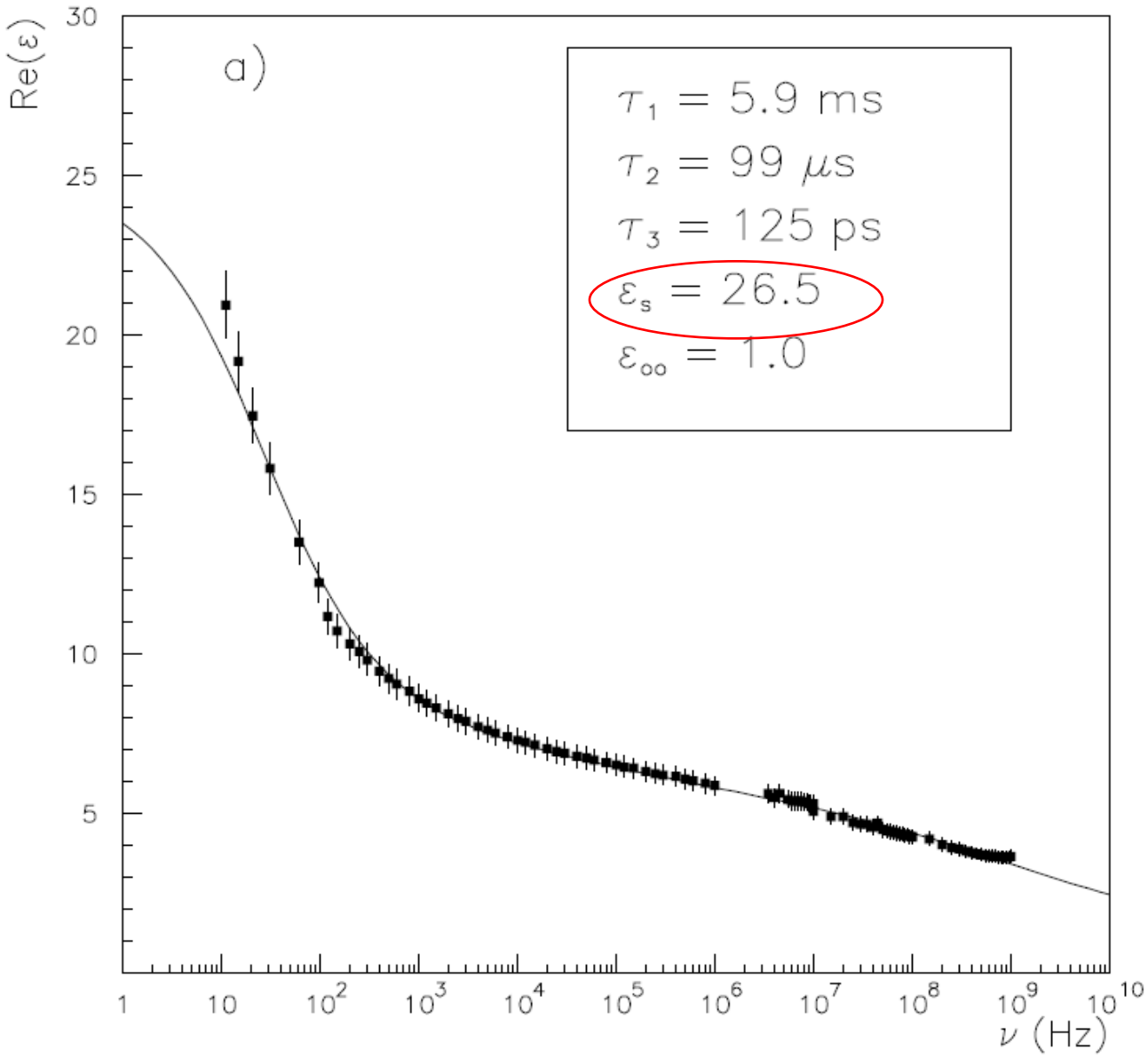
"Phenolic" refers to the used resin for the electrodes production.
Usually the bulk of a plate



Higher range expected



Simple lumped circuit model



We have measured ε_r for a phenolic sample over a frequency range of 10^8Hz

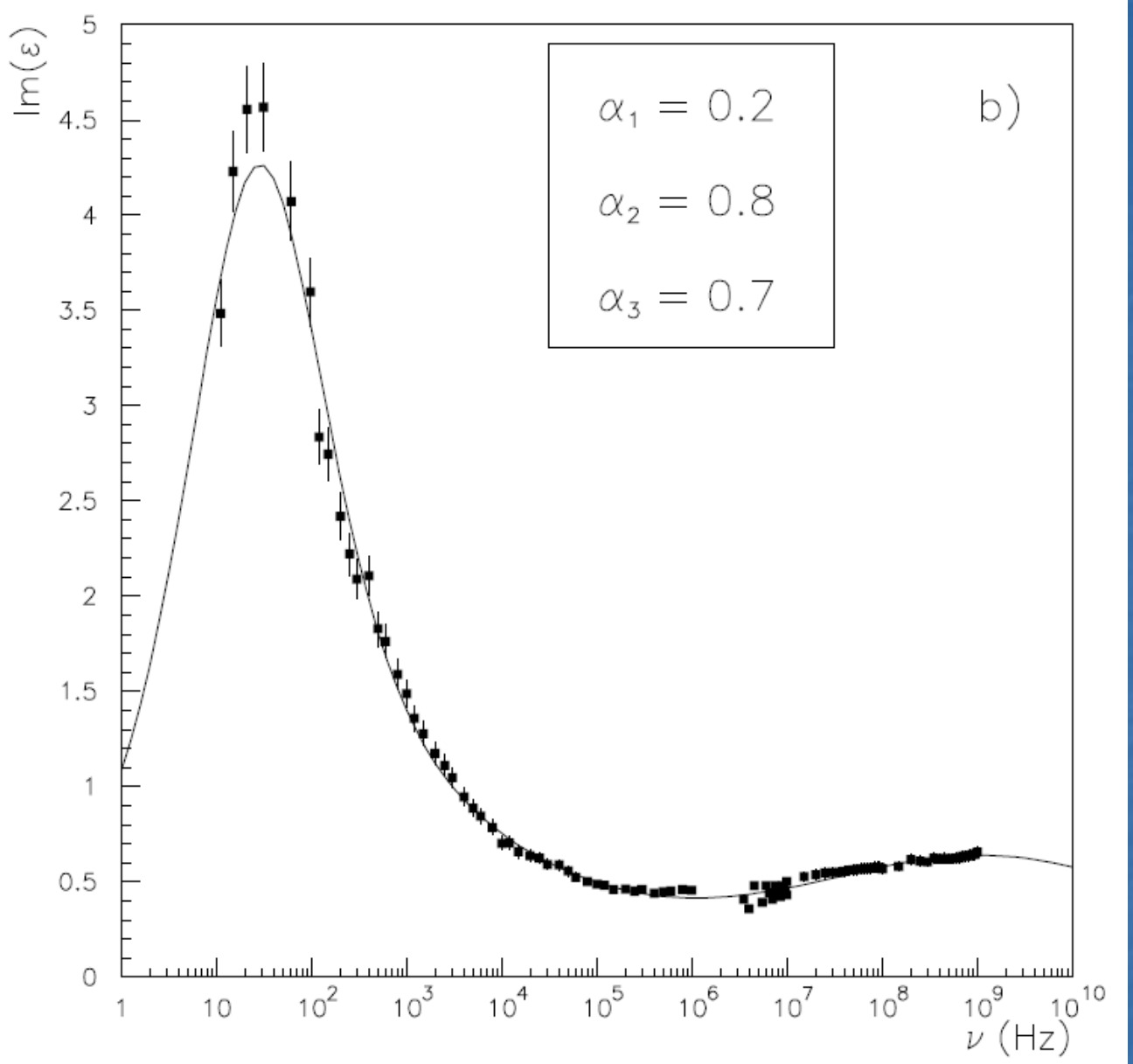
$Re(\varepsilon_r)$

ε_s STATIC

ε_{oo} OPT. LIMIT

τ_i relaxation time

$$Re(\epsilon_r) = \epsilon_\infty + \frac{1}{2}(\epsilon_s - \epsilon_\infty)\left(1 - \frac{sinh\{(1-\alpha)ln(\omega\tau_0)\}}{cosh\{(1-\alpha)ln(\omega\tau_0)\} + sin(\frac{\alpha\pi}{2})}\right)$$



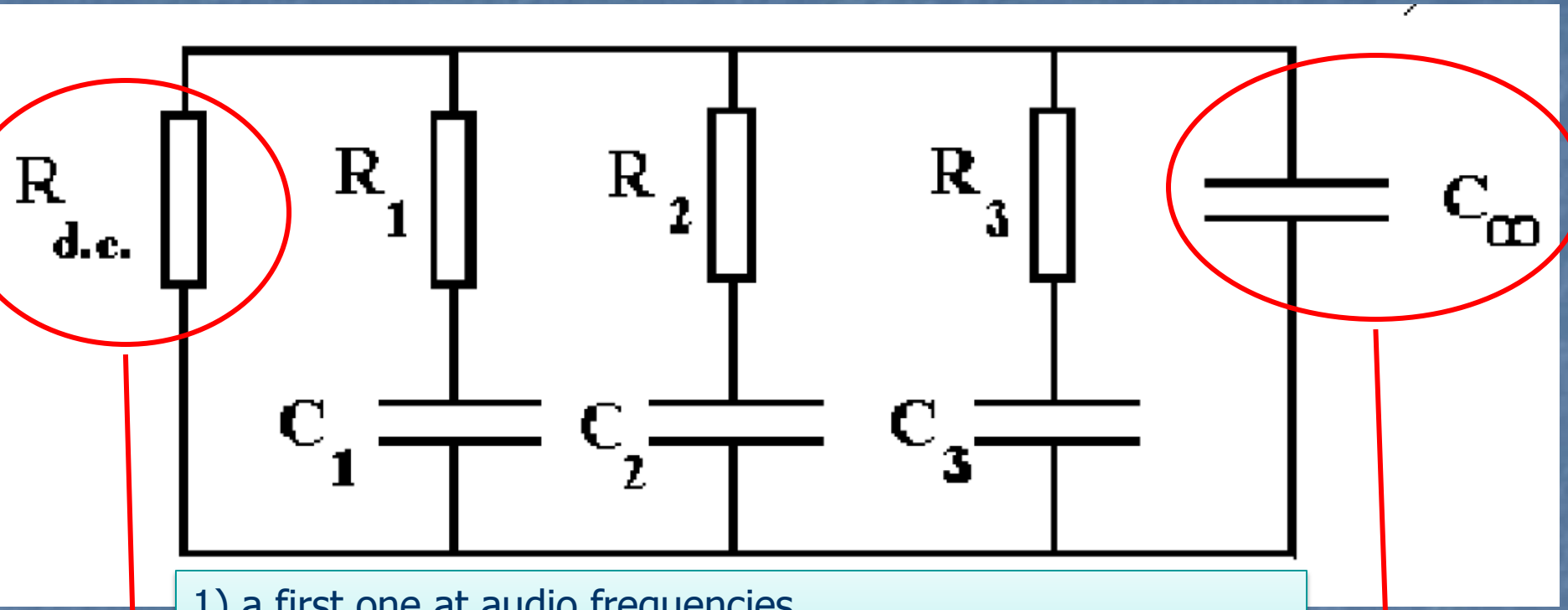
K = conductivity contribution to the imaginary part (relevant at low frequency)

α is related to the width of the relaxation time distributions

$Im(\varepsilon_r)$

$$Im(\epsilon_r) = \frac{1}{2}(\epsilon_s - \epsilon_\infty)\left(\frac{cos(\frac{\alpha\pi}{2})}{cosh\{(1-\alpha)ln(\omega\tau_0)\} + sin(\frac{\alpha\pi}{2})}\right) - \frac{K}{\omega},$$

The preceding results can be explained through the following Equivalent lumped circuit of a bakelite cell. The three RC series elements represent three different relaxation processes :



1) a first one at audio frequencies,
2) a second process around 10^4 *Hz*
3) the last at the far end of the experimental data range.

DC behaviour and conductivity losses

Ideal capacitor at high frequency

Now let's go back to the initial question and recalculate V_g with the new value (26.5) of ε_s

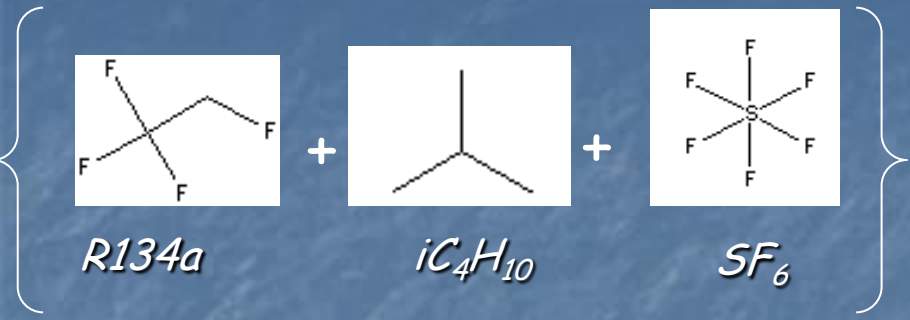
$$V_g = \frac{\varepsilon_r d}{2s + \varepsilon_r d} V_0$$

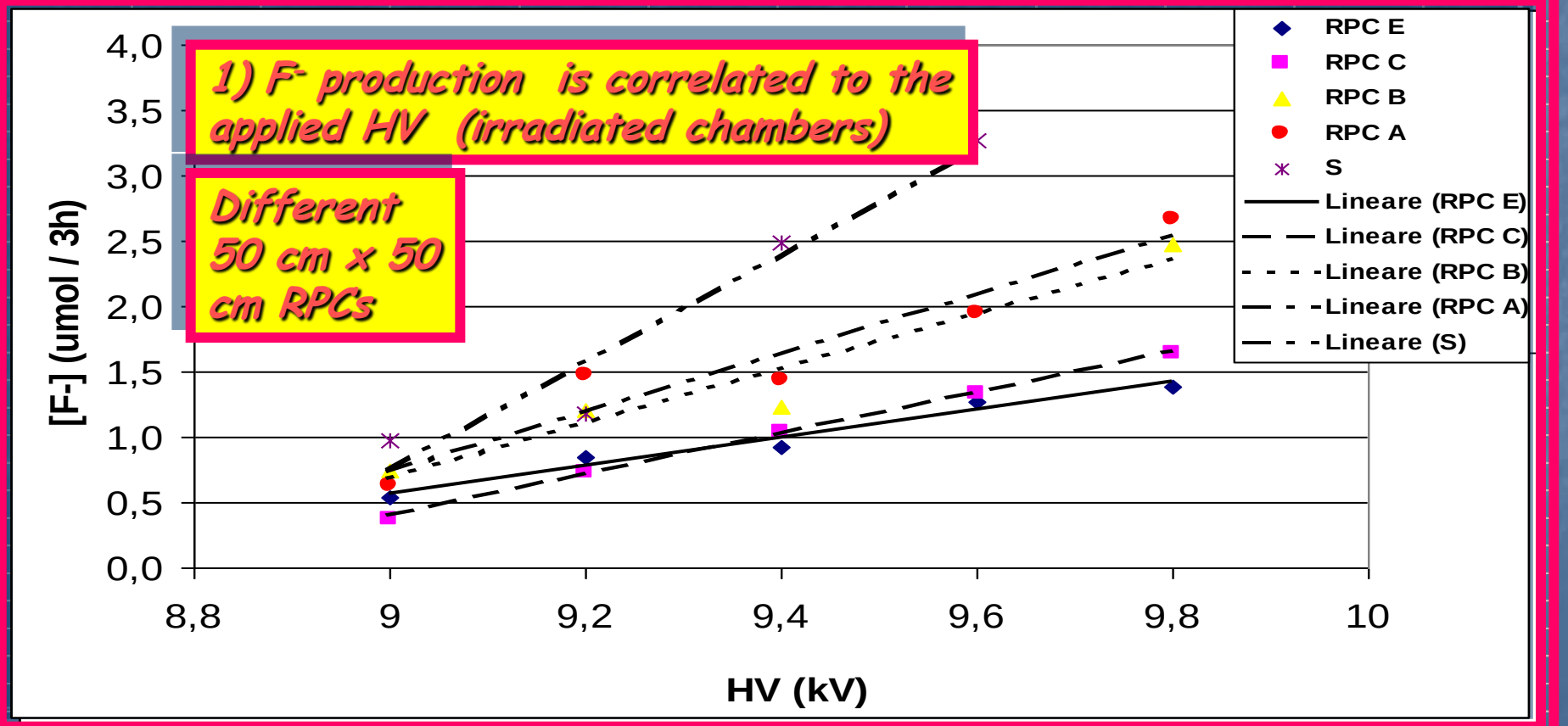
$$V_g \cong 0.93 V_0$$

(vs 0.67-0.77)

However. the presence of $R_{d.c.}$ which is many order of magnitude lower than the gas resistence makes this ratio close to 1 and all the external voltage is thus transferred to the gas gap.

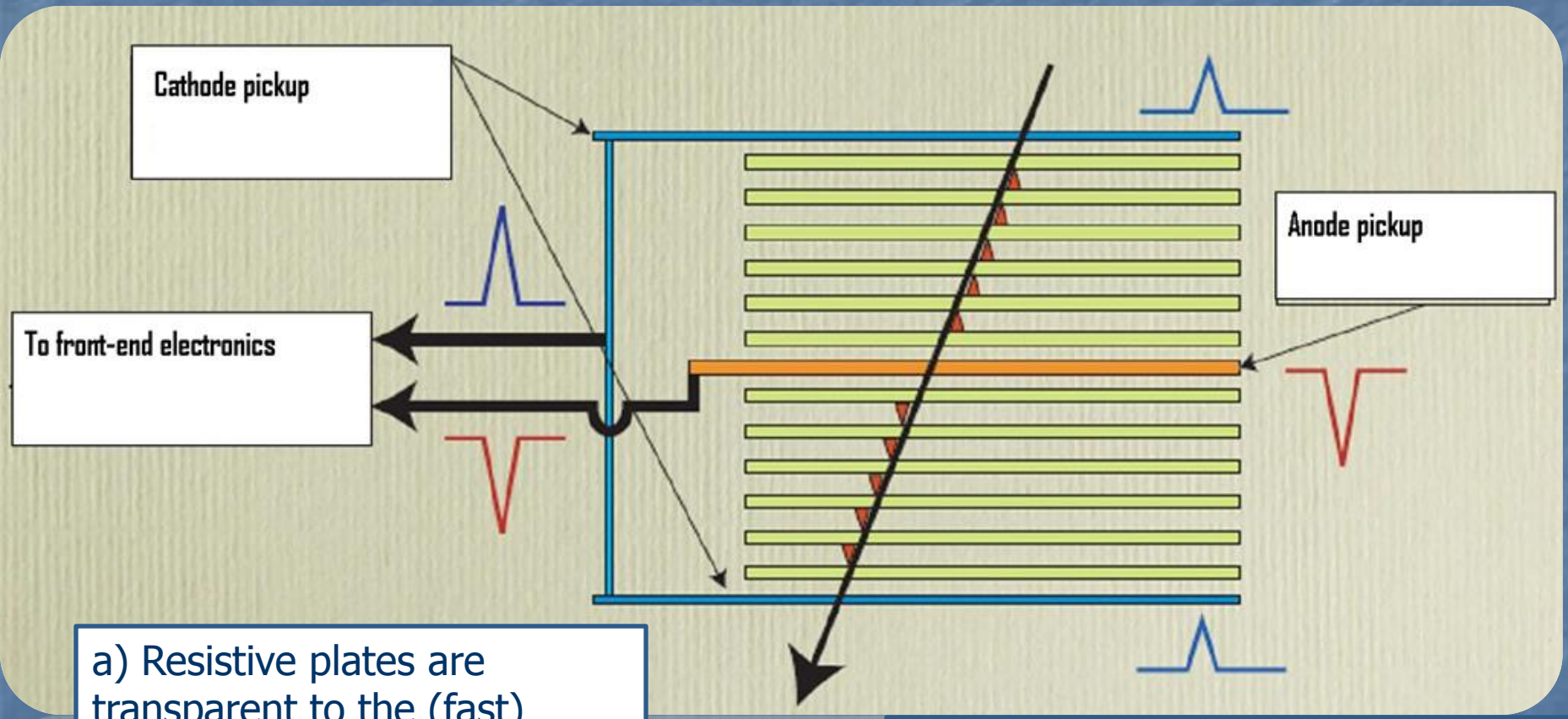
RPC aging issues: production of F⁻





The multigap concept
Williams (1996)

A stack of resistive plates kept electrically floating between two outer (resistive) cathode and anode

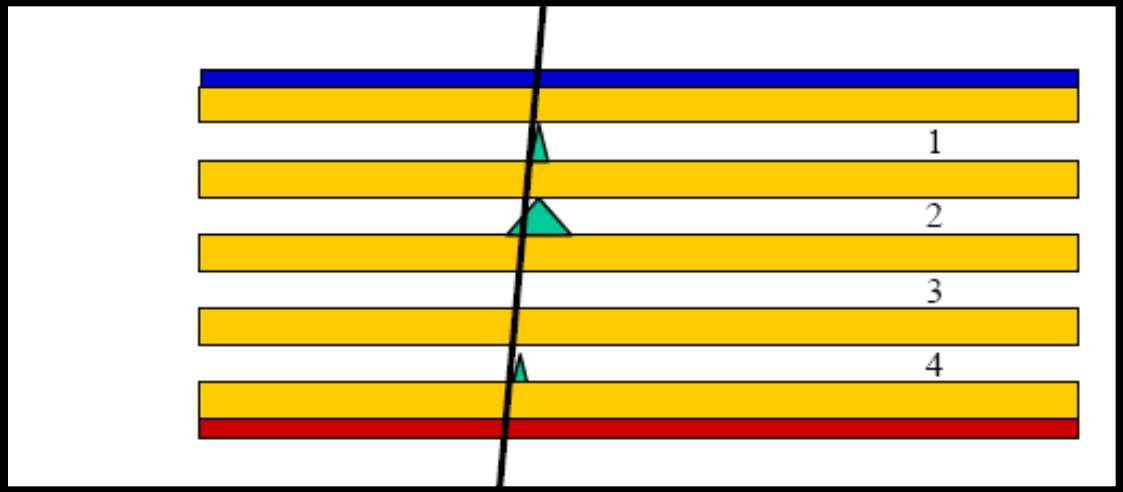


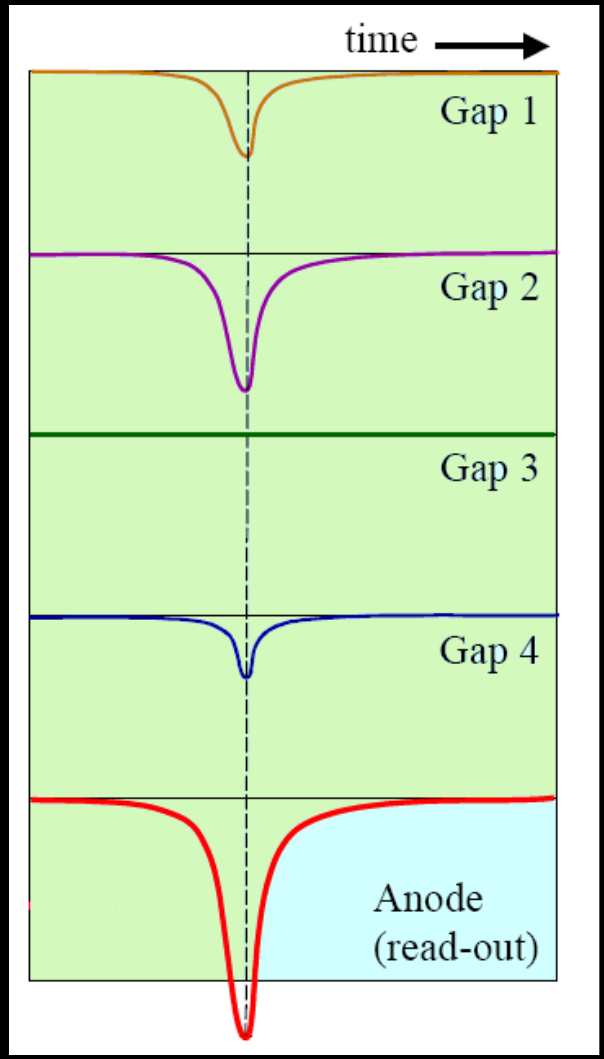
a) Resistive plates are transparent to the (fast) signal internally generated by avalanches

b) The floating plates are always in dynamic equilibrium (equal gain in each gap) due to electrons and ions flow. So they take the correct voltage

The induced signal is the analogue sum of the signals from each gap. Each avalanche has the same time development since "feels" the same electric field.

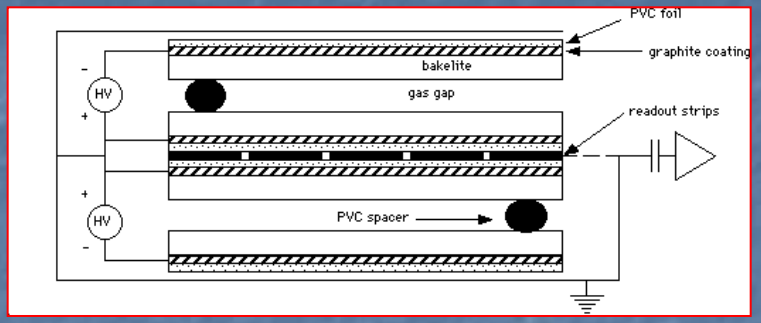
[Williams 99]



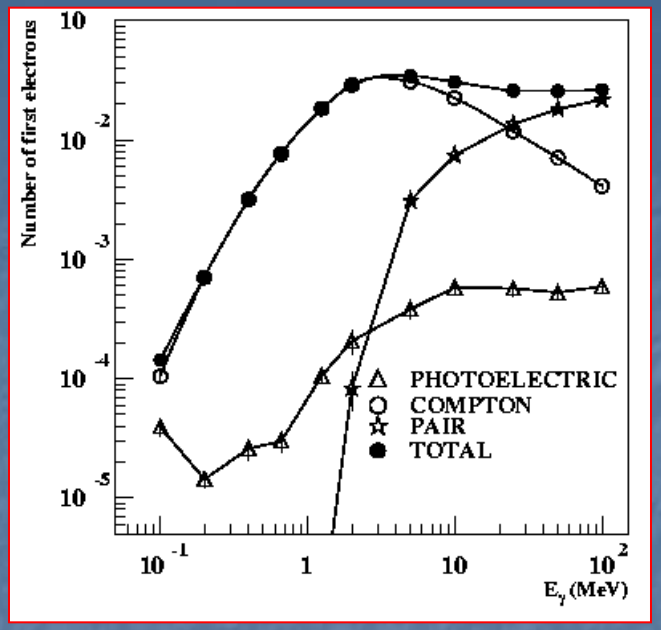


Townsend coeff much more higher than RPCs so one expect much more charge , but this is not the case … important for MRPC are space charge and/or recombination effects on the avalanche saturation…We are not discussing this item here…

γ Sensitivity of RPCs

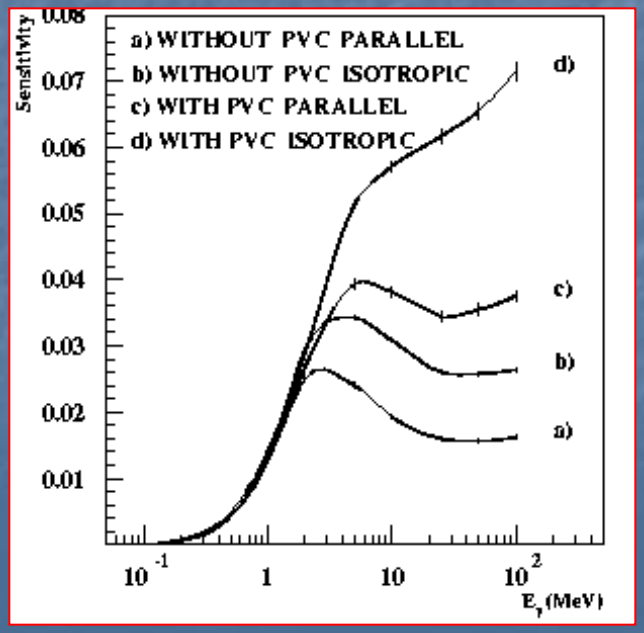


Photons interact into RPCs mainly onto the resistive electrodes



Monte Carlo

The sensitivity is a function of the chamber typology



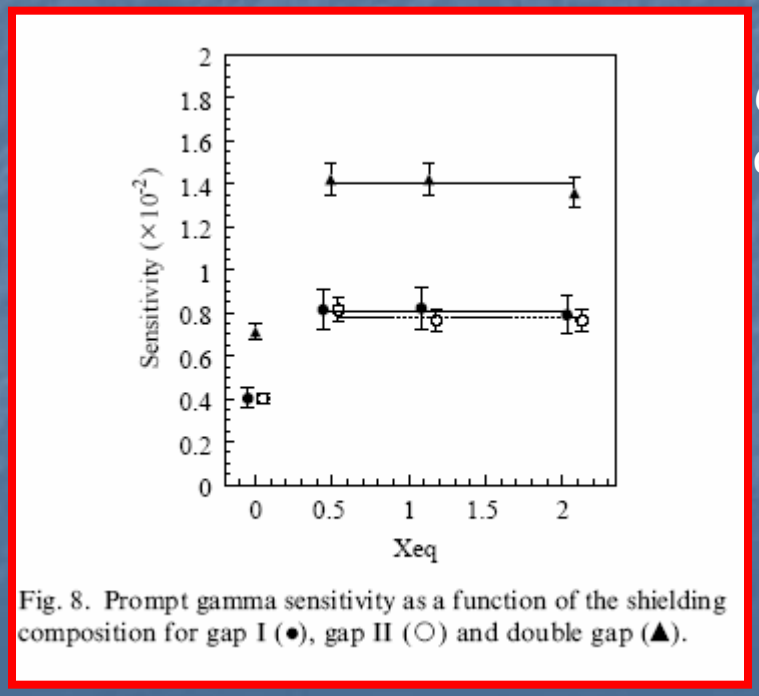
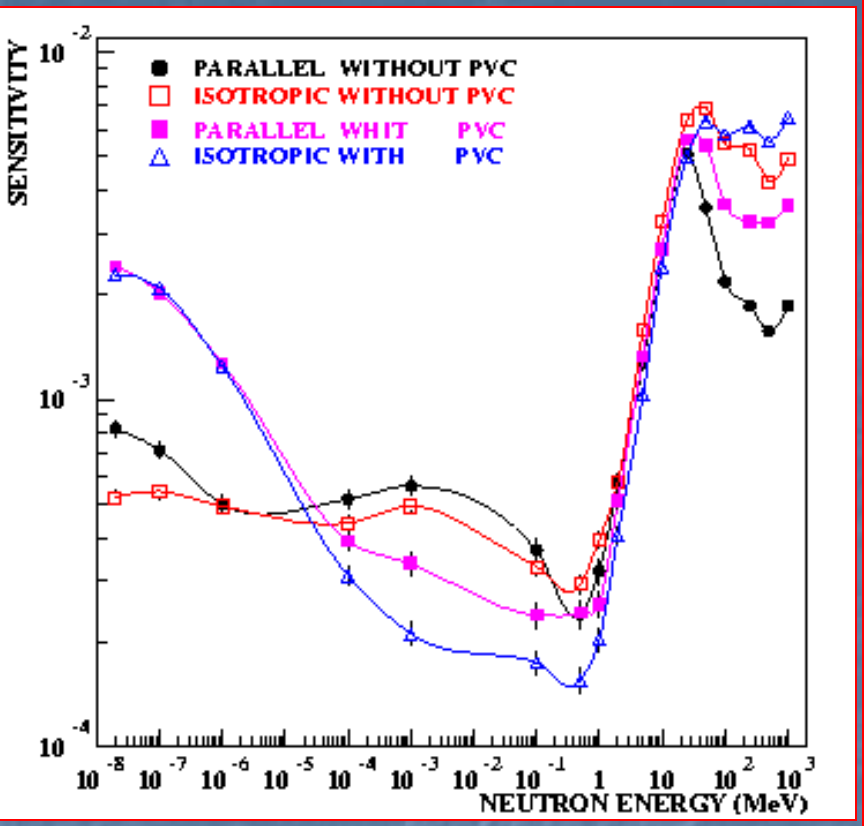


Fig. 8. Prompt gamma sensitivity as a function of the shielding composition for gap I (•), gap II (○) and double gap (▲).

Order of ~% at 1 MeV

DATA

Neutron Sensitivity of RPCs



Monte Carlo

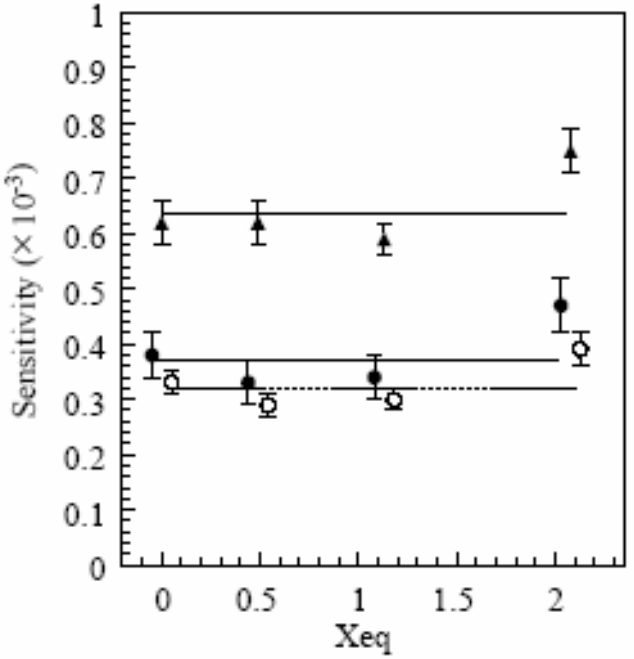
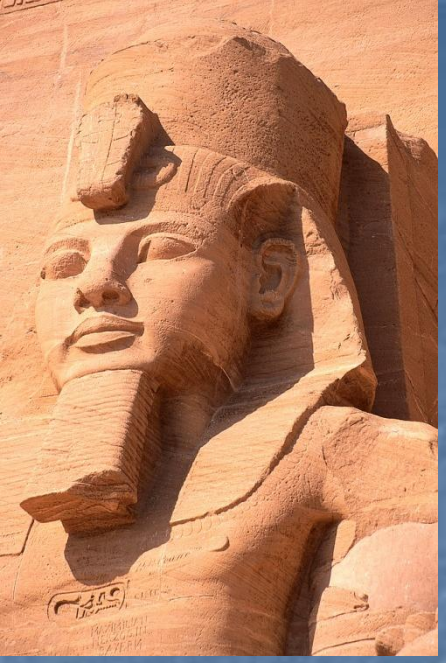


Fig. 7. Neutron sensitivity as a function of the shielding composition for gap I (•), gap II (○) and double gap (▲).

Data at 2 MeV

Neutrons can directly interact with RPC materials and with the gas



(link to a)

Brief (not comprehensive) history of Parallel Plate Detectors

Bibliography

- *Ionization chambers and counters; D.H.Wilkinson (Cambridge Univ. Press, 1950)*
- *Electron and nuclear counters; S.A. Korff (Van Nostrand, NY 1955)*
- *Electron avalanches and breakdown in gases; H. Raether (Butterworth, London 1964)*
- *Spark, Streamer, Proportional and drift chambers; P.Rice-Evans (Richelieu, London 1974)*
- *Principles of operation of multiwire proportional and drift chambers; F.Sauli (CERN 77-09 1977)*
- *Radiation detection and measurements; G.F. Knoll (Wiley, New York 2003)*
- *Techniques for nuclear and Particle Physics experiments; W.R.Leo (Springer, 1994)*
- *Particle detection with drift chambers; W.Blum, L.Rolandi (Springer, 1994)*