Electrical phenomena in gaseous media
Physical bases

Gaseous media: conductors or insulators?

- The idea of a gaseous ionization detector implies the occurrence of electrical phenomena inside the gas…but...
- A gas in itself is an ideal insulator where each electron is well bounded to its atom. How can it become a conductor?
- A gas, as any other material, is surrounded of ionizing sources that create a small number of free electrons inside it
- A gas has a very peculiar property: in presence of a sufficiently strong electric field its electrical resistivity can change of many orders of magnitude in a sub-nanoseconds time
- Speaking of resistivity as an intrinsic gas property would be therefore completely improper

Explaining the electrical conduction inside the gases (1)

- An electron drifting in the gas under the action of an electric field $\boldsymbol{E}$ has a probability $p = dl/\lambda$ of colliding with a gas molecule/atom. Here dl and λ
- are the recurred distance and the mean free path 1/nσ = λ respective
- The electron, after a free flight l, can Ionize an atom in the next collision if the condition $\boldsymbol{E}el > \mathrm{E}_i$ is fulfilled. $\boldsymbol{E}el > \mathrm{E}_i$. The minimum required distance is therefore $l_{min} = \mathrm{E}_i/\boldsymbol{E}e = V_i/\boldsymbol{E}$, E_i and V_i being the atom ionization energy and potential respectively
- The correspnding probability is $\int_{l_{min}/\lambda}^{\infty} e^{-\frac{l}{\lambda}} \frac{dl}{\lambda} = e^{-V_i/\lambda \boldsymbol{E}}$ and the number of ionizations per unit length is therefore $\alpha = \frac{1}{\lambda} e^{-V_i/\lambda \boldsymbol{E}}$
- Number of ionizations in Δl is $< n >= \frac{\Delta l}{\lambda} e^{-V_i/\lambda \boldsymbol{E}} = \alpha\, \Delta l$

Explaining the electrical conduction inside the gases (2)

- The probability of a free electron, drifting under the action of the electric field F, to produce another free electron in a trajectory element dl is
  - $dp = \alpha dl$ where α is the first Townsend coefficient
  - This model due to Townsend is the simplest model explaning the free electron multiplication inside the gas
- If there are n electrons drifting, their increase in dl is $dn = \alpha n\, dl$ →
- $n = n_0 e^{\alpha l}$ → avalanche **exponential** growth Given the great electron mobility inside the gas (drift velocity order millimeters/ns) and the achievable values of α, this explains how fast is the transition *insulator→conductor*

Avalanche saturation

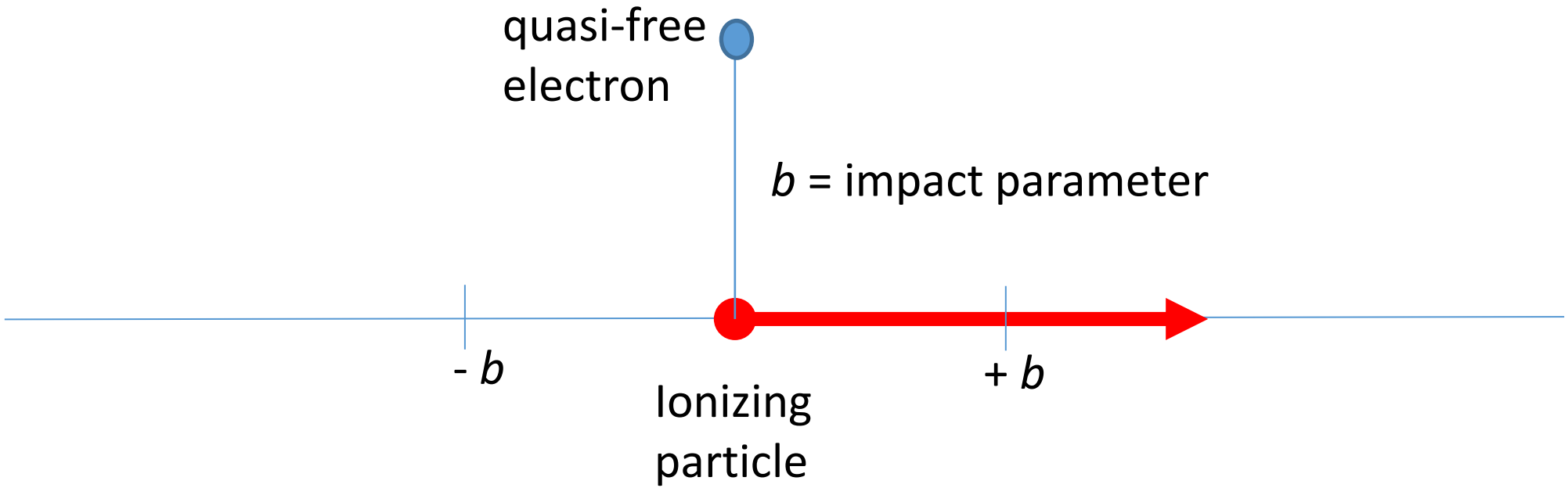
- The avalanche exponential growth, like ani exponential process, must find a saturation point
- The saturation in this case is produced by the space-charge field which reduces the intensity of the applied
- Saturation means that the number of free electrons in the avalanche remains constant
- Howere the induced signal in a ionization detector continue to grow untill the electron drift motion continues

Gas ionization by external agents

- The environment is populated by ionizing particles coming from radioactivity (MeV energy) the surronding material as well as by cosmic radiation (mostly GeV energy μ) →these particles continuously produce free electrons and ions inside a gas
- A metal sharp spike negatively charged can also inject free electrons in the gas
- In a collision of a ionizing particle with an atom an electron can be extracted and, if a sufficient kinetic energy is ganed in the collision, it can be itself a ionizing particle that can produce new free electrons
- We can therefore distinguish a *primary* and a *secondary* ionization
- The total number of free electrons produced in the gas is the sum of the primary ionizations, each one weighed for the secondary ionizations

Simplified classical model of the particle-electron interaction

- The electrostatic field of the particle produces a force ***F*** on the electron
- The electron momentum due to the interaction *is* $\boldsymbol{p}_e = \boldsymbol{F}\,\Delta t$
- $\Delta t = 2b/v$
- $E_e = \boldsymbol{p}^2/2m_e = (2b^2/m_e)\,\boldsymbol{F}^2/\,v^2$



The Bethe equation

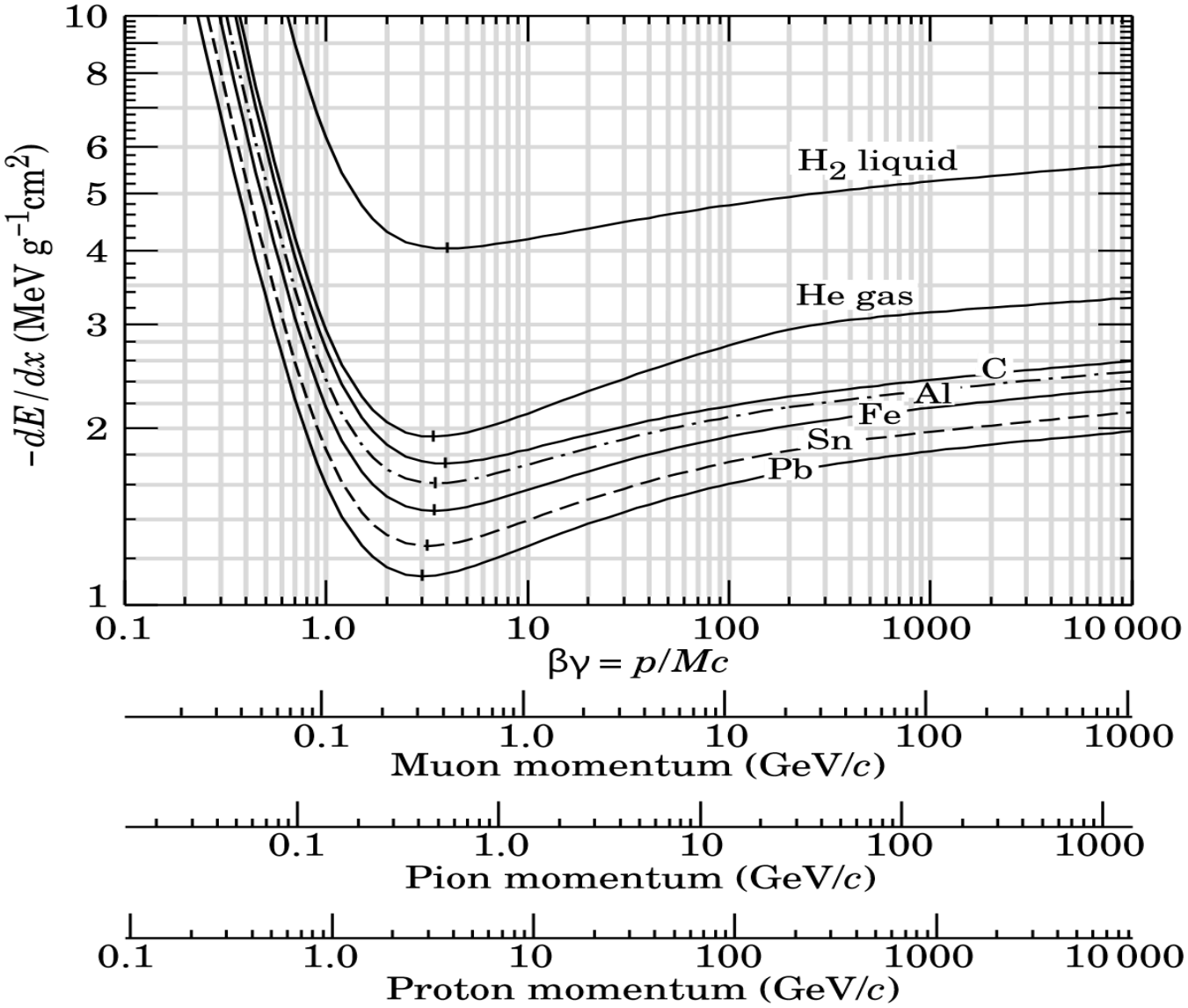
- It is a relativistic equation that can be applied to heavy charged particles (not electrons)
- Its main features however can be obtained by a simple semi-classical calculation. Here *I* is the mean excitation energy

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

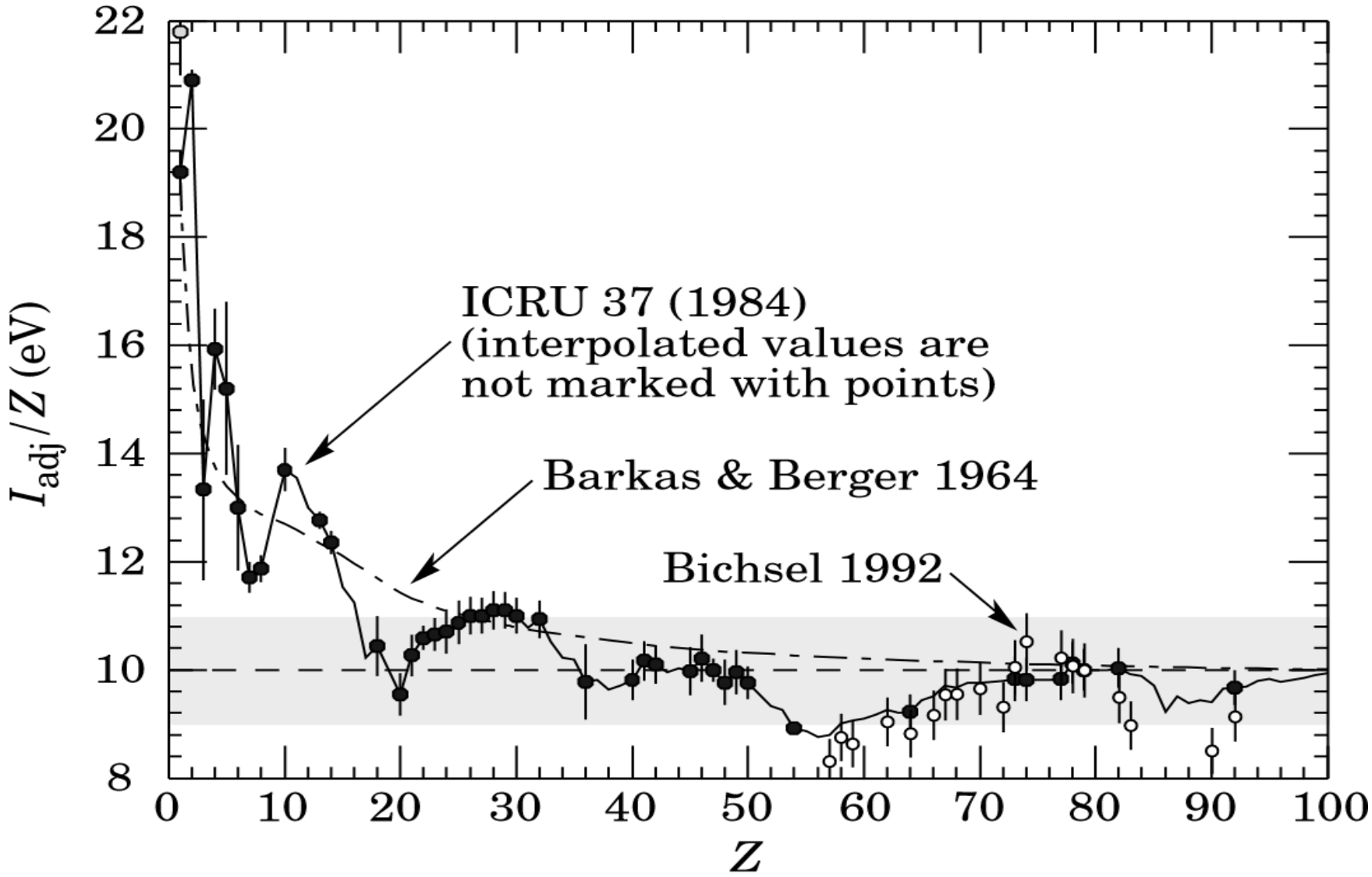
$$T_{\max} = \frac{2m_e c^2 \, \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2}$$

- The most important points concern:
  - The linear dependence of the material atomic number
  - The quadratic dependence on the particle charge
  - The inverse quadratic dependence on the particle velocity
  - The dependence on I^2
  - The presence of a minimum ionization

Stopping power of different materials around the minimum ionization point



Average ionization potential divided by Z



Energy distribution of the electrons scattered by the ionizing particle and fluctuations in energy loss

The electrons scattered by the particle in the trajectory interval *dx* can get very different kinetic energies *T*. The distribution is given by

$$\frac{d^2N}{dTdx} = \frac{1}{2} K z^2 \frac{Z}{A} \frac{1}{\beta^2} \frac{F(T)}{T^2}$$

F(T) being close to 1

In this approximation the kinetic energy distribution is close to $1/T^2$ (strange distribution which deceases much more slowly than the gaussian for increasing T!) showing that it can get very high *T* values even if with small probability

Thin targets

- The scattered electron is itself a ionizing particle crossing the material that for large T values can produce many electron- ion pairs
- For thin layers of material a high energy secondary electron can exit, thus leaving in the material only part of its energy
- For thin targets therefore T_{max} Is replaced by T_{cut} in the Bethe equation
- In the gaseous detectors the gas target is usually thin

Total ionization fluctuations

- The primary ionization follows the *Poisson* statistics
- The collision probability in an trajectory element dl is

$$dp = dl/l_0 \quad \text{with} \quad l_0 = \frac{1}{n\sigma} = average\ free\ path$$

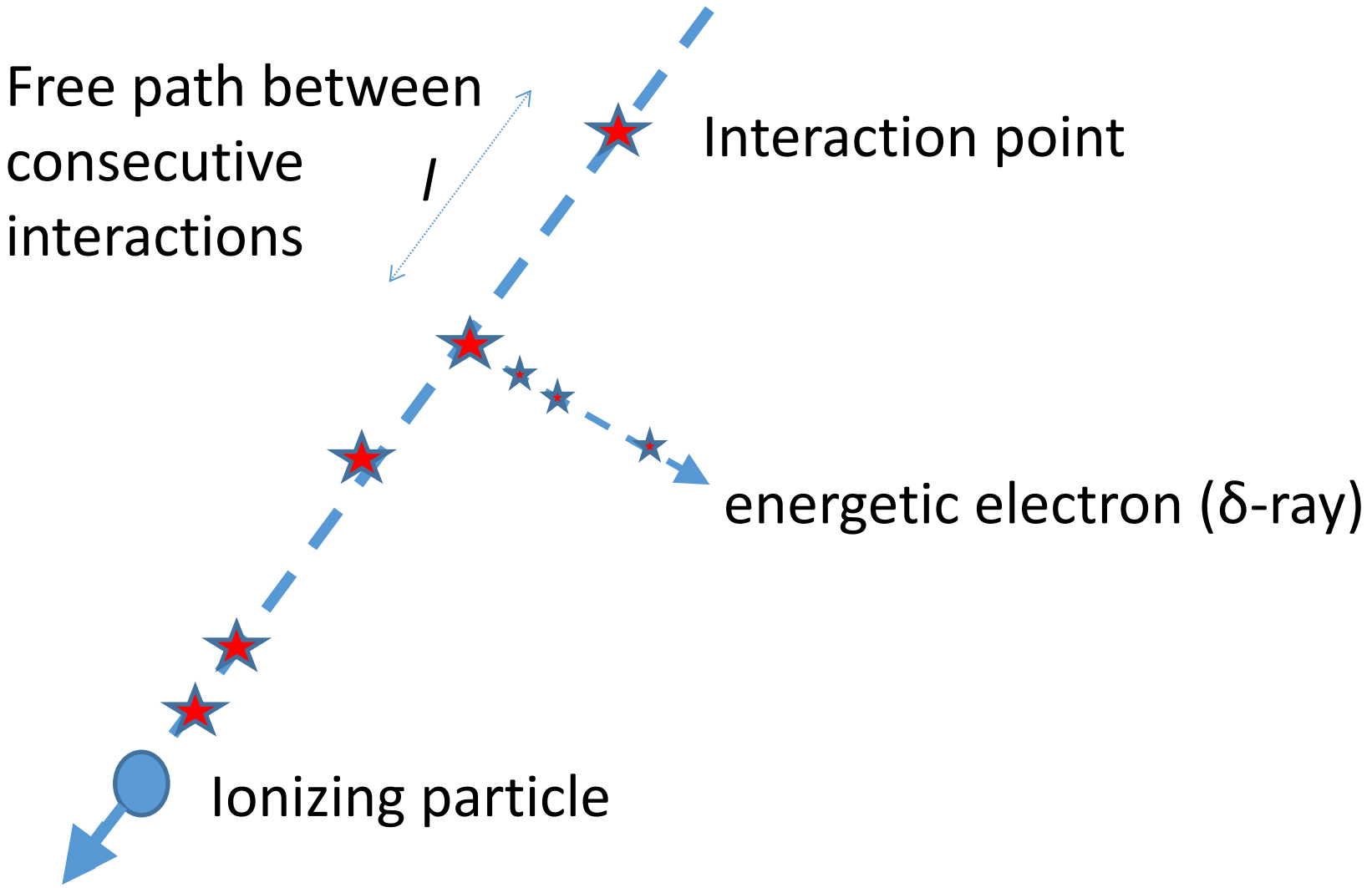
$$n = number\ of\ molecules\ per\ unit\ volume$$

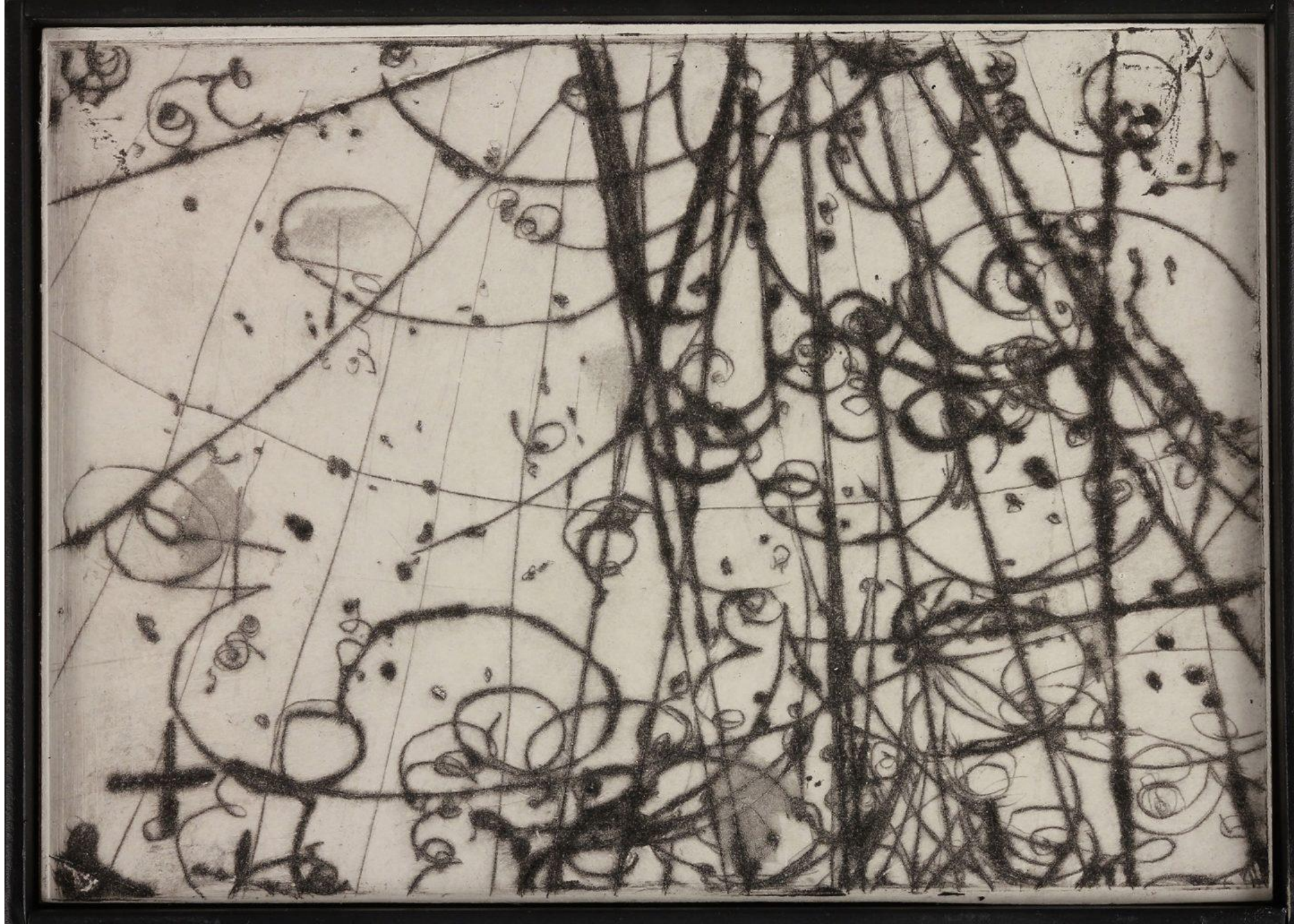
$$\sigma = total\ cross\ section$$

$$probability\ of\ n\ pair\ in\ L\ = e^{-L/l_0}\ \frac{(\frac{L}{l_0})^k}{k!}$$

- The secondary ionizatio follows the *Landau* statistics

  number of electron-ion pairs proportional the the kinetic energy T distributed like $1/T^2$


Free path between
consecutive
interactions
l
Interaction point
energetic electron (δ-ray)
Ionizing particle

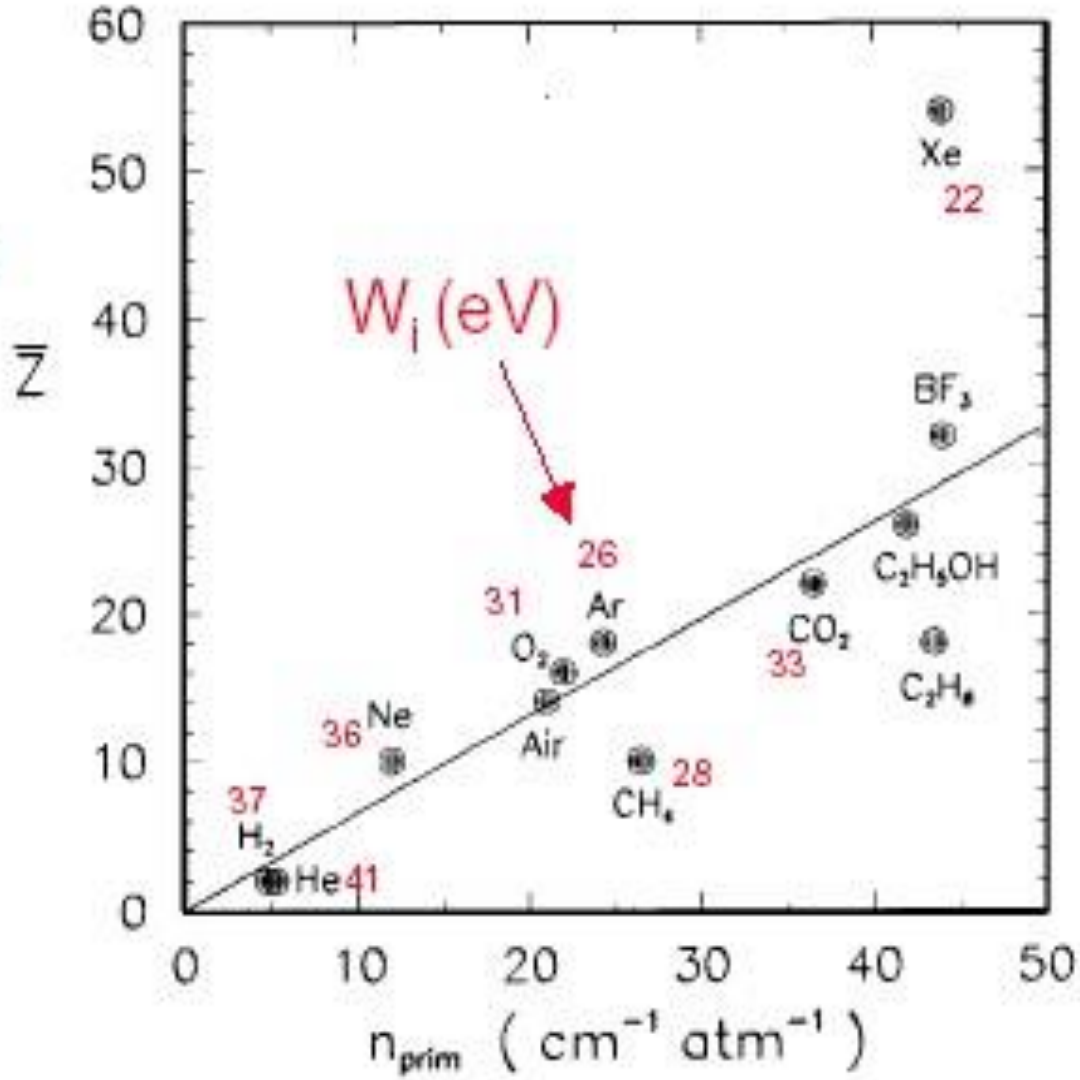


Number of collisions/cm in various gases

gas	1cm/l (# collisioni)	γ
H_2	5.32±0.06	4.0
He	5.02±0.06	4.0
Ne	12.4±0.13	4.0
Ar	27.8±0.3	4.0
Xe	44	4.0
N_2	19.3	4.9
O_2	22.2±2.3	4.3
Aria	18.5±1.3	3.5

Number of primary electron/ion pairs in frequently used (detector) gases.

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992)



Gas	Z	A	E_{ex} eV	E_i eV	I_0 eV	W_i eV	dE/dx MeV/g cm^{-2}	dE/dx KeV/cm	n_p i.p/cm	n_T i.p/cm
Ar	18	39.9	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	10.0	13.9	14.0	24	1.32	4.60	22	192
Xe	54	131.3	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	5.2	13.7	13.7	33	1.62	3.01	34	91
CH_4	10	16		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58		10.6	10.8	23	1.86	4.50	46	195

Dove: E_{ex} = energia minima di eccitazione; E_i = energia minima di ionizzazione;

I_0 =I/Z = potenziale efficace medio di ionizzazione per elettrone atomico;

W_i = perdita di energia media per produrre una coppia ione-elettrone; dE/dx = perdita di energia per particelle al minimo (MIP); n_p = numero di coppie primarie;

n_T = numero totale di coppie.

Nel caso di composti e miscugli Z, A ed I sono valori medi.

Drifting Electron elastic and inelastic collisions

- Peculiarity if the noble gases: large value of the minimum excitation energy E_{ex} and relatively short interval $\Delta = E_i - E_{ex}$ between and ionization energies E
- Ar: $= 11.6\ \Delta = 4.1\ eV$; Kr: $E_{ex} = 10.0\ \Delta = 3.9\ eV$
  Xe: $E_{ex} = 8.4\ \ \Delta = 3.7\ eV$
- A drifting electron colliding cannot tranfer an energy $E < E_{ex}$. For momentum transfer $\Delta p < \sqrt{2mE_{ex}}$ the collision must be elastic and, the atom mass being $\mathrm{M} \gg \mathrm{m}$ there is no energy transfer: the electron changes direction keeping all its kinetical energy
- The situation is different for very complex molecules like for example i-C4H10; in this case, due to the very low energy of the roto-vibrational levels very small energies can be transferred. The electron motion is similar to a motion inside a viscous liquid

Quenching mechanisms

- The same parameters can explain the discharge quenching mechanism which is crucial for controlling the avalanche growth
- An Ar atom for example can only absorb and re-emit photons of energy Egamma>11.6 eV which can ionize other kind of atoms with lower Eion in the gas. This photo-ionization would produce a further avalanche
- On the contrary, complex molecules like i-C4H10 can absorb high energy UV photons and re-emit their energy in form of the very low energy photons due to the roto-vibrational modes.
- This is the base of the quenching mechanism

Talks of tuesday

➢Delayed ionization and Penning effect

- Ar: $E_{ex} = 11.6\ eV;\ E_i = 15.7\ eV;$
- Kr: $E_{ex} = 10.0 \qquad 13.9$
- Xe: $E_{ex} = 8.4 \qquad 12.1$
- There are excited energy levels of Ar that are above the ionization e levels of Xe
- The effect is more relevant if the comparison is made with He and Ne
- In a Ar-Xe an excited Ar level can ionize a Xe atom
- This is the Penning effect

A bit of detector history

- During the 70s of the past century the gaseous detectors were dominated by two technology lines:
  - Detectors with electric field generaed by a *positively charged wire*; common ancestor the Geyger-Muller counter; continuously sensitive *DC-coupled* detector
  - Optical spark chambers: *plane multiple capacitors* with metal electrodes capable of tracking with millimeter accuracy; *triggered device*
- The idea of a *«revised spark chamber»* modified as a non triggered but continuously sensitive detector, was considered *fascinating but completely irrealistic*
- x

The Geiger-Muller counter (1)

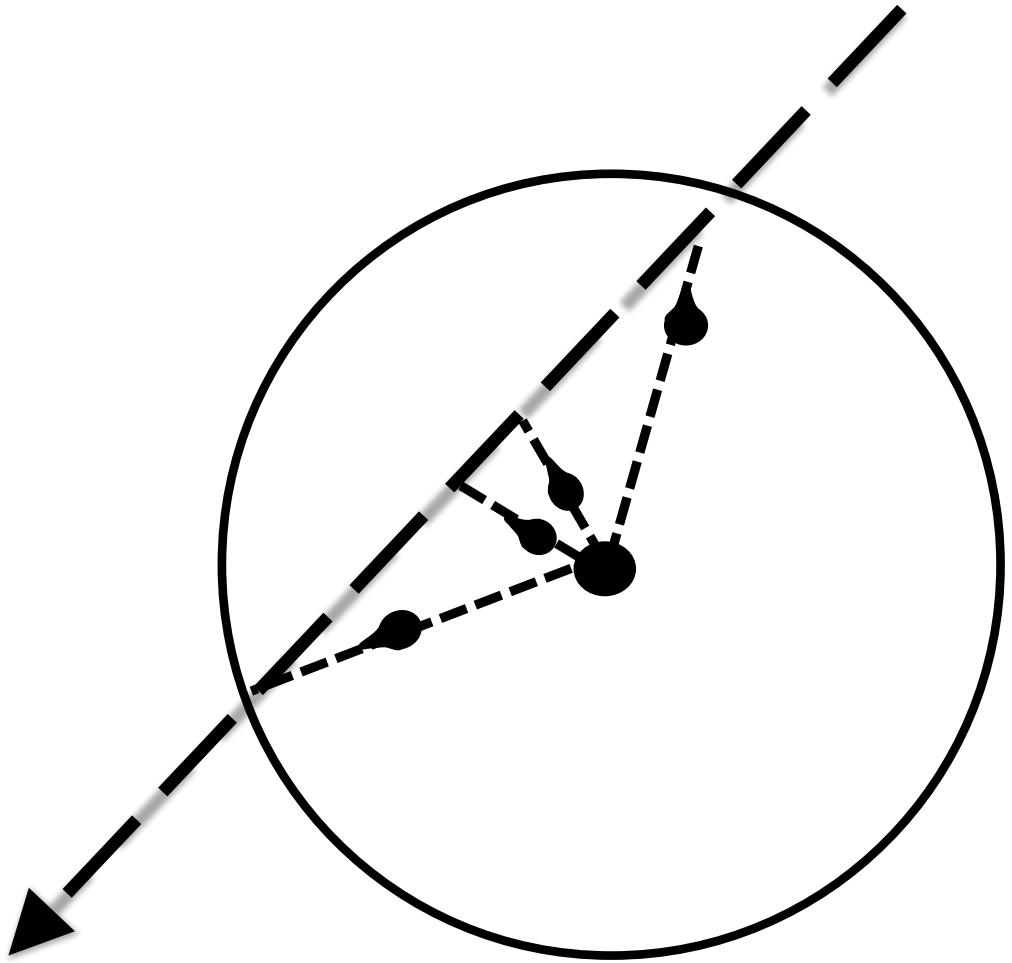
- It was the first idea (1920 decade) of a gaseous radiation detector and is a common ancestor of a *large family of the wire chambers*
- It is a metallic cylindrical tube with a well isolated metal wire in the tube axis. The tube is filled with a noble gas to which a very small amount of organic component (alcohol or hydrocarbon) is added. The wire is kept at constant *positive voltage* of about +1 kV with respect to the tube (grounded)
- The electrostatic field is

$$E = \lambda/2\pi\varepsilon_0 r = \frac{V}{r ln(r_2/r_1)}$$

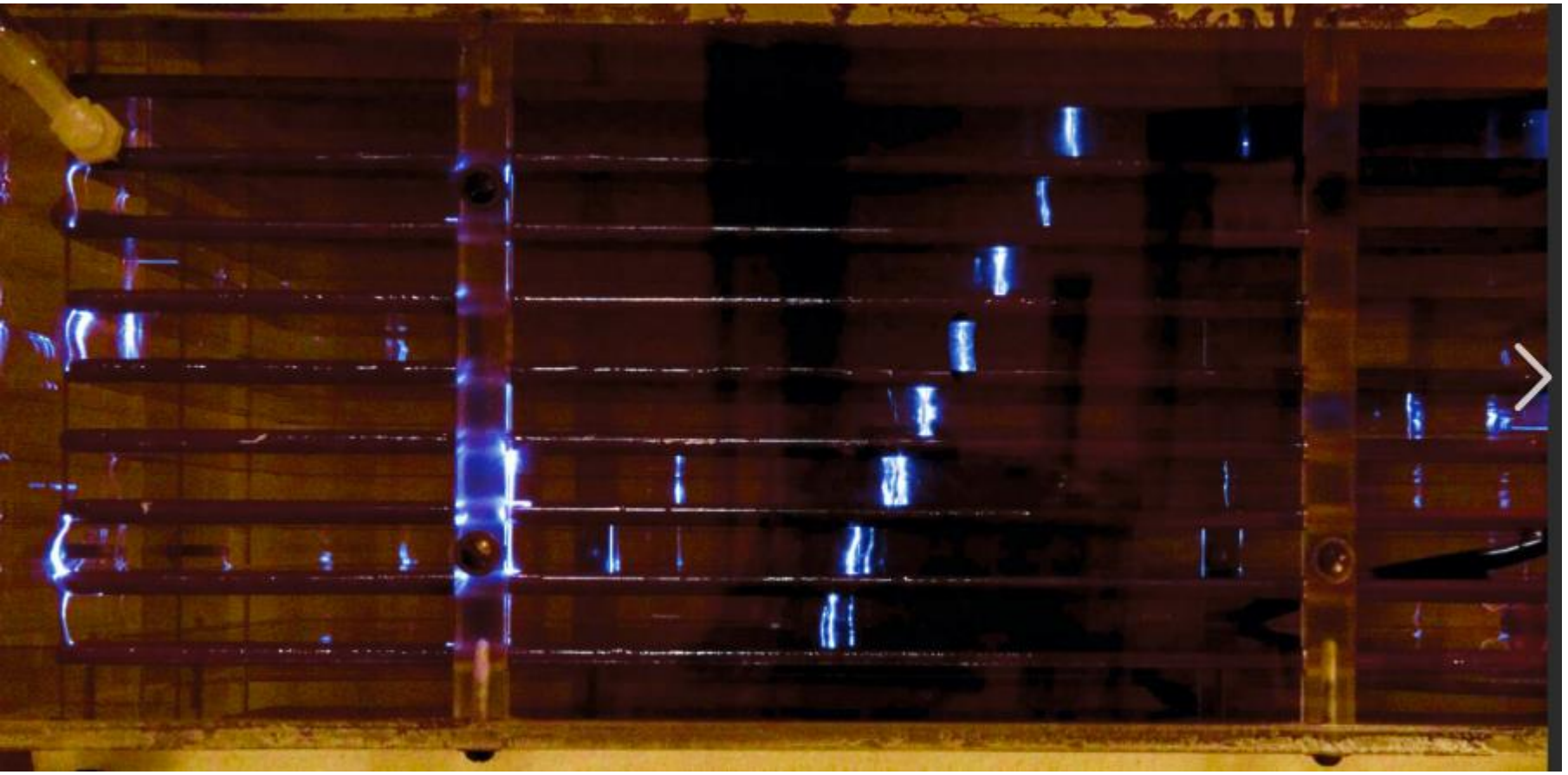
The field decreasing as $1/r$ is ***"critical"*** only *for r of the order of the wire diameter* where the gas multiplication processes can happen

Induced signal

- Field largely sub-critical in the sensitive volume; *drift and multiplication regions well separated*
- Primary clusters drift toward the anode wire and do not produce visible signal except very close to the wire
- At a distance of about one wire diameter the field is intense enough to produce multiplication
- The signal is in principle a sequence of similar pulses each one produced by a different primary cluster
- The only difference is the size of the primary cluster



The optical spark chamber



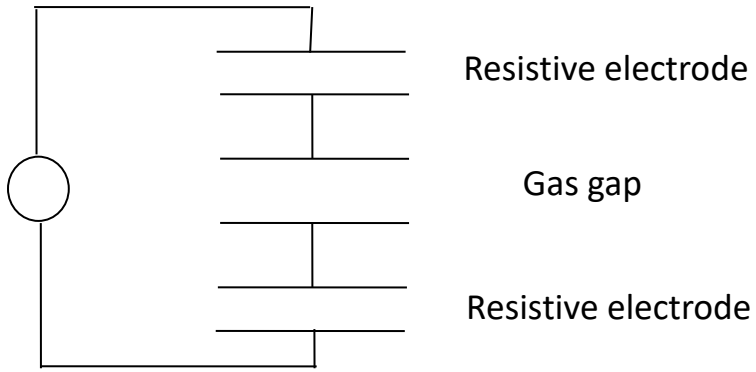
- Activated by an HV pulse
- Triggered by scintillators within about 1µs otherwise the diffusion would dispers ionization electrons
- Sparks alligned in the field, not in the trajectory direction

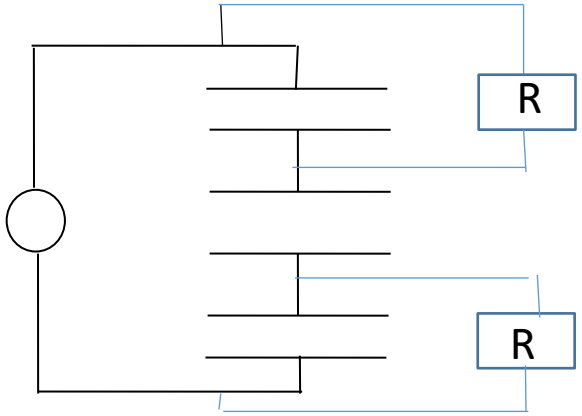
Is it conceivable the idea of DC-coupled spark chamber?

- Not with metal electrodes that produce full discharge of the capacitor in the point where the spark was generated
- A plane capacitor gaseous detector is only conceivable with high resistivity electrodes; this would avoid the full discharge of the capacitor, limiting it at a small region around the ionization point
- The full sensitive volume would be at the same time drift and multiplication region → very fast detector with high timing accuracy

The basic idea

- The “elementary cell” is schematically represented as in fig, where the central capacitor C represents the gas gap and the other two capacitors C* the resistive plates with the relative resistors R* in parallel. Indicating by ΔS the cell area: $C = \varepsilon_0 \, \Delta S / g \quad C^* = \varepsilon_0 \, \varepsilon_r \, \Delta S / d \quad R^* = \rho \, d / \Delta S$





The basic idea (2)

- The characteristic discharge time of the electrode capacitors is

  $\tau = R^* C^*$ with $C^* = \varepsilon_0 \, \varepsilon_r \, \Delta S / d \quad R^* = \rho \, d / \Delta S$

  $\tau = R^* C^* = \varepsilon_0 \, \varepsilon_r \, \rho$

This time is much longer than the *discharge duration, of tens of ns*

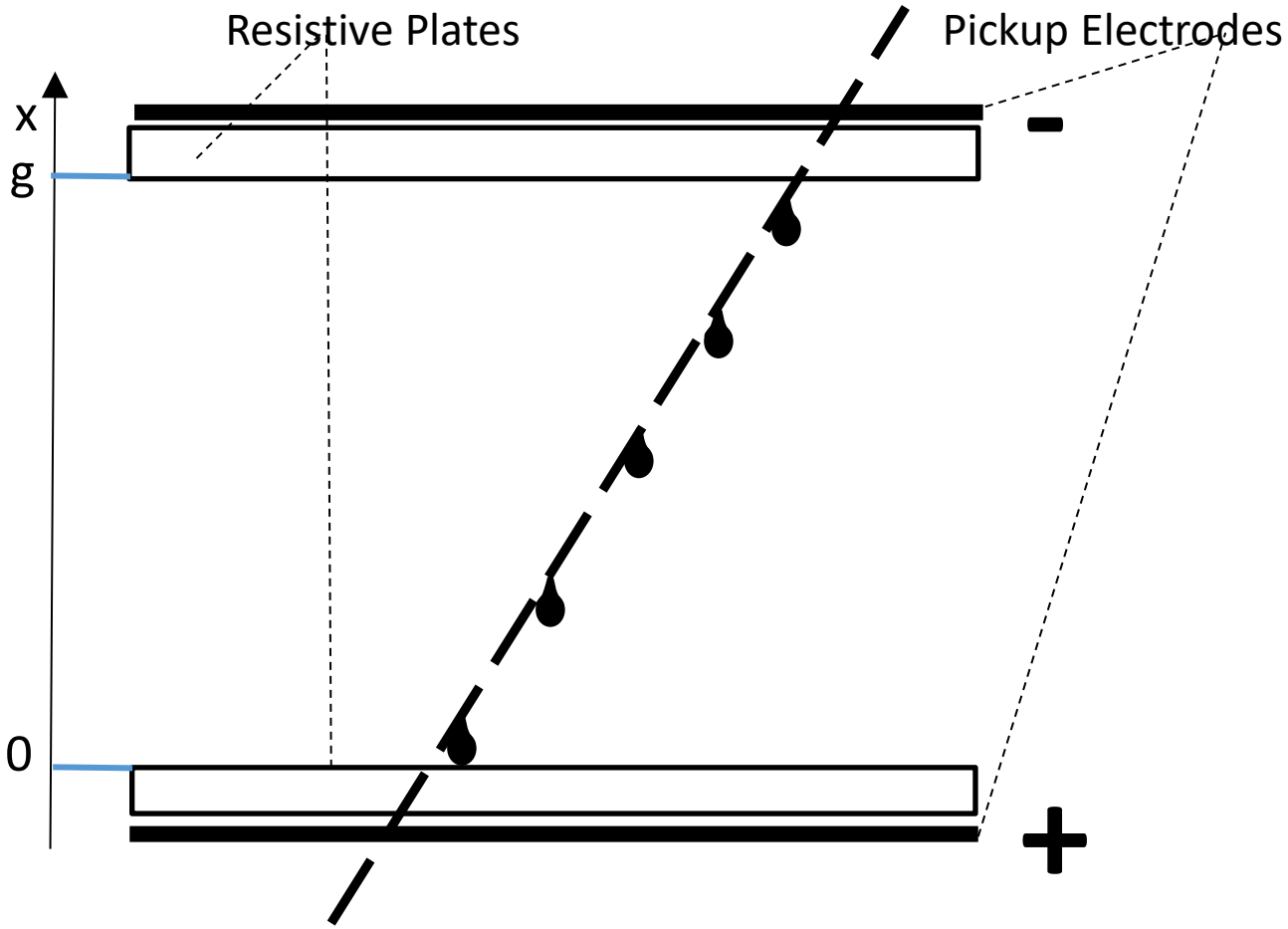
E.g. for a material with ε_r = 3 and ρ = 10^11 Ohm*cm → τ = 27 ms

→ The avalanche can *only be sustained by the electrostatic energy of a small volume around the ionization point*

- The electrostatic laws are valid only for t << τ. In steady conditions and in absence of ionization the supplied voltage is totally applied to the gas gap. The field is zero inside the resistive electrodes

Induced signal in a planar detector

- All primary clusters drift toward the anode plate with velocity *v* and simultaneously originate avalanches
- Very fast induced signal with good time resolution
- A cluster is eliminated as soon it reaches the anode plate



Induction from a moving charge

The motion of the charge Q induces a current in the cirquit

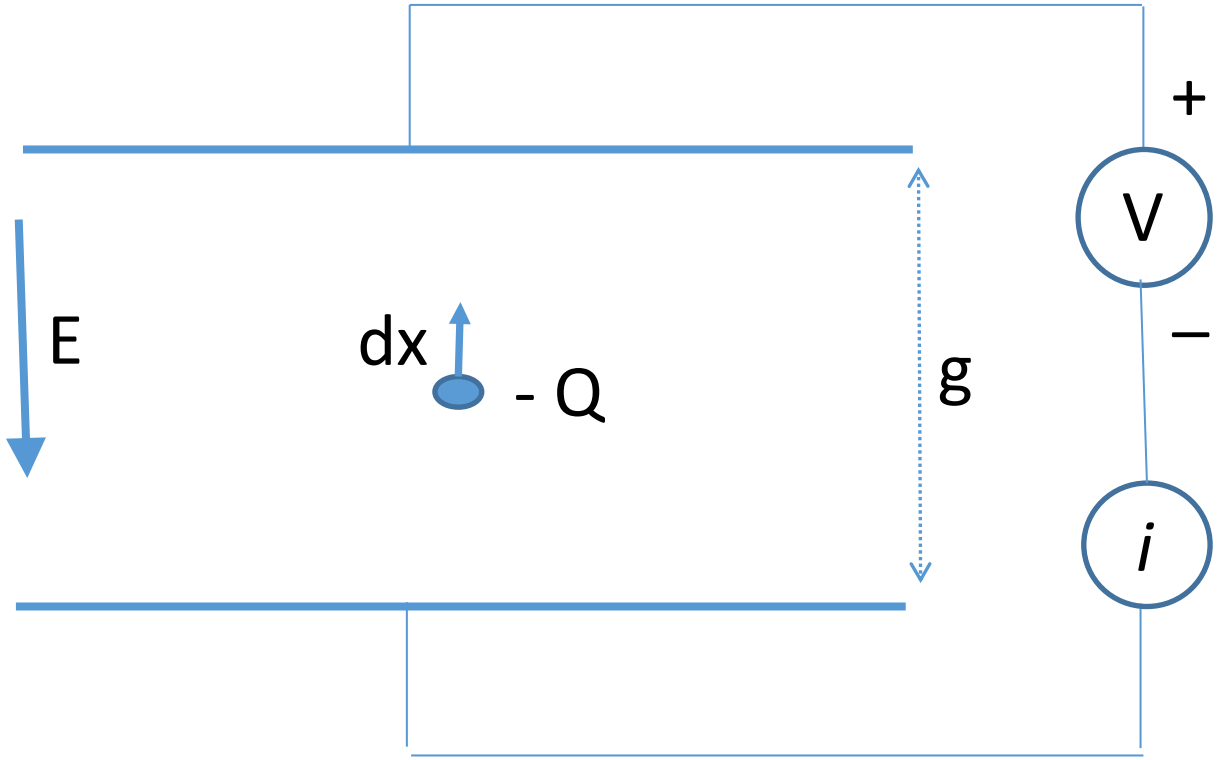
$$dW = EQdx = iVdt = V\,dq$$

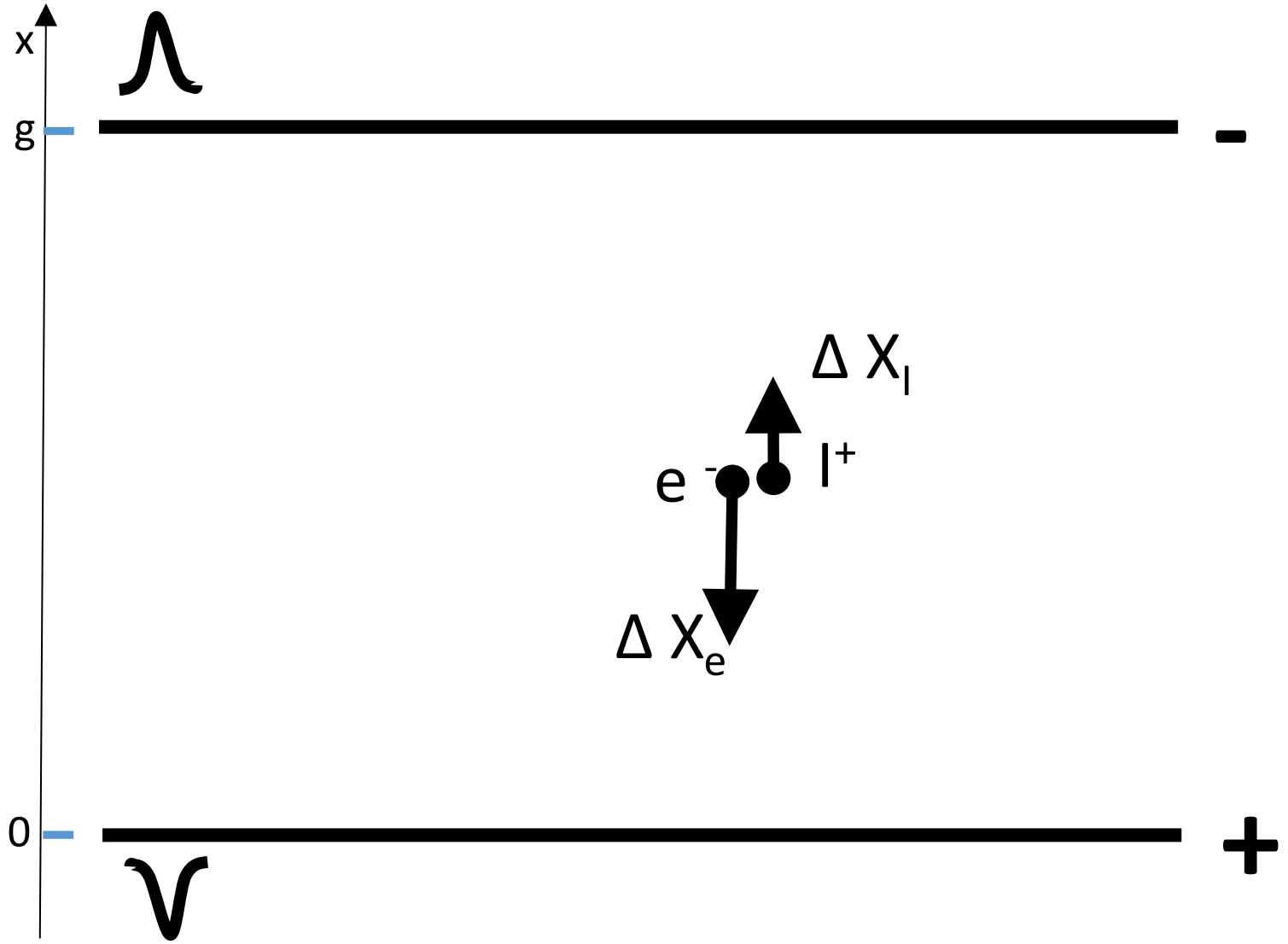
The induced charge is

$$EQdx/V = dq$$

$$dq = Q\,dx/g$$

The same equation is true even if the voltage supply is removed




x
g
0
-
+
Δ X_I
e⁻
I⁺
Δ X_e

Induced signal in a planar detector

- The charge induced on the pick electrodes, according to elementary relationships is

$$dq = (-e\, dx_e + e\, dx_I)/g$$

- The induced current of a single pair

$$i = dq/dt = e(v + V)/g\, v$$

- The *prompt signal* $i \sim ev/g$ is due to the electron drift motion
- The *ionic signal* is much smaller and much longer because $V \sim 10^{-3} v$
- The total charge is the sum of prompt and ionic charge
- It is dominated by the ion drift

Prompt-to-total charge ratio in a purely exponential avalanche model

- The average ratio of the prompt to total charge q/Q can be obtained by a simple analytical calculation assuming
  - A purely exponential discharge (saturation disregarded)
  - A ionization charge uniformly distributed in the gap (charge quantization and fluctuations disregarded)
- The result is $q/Q = 1/\alpha g$ Assuming the Meek condition for the avalanche to streamer transition $\alpha g = 20$ → the prompt charge would be only 5% of the total charge. Indeed most free electrons are produced very near to the anode plate and their path is much shorter than the ion one
- However the avalanche development shows always a certain level of saturation that reduces moderately the value of αg below 20

The avalanche-to-streamer transition

- When the avalanche growth reachs the Meek limit the avalanche evolves to streamers via multiple photoionization events that create new avalanches
- We can describe the streamer as a thin plasma column interconnecting the two electrodes
- Electrons and ions are uniformly distributed in the plasma and therefore in the gap thickness
- In this condition electron and charges have the same value and

$$q/Q = 1/2$$

The avalanche to streamer transition in RPCs

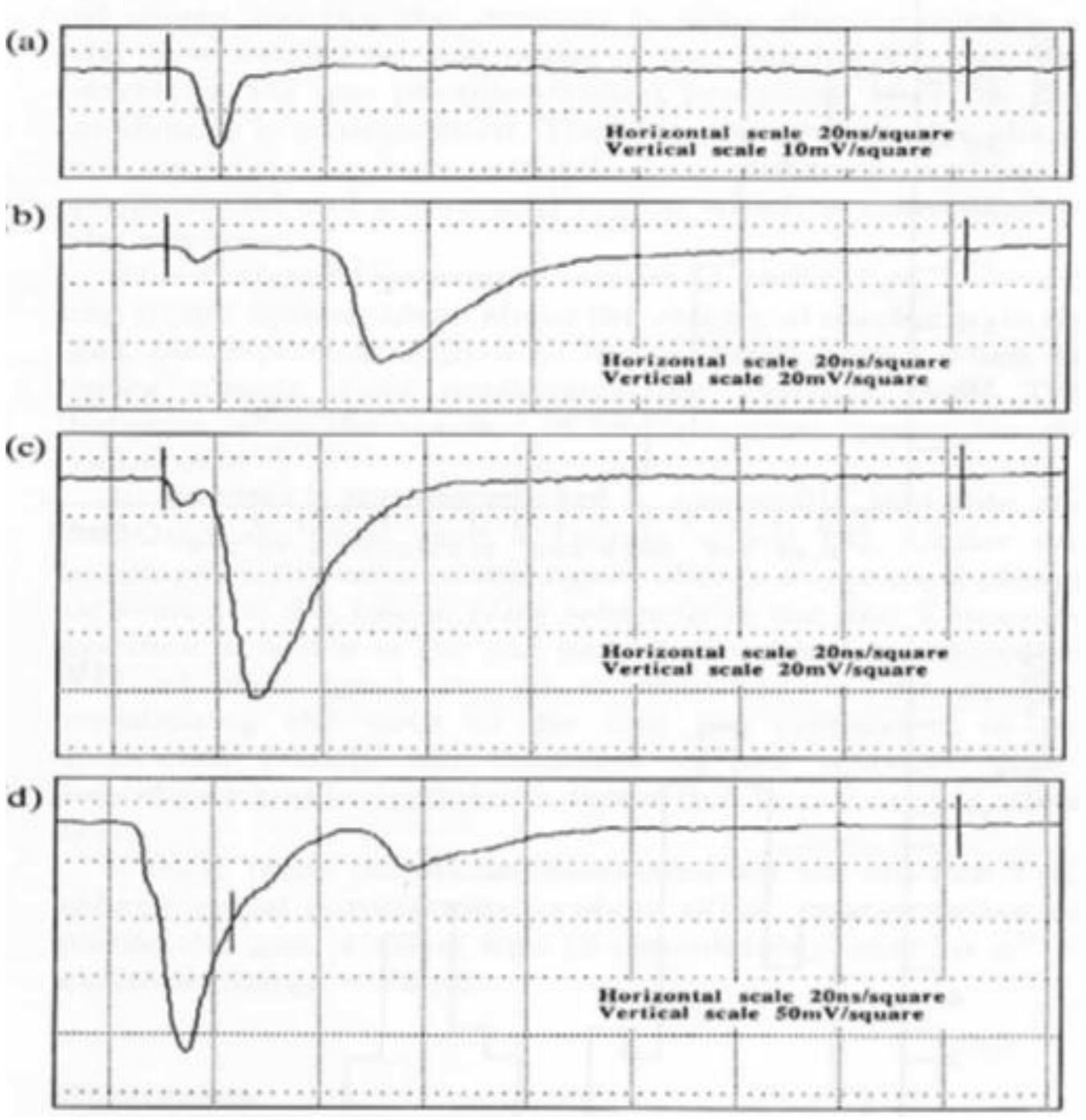
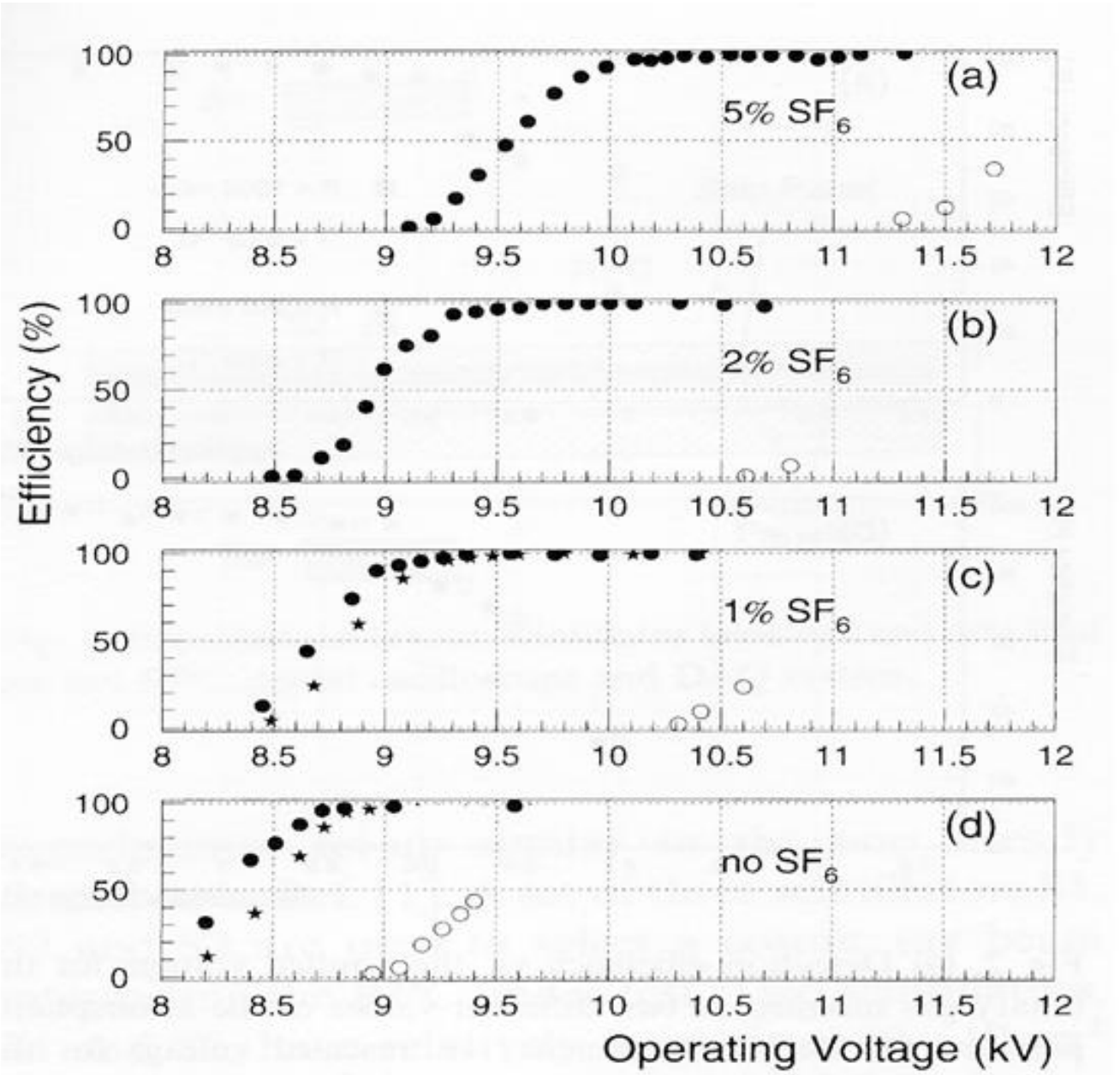


Fig. 2. Signal waveforms at different opearting voltages. The avalanche signal (a, 9.4 kV) has a typical duration of 4–5 ns FWHM. A streamer signal follows the avalanche with a delay of 38 ns (b, 9.6 kV). At higher voltages (c, 10.2 kV) the avalanche to streamer delay becomes gradually shorter and finally (d, 11.4 kV) the avalanche and streamer signals merge into a single pulse. Multistreamer signals are also observed.

Streamer suppression with SF6



● EFFICIENCY (threshold = 30 mV)
★ EFFICIENCY (threshold = 100 mV)
○ STREAMER FRACTION

Fig. 4. Detection efficiency and streamer probability vs. operating voltage for (a) 5%, (b) 2%, (c) 1% SF_6 concentrations and (d) no SF_6.

Avalanche →Streamer →???

- Sometimes, in the common language, a particularly big charge is called *«spark»*
- Is the streamer-to-spark transition in a RPC? The answer is *NO* because the energy available for discharge due to the electrostatic energy of a small volume around the ionization point
- As a comparison we can take the case of the spark chamber where the full energy of the capacitor is discharged in the ionization point
- This is not possible inside an RPC. If for example we force a big discharge using pure Argon the capacitor can spend all its energy not in a single point but transforming in plasma the full volume of the gas

- When the there is no more energy the plasma switches OFF to reappear again after a time $\tau = R^* C^* = \varepsilon_0 \, \varepsilon_r \, \rho$ that the system needs to recuperate its initial condition…and so on
- The resistive electrodes forbid the streamer-to-spark transition
- This is not true for the avalanche-to-streamer transition because the local energy is sufficient to produce a streamer
- In this case only the gas properties can forbid the transition

Intrinsic RPC efficiency

- The RPC achievable efficiency is limited, as for any real detector, by blind areas due to structural elements like spacers and edge frame
- If the effect of the blind areas is discounted the residual inefficiency is intrinsic to the detector
- If $\langle N \rangle$ is the average number of effective primary clusters contributing to the efficiency

$$1-\varepsilon=e^{-\langle N \rangle} \quad ln(1-\varepsilon)=-\langle N \rangle$$

Average number of primary clusters contributing to the efficiency

- Streamer mode operation ???
- Anyway depending on the sensitivity of the front end electronics