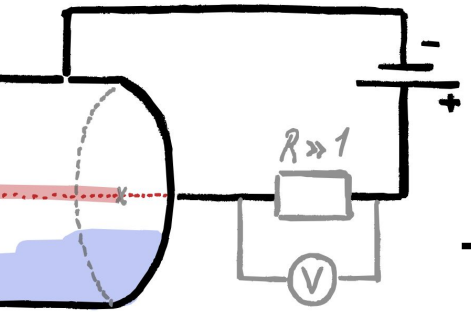


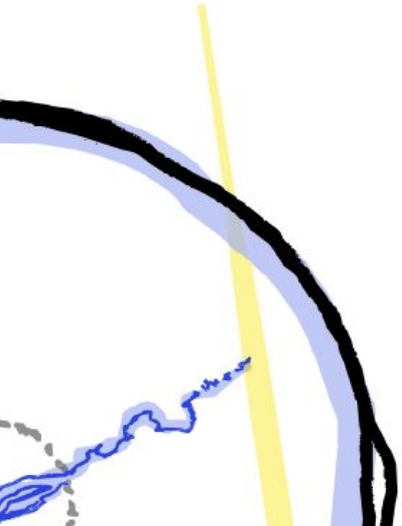


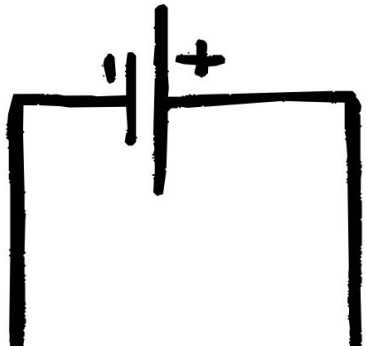
The first chapter of the book

Resistive Gaseous Detectors

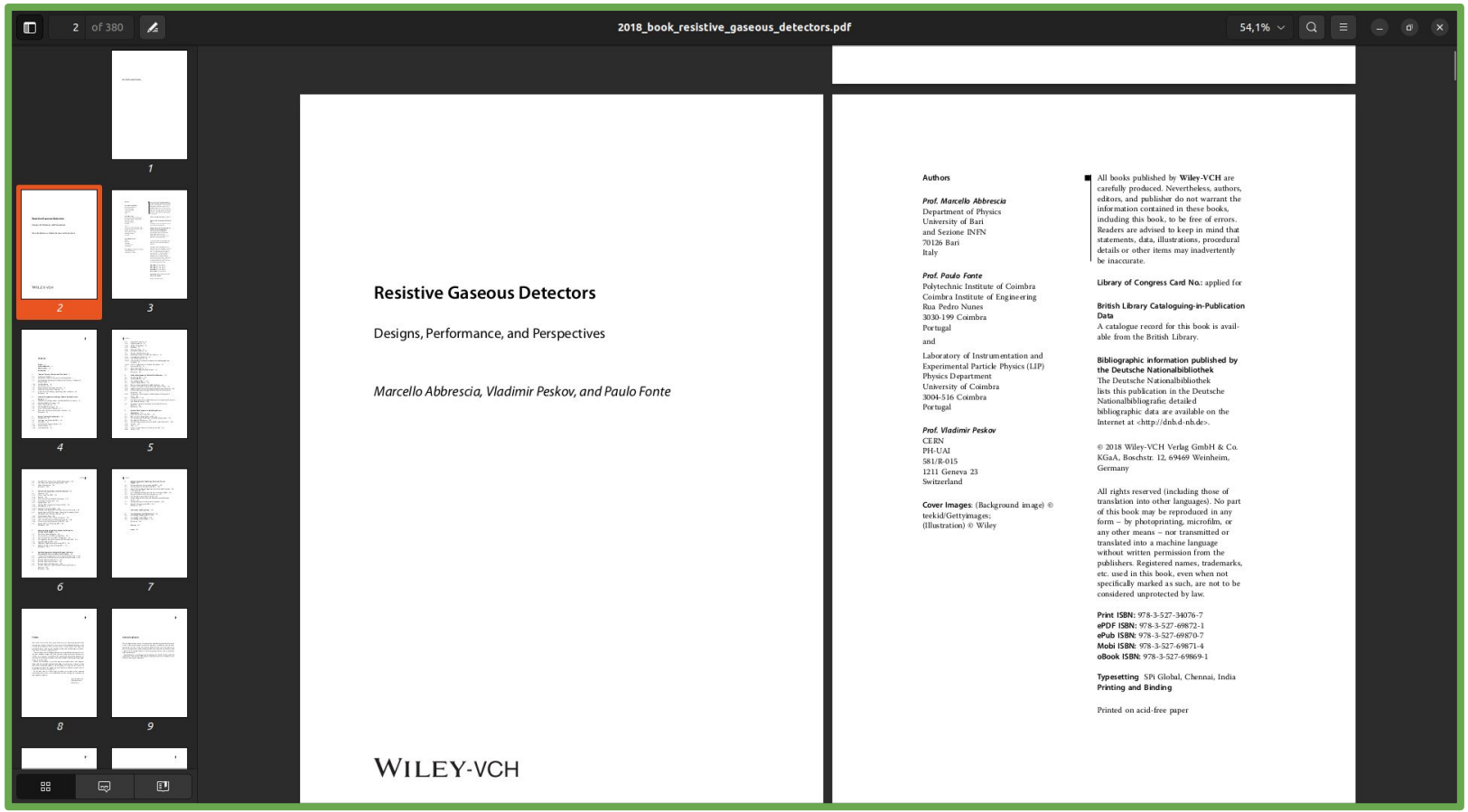
by Fonte, Abbrescia and Pestov

C. Soneira-Landín
October 15th, 2026
DFH-IFIN, Magurele, Romania





Let’s read together the first chapter of the book!



Objective

Explain the basics of Resistive Plate Chambers (RPCs) reviewing some historic detectors and key concepts

- **For those new in the field…**
  - maybe a good introduction to gaseous detectors and RPCs
- **For those already in the field…**
  - maybe a good introduction to the book
  - and to refresh some concepts

Unless said the opposite:

- Figures come directly from the book
  - same numbering in case you want to find them.

Index of the book

1. **“Classical” Gaseous Detectors and Their Limits**
2. Historical Developments Leading to Modern Resistive Gaseous Detectors
3. Basics of Resistive Plate Chambers
4. Further Developments in Resistive Plate Chambers
5. Resistive Plate Chambers in High Energy Physics Experiments
6. Materials and Aging in Resistive Plate Chambers
7. Advanced Designs: High-Rate, High-Spatial Resolution Resistive Plate Chambers
8. New Developments in the Family of Gaseous Detectors: MPGD with Resistive Electrodes
9. Applications beyond High Energy Physics and Current Trends

The index of the chapter, and of the talk:

1. “Classical” Gaseous Detectors and Their Limits

1.1. Ionization Chambers
1.2. Single-Wire Counters Operated in Avalanche Mode
1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields
1.4. Pulsed Spark and Streamer Detectors (skipped)
1.5. Multiwire Proportional Chambers
1.6. A New Idea for Discharge Quenching and Localization

Introduction

A key foundation:

- **1900s**: Ionization Chambers
- **1908**: Geiger Counters

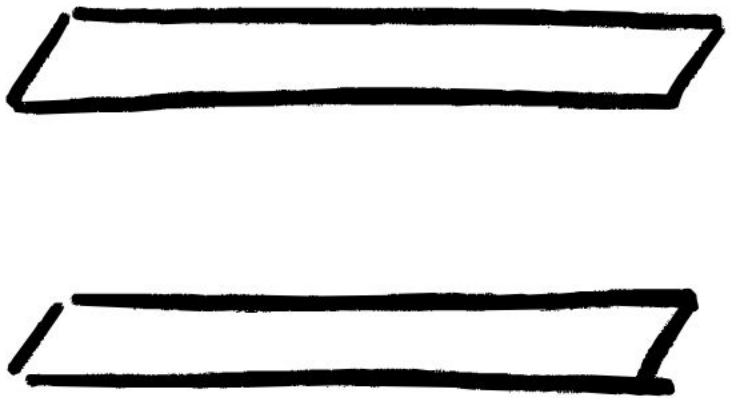
After that, three major breakthroughs marked important milestones in this field:

- **1968**: Multi-Wire Proportional Chambers, by Georges Charpak (Nobel ‘92)
- **1980s beginning**: Resistive Plate Chambers
- **1990s ending**: Micro-Pattern Gaseous Detectors *(not in this talk)*

1. “Classical” Gaseous Detectors and Their Limits

1.1. Ionization Chambers (1900s)

A gas volume between two electrodes

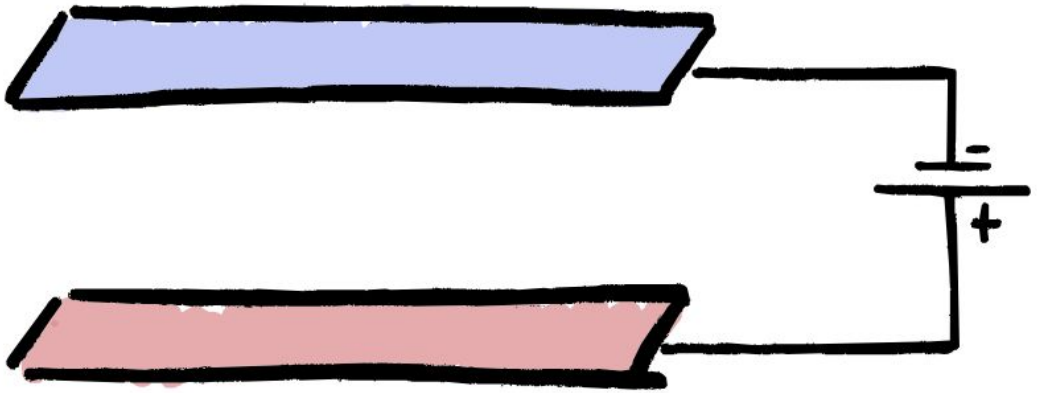


Original figure

1.1. Ionization Chambers (1900s)

A gas volume between two electrodes

with fixed ΔV

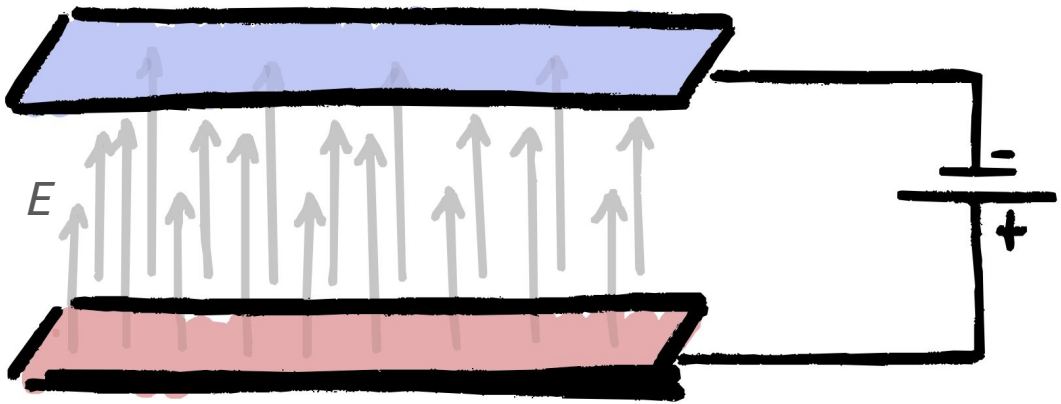


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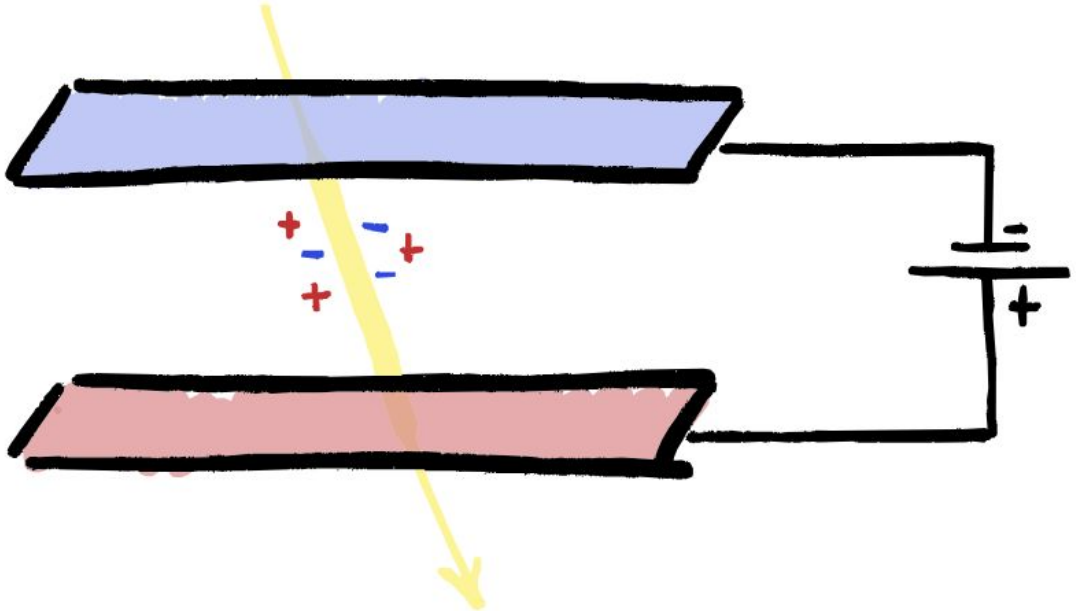
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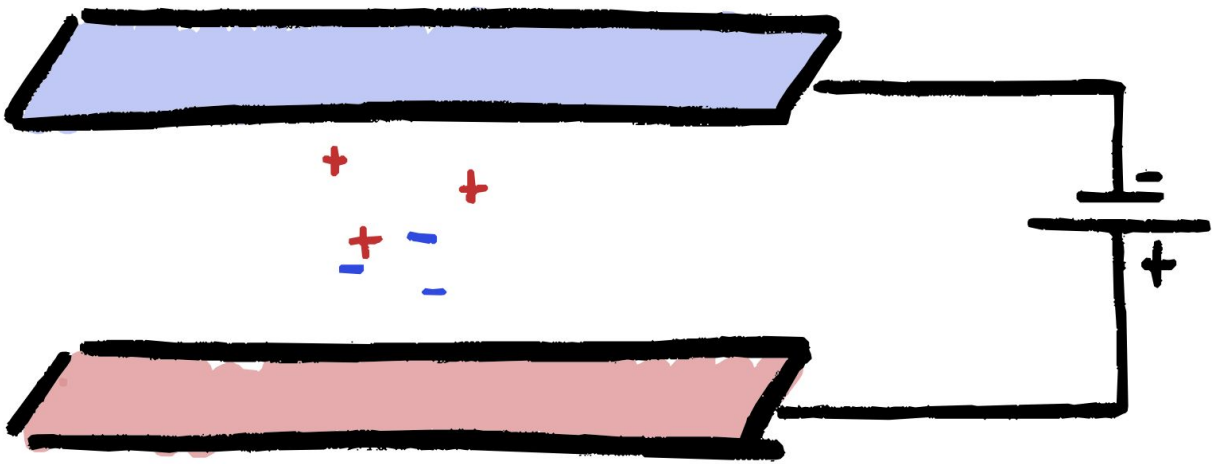
Arriving particles ionize the gas, creating **ion-electron pairs**



Original figure

1.1. Ionization Chambers (1900s)

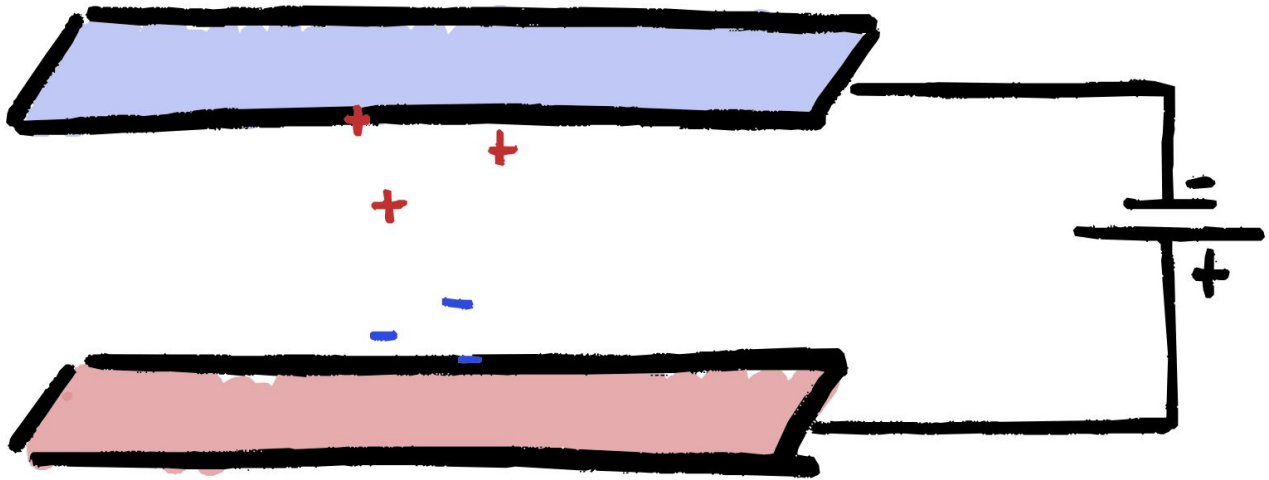
Electric field moves e- and ions to the electrodes for collection



Original figure

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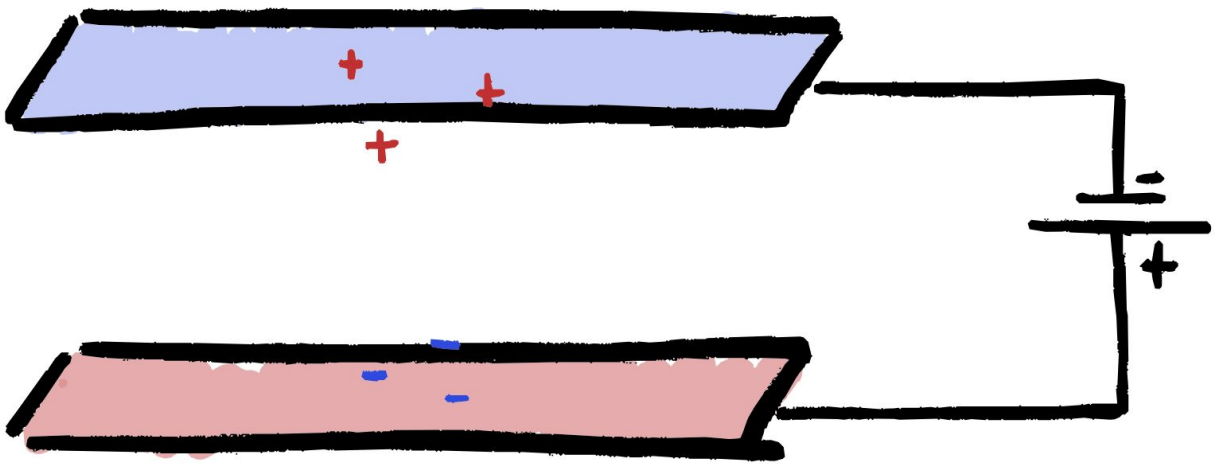
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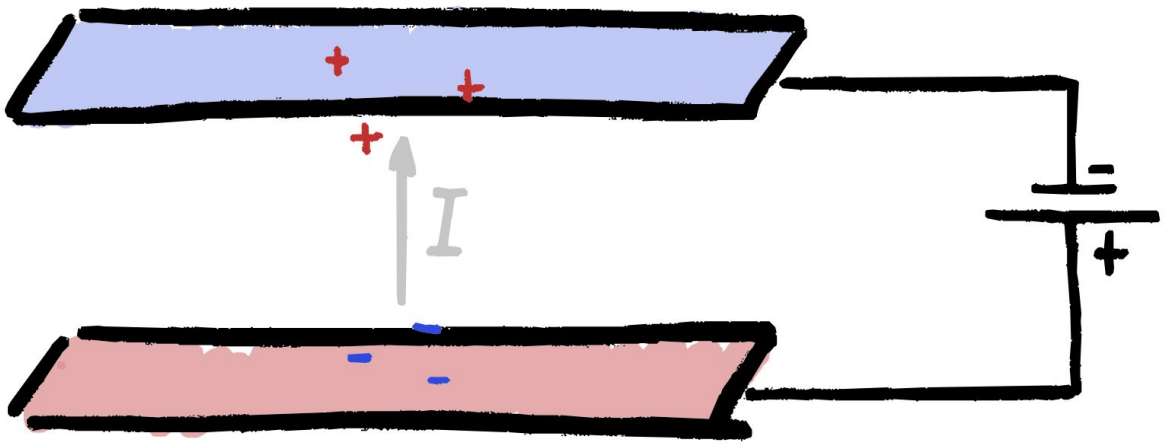


Original figure

1.1. Ionization Chambers (1900s)

Electric field
moves e- and ions
to the electrodes
for collection

Charges arriving / time
→ **Current!**



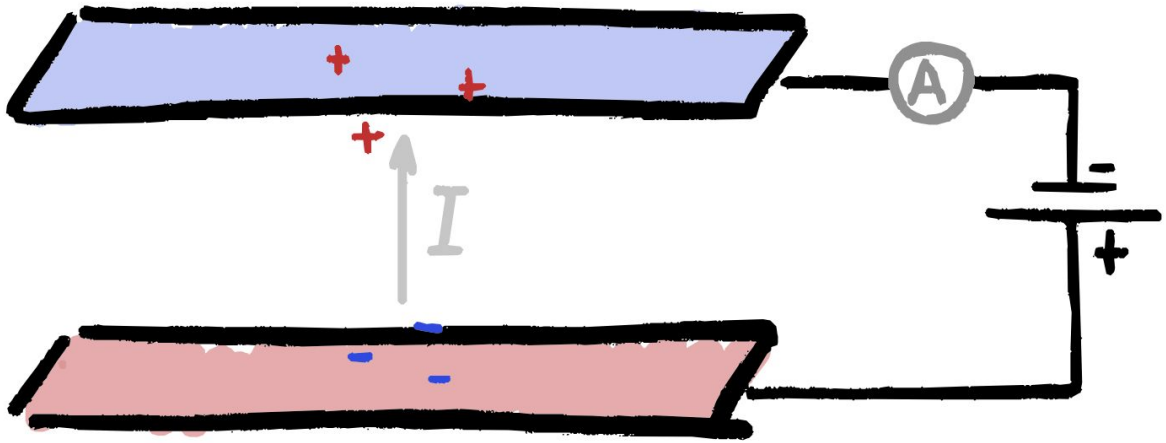
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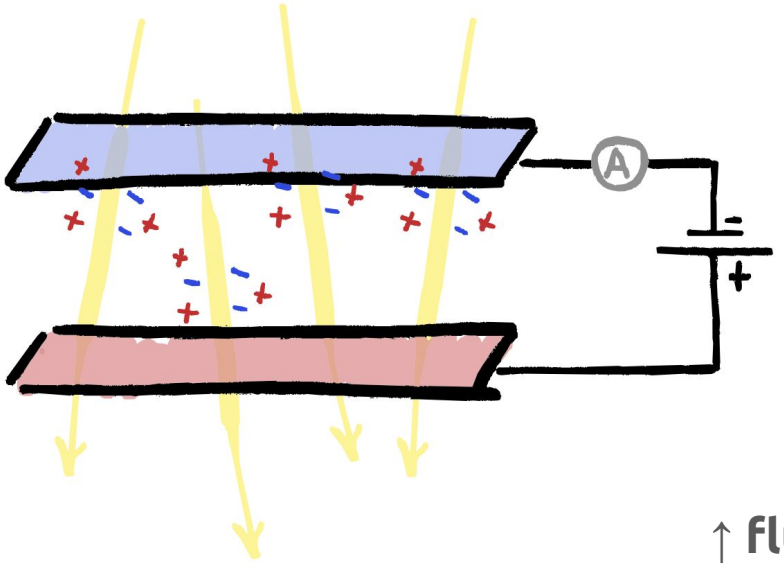
I(t) as a proxy for
collective particle rate

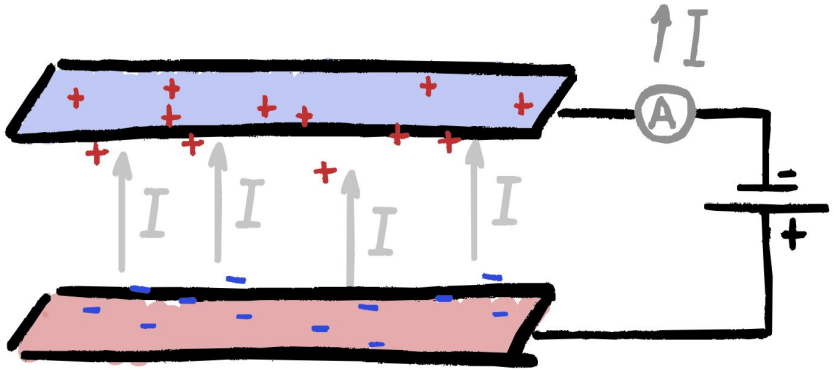


Original figure

1.1. Ionization Chambers (1900s)

I(t) as a proxy for collective particle rate





↑ **flux** ⇒ ↑ ***I(t)***

Original figure

1.1. Ionization Chambers (1900s)

Main figure: the **I vs V diagram at constant flux**

Shows two features:

- *Recombination region*
- *Full collection region*

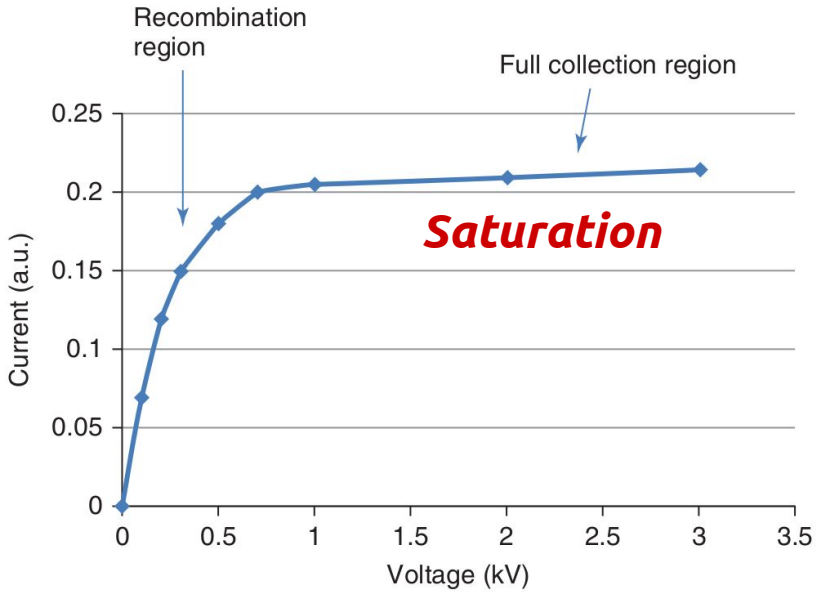
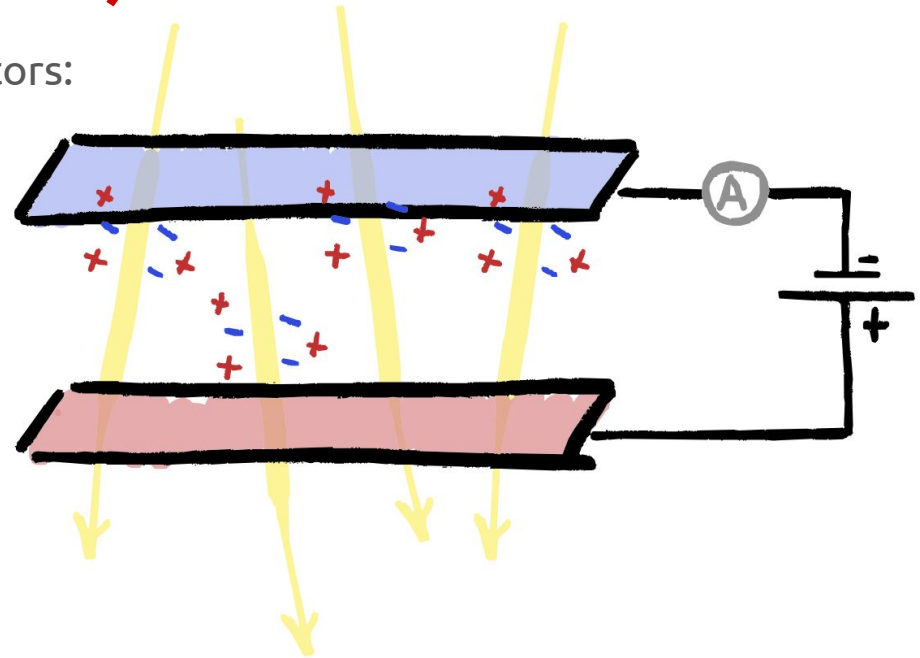


Figure 1.2 Typical current versus applied voltage curve, measured with an ionization chamber, when irradiated by a flux of photons or charged particles.

1.1. Ionization Chambers (1900s)

Include most basic elements of gaseous detectors:

- **Two electrodes** (any geometry) at **kV**
- active volume of **gas**, ionized by particles
- charged species move

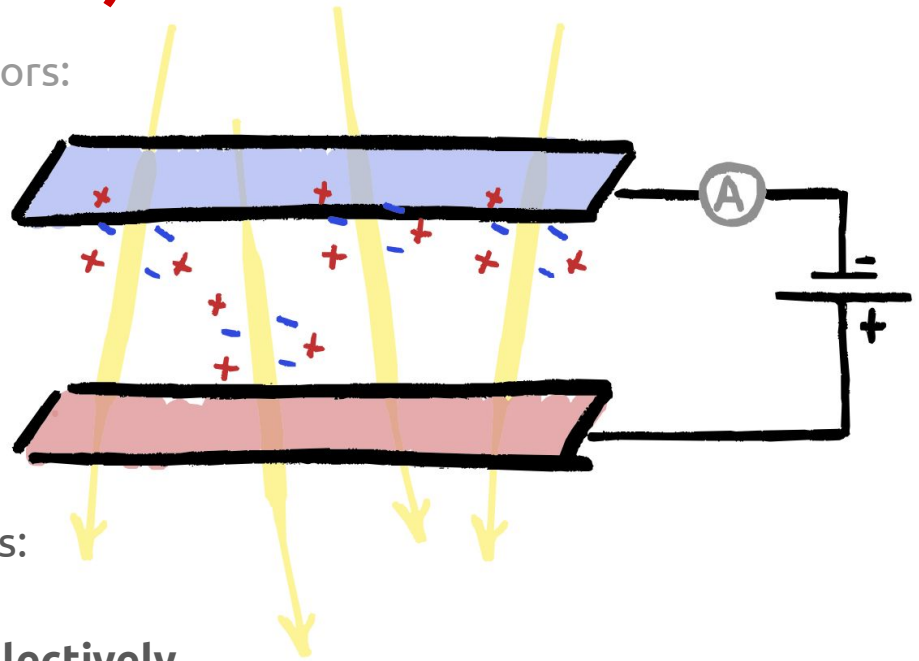


Original figure

1.1. Ionization Chambers (1900s)

Include most basic elements of gaseous detectors:

- **Two electrodes** (any geometry) at **kV**
- active volume of **gas**, ionized by particles
- charged species move



Though:

- Only ionization charge recollection
  - *(no avalanches, but this is a spoiler)*
- Measured with slow electrical components:
  - **current meter**
- only relatively high intensity radiation, **collectively**
  - ***no individual events***

Original figure

A comment regarding geometries

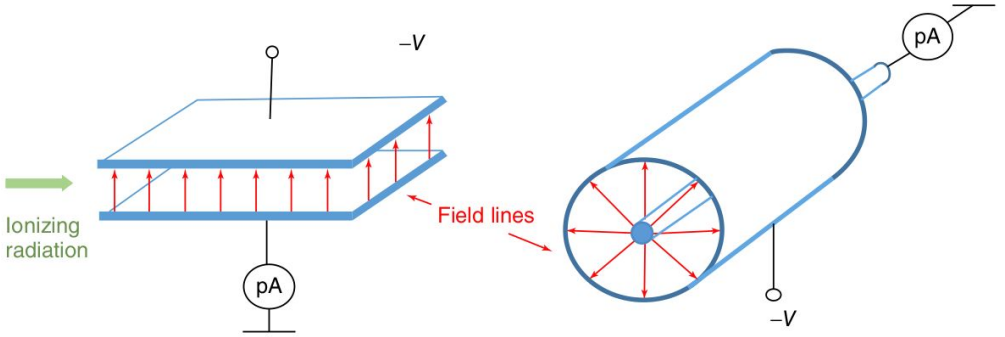


Figure 1.1 Schematic drawings of a planar and a cylindrical ionization chamber; "pA" stands pico-Amperometers, i.e. devices used to measure very small amounts of current.

Arbitrary geometry of the electrodes
→ different E field

Two patterns widely used, still today

Let's take a look at their electric field

A comment regarding geometries

Plane parallel case

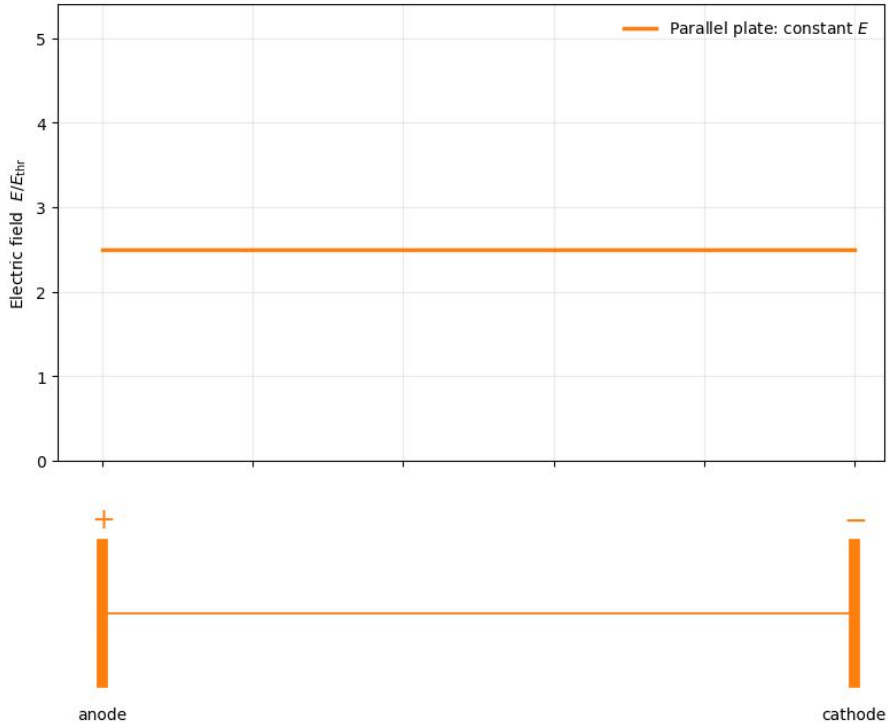
d: gap size

E = V/d = constant

↓

Boring… but good

We'll come back to this!



Original figure

A comment regarding geometries

Cylindrical case

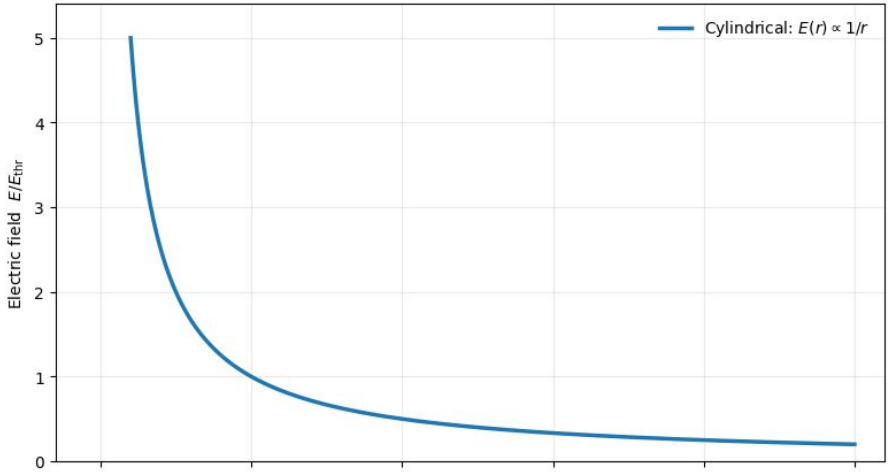
a: wire radius

b: cylinder radius

E ∝ V/r

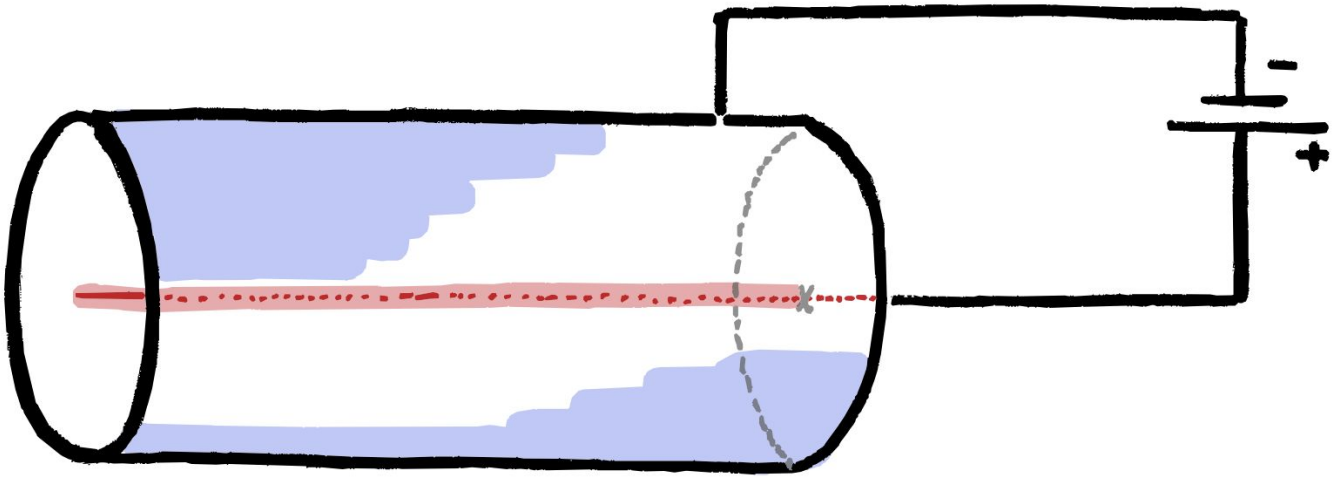
Non-constant!





Original figure

Back to the ionization chamber, for example, cylindrical:



Let’s increase a bit the voltage…

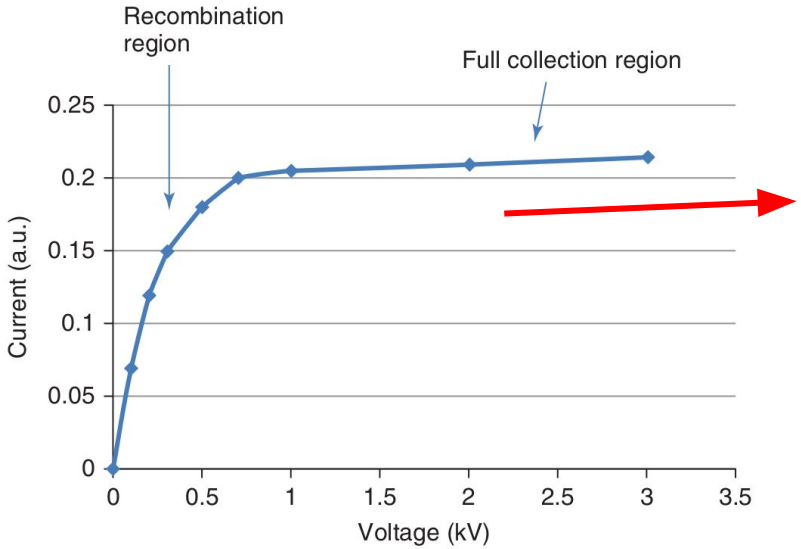
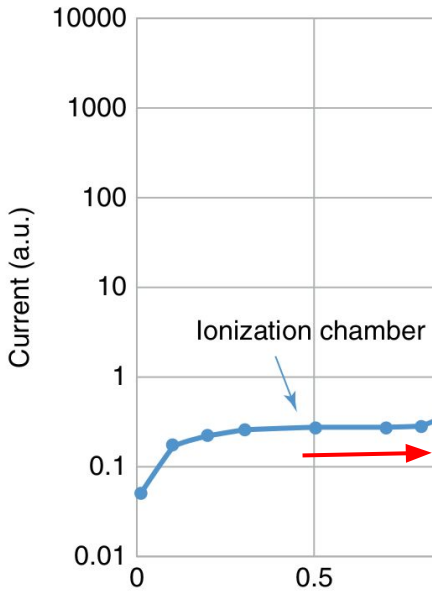
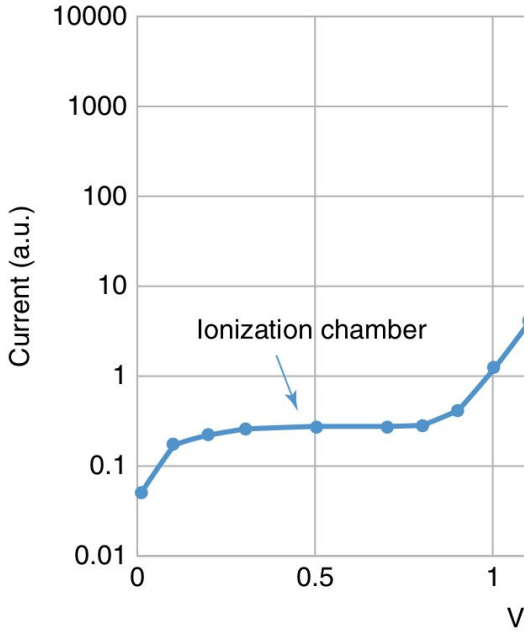


Figure 1.2 Typical current versus applied voltage curve, measured with an ionization chamber, when irradiated by a flux of photons or charged particles.

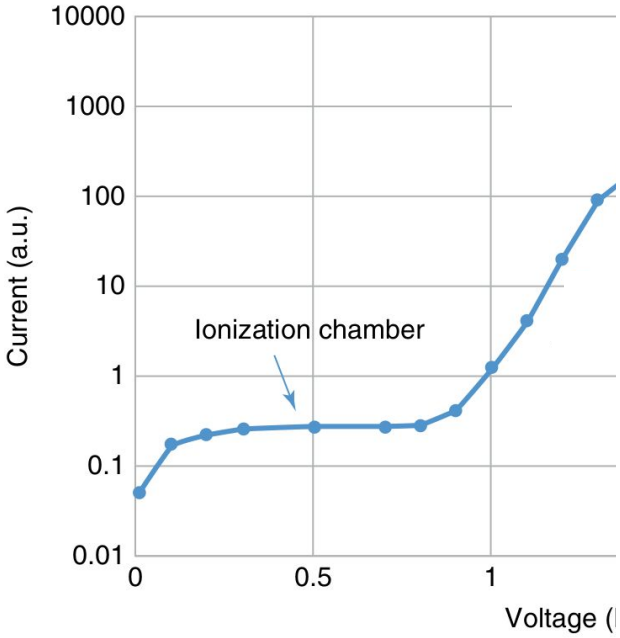
Let’s increase a bit the voltage…



Let’s increase a bit the voltage…



Let’s increase a bit the voltage…



!?

Weren’t we in saturation?

Where do the **extra electrons** come from?

1.2. Single-Wire Counters Operated in Avalanche Mode

Well…

we just rediscovered the *avalanche counter*

originally created by Rutherford and Geiger, 1908

The first gaseous detector able to record individual photons and particles

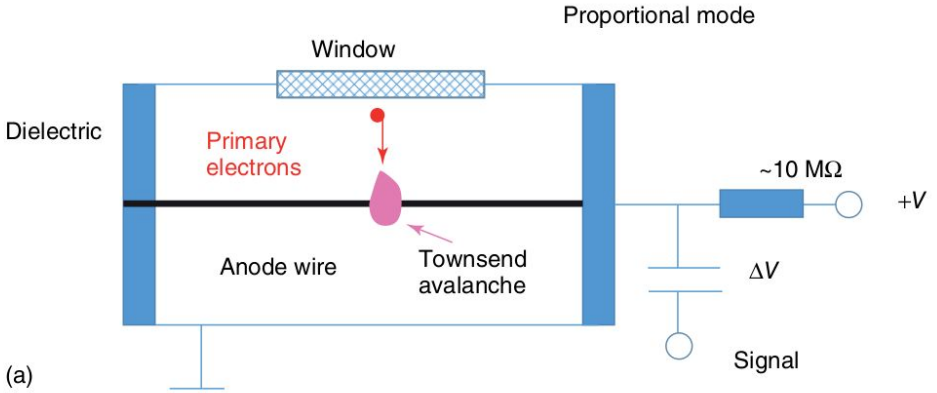


Figure 1.3 Schematic drawings of a single-wire cylindrical counter invented by Geiger and Rutherford in 1908. This detector is usually exploited either in a proportional mode (a) or in a so-called Geiger mode (b).

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

1st time today that *avalanches* appear…

The avalanche is the core process inside of the RPC. It is ***the process.***

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

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The avalanche is the core process inside of the RPC. It is ***the process.***

Electron avalanche multiplication in gases…

*… 1st observed and studied by **Townsend** (1897-1901)*

Let's see what he says…

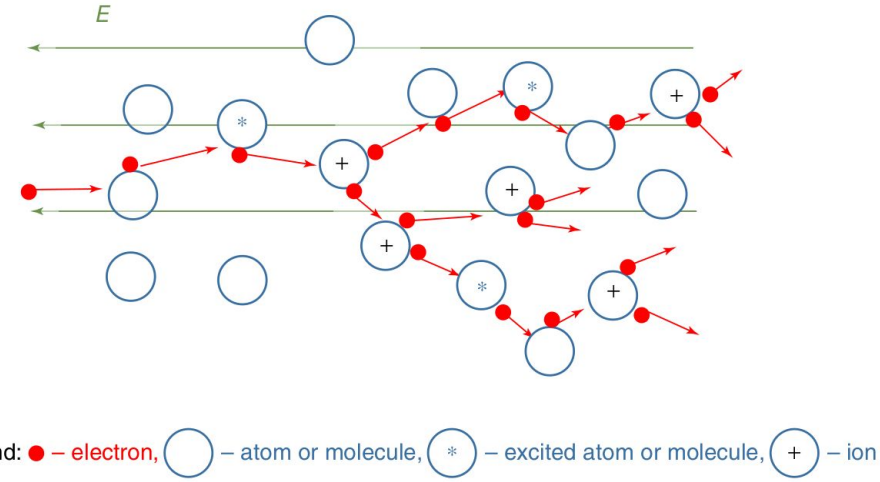


Figure 1.5 Schematics of the Townsend avalanche development in a gas: a free electron (coming from the left) drifting in an electric field intense enough experiences elastic and inelastic collisions with atoms and molecules, resulting in the creation of new free electrons, plus excited or ionized atomic or molecular species.

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

1st Townsend coef. $\alpha \rightarrow$ **avg. num. of e-/ion pairs per unit length** by each e-. $\alpha = \alpha(E)$. We write the infinitesimal growth of the avalanche as:

$$\mathrm{d}n_\mathrm{e} = \alpha n_\mathrm{e} \mathrm{d}x$$

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$$\mathrm{d}n_\mathrm{e} = \alpha n_\mathrm{e} \mathrm{d}x$$

If *E = constant* during the avalanche

$$\Rightarrow n_\mathrm{e} = n_0 \exp(\alpha d)$$

then it's said to be in **proportional regime**

The mult. factor is called the *gas gain*

$$A = \exp(\alpha d)$$

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

About drift velocities:

$v_{e-} \approx 1000\ v_{ion}$

⇒ Avalanche components:

- **ns**: fast e- *head* toward anode
- **µs**: ionic slow conical-shape *body* in the opposite direction

So another RPC key concept first appearance:

→ *different timescales in avalanches*

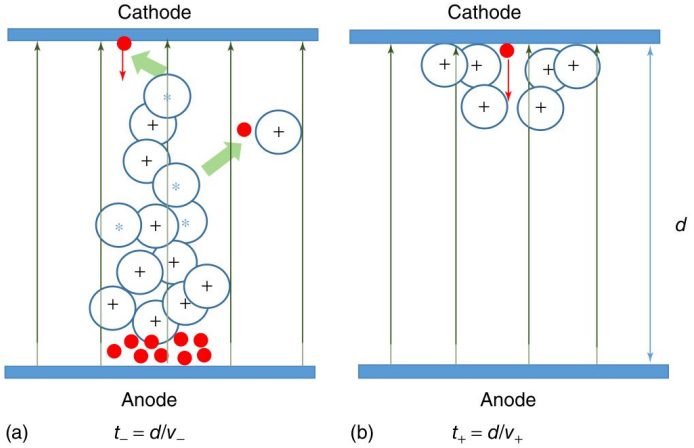


Figure 1.6 Schematic representation of the avalanche structure at two time intervals (a) $t_- = d/v_-$ showing also an electron created by gas self-photoionization; (b) $t_+ = d/v_+$, showing also a possible ion-ejected electron; $t = 0$ corresponds to the time when the avalanche was started by a single electron at the cathode. Small filled circles are electrons, open circles with a "+" sign in the center represent positive ions.

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

Avalanches have secondary processes involved, for example:

- **Photoelectrons (*electron–photon feedback process*)**

  e- excite molecules (γ_{ph}) →

  → UV photon emission ($t << t_{e-}$) →

  → photoionization of surroundings*

- **Ion feedback**

  ion approaches cathode surface →

  → takes electrons from material (γ_+) →

  → This e- starts new avalanche

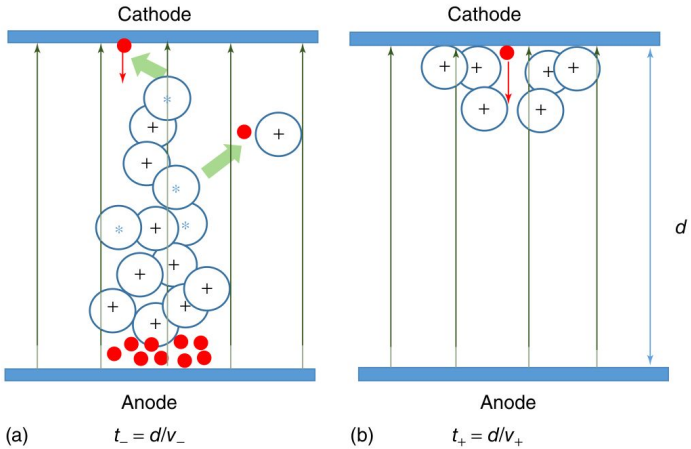
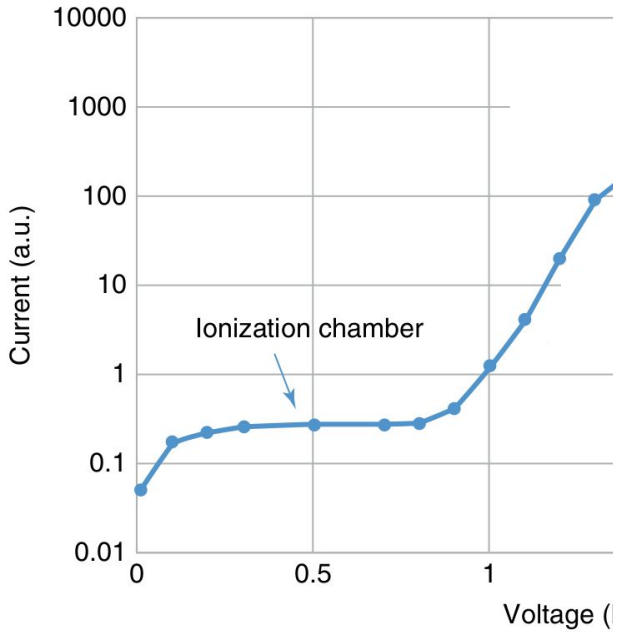


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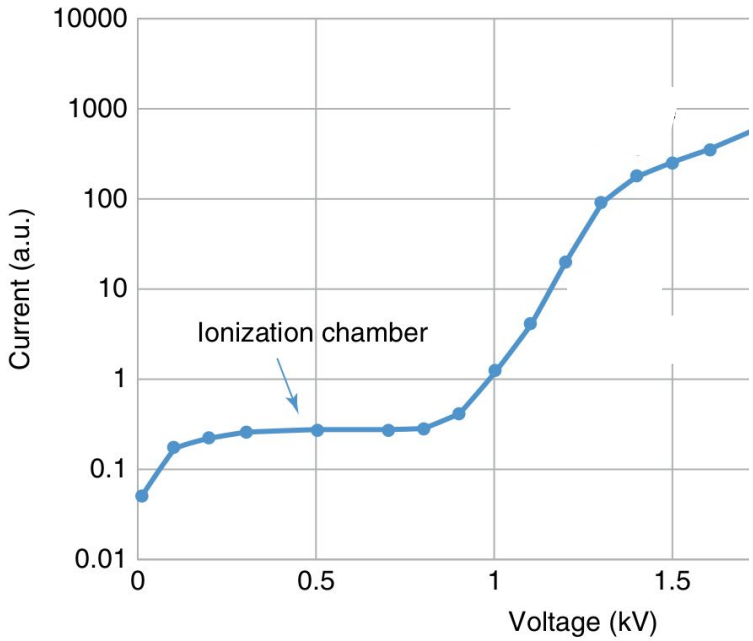
γ_+ → *2nd Townsend coef.*

*inside and outside the avalanche volumes

Now that we understand proportional avalanches, let's increase a bit (more) the voltage…



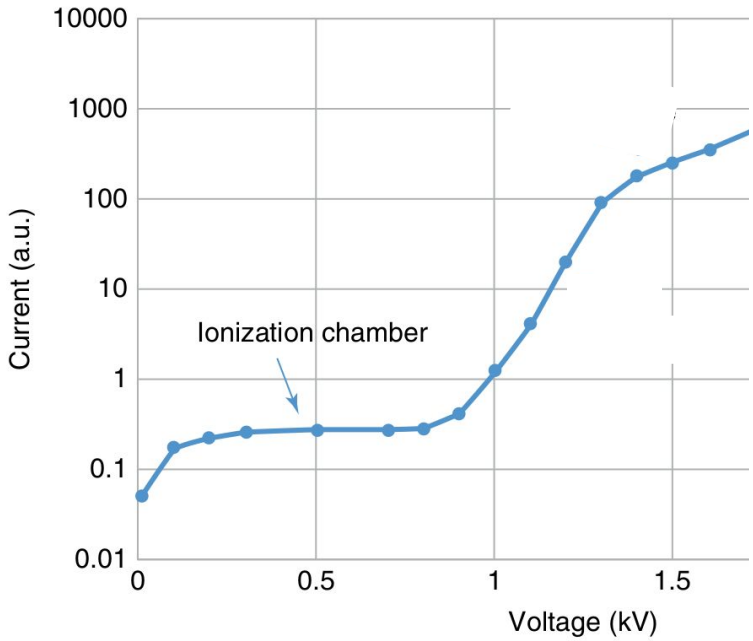
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Weren't we in avalanche?

!? Now it saturates again?

Now that we understand proportional avalanches, let's increase a bit (more) the voltage…



!?

Weren't we in avalanche?

Now it saturates again?

1st time today avalanche **saturation** appears

→ *Key in RPC behaviour*

Why does it appear?

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

We said:

if E = constant during avalanche

→ Townsend formula holds

→ proportional

Christian Lippmann, Werner Riegler (2004-01). Space charge effects in Resistive Plate Chambers. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. https://doi.org/10.1016/j.nima.2003.08.174

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

We said:

if E = constant during avalanche

→ Townsend formula holds

→ proportional

but if avalanche is **large**

→ **its own charges modify the field**

→ **saturation** *(and others)*

This is the so called ***space-charge effect***

Christian Lippmann, Werner Riegler (2004-01). Space charge effects in Resistive Plate Chambers. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. https://doi.org/10.1016/j.nima.2003.08.174

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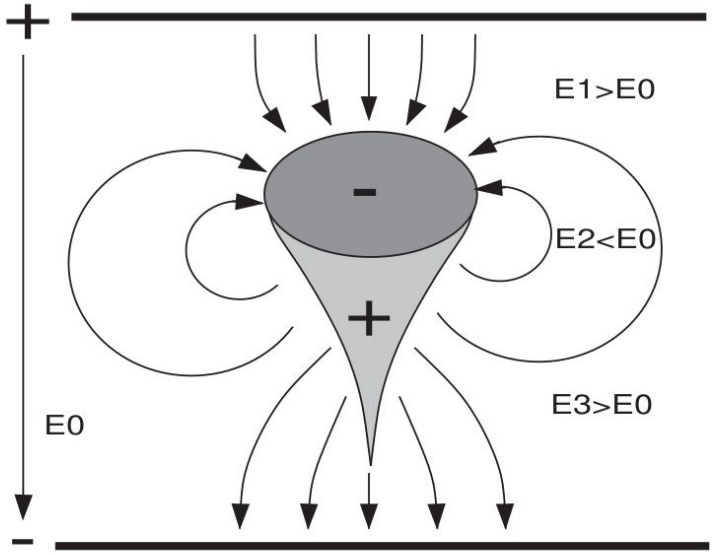
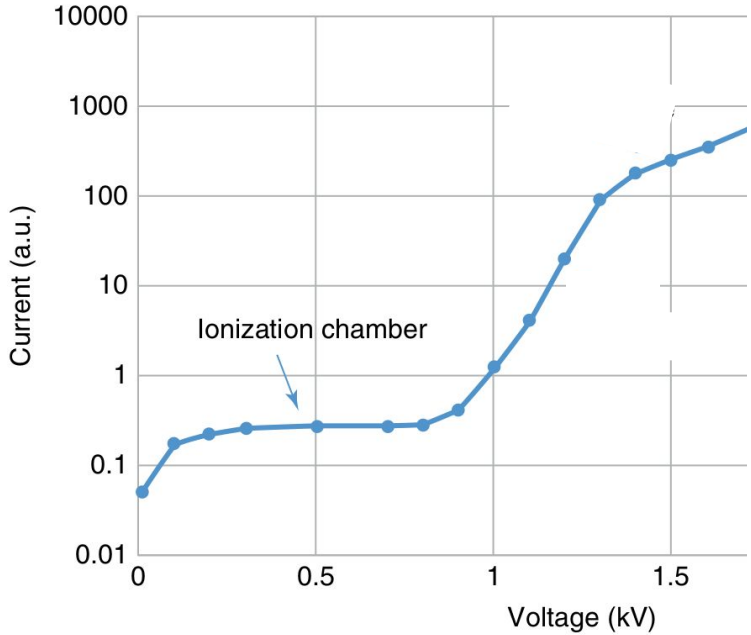


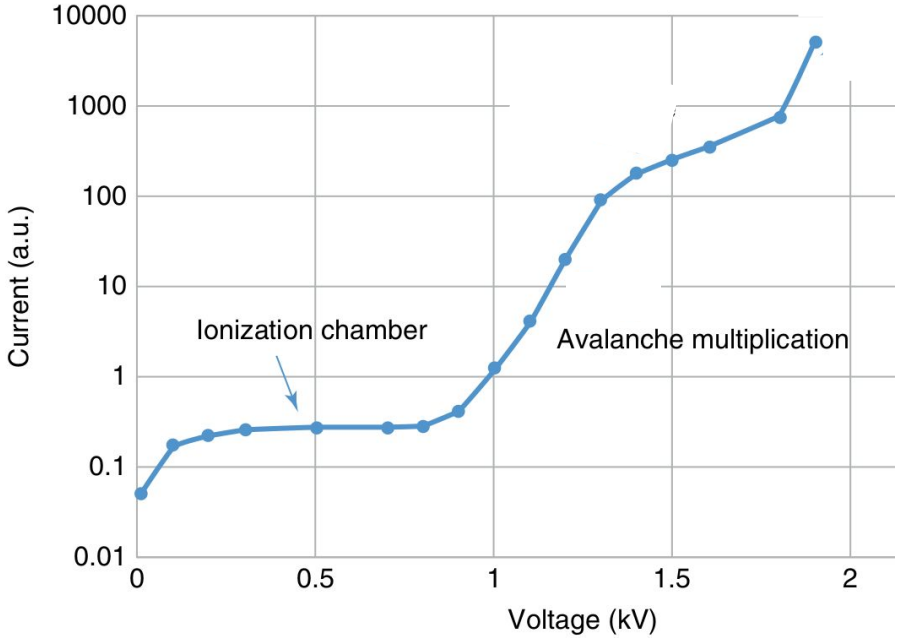
Fig. 2. A schematic picture of an avalanche and the electric field deformations caused by the avalanche charge carriers. At the tip and the tail of the charge distribution the fields E_1 and E_3 are higher than the applied electric field E_0. In the center of the charge distribution the field E_2 is lower than E_0. As a consequence, the values of the gas parameters like drift velocity and Townsend coefficient are not uniform in the gas gap.

Christian Lippmann, Werner Riegler (2004-01). Space charge effects in Resistive Plate Chambers. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. https://doi.org/10.1016/j.nima.2003.08.174

Now that we understand the space-charge effect, let's increase a bit (even more) the voltage…

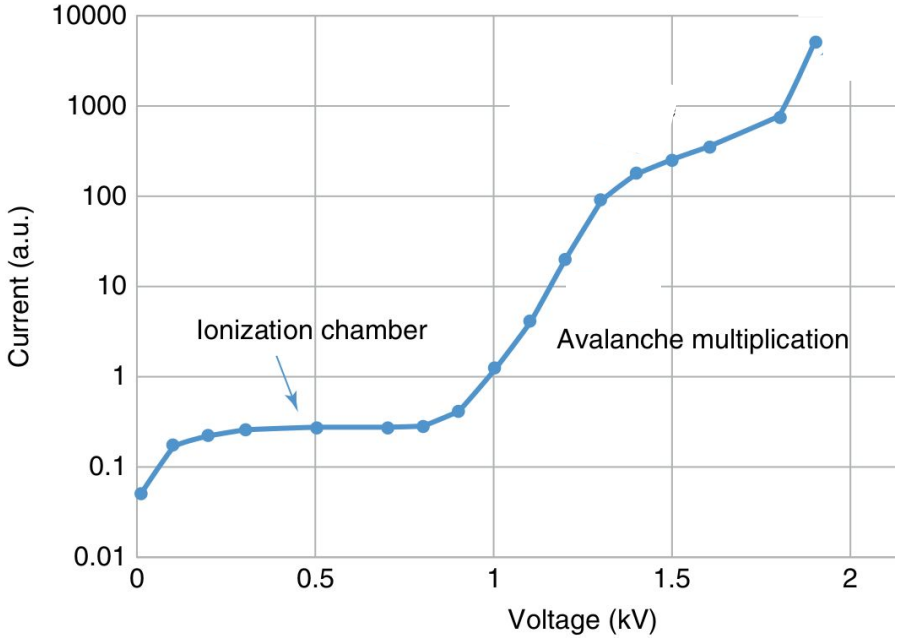


Now that we understand the space-charge effect, let's increase a bit (even more) the voltage…



Now it enters in *continuous discharge*!

Now that we understand the space-charge effect, let's increase a bit (even more) the voltage…



Now it enters in *continuous discharge*!

But we already know how ***feedback*** can arise:

- photoelectrons
- ions in cathode

Sort of a ***slow breakdown***

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

With avalanche comes breakdown:

- **Fast breakdown, ns (avalanche time)**:
  Raether limit = 10^8 electrons
  called streamer, or Kanal mechanism
  we are definitely not entering here,
  but could turn into sparks

- **Slow breakdown, ms:**
  feedback conditions satisfied before avalanche reaches the Raether limit.
  What we just saw.

Take-home message:
avalanches are complicated and many correlated effects participate in them

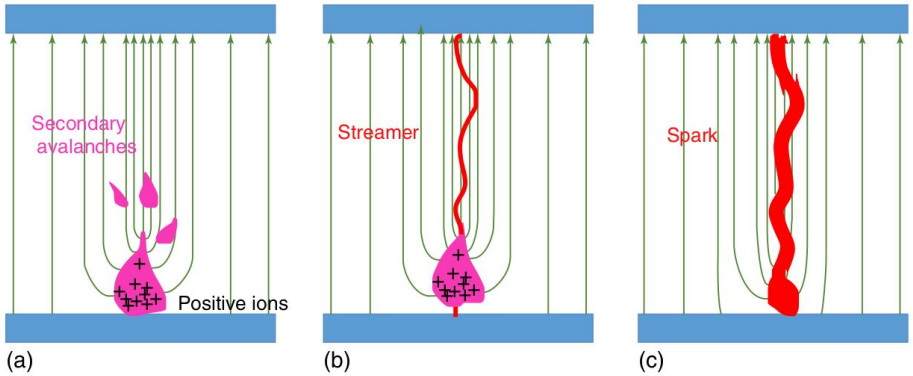


Figure 1.8 Three stages of spark development, when the total charge in the avalanche reaches the Raether limit: (a) field lines close to the avalanche experience a focusing effect and some secondary avalanches start moving toward the positive ions "body"; (b) a thin plasma filament – a streamer (or Kanal) – is formed; (c) when the streamer reaches the electrodes, a spark happens through the channel opened in this way.

So we have the full picture of the Geiger!

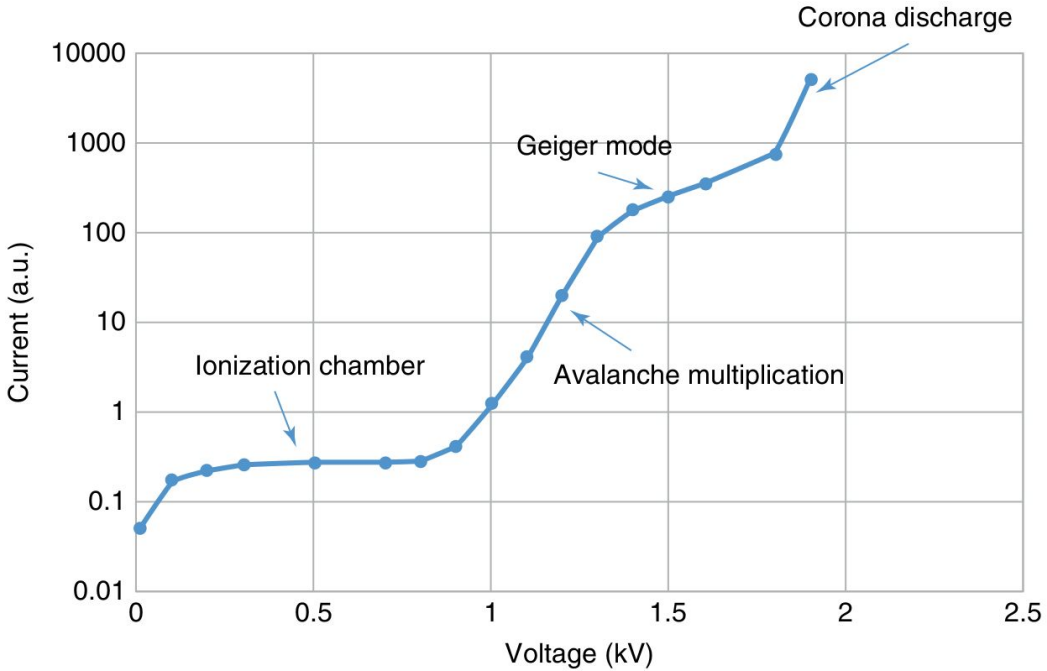
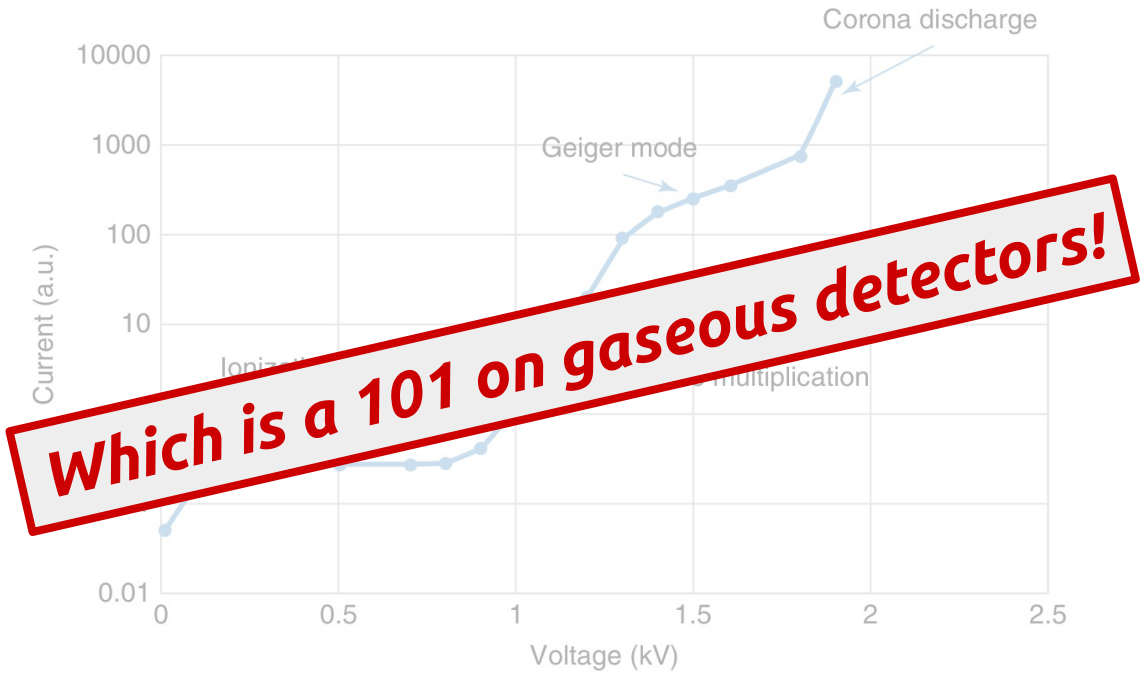


Figure 1.4 Typical voltage–current characteristics for a single-wire counter irradiated by photons or charged particles.

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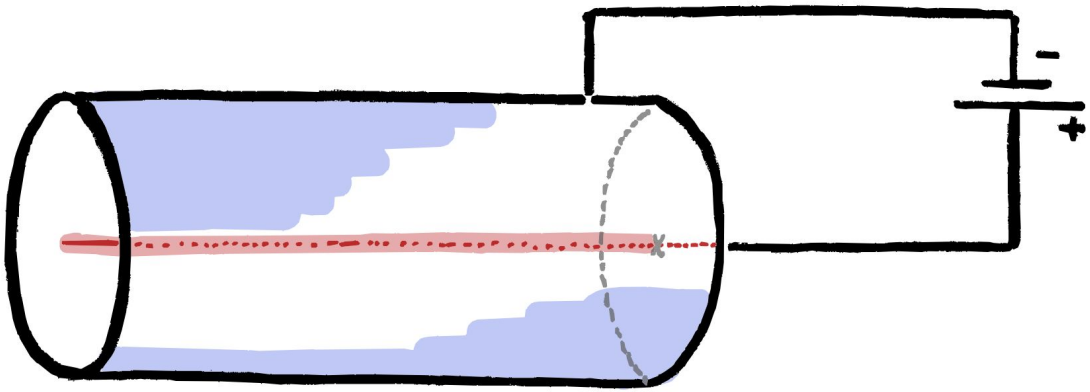


Which is a 101 on gaseous detectors!

Figure 1.4 Typical voltage–current characteristics for a single-wire counter irradiated by photons or charged particles.

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

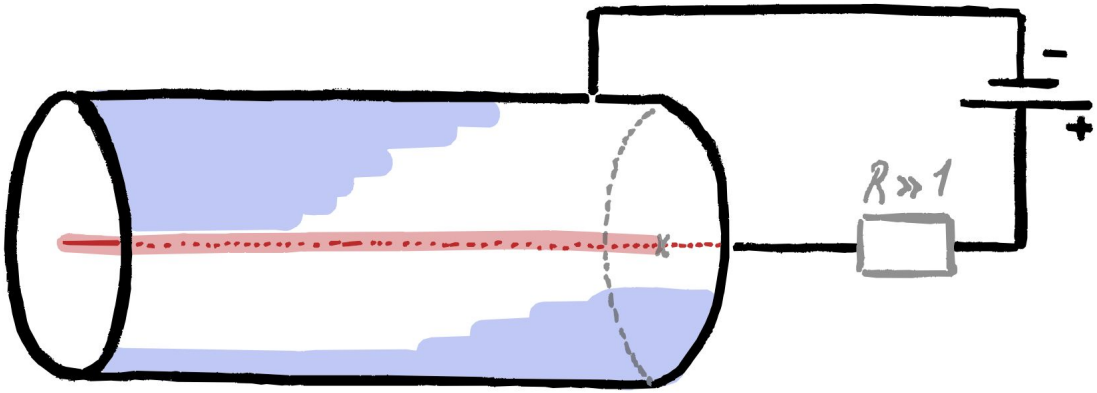
Early single-wire counters had a big problem with discharges and feedback, so one idea was introduced



1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

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>100 MΩ in series with HV source



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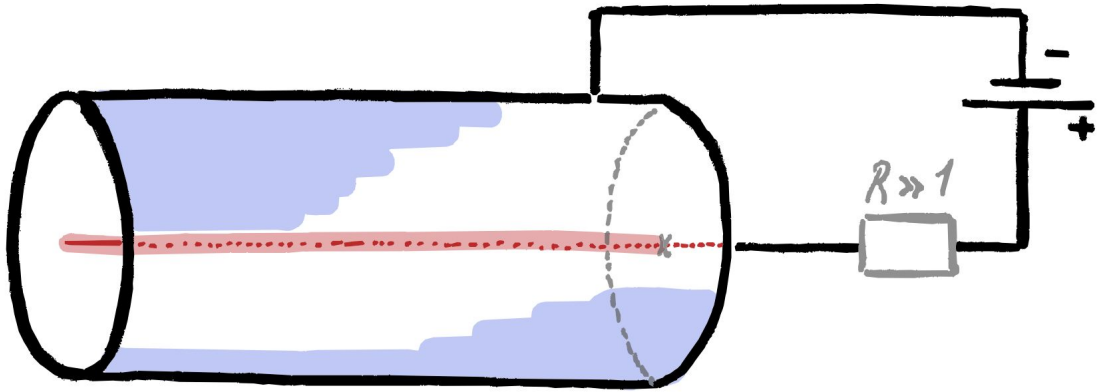
>100 MΩ in series with HV source

Corona current (μA) into resistor

→ drop ΔV ≈ 100s V in resistor

→ **drop E in the detector**

→ stop of corona discharge



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Early single-wire counters had a big problem with discharges and feedback, so one idea was introduced

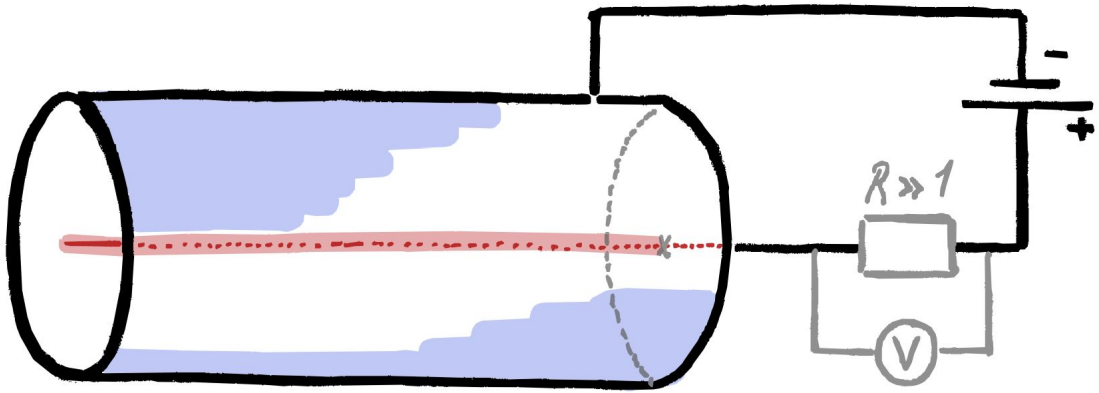
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Signal taken from V across the quenching resistor

Drop ΔV ⇒ particle

1.3. Avalanche and Discharge Development in Uniform or Cylindrical Electric Fields

Early single-wire counters had a big problem with discharges and feedback, so

>

Corona current (μA) into resistor

→ drop ΔV ≈ 100s V in resistor

or

ischarge

cross

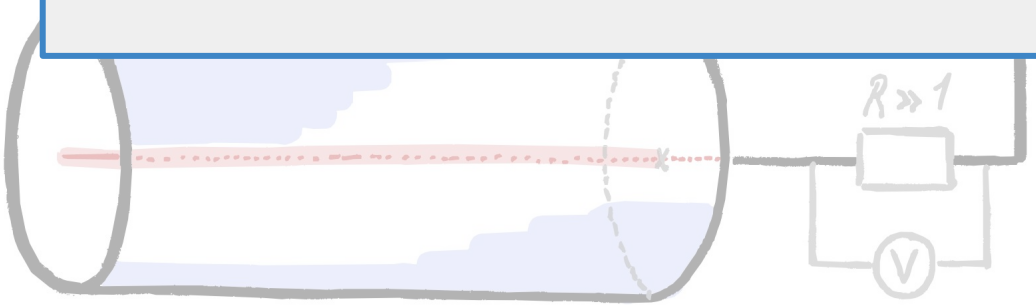
the quenching resistor

Drop ΔV ⇒ particle

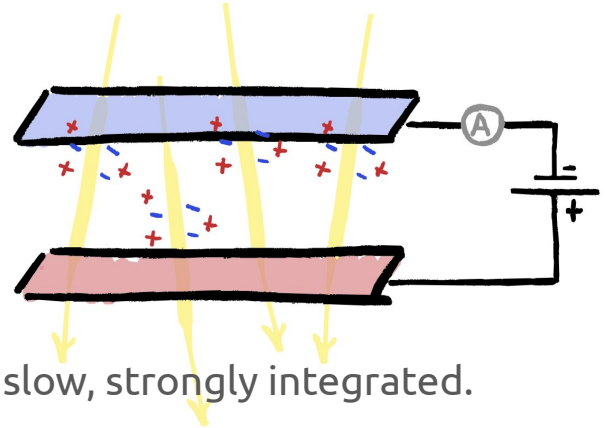
Single-wire counters are not resistive detectors,

but use **discharge quenching by resistive elements**

→ not so different to modern resistive detectors…



Summarizing until here

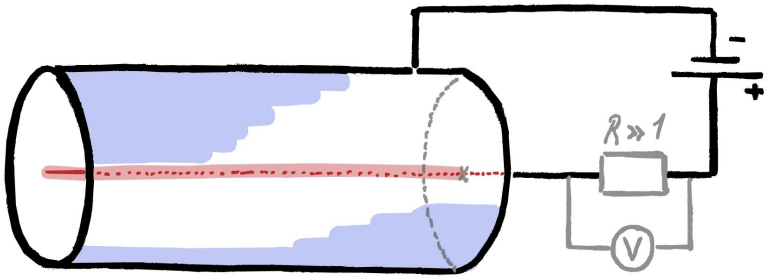


We saw **ionization detectors**:

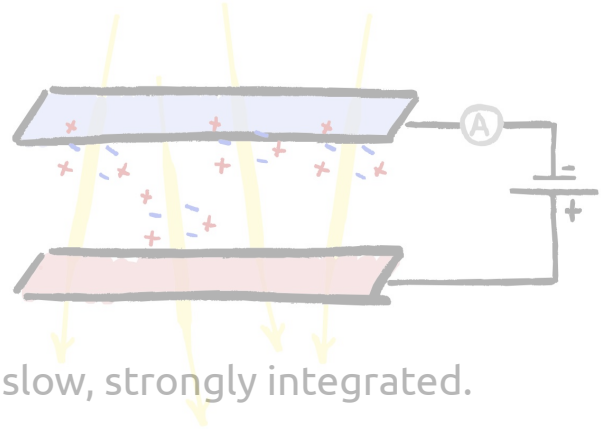
- use current measured with a pico-amperimeter, this is slow, strongly integrated.

We explained the **Geiger**, for individual particle counting:

- Uses drop of V in the resistor as a proxy.



Summarizing until here

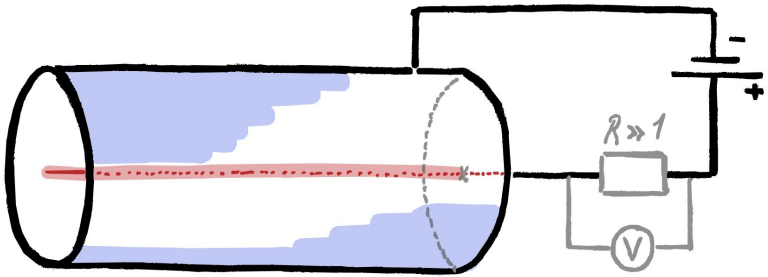


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- **collect charge from avalanches**
- **establish the HV**
- **read out the signal**

Charge collection and signal measurement

Another interesting effect…

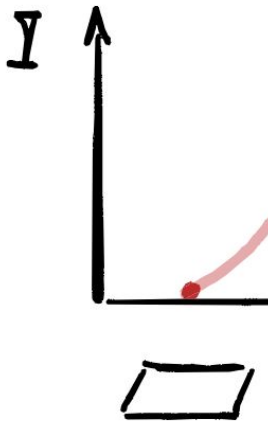
As charges ***move*** in *space*,

they ***induce charge*** in *electrodes*

Described by the Ramo-Shockley theorem:

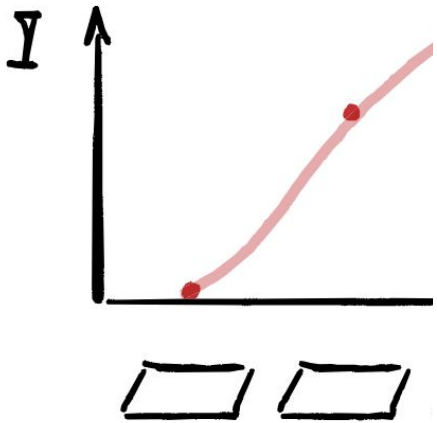
$i_k = q \, \mathbf{v} \, \mathbf{E}_{w,k}$

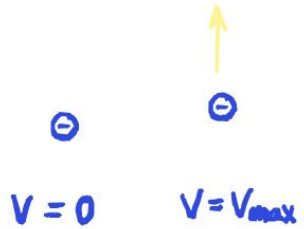
Charge collection and signal measurement



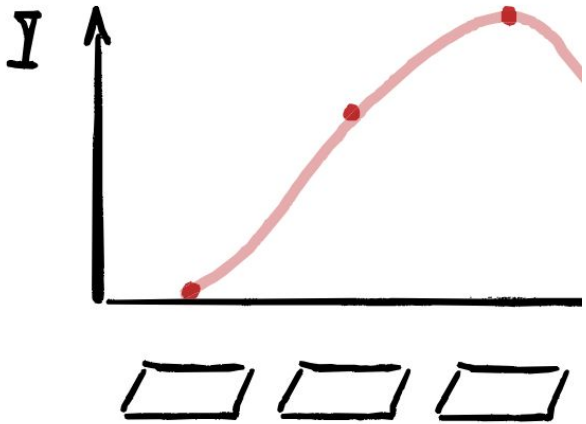


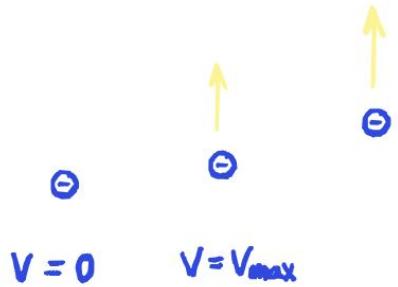
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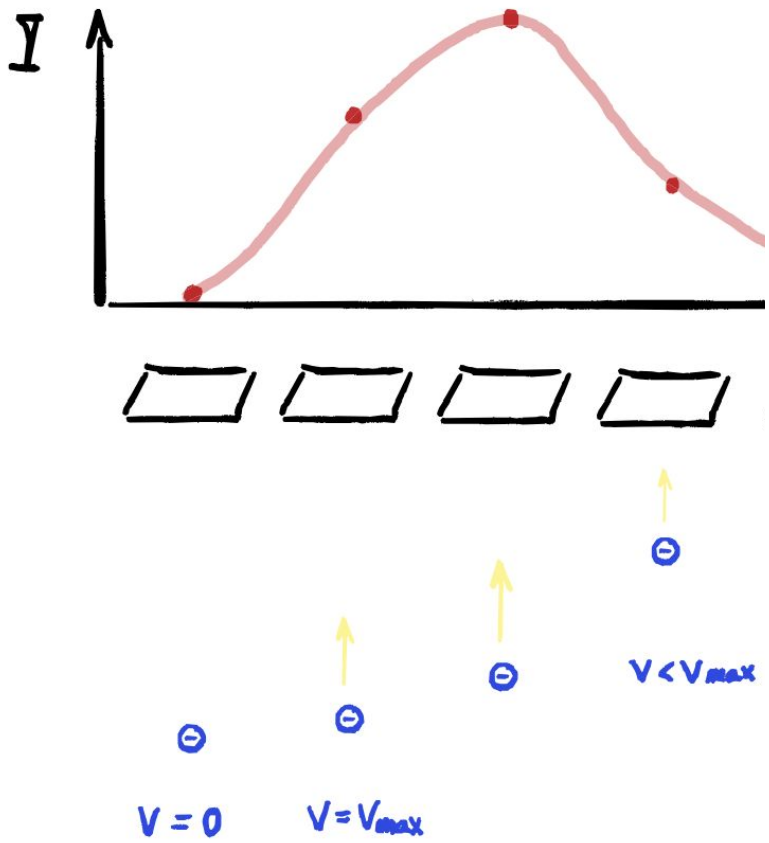


Charge collection and signal measurement

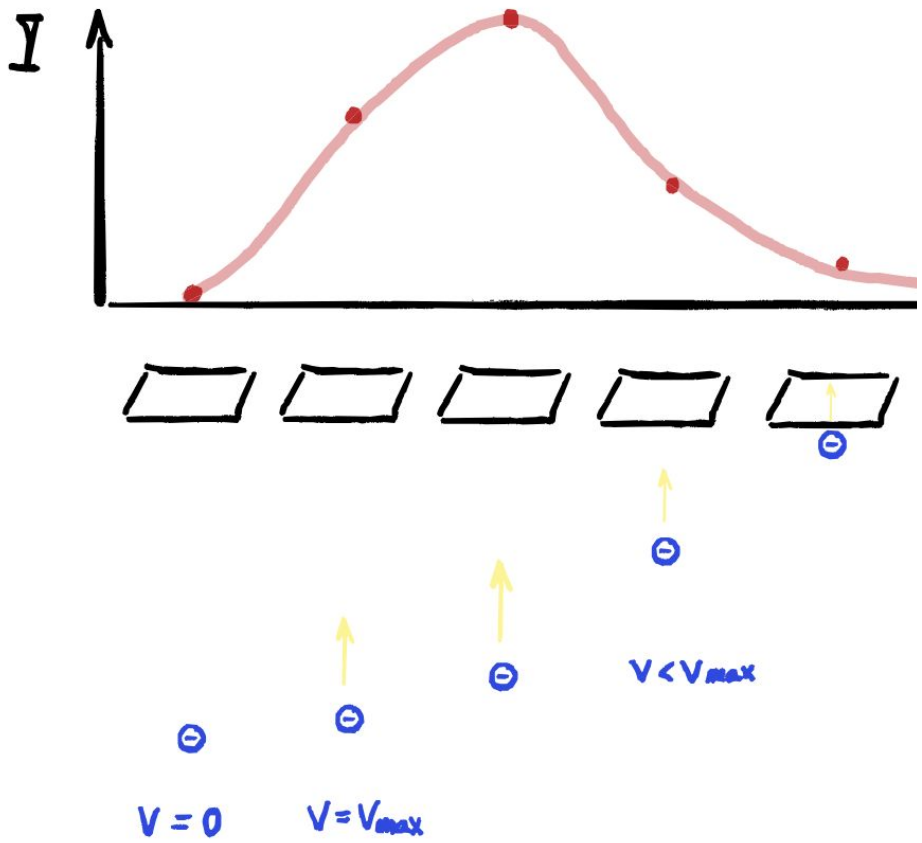




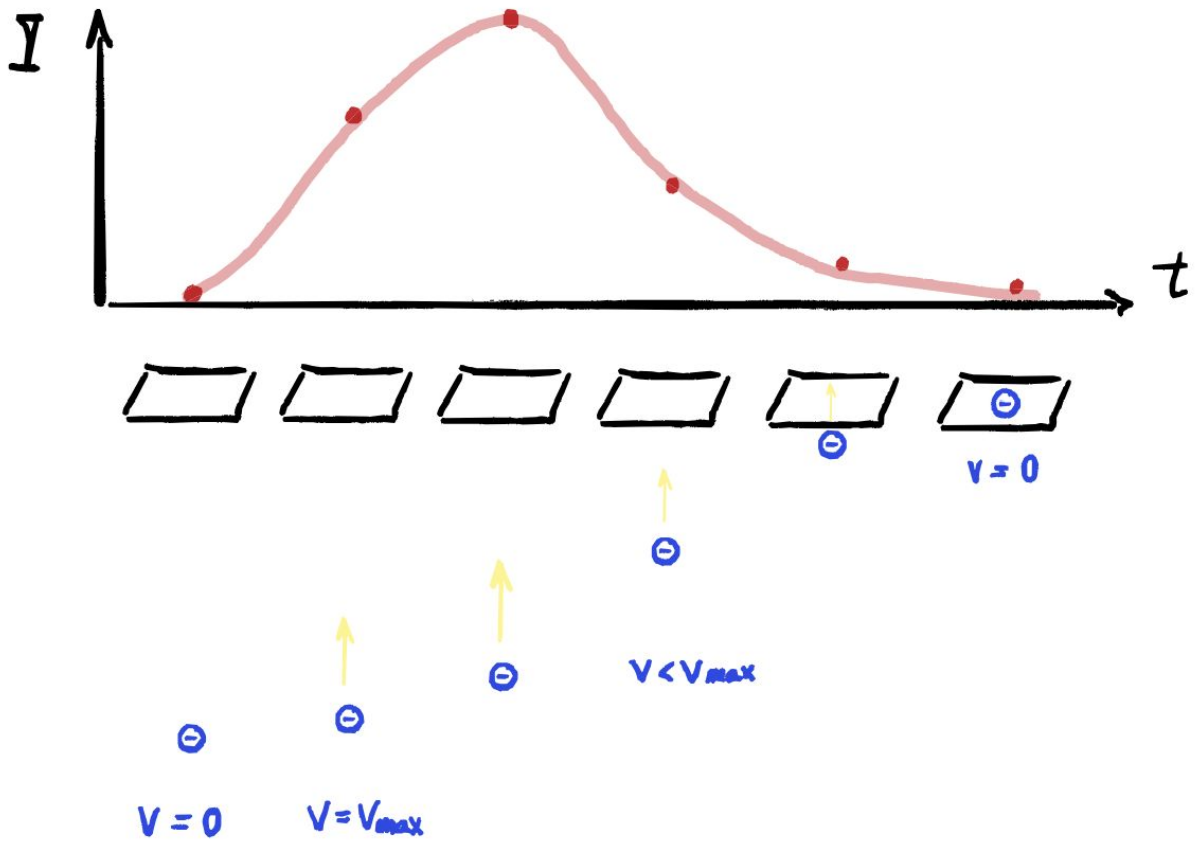
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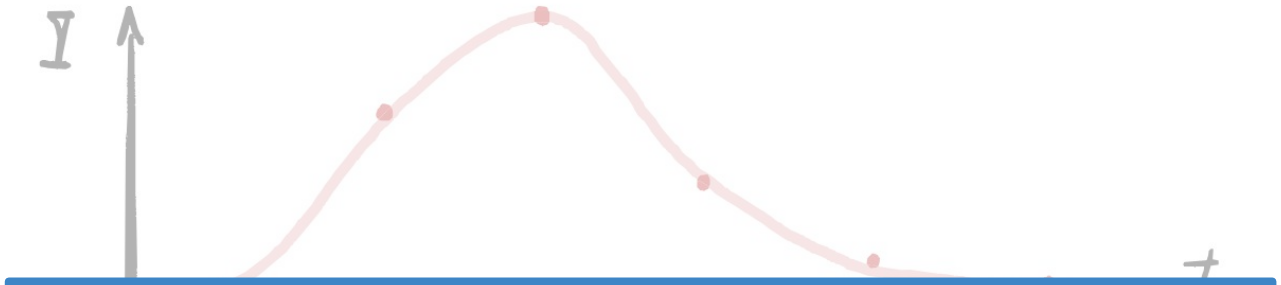
Charge collection and signal measurement



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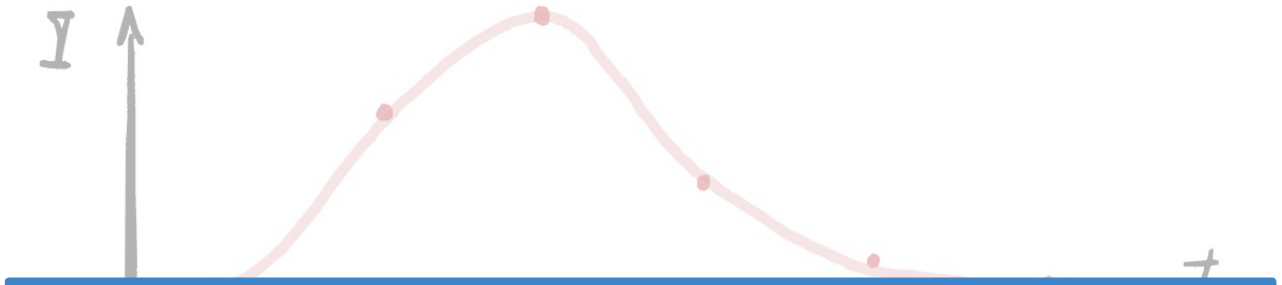


⇒ No need for charge collection to give rise to signal!

⇒ **readout can be separated**



Charge collection and signal measurement



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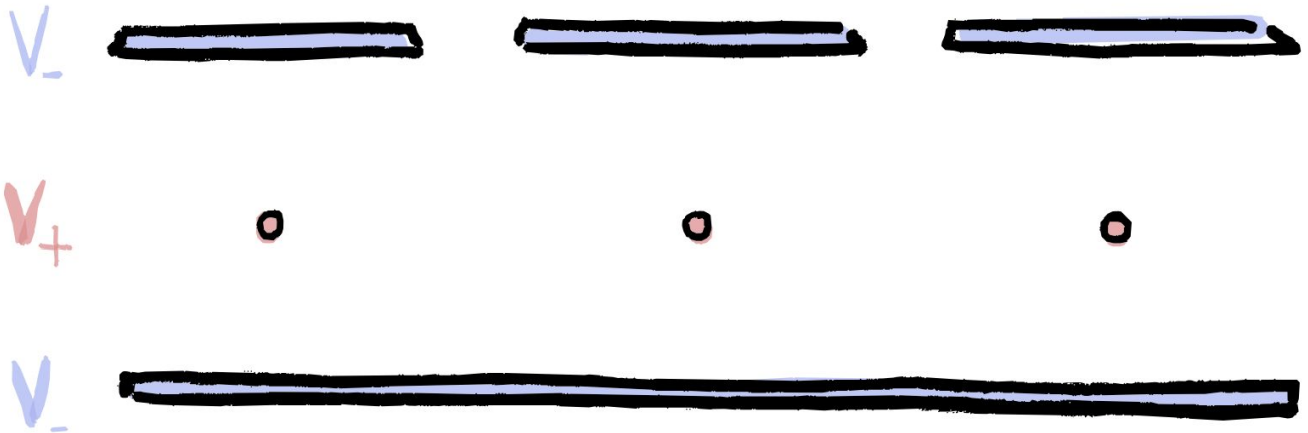
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This defined the next step…

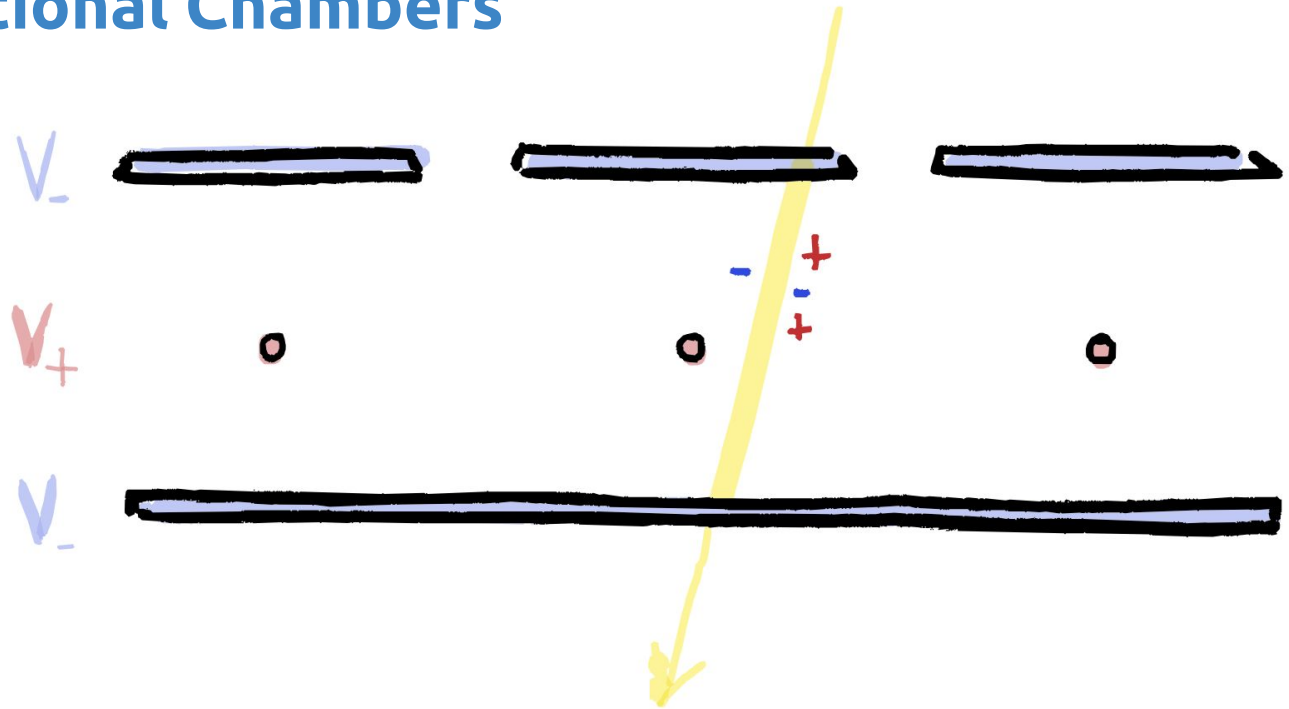
1.5. Multiwire Proportional Chambers

MWPC, G. Charpak, 1968



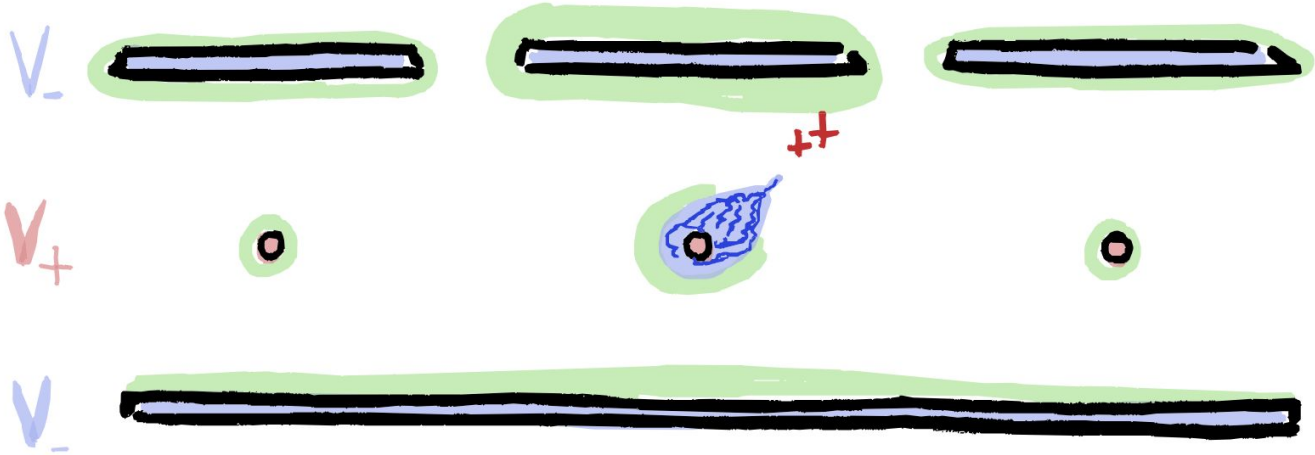
1.5. Multiwire Proportional Chambers

MWPC, G. Charpak, 1968



1.5. Multiwire Proportional Chambers

MWPC, G. Charpak, 1968



Induced current in neighbour electrodes

1.5. Multiwire Proportional Chambers

MWPC, G. Charpak, 1968

- proportional mode
- *high rate (even up to 10^5 Hz/wire)*
- *multiple tracks*
- sparks rarely happen
    - *if well-designed*

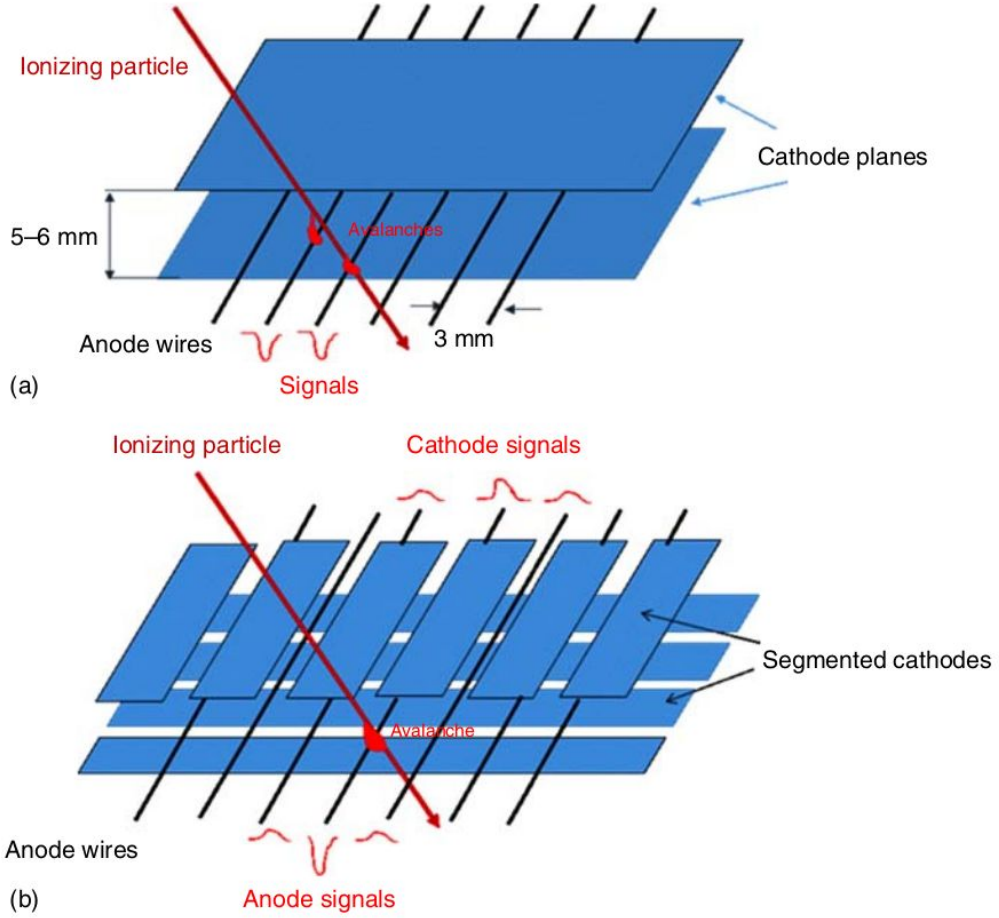


Figure 1.12 Schematics of a MWPC: (a) the first version of an MWPC with unsegmented cathode plane and (b) modern design of a bi-dimensionally sensitive MWPC, with cathodes segmented for isolation from each other's parts (strips, wires, etc.).

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- sparks rarely happen
  - *if well-designed*

Great success, except for:

- $\sigma_t \approx \mu s \rightarrow$ ***Why?***

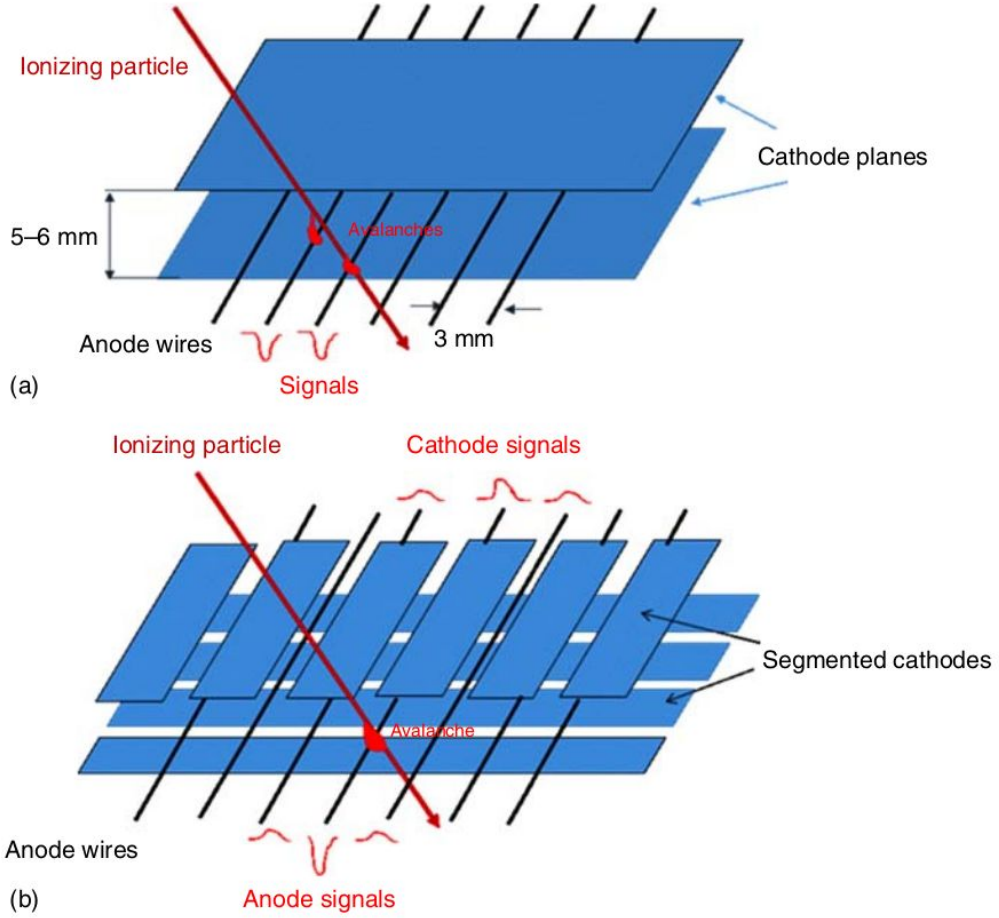


Figure 1.12 Schematics of a MWPC: (a) the first version of an MWPC with unsegmented cathode plane and (b) modern design of a bi-dimensionally sensitive MWPC, with cathodes segmented for isolation from each other's parts (strips, wires, etc.).

The importance of the parallel-plate geometry

In the light of avalanche creation difference between geometries is key!

Let’s see it again

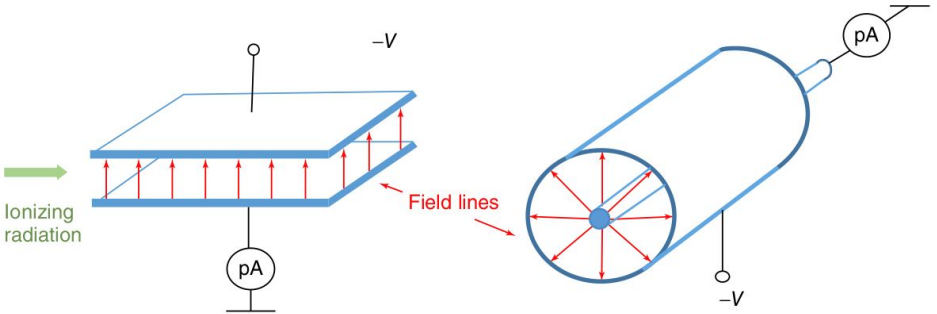


Figure 1.1 Schematic drawings of a planar and a cylindrical ionization chamber; “pA” stands pico-Amperometers, i.e. devices used to measure very small amounts of current.

The importance of the parallel-plate geometry



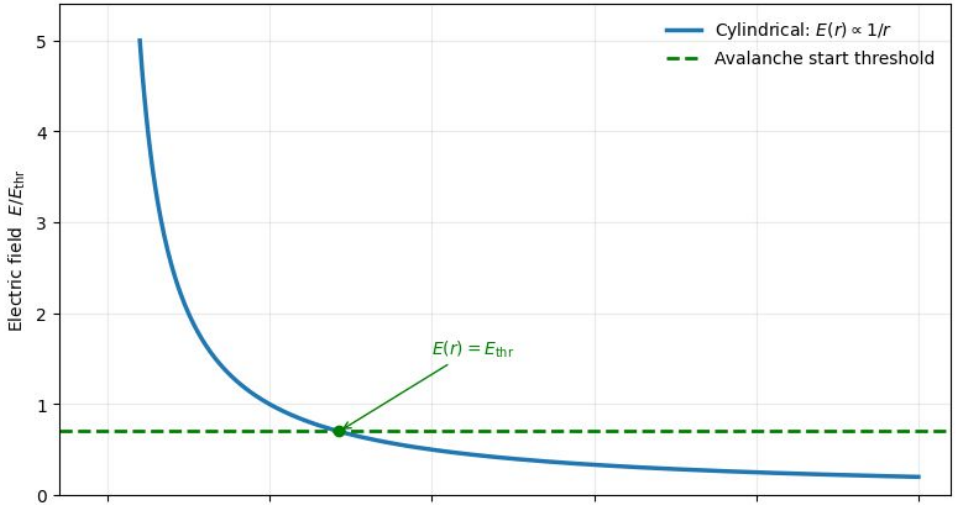
Cylindrical case

a: wire radius

b: cylinder radius

E ∝ V/r

Electrons must drift until reaching the amplification region



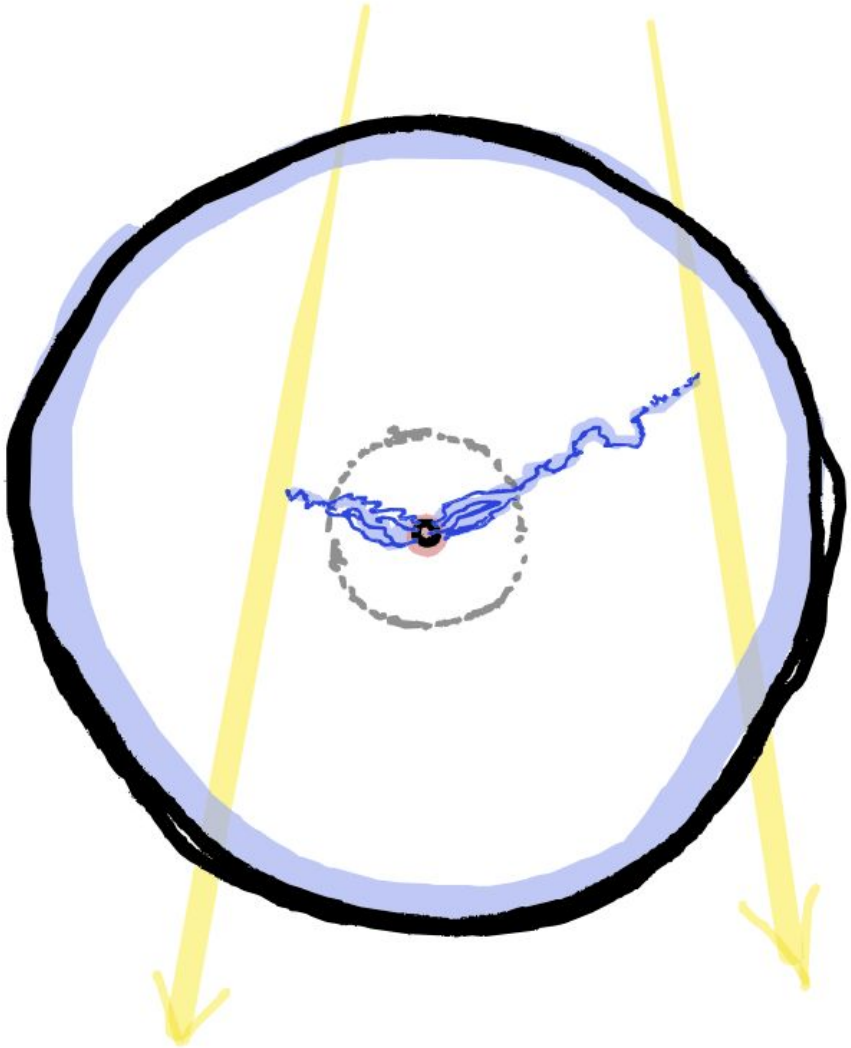
Original figure

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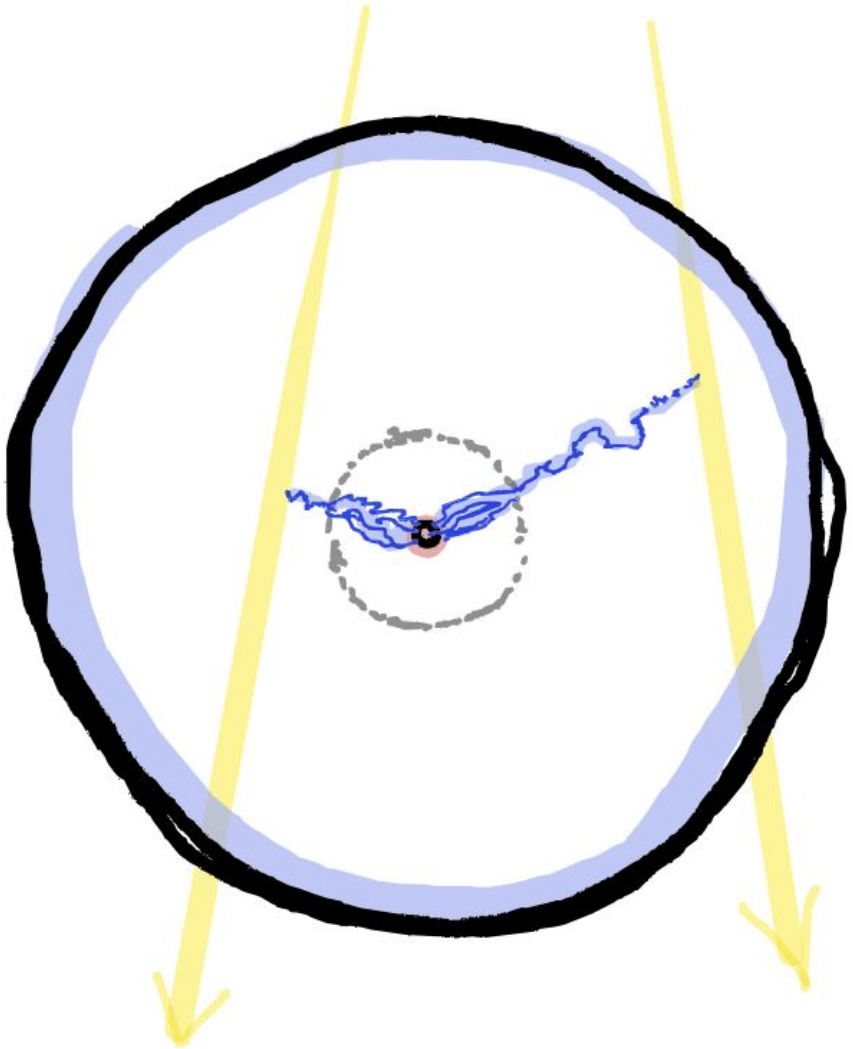
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⇒ Time jitter is almost equal to the maximum drift time



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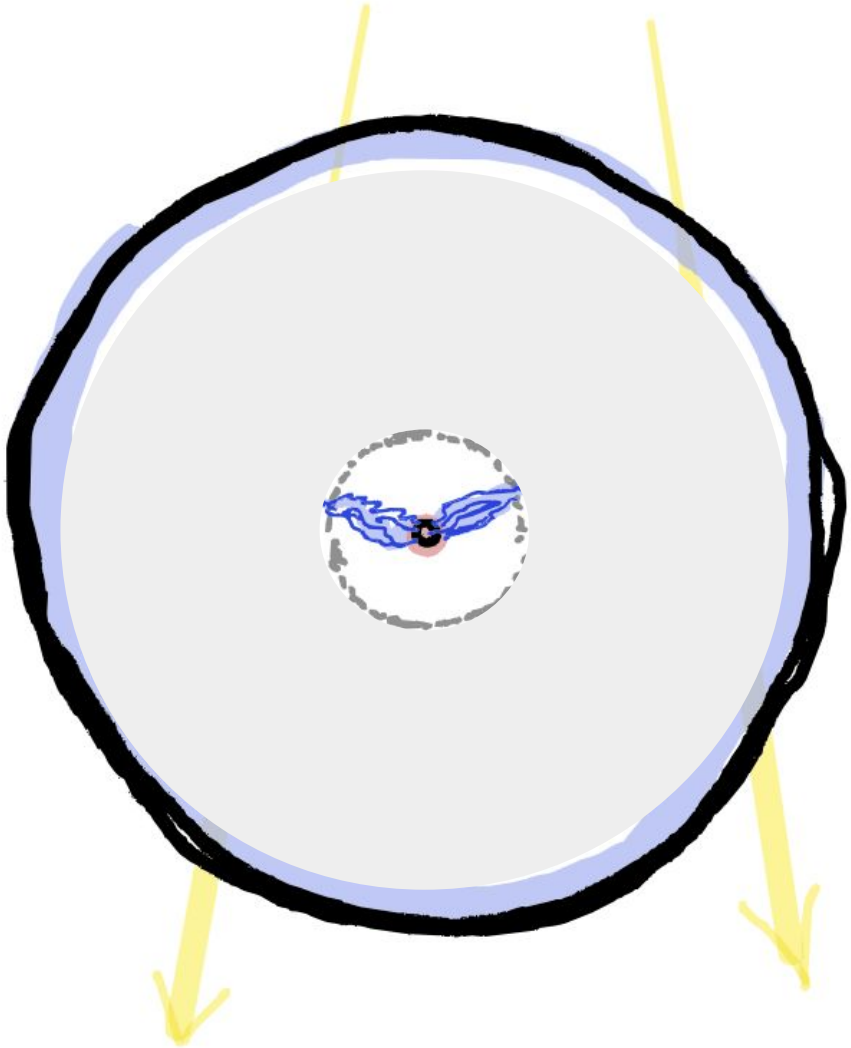
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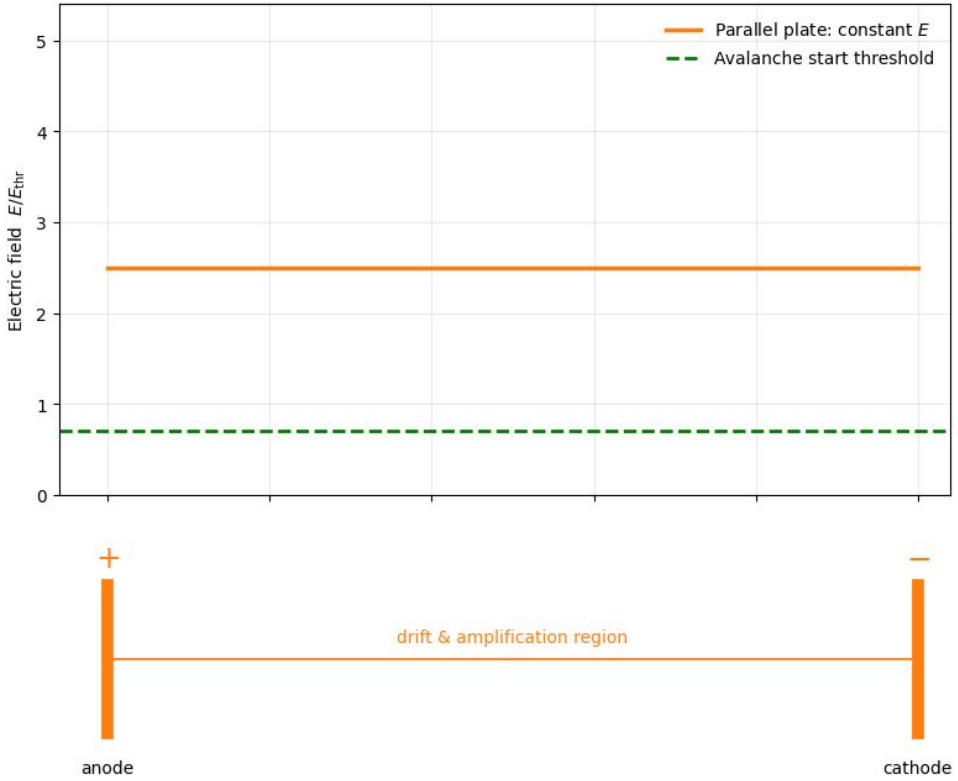
The importance of the parallel-plate geometry

Plane parallel case

d: gap size

E = V/d = constant

Drift and amplification region are the same!

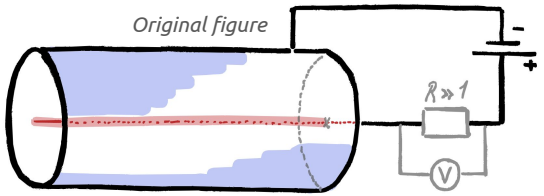


Original figure

High voltage setting, charge collection and signal measurement

Note that Geiger counter uses:

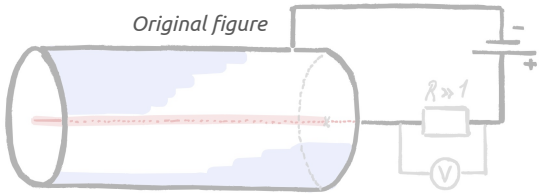
- *anode wire* to:
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High voltage setting, charge collection and signal measurement

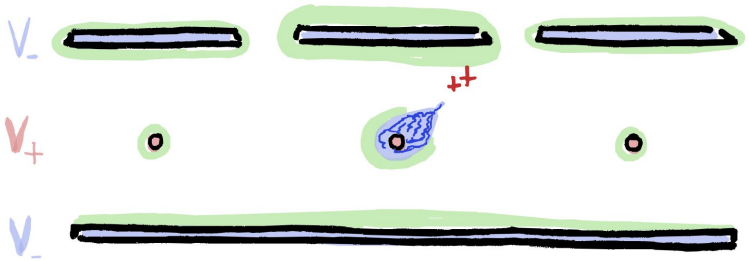
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Now we saw that MWPC splits:

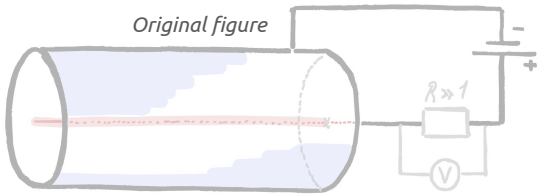
- wire and plane electrode to:
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High voltage setting, charge collection and signal measurement

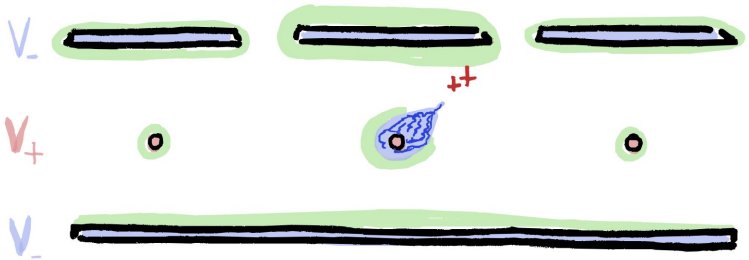
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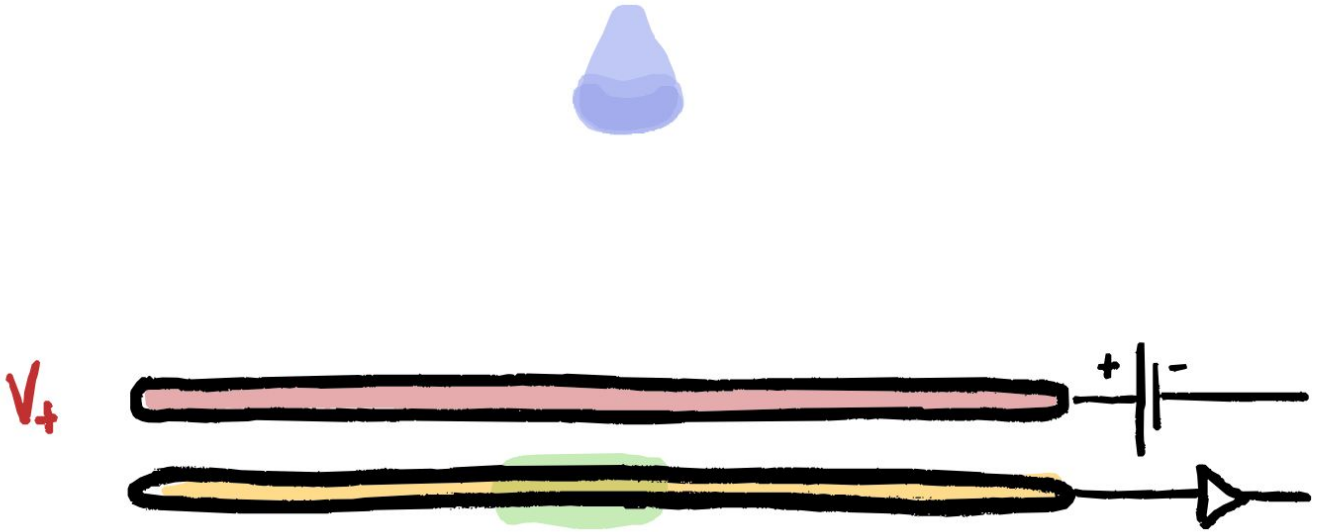


Next step → separate charge collection from HV?

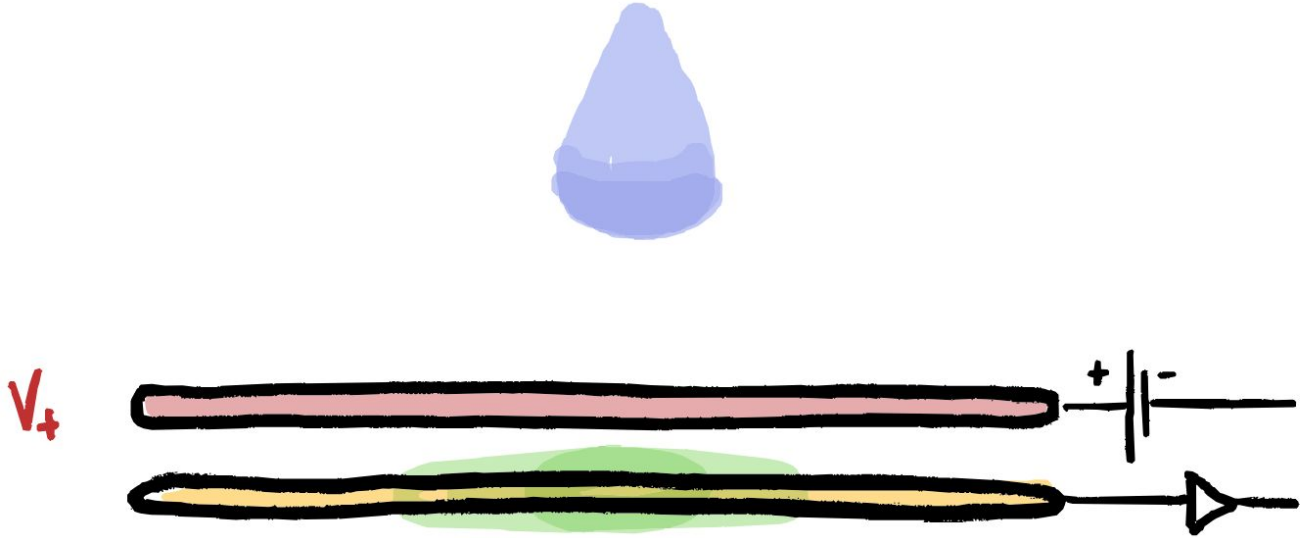
1.6. A New Idea for Discharge Quenching and Localization



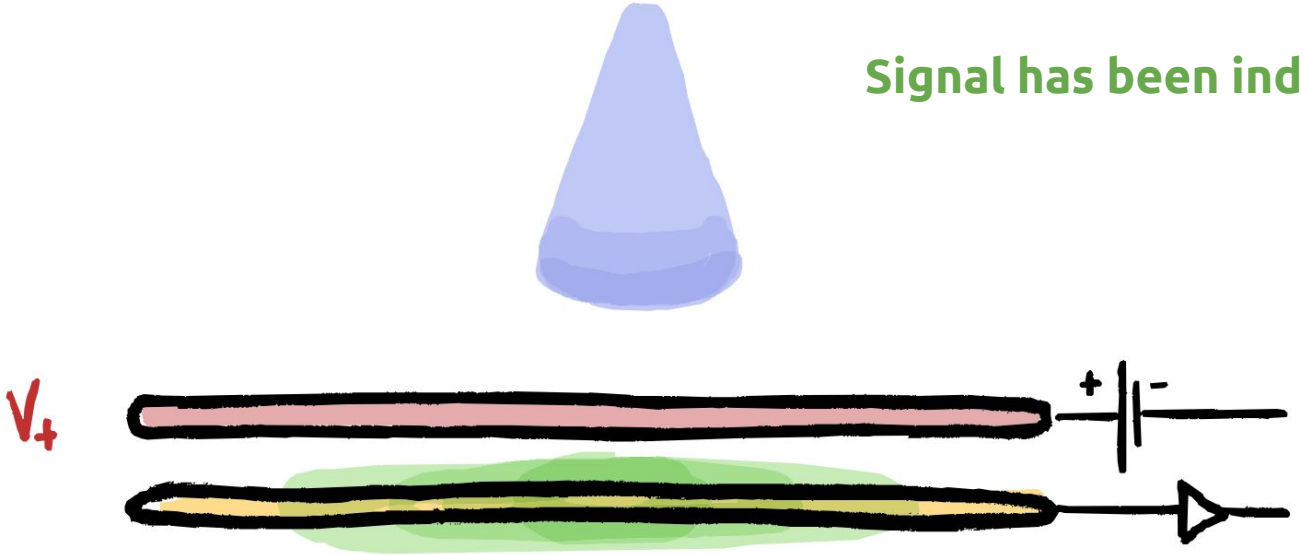
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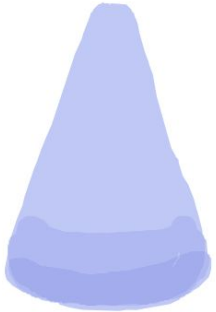
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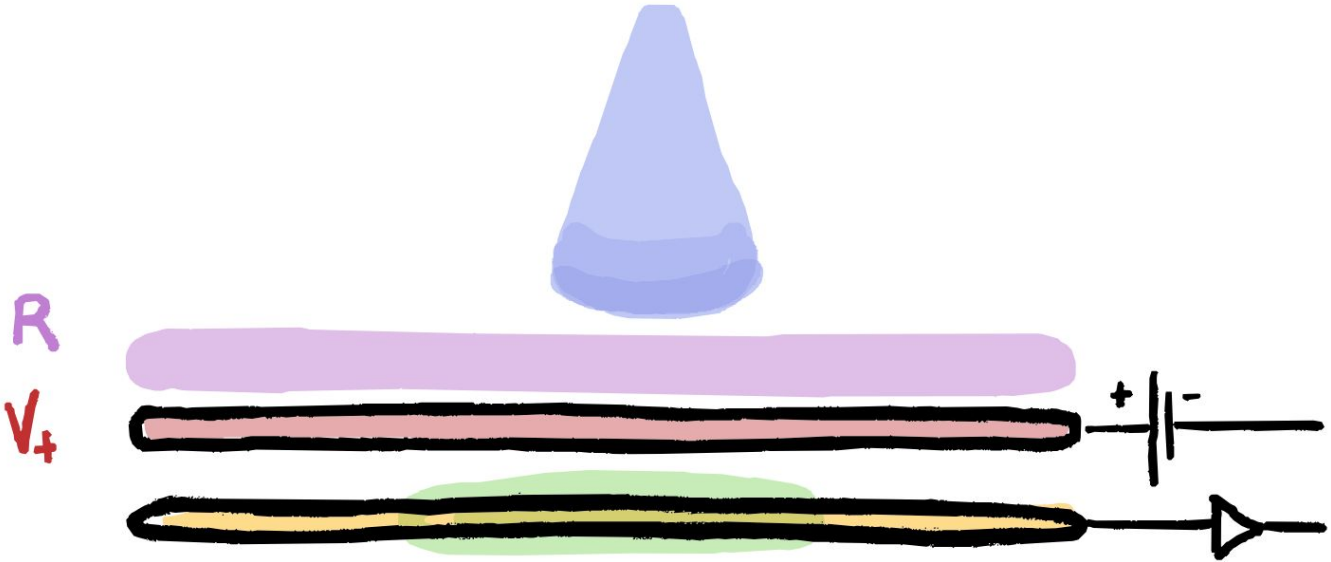


Signal has been induced!

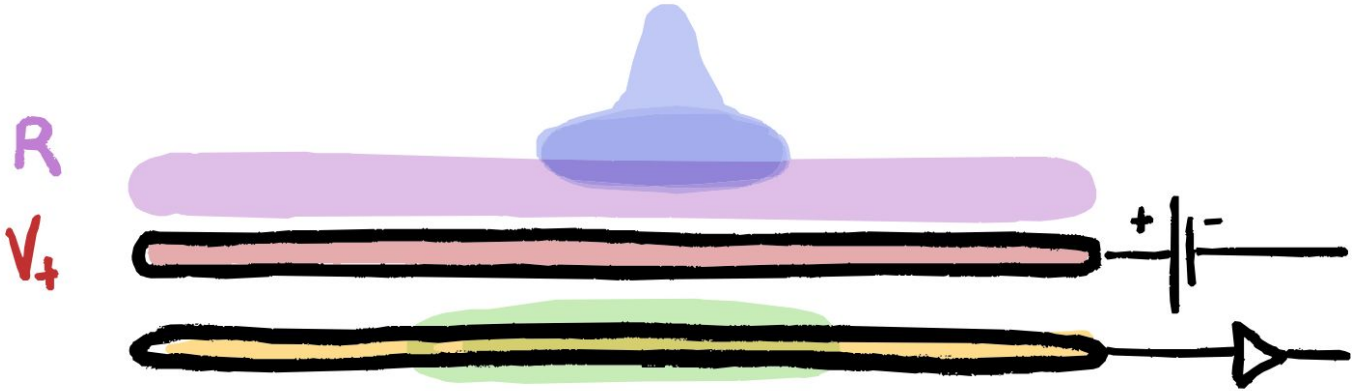
Let's avoid the avalanche from reaching the HV!



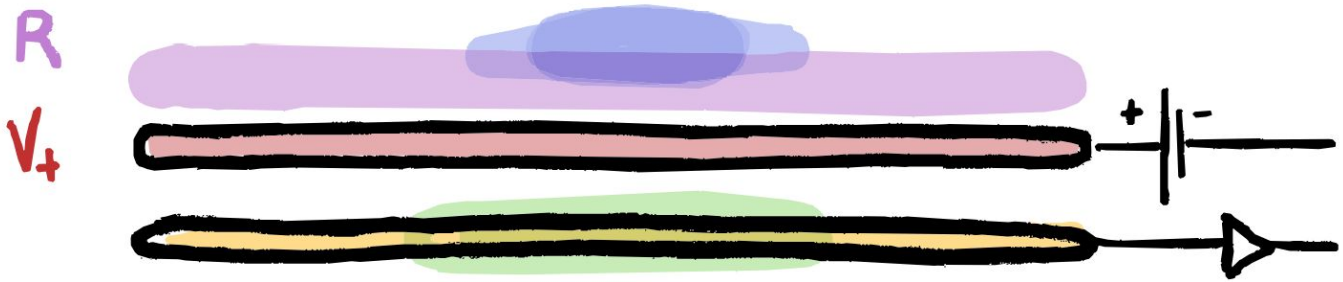
1.6. A New Idea for Discharge Quenching and Localization



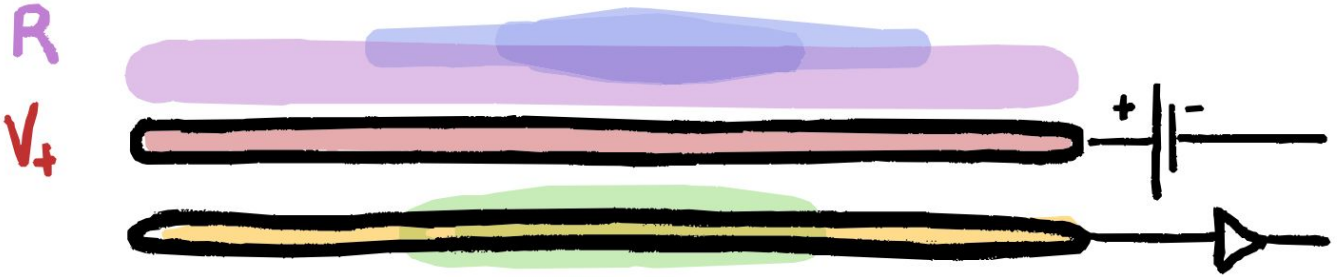
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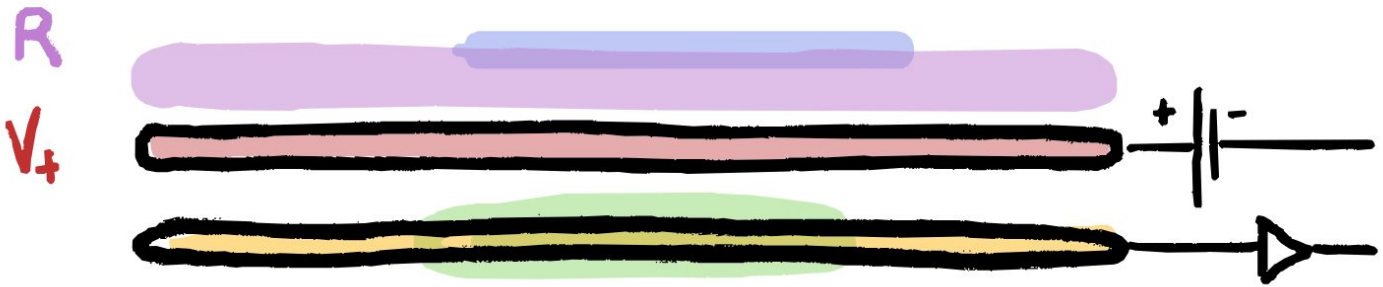
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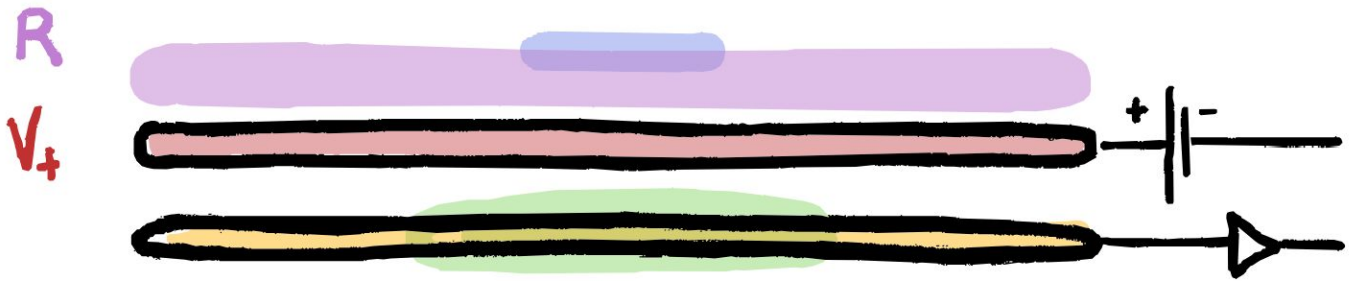
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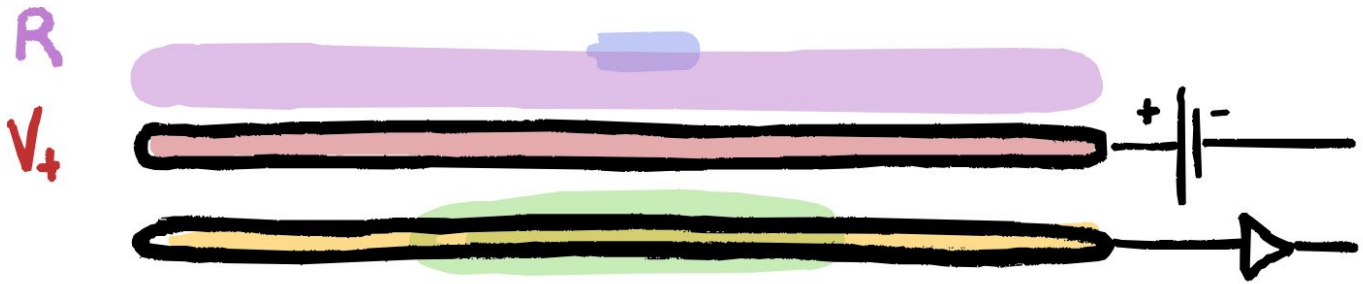
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1.6. A New Idea for Discharge Quenching and Localization



1.6. A New Idea for Discharge Quenching and Localization



1.6. A New Idea for Discharge Quenching and Localization

Ready to measure again!



Santonico and **Cardarelli** put in place all together the basic idea of the **modern RPCs**

3.2. Santonico and Cardarelli's RPCs (1980s beginning)

- *plane geometry → better timing*
- *detectors easy to build, suitable for large surfaces*

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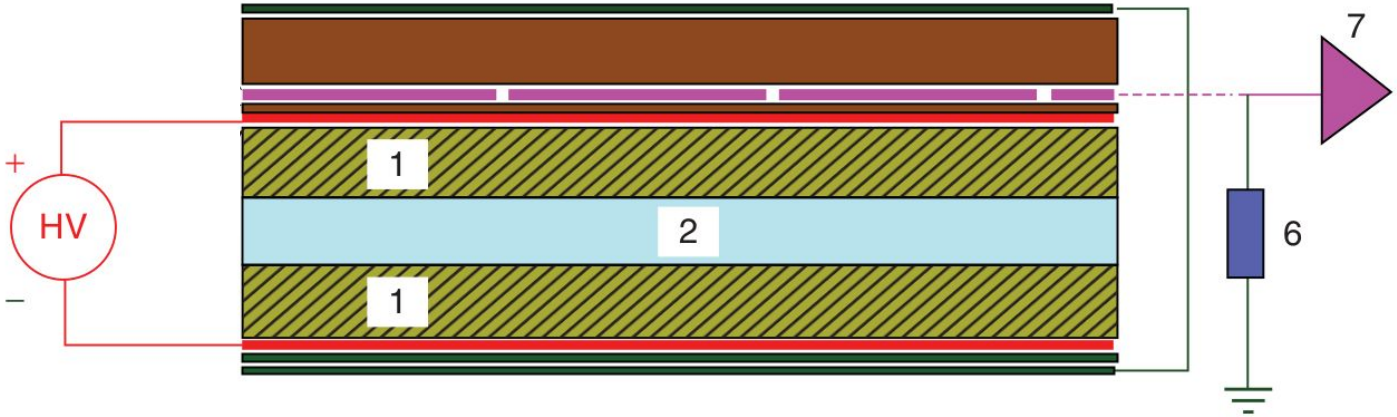


Figure 3.2 Schematics of Santonico and Cardarelli's RPC. (1) Bakelite electrodes (2 mm), (2) gas gap (2 mm), (3) HV electrodes (200 μm of graphite), (4) Mylar insulator (50 μm), (5) readout strips, (6) resistor, and (7) readout electronics.

3.2. Santonico and Cardarelli's RPCs (1980s beginning)

- *plane geometry → better timing*
- *detectors easy to build, suitable for large surfaces*

set the HV
(signal-transparent
resistive layer)

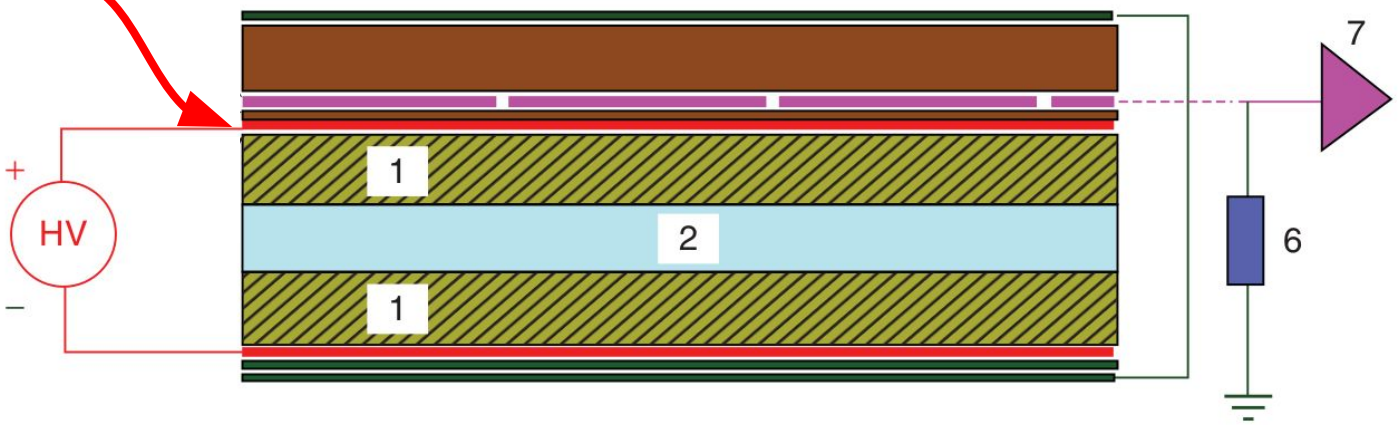


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read out the signal

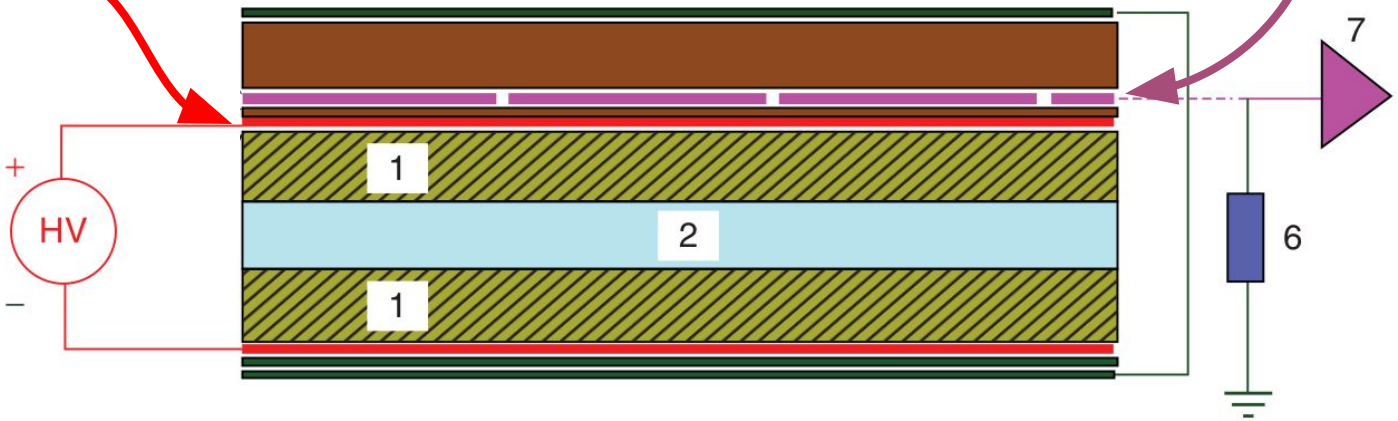


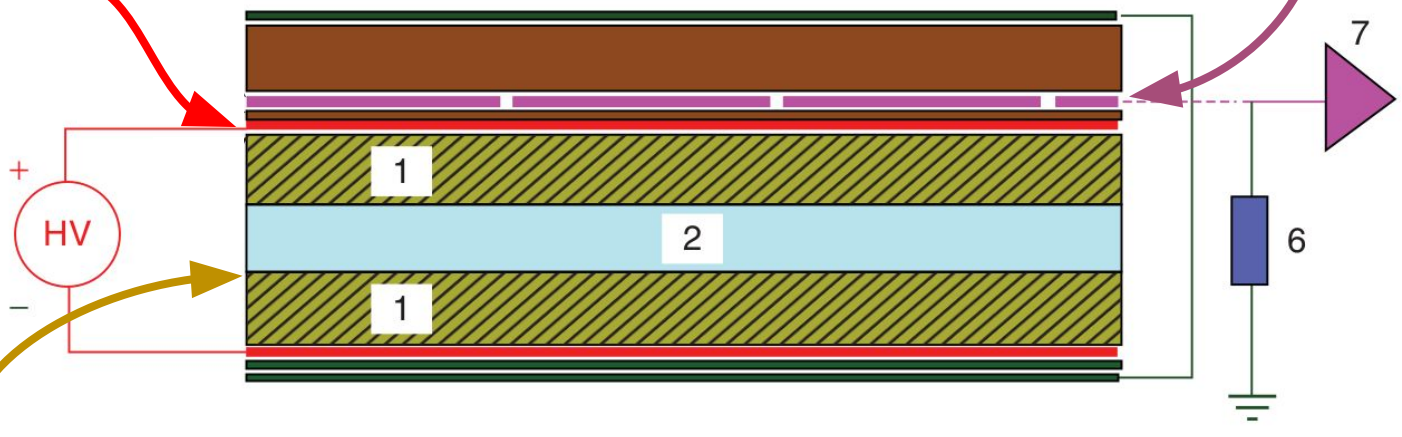
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3.2. Santonico and Cardarelli's RPCs (1980s beginning)

- *plane geometry → better timing*
- *detectors easy to build, suitable for large surfaces*

read out the signal

set the HV
(signal-transparent resistive layer)



collect avalanche charge in resistive element
(detector self-quenching and no need for a pulsed operation mode)

Figure 3.2 Schematics of Santonico and Cardarelli's RPC. (1) Bakelite electrodes (2 mm), (2) gas gap (2 mm), (3) HV electrodes (200 μm of graphite), (4) Mylar insulator (50 μm), (5) readout strips, (6) resistor, and (7) readout electronics.

Thank you!

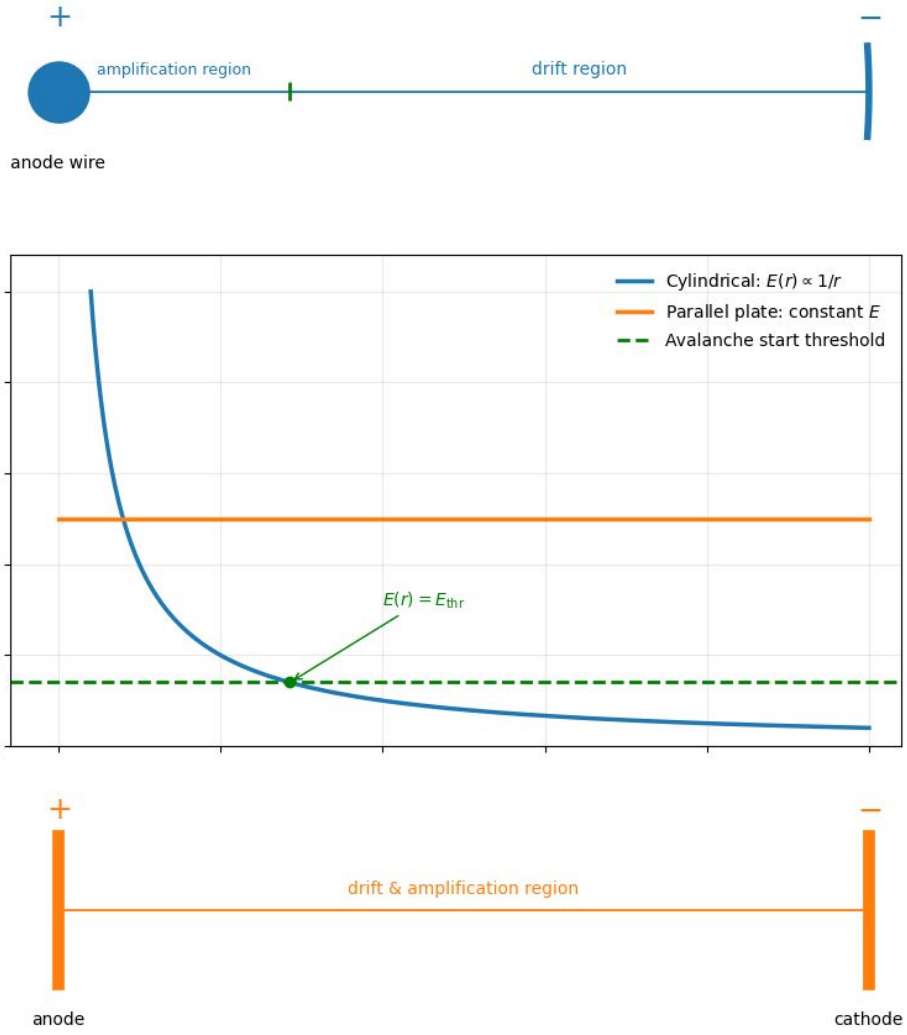
Obrigado!

Mulțumesc!

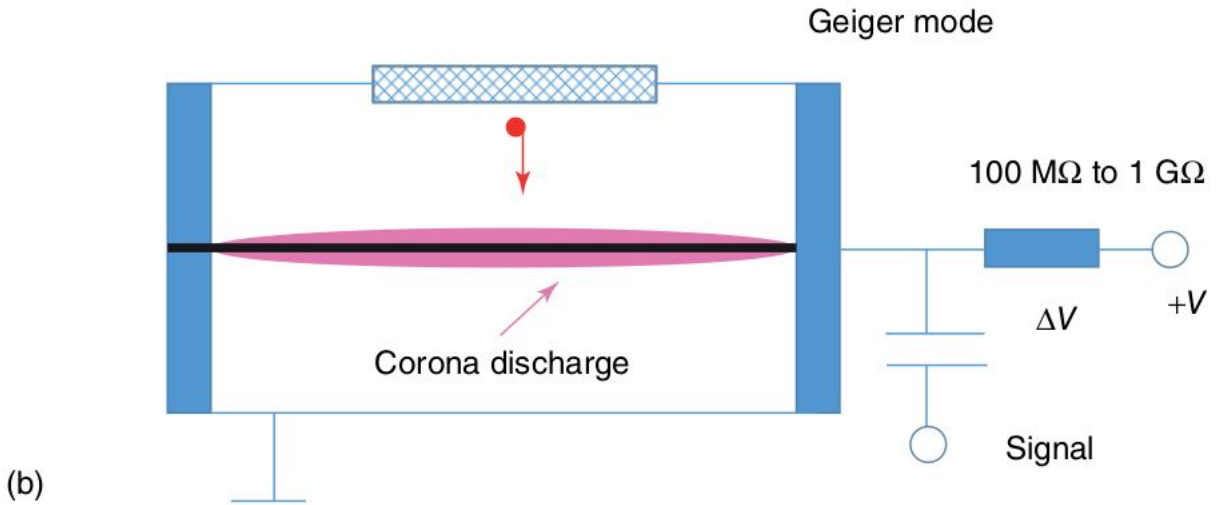
¡Gracias!

Backup

The importance of the parallel-plate geometry



Original figure


Geiger mode
100 MΩ to 1 GΩ
ΔV
+V
Corona discharge
Signal
(b)

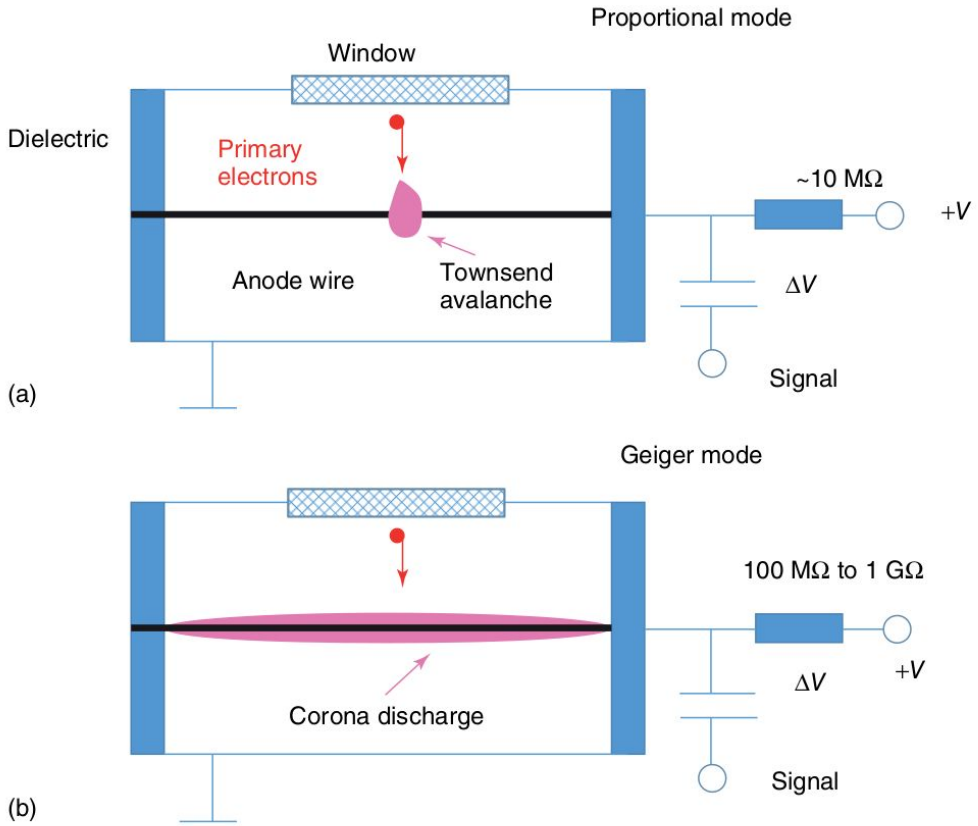


Figure 1.3 Schematic drawings of a single-wire cylindrical counter invented by Geiger and Rutherford in 1908. This detector is usually exploited either in a proportional mode (a) or in a so-called Geiger mode (b).

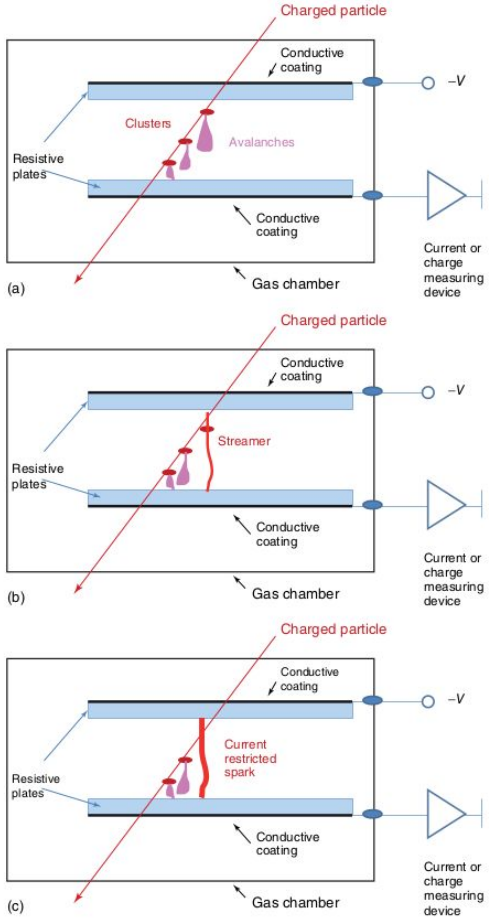


Figure 1.13 Schematic drawing of an RPC illustrating its design and operation principle: (a) creation of avalanches by primary electrons produced by ionizing charged particles crossing the detector; (b) if the total charge in the avalanche reaches the Raether limit, the avalanche transforms to a streamer; (c) when the streamer reaches the resistive electrodes, it causes a local discharge; nevertheless, the released energy in the spark is strongly limited by the resistance of the plates.

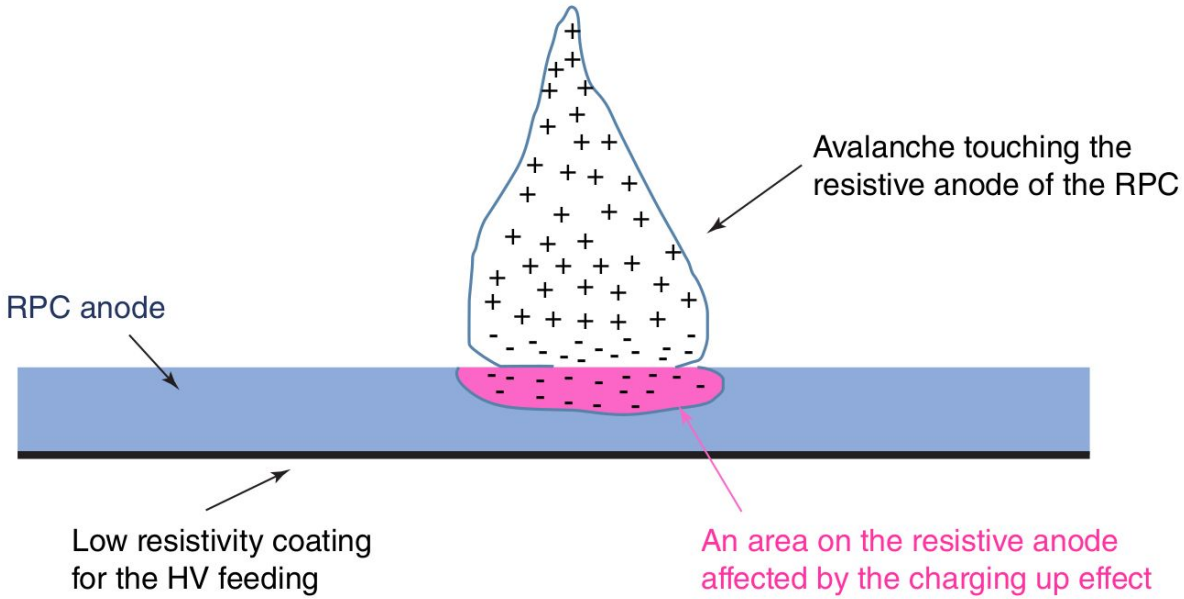


Figure 1.14 Schematic representation of the avalanche and the local partial anode discharging at the moment when the avalanche touches the dielectric anode.

1. “Classical” Gaseous Detectors and Their Limits
2. **Historical Developments Leading to Modern Resistive Gaseous Detectors**
    - 2.1. Introduction: the Importance of the Parallel-Plate Geometry
    - 2.2. First Parallel-Plate Counters
    - 2.3. Further Developments
    - 2.4. The First RPC Prototypes
    - 2.5. Pestov’s Planar Spark Chambers
    - 2.6. Wire-Type Detectors with Resistive Cathodes

2.2. First Parallel-Plate Counters

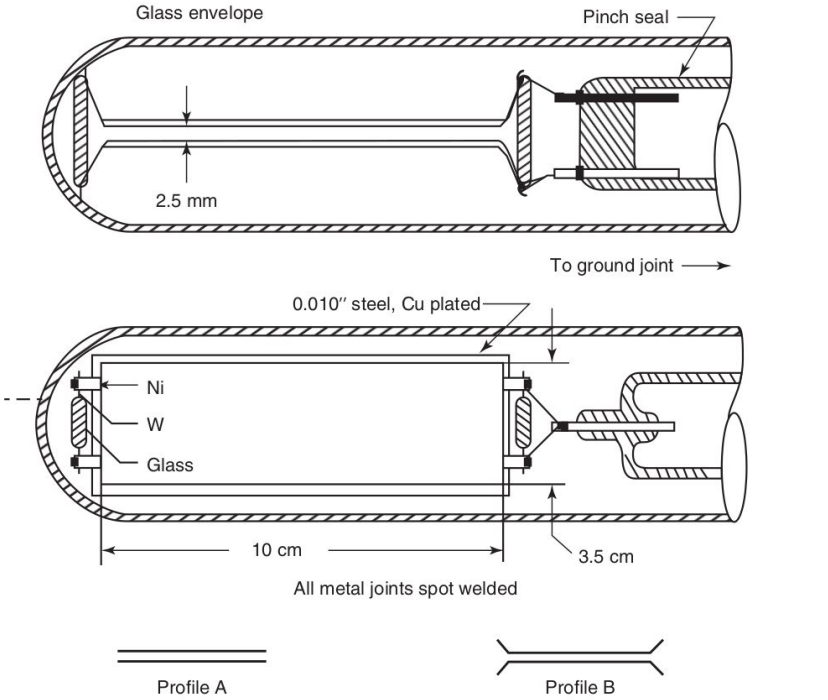


Figure 2.4 Layout of one of the original parallel-plate counters built by Keuffel. (Keuffel 1949. Reproduced with permission of American Institute of Physics.)

2.4. The First RPC Prototypes

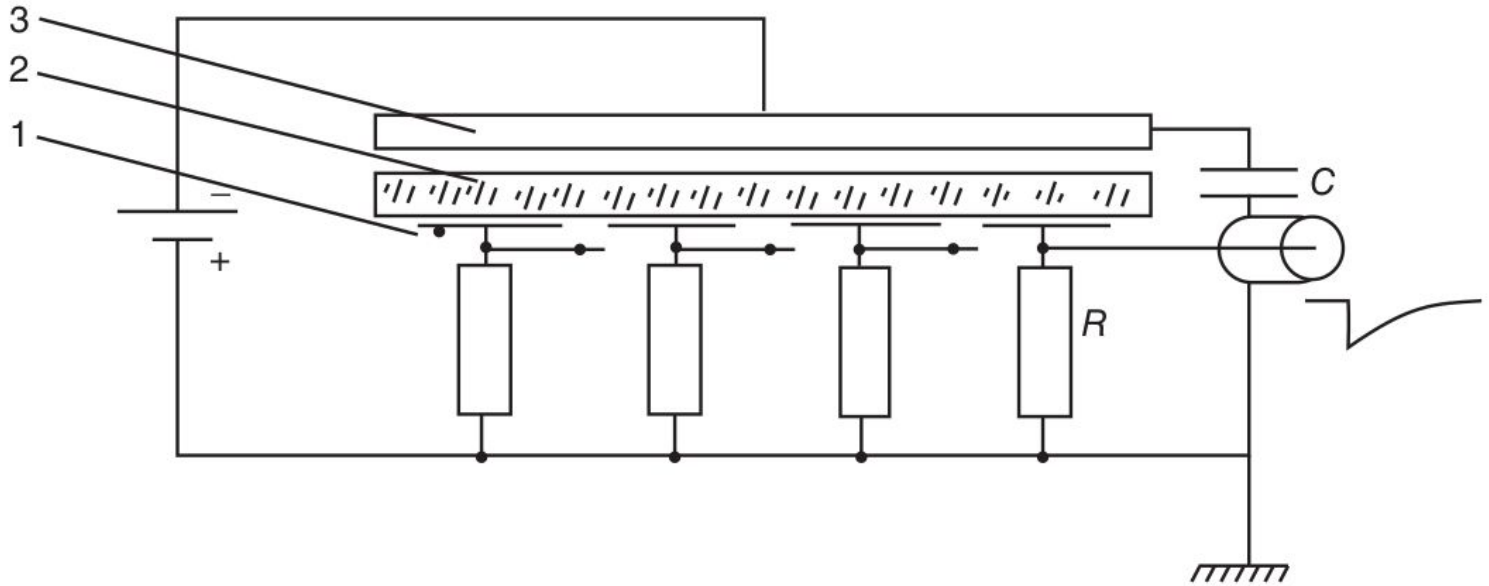


Figure 2.11 Schematics of the first design of the RPC constructed and tested by Parkhomchuk *et al.*; the various materials indicated in the figure are 1 – conductive layer, 2 – semiconductive glass, 3 – copper cathode. (Parkhomchuk *et al*. 1971. Reproduced with permission of Elsevier.)

2.5. Pestov's Planar Spark Chambers

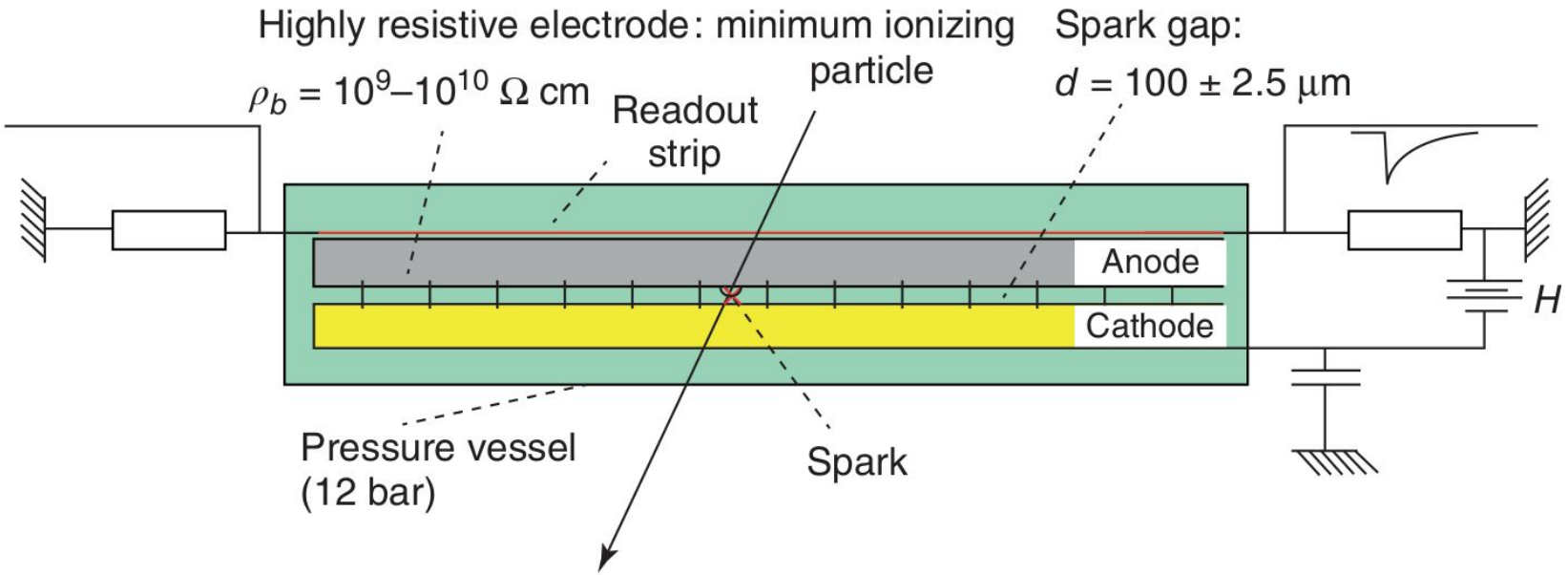


Figure 2.14 Transversal view of a Pestov detector. (Badura *et al*. 1996. Reproduced with permission of Elsevier.)

1. “Classical” Gaseous Detectors and Their Limits
2. Historical Developments Leading to Modern Resistive Gaseous Detectors
3. **Basics of Resistive Plate Chambers**
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    - 3.2. Santonico and Cardarelli’s RPCs
    - 3.3. Glass RPCs
    - 3.4. Avalanche and Streamer Modes
        - 3.4.1. Streamer Mode
        - 3.4.2. Avalanche Mode
    - 3.5. Signal Development
        - 3.5.1. Signal Formation
        - 3.5.2. Charge Distribution
        - 3.5.3. Efficiency
        - 3.5.4. Time Resolution
        - 3.5.5. Position Resolution
    - 3.6. Choice of Gas Mixtures
        - 3.6.1. Main Requirements for RPC Gas Mixtures
        - 3.6.2. Quenching Gas Mixtures
            - 3.6.2.1. General Information
            - 3.6.2.2. Historical Review about Gas Mixtures for Inhibiting Photon Feedback
            - 3.6.2.3. Some Considerations on Delayed Afterpulses
    - 3.7. Current in RPCs
    - 3.8. Dark Counting Rate
    - 3.9. Effects of Temperature and Pressure

1. “Classical” Gaseous Detectors and Their Limits
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4. **Further Developments in Resistive Plate Chambers**
    - 4.1. Double Gap RPCs
    - 4.2. Wide-Gap RPCs
    - 4.3. The Multi-gap RPCs
    - 4.4. “Space-Charge” Effects
    - 4.5. Review of Analytical Models of RPC Behavior
        - 4.5.1. Electron Avalanches Deeply Affected by Space Charge
        - 4.5.2. Highly Variable Currents Flowing through Resistive Materials
        - 4.5.3. Electrical Induction through Materials with Varied Electrical Properties
        - 4.5.4. Propagation of Fast Signals in Multiconductor Transmission Lines
    - 4.6. Timing RPCs
    - 4.7. The Importance of Front-End Electronics for Operation in Streamer and Avalanche Modes
    - 4.8. Attempts to Increase Sensitivity via Secondary Electron Emission

4.6. Timing RPCs

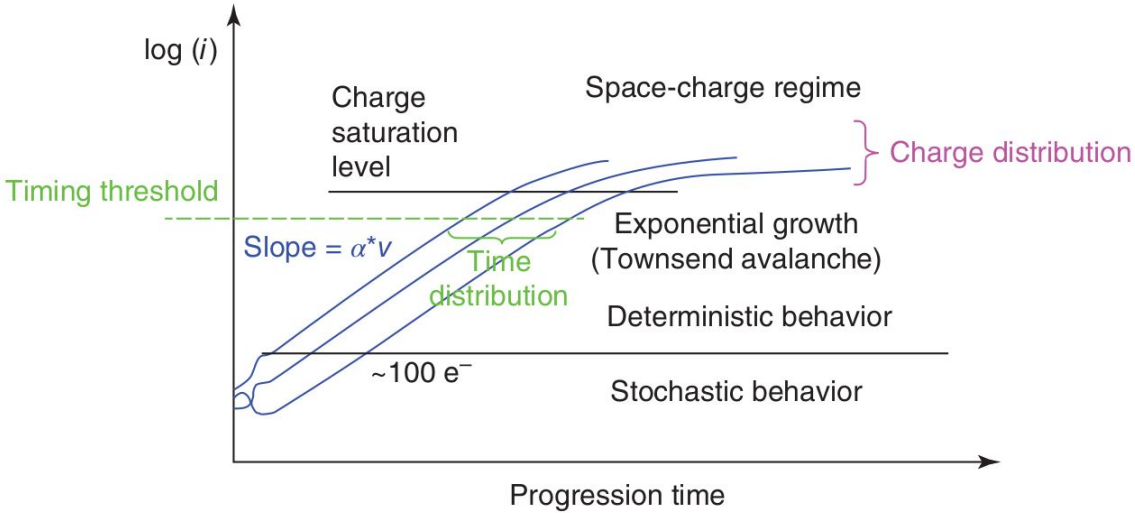


Figure 4.27 Qualitative representation of the different phases of the avalanche, as they are currently understood, and the origin of the observable time and charge distributions. The initial current grows exponentially in time until the discriminating level is reached. The time delay is independent of the position occupied by the initial charges, being the observed timing jitter dependent on the avalanche and cluster statistics (stochastic behavior) and, inversely, on the current growth (ionization) rate $\alpha^* v_d$.