Physics of the Resistive Plate Chambers

DRD1 School

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Gaseous media, conductors or insulators?

- Gaseous ionization detector require 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?
- Ionizing sources surrounding the gas can 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 increase of many orders of magnitude in a sub-nanoseconds time

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 $dp = dl/\lambda$ of colliding with a gas molecule/atom. Here dl and λ are the recurred distance and the mean free path respectively with $1/n\sigma = \lambda$
- The electron, after a free flight l , can Ionize an atom in the next collision if the condition $\boldsymbol{E}e * \boldsymbol{l} > E_i$ is fulfilled, E_i being the ionization energy. The minimum required distance is therefore $l_{min} = V_i/\boldsymbol{E}, V_i = \frac{E_i}{e}$ being the atom ionization potential
- The corresponding probability is $\int_{l_{min/\lambda}}^{\infty} e^{-\frac{l}{\lambda}} \frac{dl}{\lambda} = e^{-V_i/\lambda \boldsymbol{E}}$
- → Number of ionizations per unit length $\alpha = \frac{1}{\lambda} e^{-V_i/\lambda \boldsymbol{E}}$

→ 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
  - $dp = \alpha dl$ α is the first Townsend coefficent
  - This model due to Townsend is the simplest model explaining 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 any 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
- However, the induced signal in a ionization detector continue to grow untill the electron drift motion continues

Quenching mechanisms

- In order to avoid that the discharge generated in one point propagates to other points through UV-photons emission the primary discharge must be quenched
- An Ar atom for example can only absorb and re-emit photons of energy $E_{gamma} > 11.6 \text{ (minimum excitation energy)}$ 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

The first gaseous detector: the Geiger counter

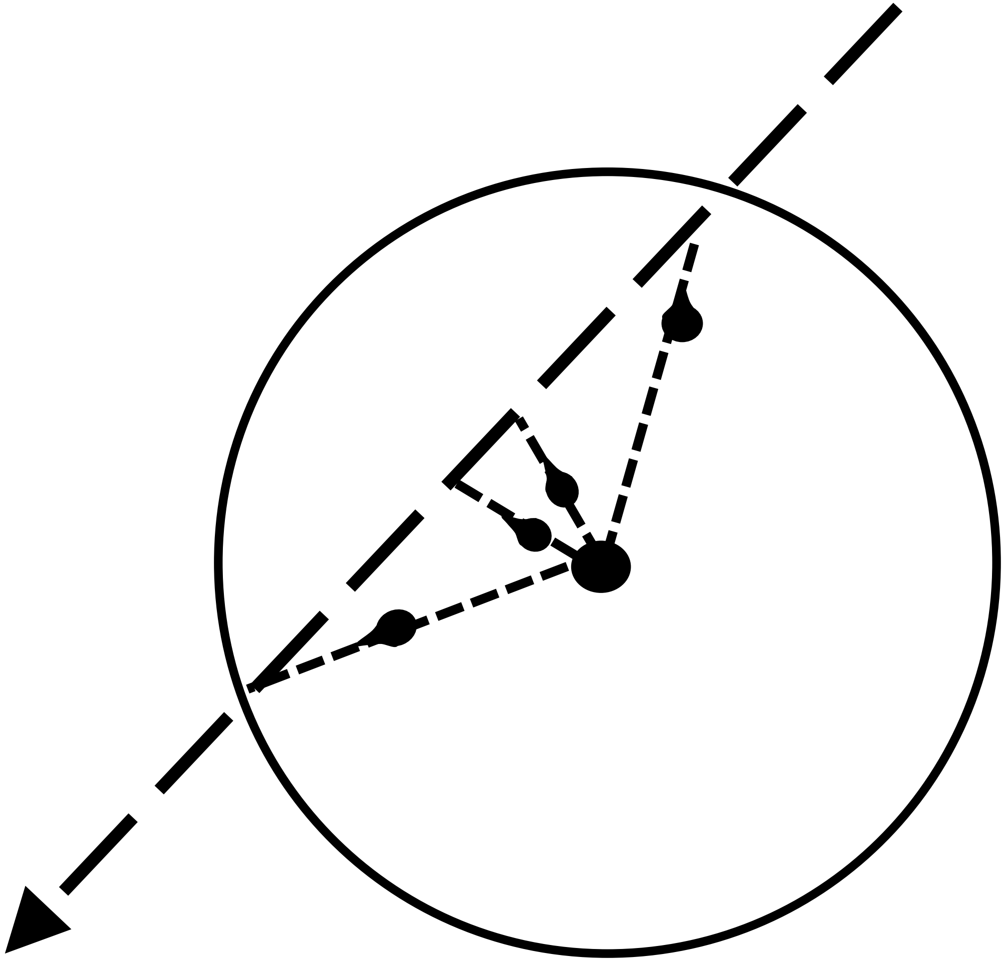
- It was the first idea (1920 decade) of a gaseous radiation detector and is a common ancestor of a *large family of the wire chambers*
- It is a metallic cylindrical tube with a well isolated metal wire in the tube axis. The tube is filled with a noble gas to which a very small amount of organic component (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

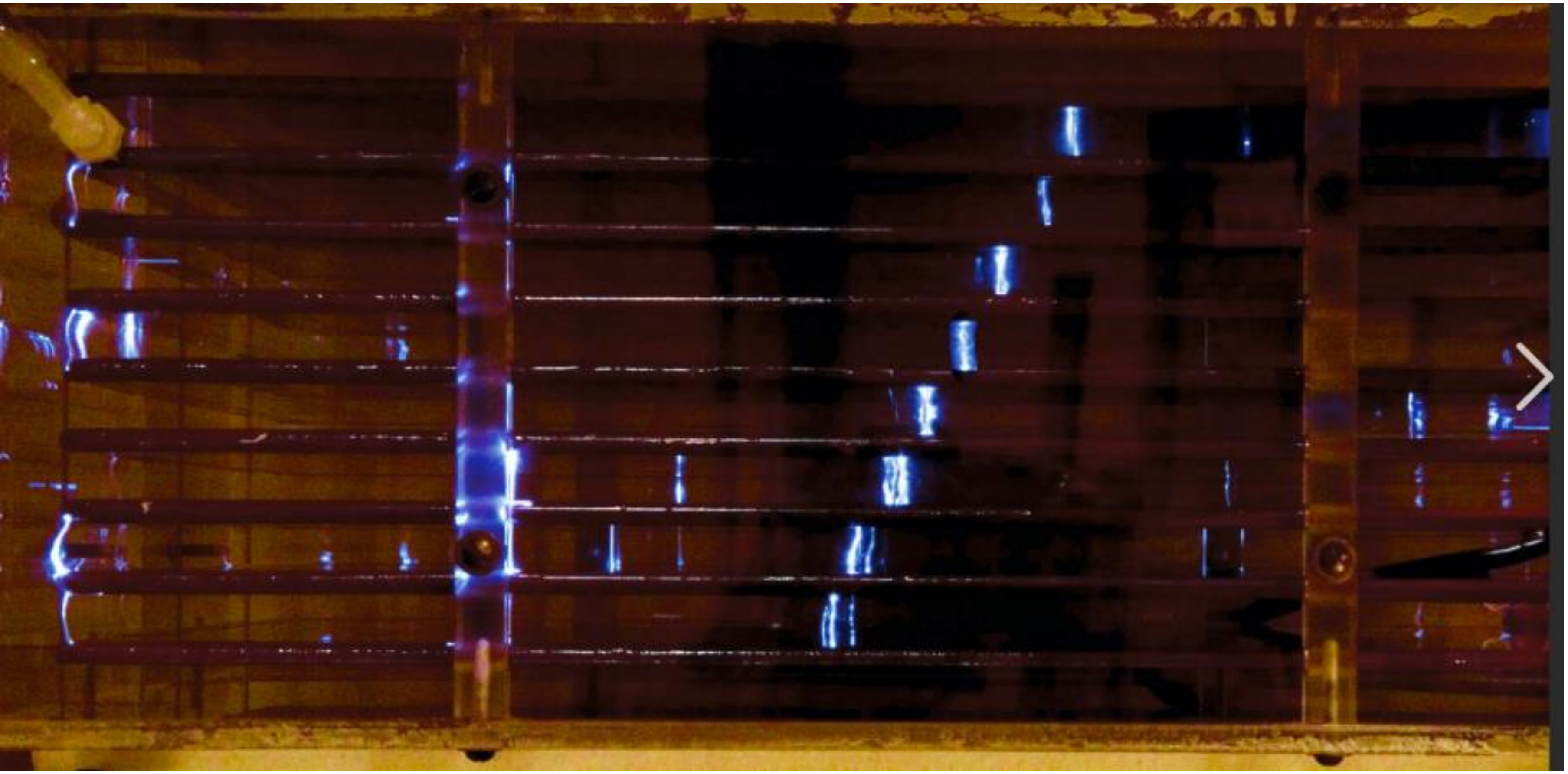
- Field largely sub-critical in the sensitive volume; *drift and multiplication regions well separate*
- Primary clusters drift toward the anode wire and do not produce visible signal except very close to the wire, tens of microns in diameter, where the field is strong enough to produce multiplication
- 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



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: *multiple plane 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*

The optical spark chamber



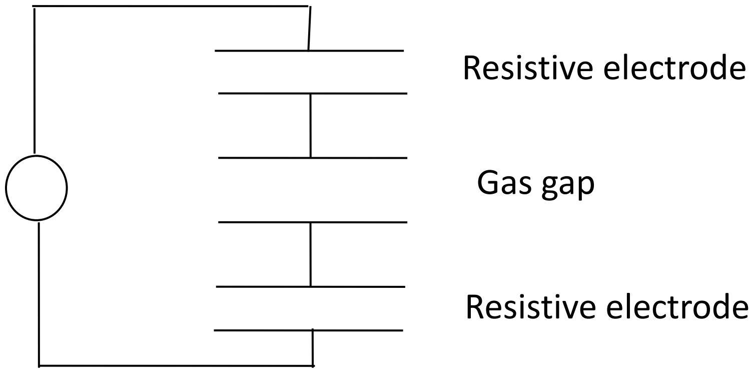
- Activated by an HV pulse
- Triggered by scintillators within about 1μs otherwise the diffusion would dispers ionization electrons
- Sparks alligned in the field, not in the trajectory direction

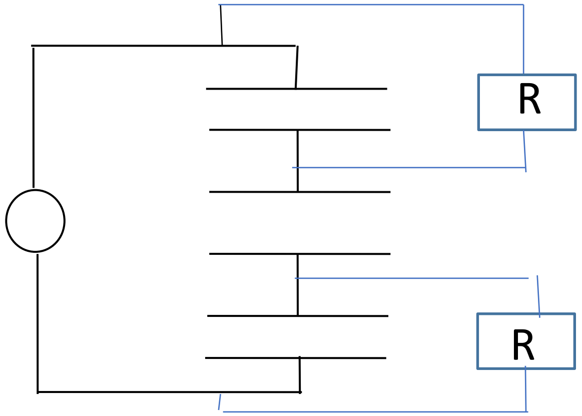
Is it conceivable the idea of DC-coupled spark chamber?

- 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*. 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

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

  τ = R^*C^*= $\varepsilon_0\ \varepsilon_r\ \rho$ only dependent on the electrode material

For t >> τ the material is a (modest) conductor → in steady condizion the supplied voltage is totally applied to the gas gap. The field is zero inside the resistive electrodes

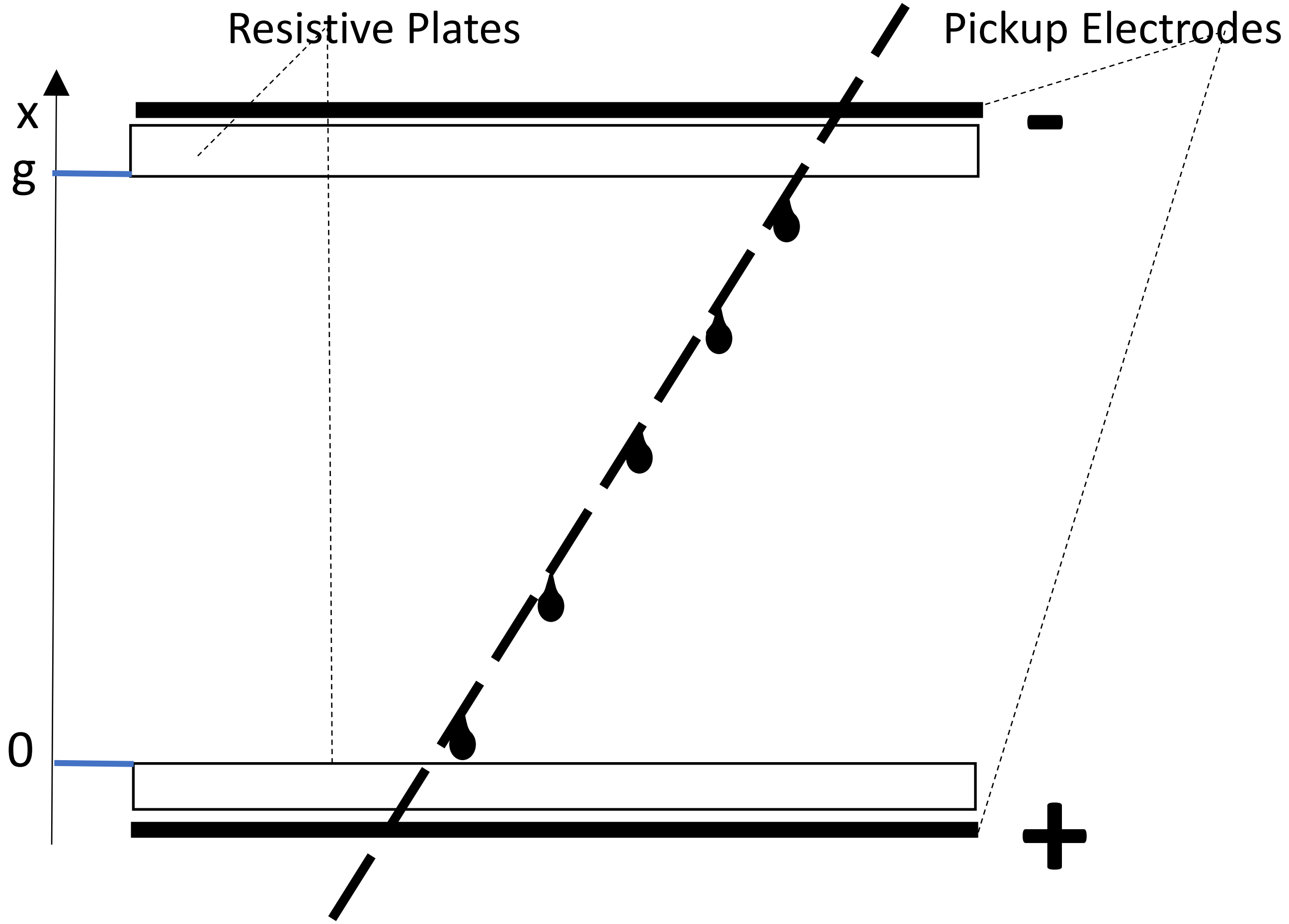
For t<< τ Is an insulator → the *discharge duration, of tens of ns << τ*

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

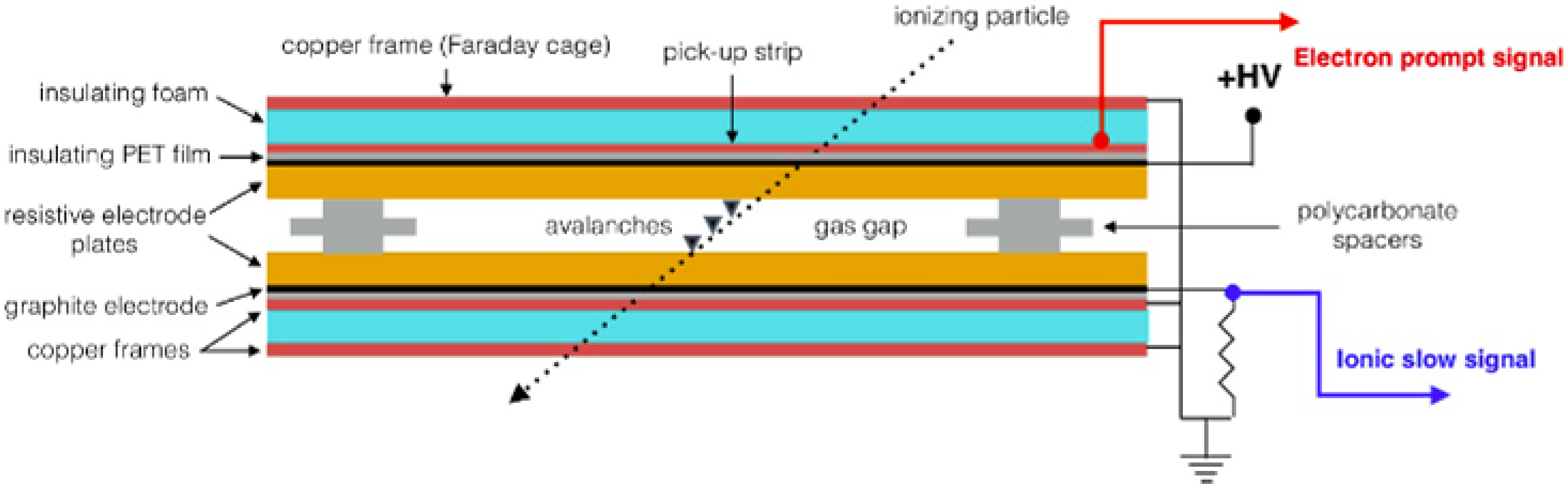
→ The avalanche can *only be sustained by the electrostatic energy of a small volume around the ionization point*

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
- BUT clusters produced close the anode are very uneffective



Sketch of a real RPC



Ionization related fluctuations

- The primary ionization follows the *Poisson statistics.*The collision probability in an trajectory element dl is $dp = dl/l_0$ with
- $l_0 = \frac{1}{n\sigma} = average\ free\ path,\ \sigma = total\ cross\ section$

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

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

- The secondary ionization follows the *Landau statistics*

  number of electron-ion pairs proportional the the kinetic energy T

  distributed like $1/T^2$

- Further fluctuations in RPCs are related to thedifferent distance of each cluster from the anode

Induction from a moving charge

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

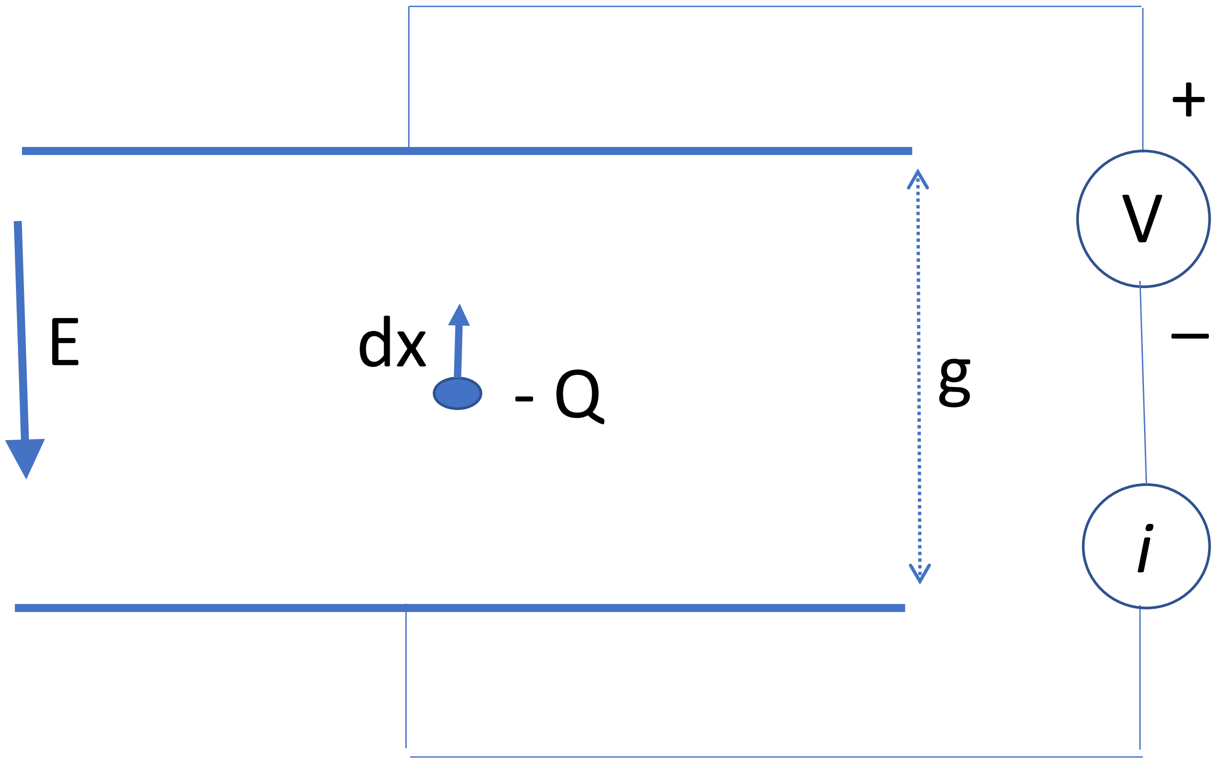
$dW = EQdx = iVdt = V\,dq$

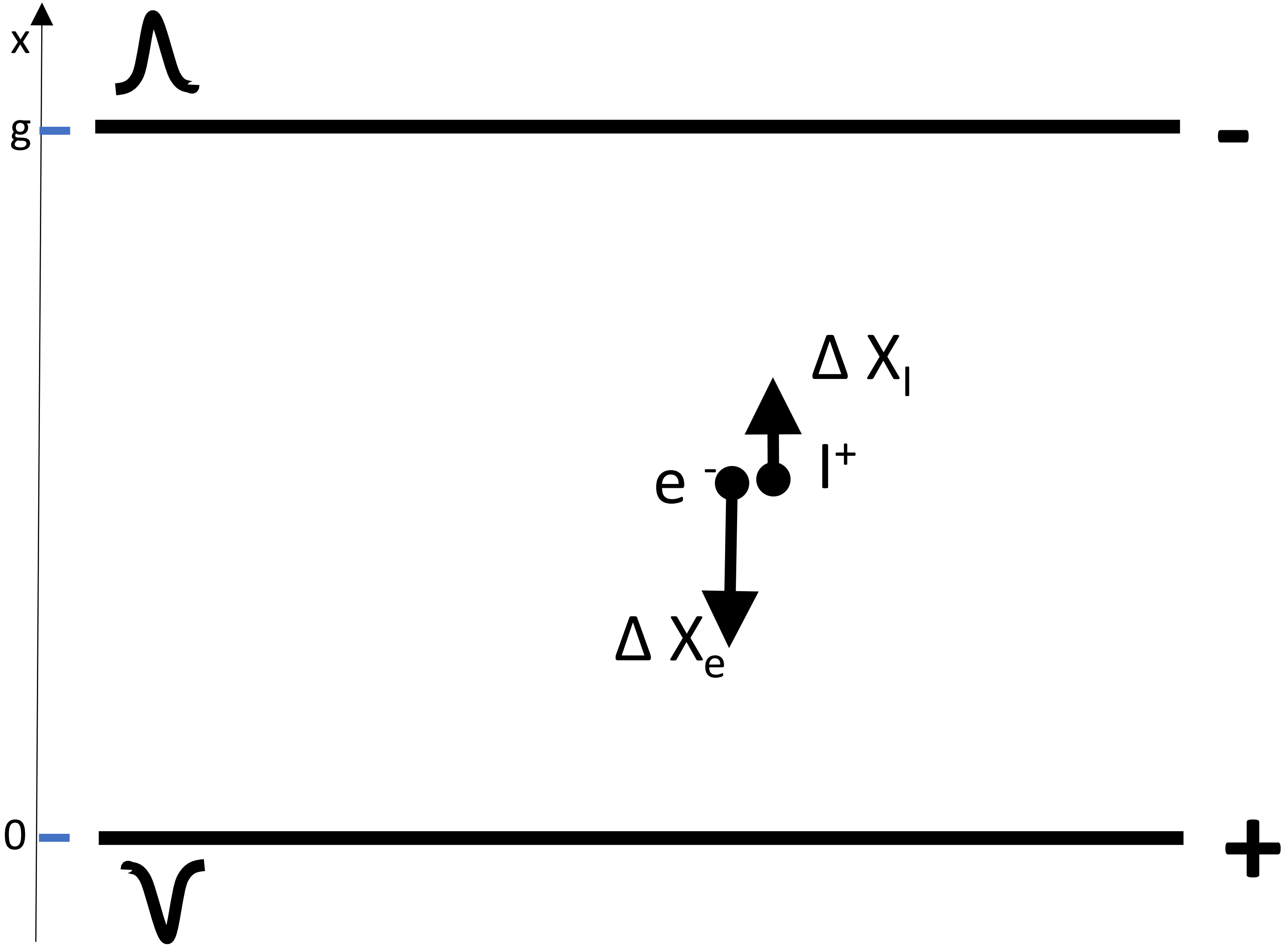
The induced charge is

$EQdx/V = \ dq$

$dq = Q\ dx/g$

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




x
g
0
Λ
V
-
+
Δ X_l
l+
e-
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

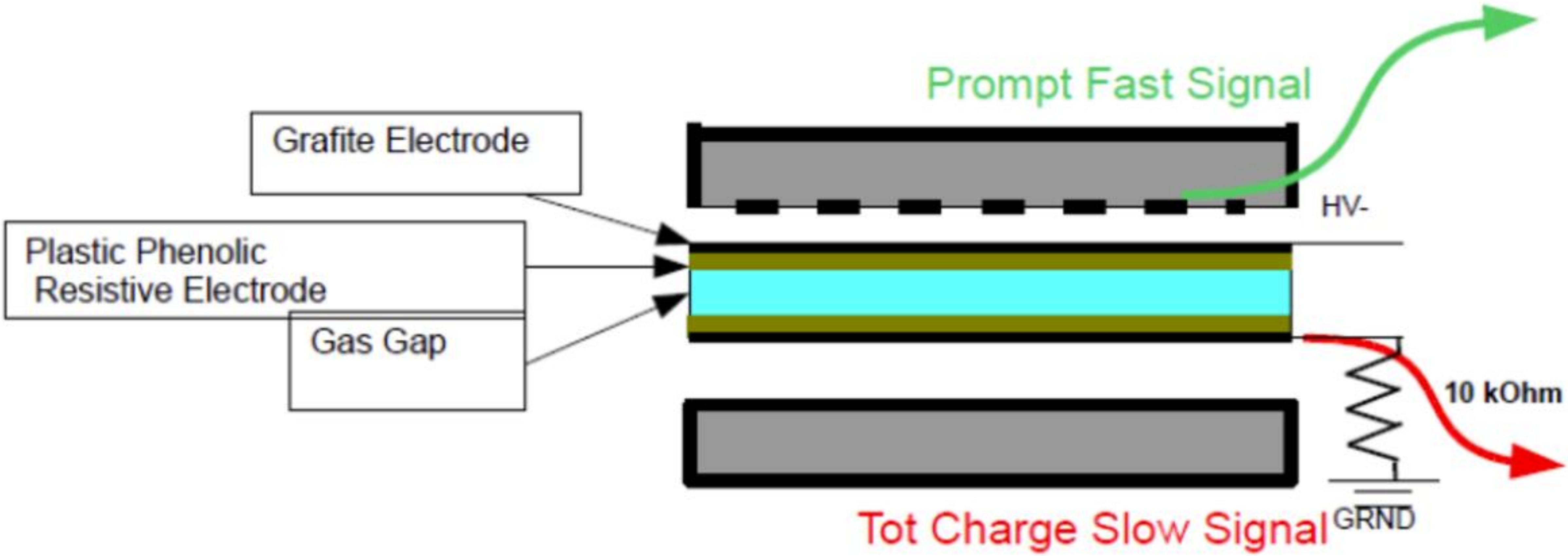
$$i = dq/dt = e(v+V)/g$$

- 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 close 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 the value of αg below 20

Measurement of the ionic signal



The avalanche to streamer transition in RPCs

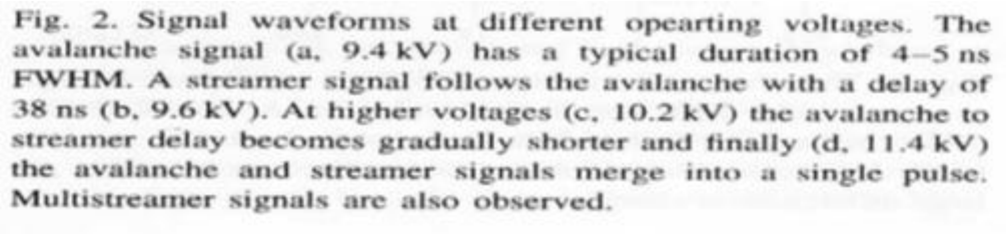
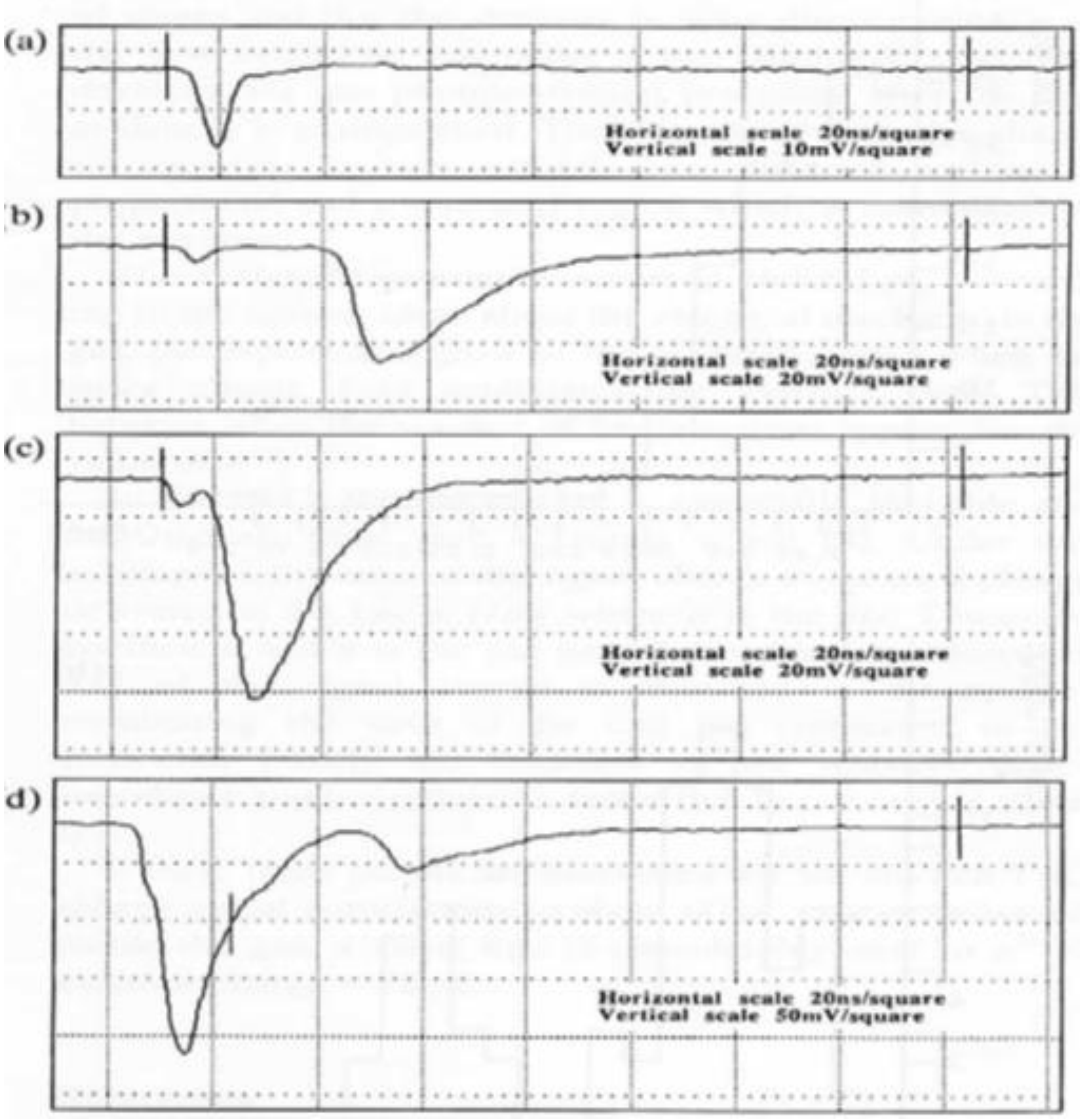
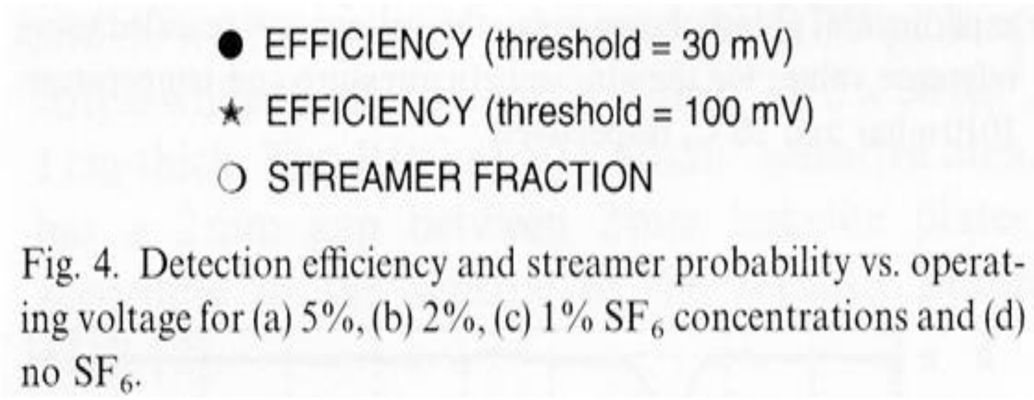


Fig. 2. Signal waveforms at different opearting voltages. The avalanche signal (a, 9.4 kV) has a typical duration of 4–5 ns FWHM. A streamer signal follows the avalanche with a delay of 38 ns (b, 9.6 kV). At higher voltages (c, 10.2 kV) the avalanche to streamer delay becomes gradually shorter and finally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

Standard gas mixture
C2H2F4/i-C4H10/SF6=94.7/5/0.3



Streamer suppression with SF6



● EFFICIENCY (threshold = 30 mV)

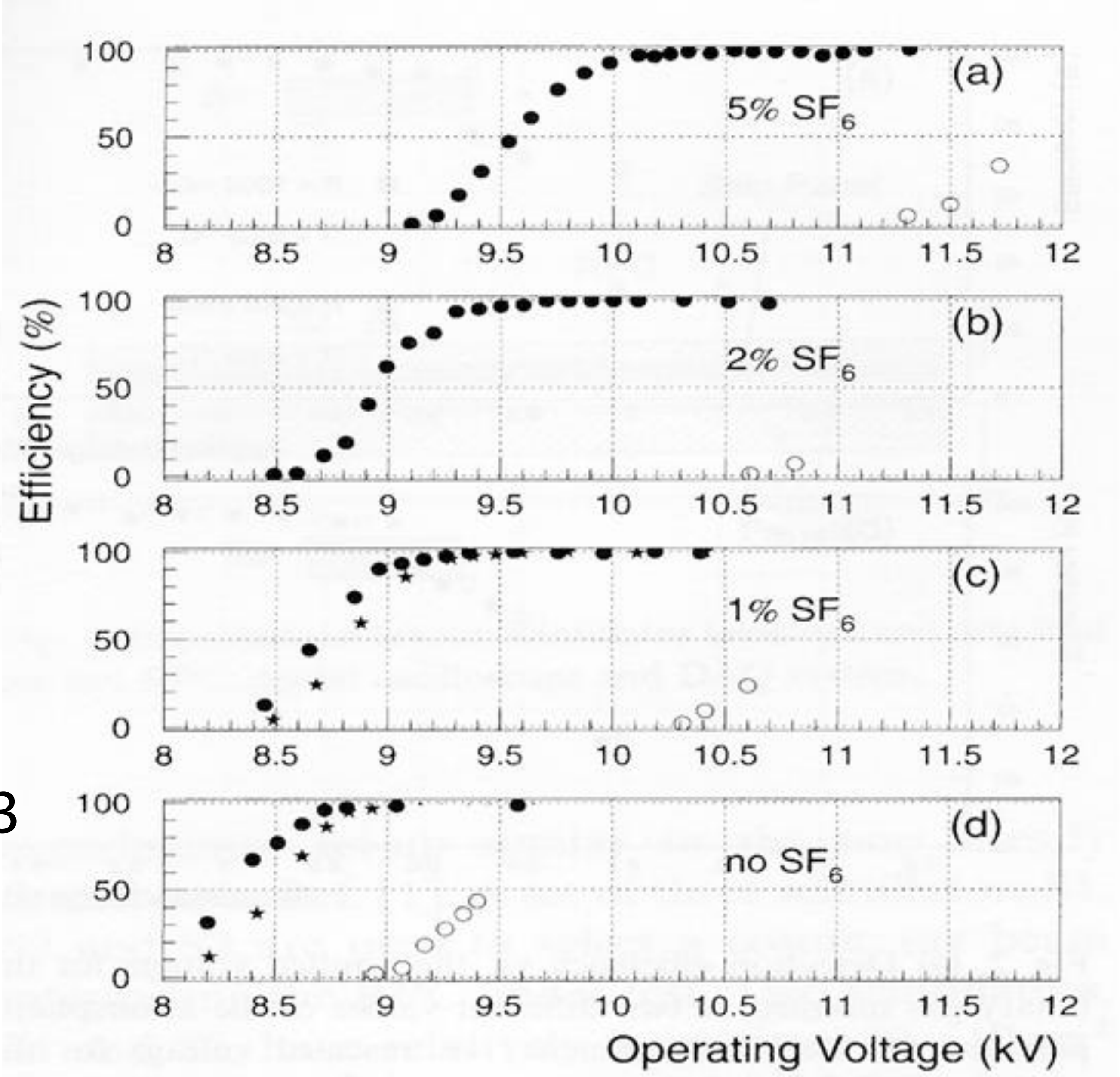
★ EFFICIENCY (threshold = 100 mV)

○ 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.

Standard gas mixture

C2H2F4/i-C4H10/SF6=94.7/5/0.3



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 τ = $R^{*}C^{*}$= $\varepsilon_0 \ \varepsilon_r \ \rho$ 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

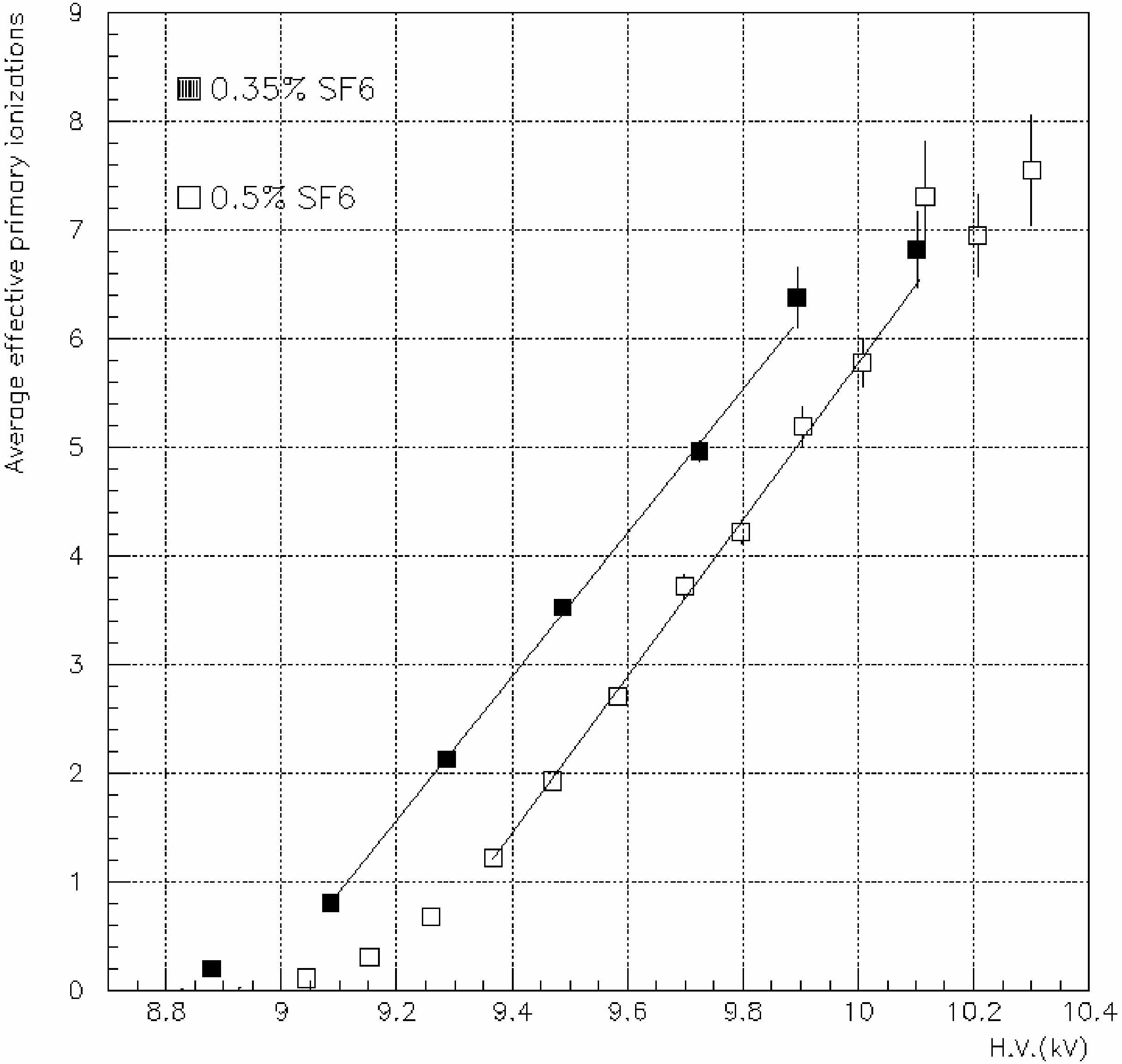
Intrinsic RPC efficiency

- 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 $<N>$ is the average number of effective primary clusters contributing to the efficiency

$$1-\varepsilon=e^{-\prec N>} \quad \ln(1-\varepsilon)=-<N>$$

Average number of primary clusters contributing to the efficiency

- ➢ Streamer mode operation ???
- ➢ Depending on the sensitivity of the front-end electronics



Improving the RPC time resolution

- The «delay» of the RPC answer the interval between the time when a particle ionizes the gas and the time when the corresponding signal passes the discrimination thresld
- The jitter of this delay, which is due to the fluctuations of the primary ionization, is the RPC time-resolution. → the shorter is the delay the smaller are its fluctuations and the better is the resolution
- How can this delay be shortned? The signal growth time profile is dominated by the factor $e^{\alpha v t}$, $\alpha = \text{first Townsend coeff}$ and $v = \text{drift velocity}$.
- → Increasing $\alpha(\mathrm{V})$, for approximately constant v, by increasing the operating voltage V, is the way for improving the timing. What happens after the signal has passed the threshold does not matter. BUT…
- The above statement is only theoretical. A high value of V can induce streamer or multi-streamer regime. The operating voltage cannot be raised much above the avalanche saturation point

The multigap-RPC idea (1)

- The experiment shows that reducing the gap size requires a (obvious) reduction of the operating voltage that is, however, less than proportional to the gap reduction → a higher electric field is required
- The rule -*the thinner is the gap the higher is the electric field*- suggests the best way to improve the RPC timing by reducing the gap size. BUT…
- The gas primary ionization decreases with the gap size and the *zero-probability* becomes more and more important, according to the Poisson distribution. This cannot be compensated by increasing the FE circuit amplification

The multigap-RPC idea (2)

- This limit, in the RPC historical development, was removed by the idea of the multigap-RPC, mRPC
- The single gap is replaced by a number of tinner gaps by means of intermediate floating electrodes separating them
- This allows to strongly improve the electric field and therefore the timing performance, while limiting the growth of the signal
- Tens of pico-second time resolutions are reached
- Very important result for Time-of-Flight applications to momentum-vs-velocity combined measurement for particle identification

On a new environment-friendly gas mixture for Resistive Plate Chambers [ref]

- ➢This research aims to replace the «standard mixture», C2H2F4/i-C4H10/SF6=95/4.7/0.3 with a more ecofriendly gas, without penalizing the RPC performance
- ➢The use of the two following molecules replacing C2H2F4 and SF6 respectively, gave v

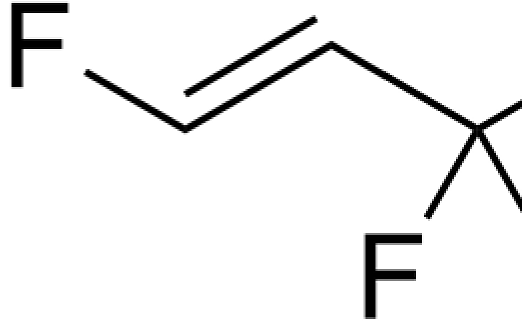


Figure 1: 1,3,3,3-Tetrafluoropropene molecule.

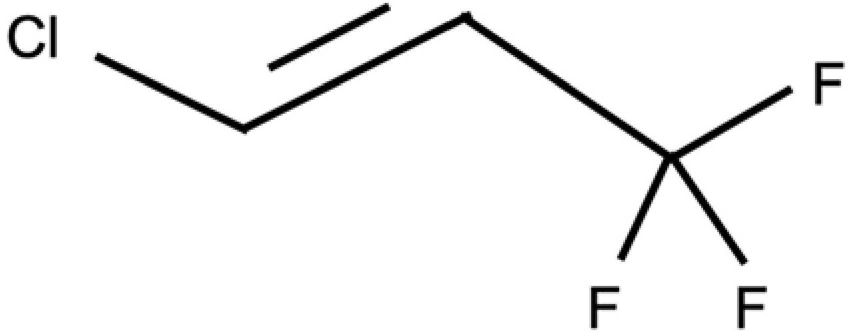


Figure 2: 1-Chlorine-3,3,3-Trifluoropropene molecule.

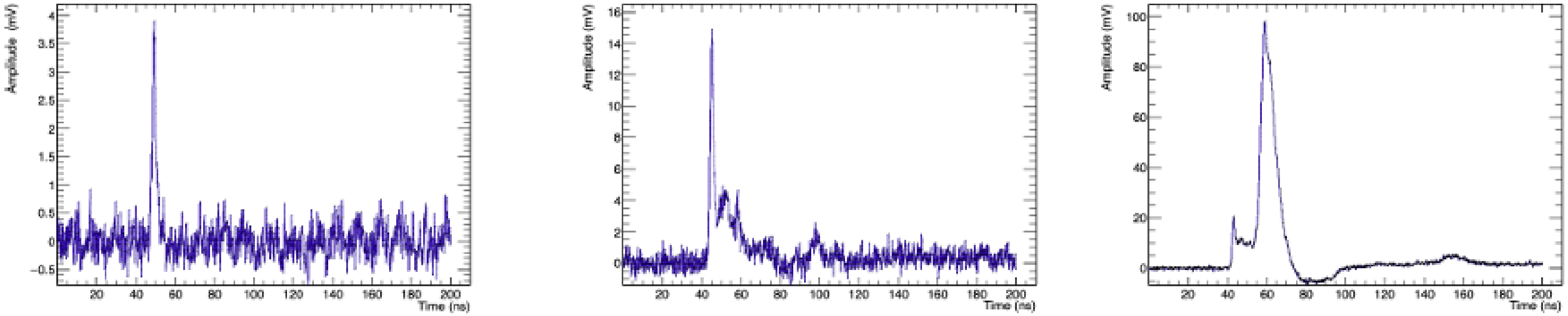
Systematic test of the new gas mixture

- 4-component gas mixture of:

F-HFO / CO_2 / i-C_4H_{10} / Cl-HFO, with CO_2 as the main component and the other 3 gases with a few units GWP

- Specific purposes of the test:
  - Maximize the CO2 with respect to the F-HFO fraction
  - Study the performance of Cl-HFO as a SF6 replacement
- Therefore the test was carried ot with
  - HFO/i-C4H10 kept at constant concentration of 15% and 7% respectively and
  - CO2/Cl-HFO ratio ranging from 77/0 to 71/6 in steps of 1%

New gas typical signals of 3 different working modes



(a) (b) (c)

Figure 6: Signal waveforms: (a) Avalanche signal, (b) Transition charge signal and (c) Streamer signal

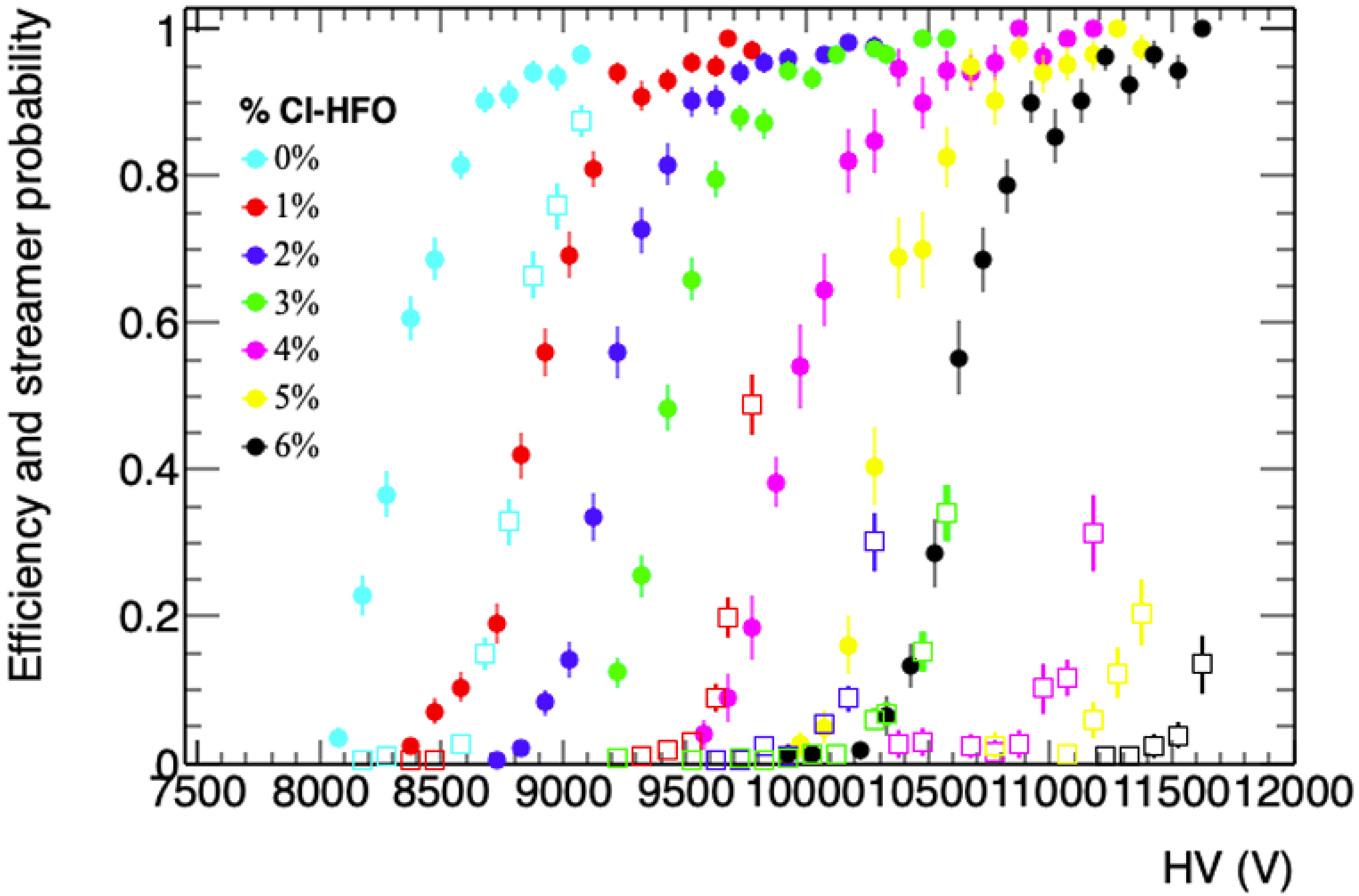


Figure 7: Efficiency and streamer probability as a function of the high voltage for different Cl-HFO concentration. The blank markers are referred to the prompt efficiency, while the empty markers represent the streamer probability.

Efficiency vs streamer and transition probability

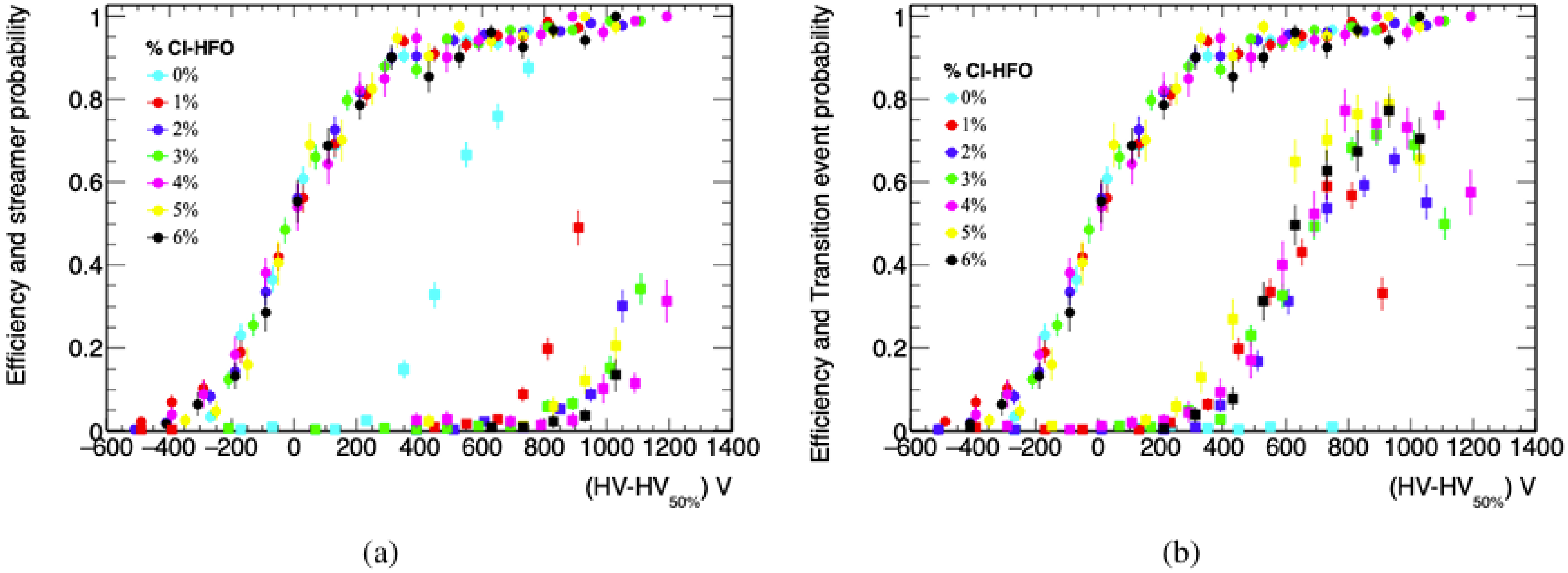


Figure 8: Efficiency and streamer probability (a) and transition event probability (b) as a function of the high voltage for different Cl-HFO concentration. The curves have been aligned respect to the high voltage value which corresponds to the 50% of efficiency. The transition event probability grows until a maximum and then starts to decrease due to the transition to streamers.

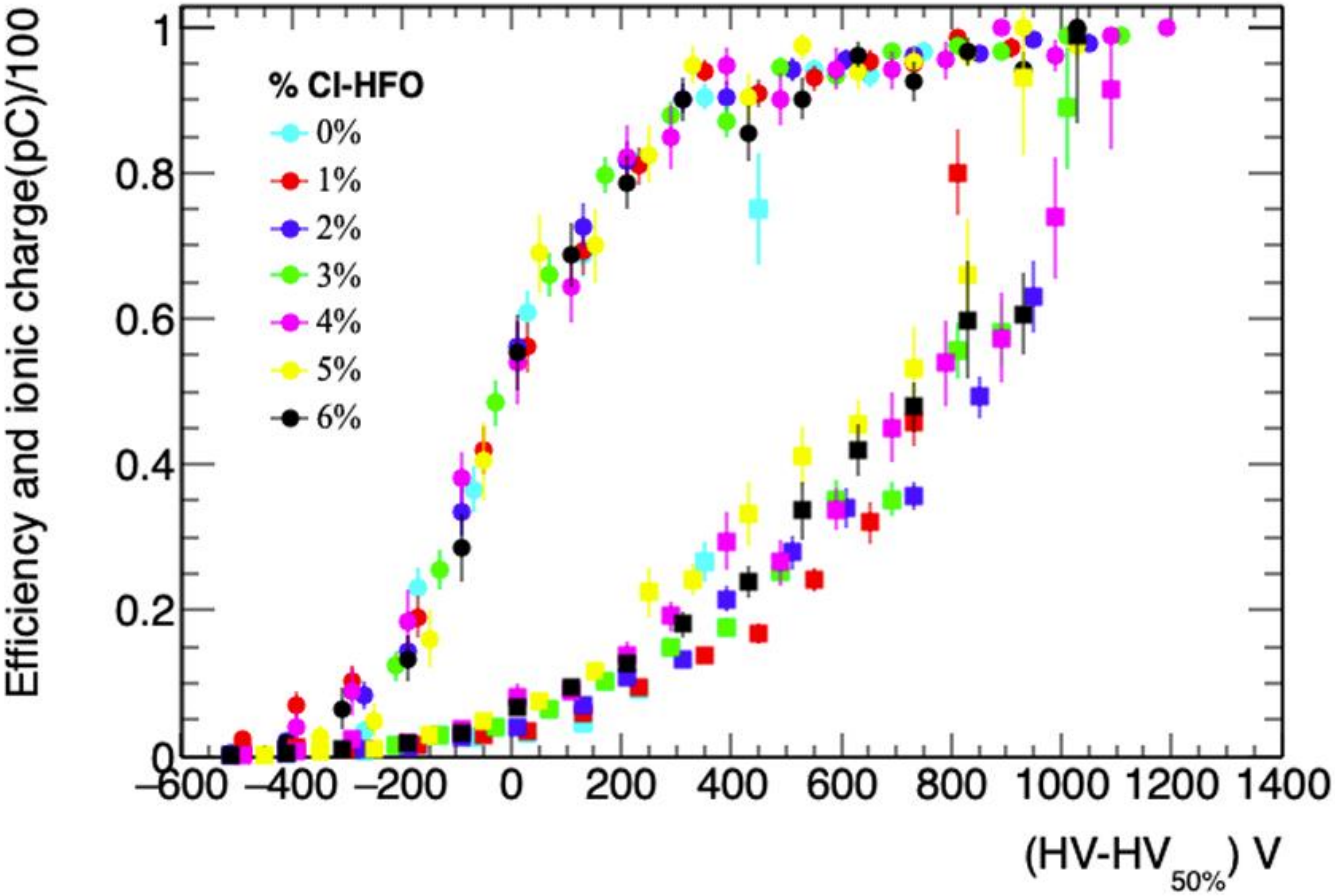


Figure 9: Ionic charge as a function of the high voltage for different Cl-HFO concentration

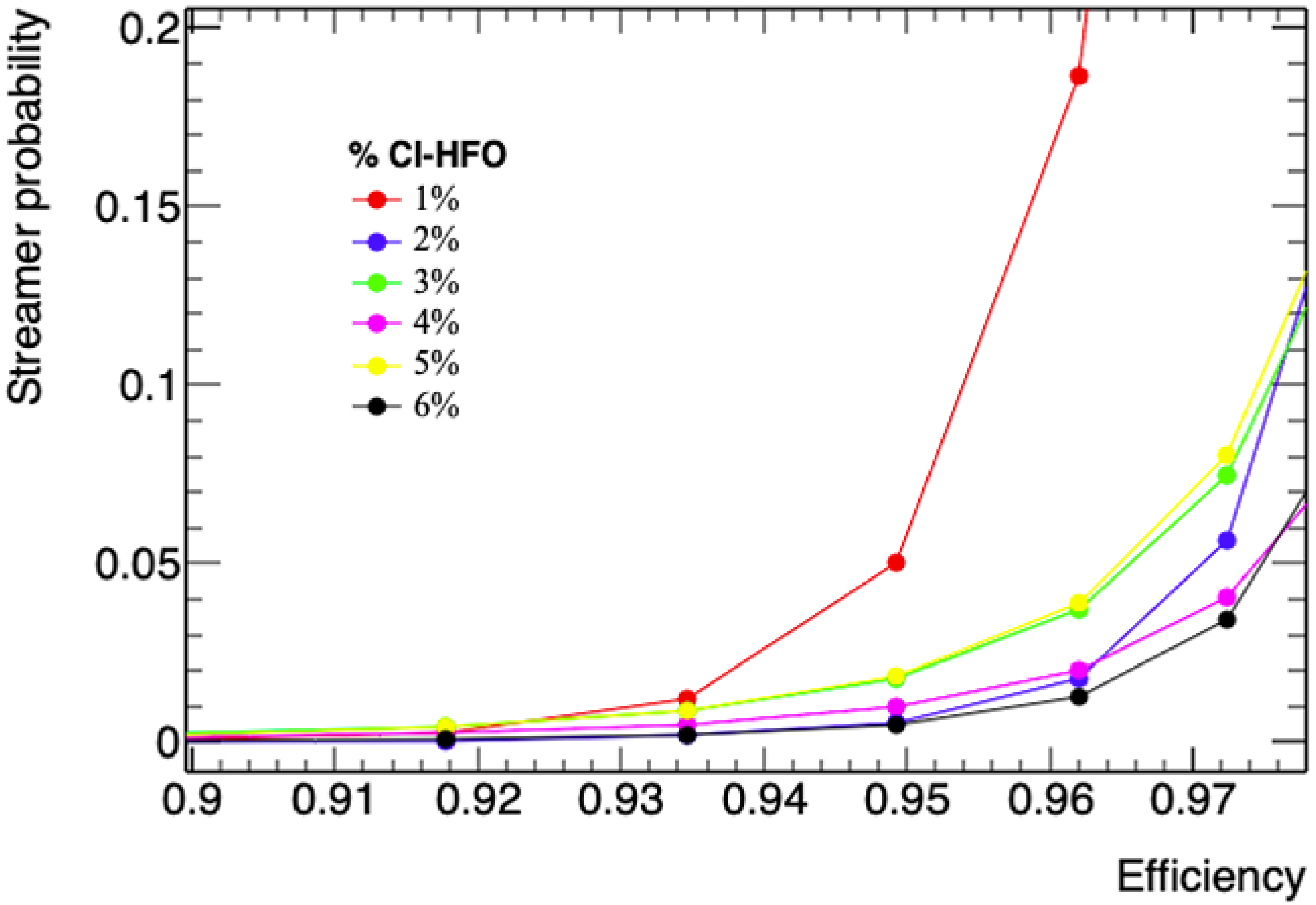


Figure 12: Streamer probability as a function of the efficiency

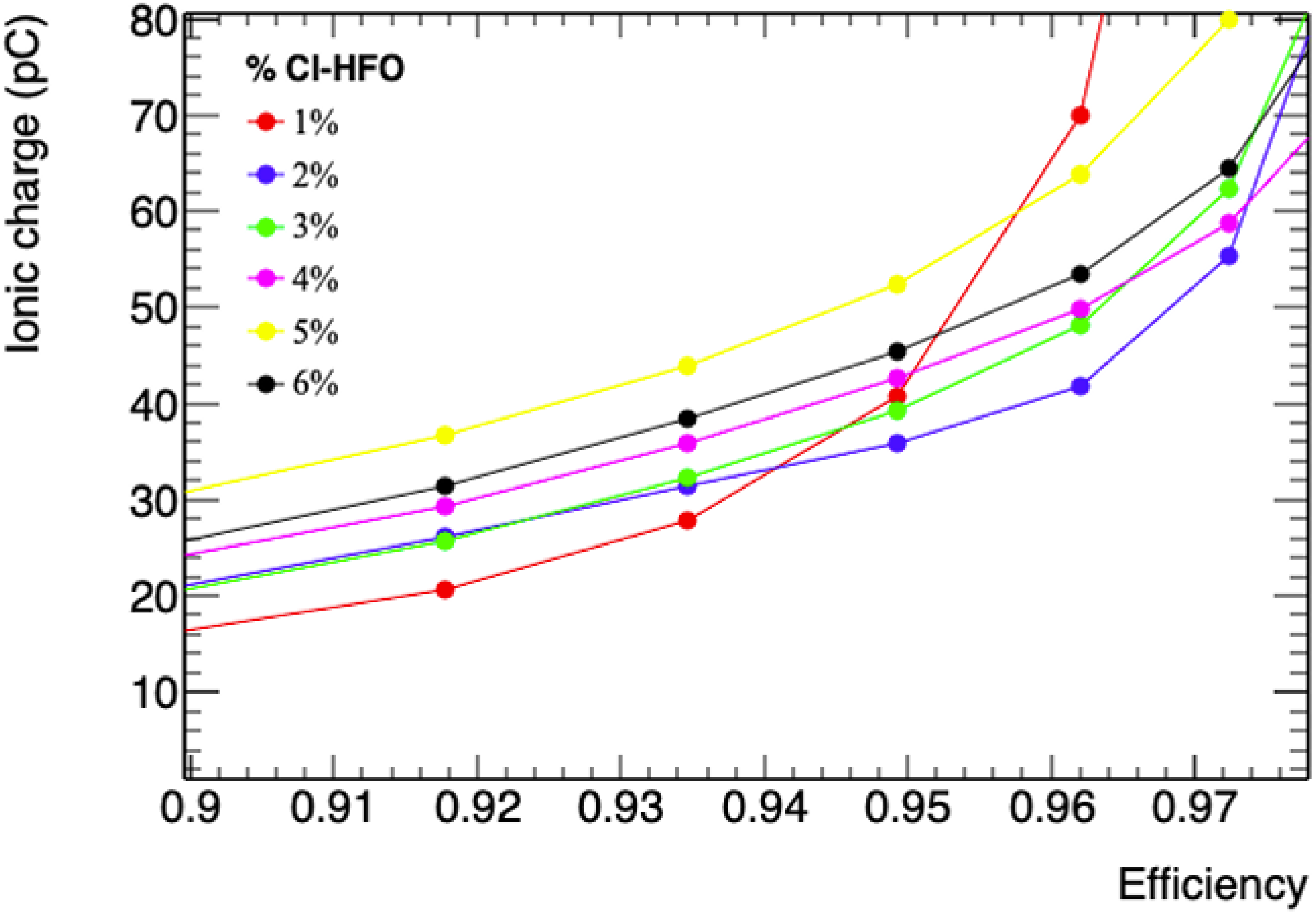
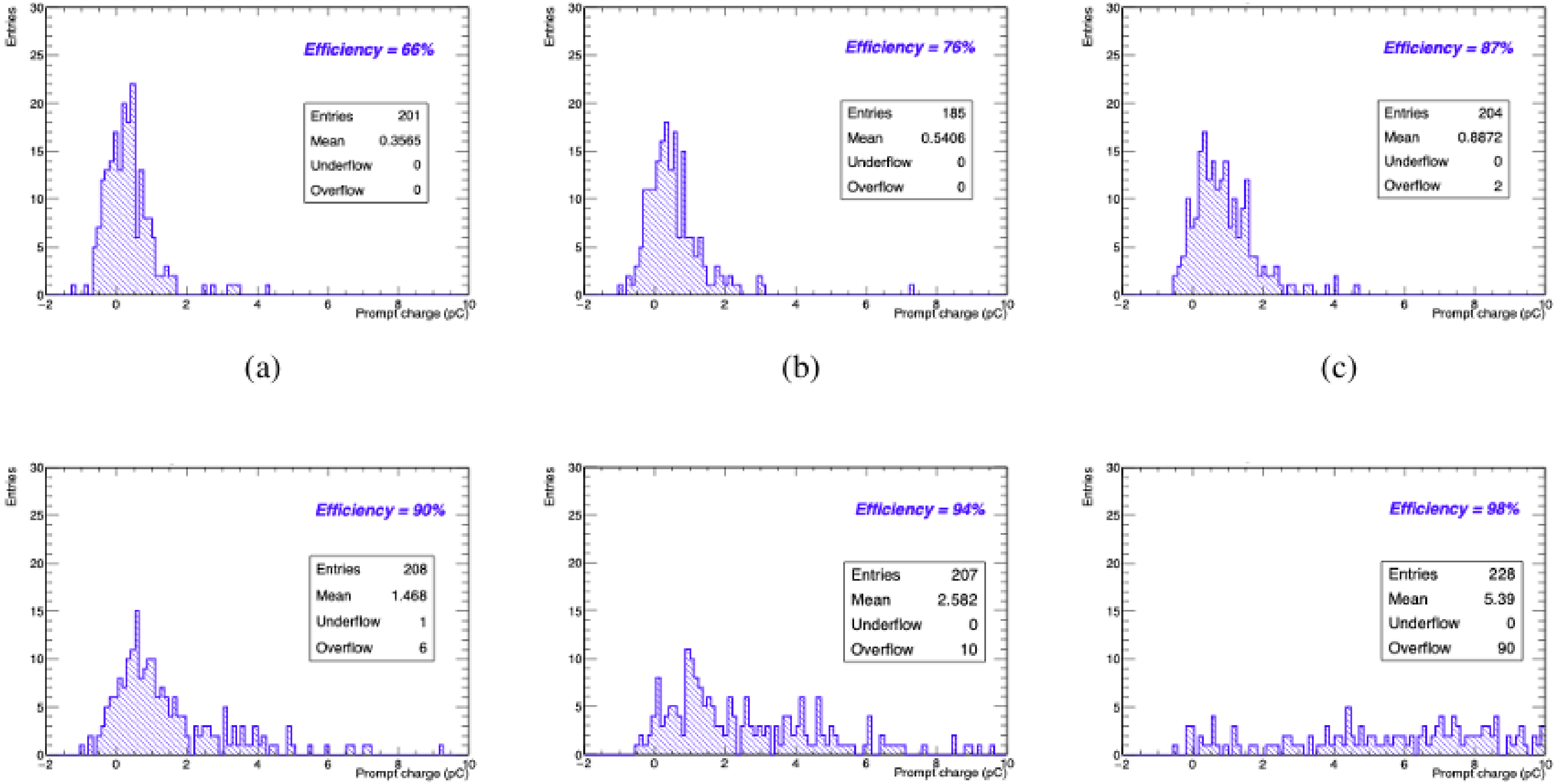


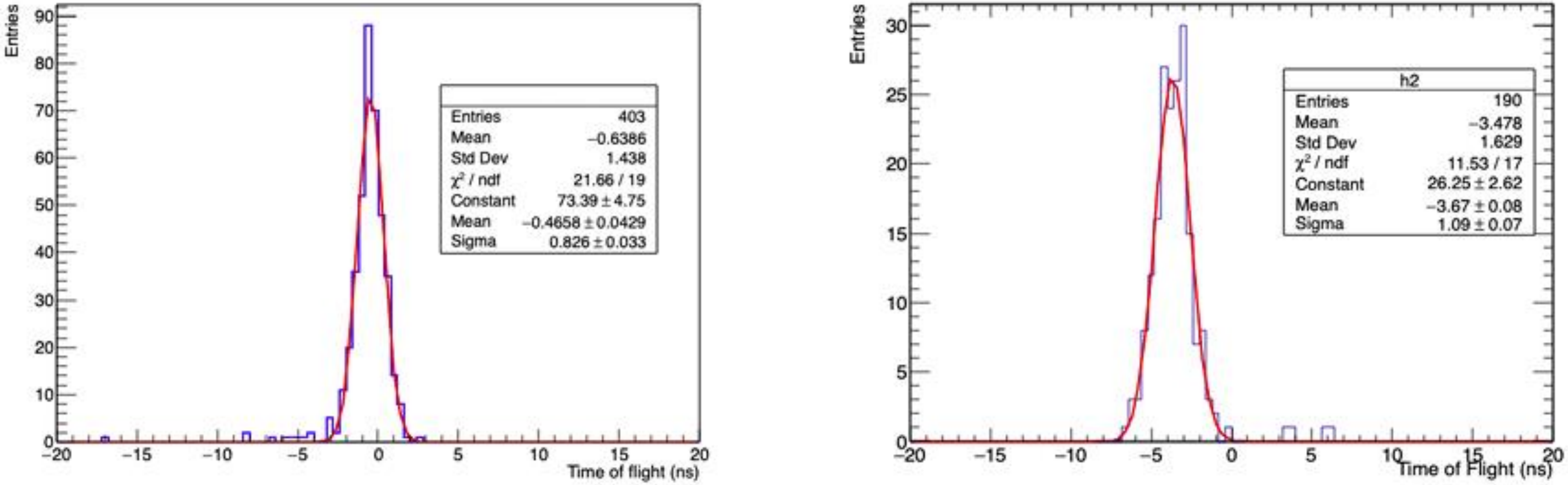
Figure 13: Ionic charge as a function of the efficiency



(a) (b) (c)

(d) (e) (f)

Figure 14: Total prompt charge distribution at different efficiencies for the eco-gas mixture composed of CO_2/F-HFO/i-C_4H_{10}/Cl-HFO=76/15/7/2



(a)

(b)

Figure 15: Time resolution for the (a) eco mixture (CO_2/F-HFO/i-C_4H_{10}/Cl-HFO=76/15/7/2) and the (b) standard mixture($C_2H_2F_4$/i-C_4H_{10}/SF_6=94.5/5/0.3)