Detector Physics

Ionization Detectors

GAPS Postdoc Lecture Series – October 26, 2015

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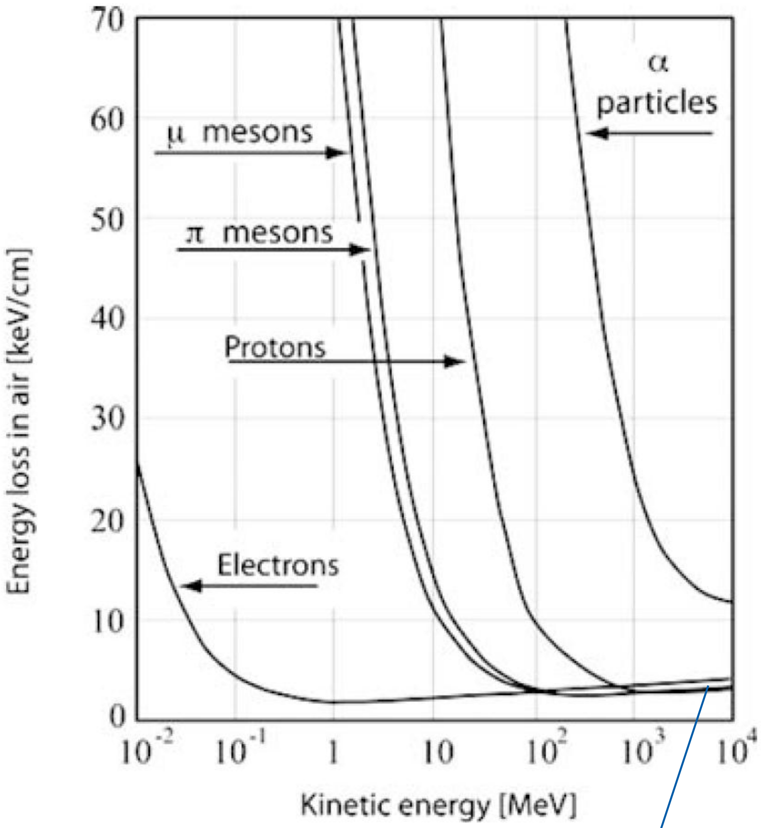
Outline

- Ionization Detectors
  - Behavior in the detector
    - Deposition of energy
    - Transport within the detector
    - Avalanche multiplication
  - Detector Types
    - Proportional counters
    - Multiwire Proportional Counters (MWPCs)
    - Gas Electron Multipliers (GEMs)
- Limits

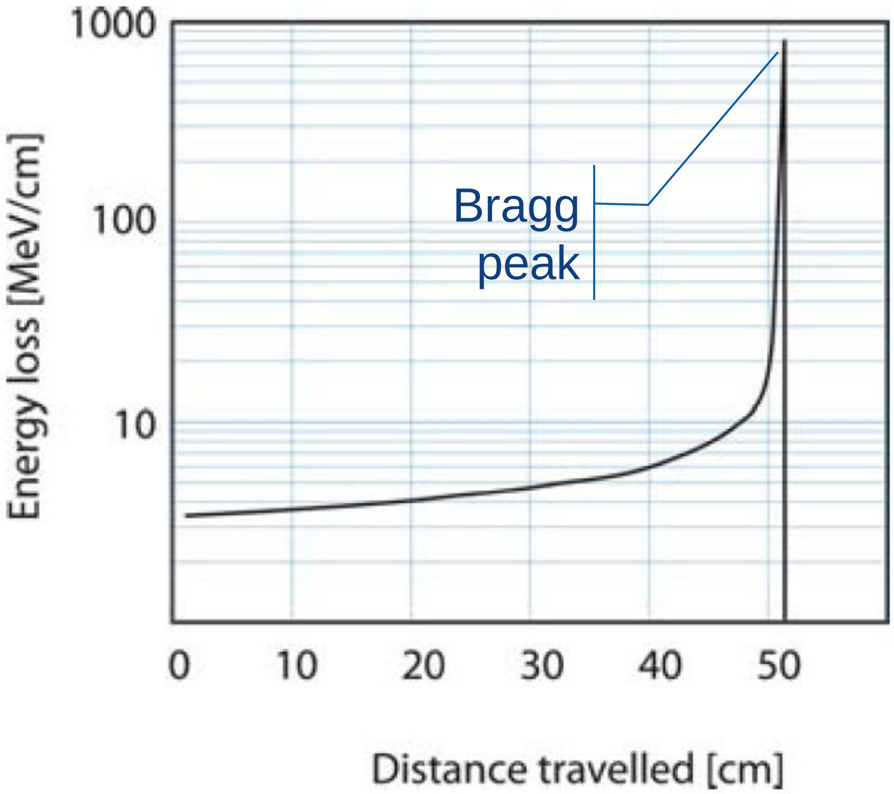
Gas a detector medium

- Gas is pretty cheap.
- E deposited in the form of electron-ion pairs.
- You can take advantage of electric fields to perform charge separation.
- You can make the detector portable.
- Sensitivity is improved with advances in electronics.

Charged particle energy loss – Due to e⁻



Electrons don’t have much mass



Range: The distance a particle travels in medium before coming to rest

E loss due to e^-: 2 types

Excitation $X + p \rightarrow X^* + p$

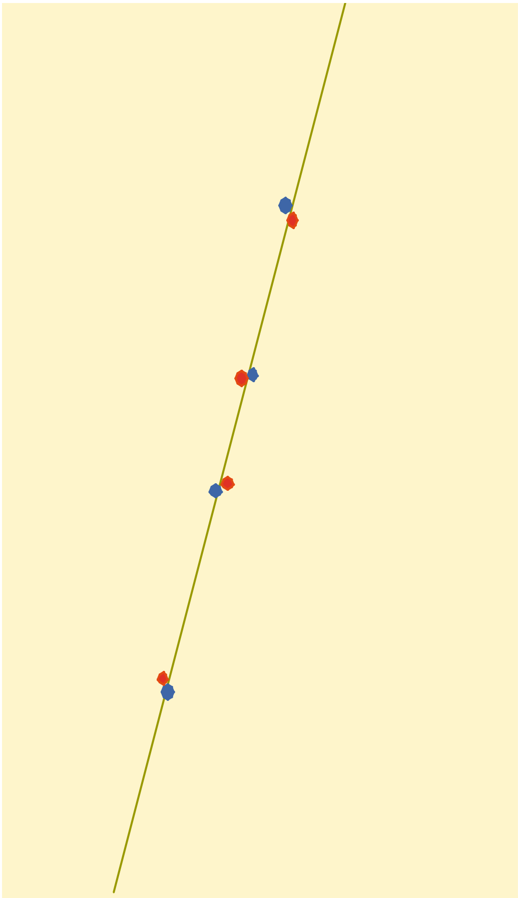
- $\sigma \sim 10^7$ b at resonance
- Dominates due to lower energy
- No free electrons created
- Excited ions can participate in subsequent ionizing reactions

Ionization $X + p \rightarrow X^+ + p + e^-$

- $\sigma \sim 10^8$ b
- Higher energy threshold makes this less likely
- What's most important in gaseous detectors
- Penning Effect:
  $Ne^* + Ar \rightarrow Ne + Ar^+ + e^-$

Charged particles with molecules

PRIMARY IONIZATION: ELECTRON-ION PAIRS



Minimum ionizing particles:

GAS (STP)	Helium	Argon	Xenon	CH_4	DME
dE/ dx (keV/ cm)	0.32	2.4	6.7	1.5	3.9
n (ion pairs/ cm)	6	25	44	16	55

Statistics of primary ionization:

Poisson: $$P_k^n = \frac{n^k}{k!} e^{-n}$$

***n**: average*
***k**: actual number*

(Maximum) detection efficiency:

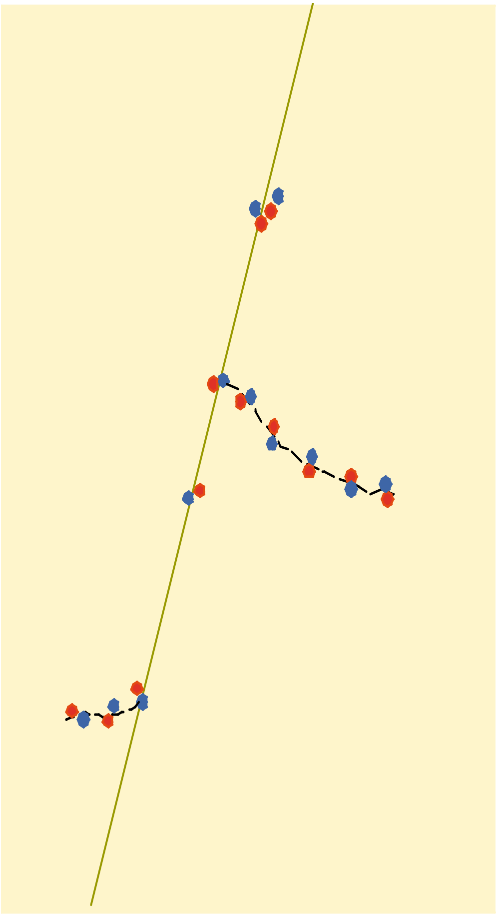
$$\varepsilon = 1 - e^{-n}$$

GAS (STP)	*thickness*	ε (%)
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

Slide courtesy of *F. Sauli IEEE-NSS 2002*

Secondary & total ionization

CLUSTERS & δ ELECTRONS:



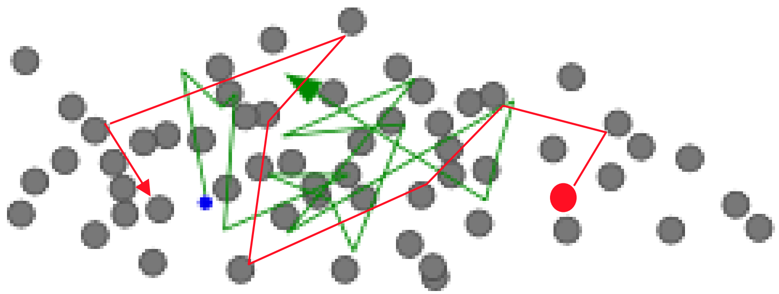
Gas	Ionization Potential (eV)	$\frac{\overline{E}}{\overline{N}} = W$ (eV)	E-Loss (keV/cm)	N (cm^{-1})
Ar	15.7	25	2,53	106
Xe	12.1	22	6.87	312
He	24.5	41.6	0.345	8.3
H_2	15.6	36.4	0.32	8.8
N_2	15.5	34.8	1.96	56.3
O_2	12.5	30.2	2.26	74.8
CH_4	12.6	30	1.61	54
C_2H_6	11.5	26	2.91	112
C_4H_{10}	10.6	26	5.67	220
CO_2	13.8	34	3.35	100

Statistical nature of ionization means W not strongly dependent on particle type or gas

DRIFT

DRIFT AND DIFFUSION OF CHARGES IN GASES

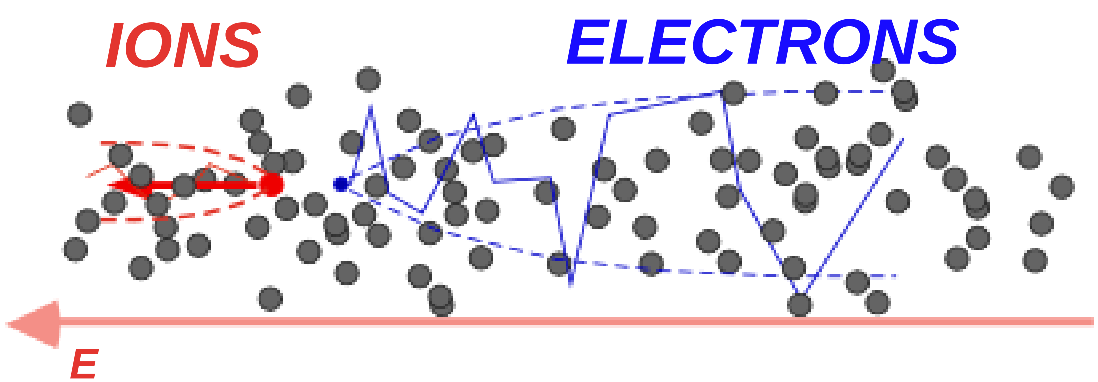
ELECTRIC FIELD E = 0: THERMAL DIFFUSION



$$v = v_t$$

ELECTRIC FIELD E > 0: CHARGE TRANSPORT AND DIFFUSION

$$v = v_{\text{drift}} + v_t$$



Can we derive v_{drift}?

$$\text{KE} = \frac{1}{2} m v_t^2 = \frac{3}{2} kT \rightarrow v_t = \sqrt{\frac{3kT}{m}} \approx \begin{cases} 500 \text{ m/s for } \text{N}_2 \\ 420 \text{ m/s for Ar} \\ 10^5 - 10^6 \text{ m/s for } e^- \end{cases}$$

$$\overline{\Delta t} = \frac{\lambda}{v_t}$$

Mean free path

Average time between collisions

Mean free path - λ

- Given a $P(x)$ we can get $W(x)$ – the Probability density function
  - As long as the cumulative distribution function of $P(x)$ is continuous.
- From there, λ is just the expectation value of x

$$W(x) = \frac{d}{dx}P(x)$$
$$= \frac{d}{dx}(1 - e^{-n\sigma x})$$
$$= n\sigma e^{-n\sigma x}$$

$$\lambda = \int_0^\infty xW(x)dx$$
$$= \int_0^\infty xn\sigma e^{-n\sigma x}dx$$
$$= \frac{1}{n\sigma}$$

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$$\overline{\Delta t} = \frac{\lambda}{v_t} = \lambda \sqrt{\frac{m}{3kT}}$$

$$a = \frac{eE}{m}$$

Electric field

Can we derive v_{drift}?

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$$\overline{\Delta t} = \frac{\lambda}{v_t} = \lambda \sqrt{\frac{m}{3kT}} \qquad a = \frac{eE}{m}$$

$$v_{\mathrm{drift}} = \frac{1}{2} a \cdot \Delta t = \frac{1}{2} \frac{eE}{m} \lambda \sqrt{\frac{m}{3kT}} = \boxed{\frac{e\lambda}{\sqrt{12kTm}}} E$$

Ion Mobility

μ

Can we derive v_{drift}?

$$\text{KE} = \frac{1}{2}mv_t^2 = \frac{3}{2}kT \rightarrow v_t = \sqrt{\frac{3kT}{m}} \approx \begin{cases} 500\ \text{m/s for N}_2 \\ 420\ \text{m/s for Ar} \\ 10^5 - 10^6\ \text{m/s for } e^- \end{cases}$$

$$\overline{\Delta t} = \frac{\lambda}{v_t} = \lambda\sqrt{\frac{m}{3kT}} \qquad a = \frac{eE}{m}$$

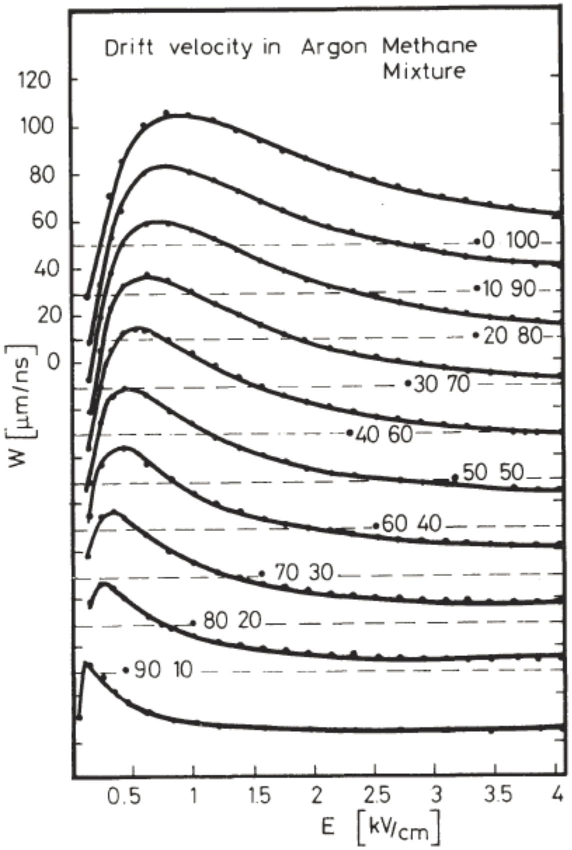
$$v_{\text{drift}} = \frac{1}{2}a \cdot \Delta t = \frac{1}{2}\frac{eE}{m}\lambda\sqrt{\frac{m}{3kT}} = \frac{e\lambda}{\sqrt{12kTm}}E = \mu E$$

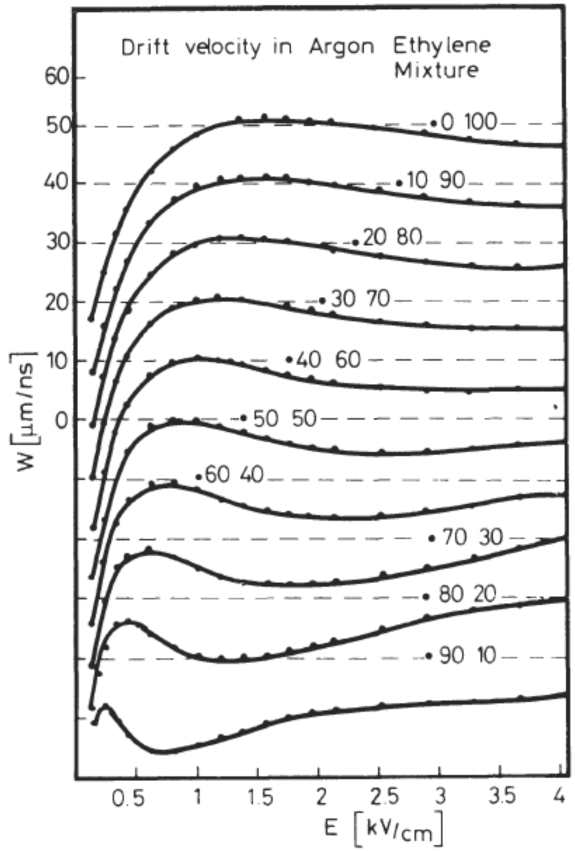
- Given a drift field of 1 kV/cm:

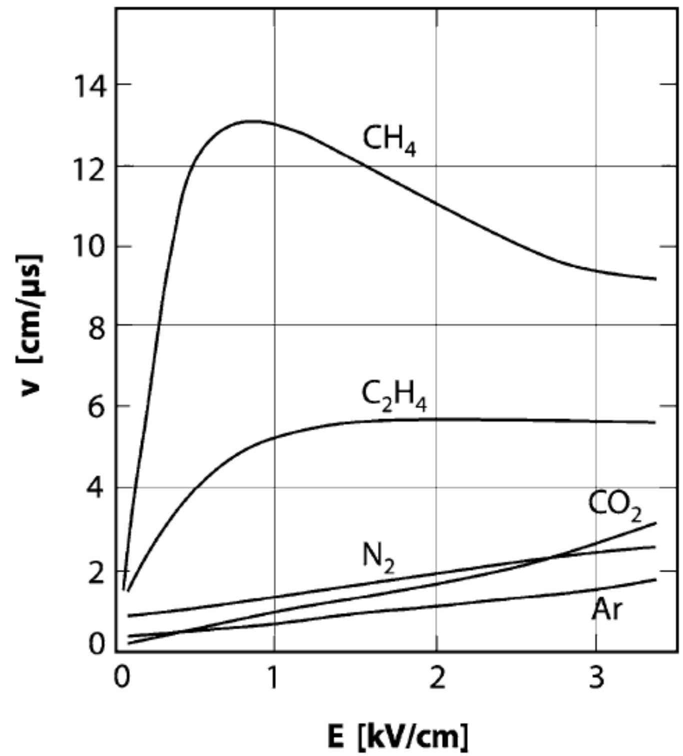
$$v_{\text{drift}}(\text{N}_2) = 34\ \text{m/s} \qquad v_{\text{drift}}(e^-) \sim 10{,}000\ \text{m/s}$$

$$v_{\text{drift}} < v_{\text{thermal}}$$

Gas mixture matters

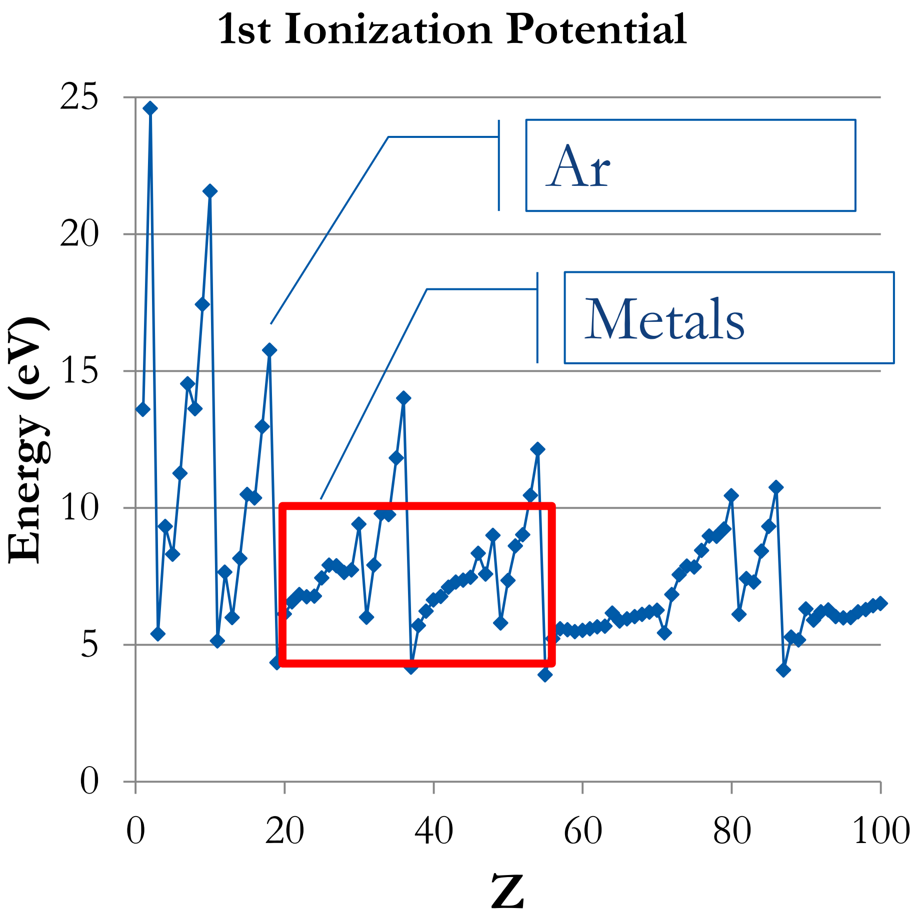






What is going on in the gas?

- After recombination, Ar emits photon
  - High prob. of e^- from cathode
- During recombination, collision with cathode likely emits more than 1 e^-
- Enough extra e^- could cause a discharge



What is going on in the gas?

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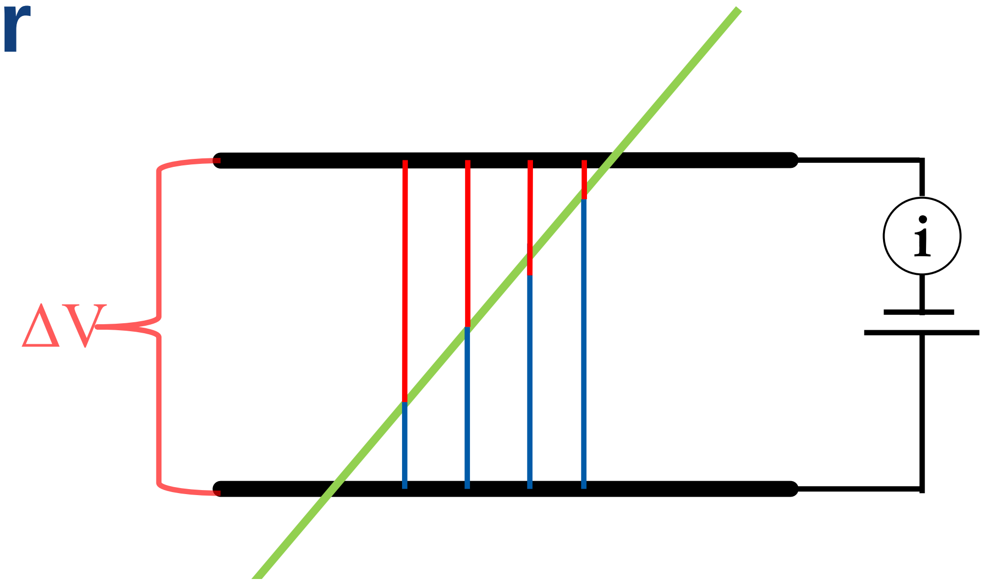
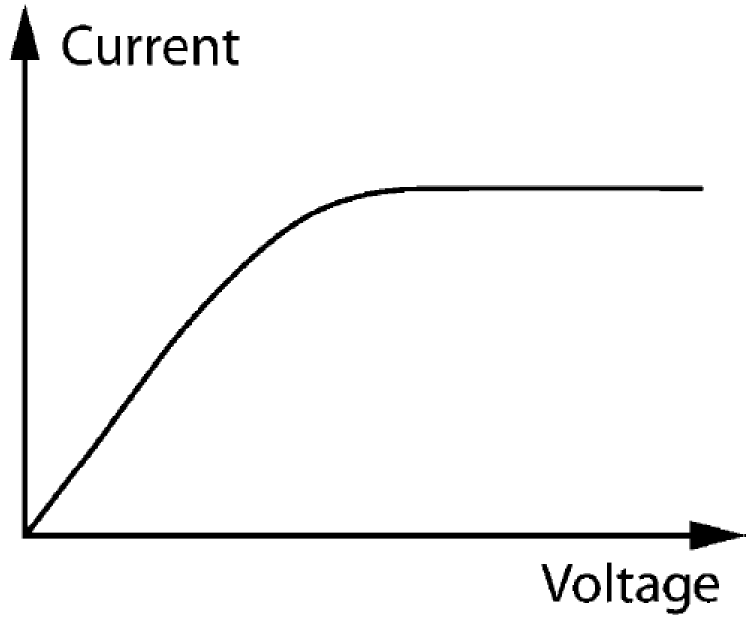
- Introduce polyatomic *quenching* gas (hydrocarbon).
  - CH_4 (Methane)
  - C_4H_{10} (Isobutane)
- Many rotational & vibrational degrees of freedom
  - Absorbs photons
  - Charge exchange with Ar^+ ions

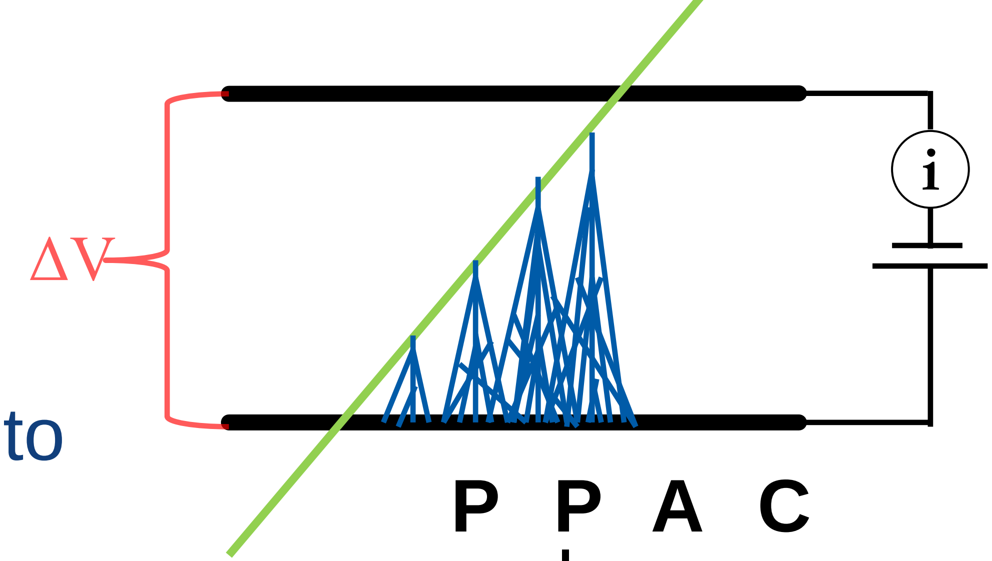
Ionization chamber

- The most basic ionization detector.
- Used for prompt radiation detection.
- Low current: Given 1000 α/s and each track is $\overline{2\ \mathrm{cm}}$
  - 19 **fA**
- **What happens when 1 e^- is deposited?**





Challenge:

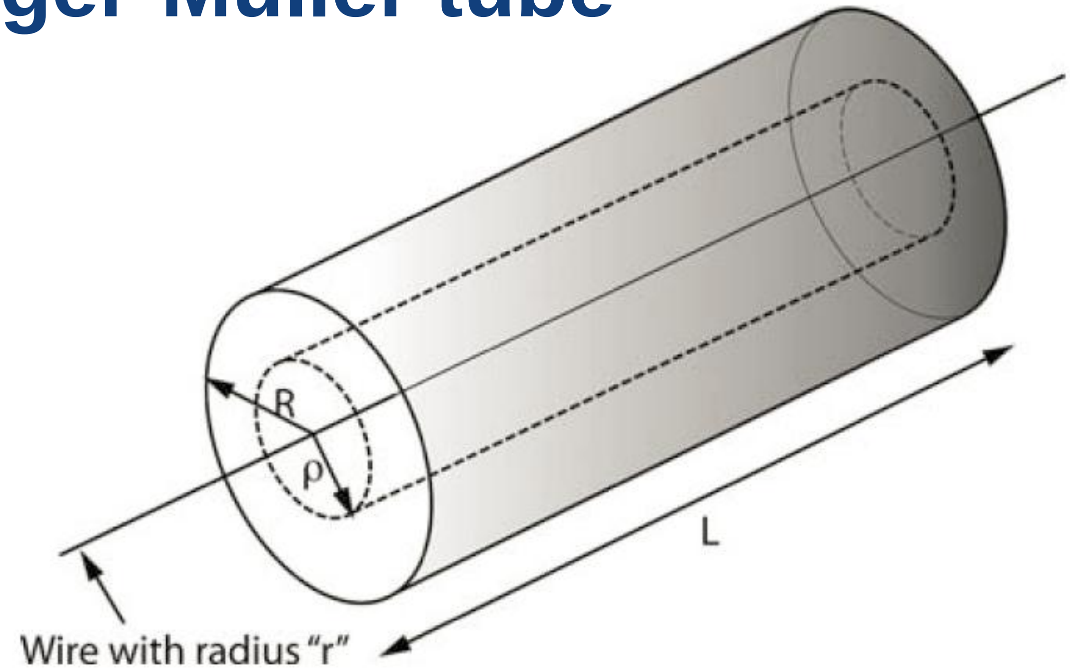


- Single electrons are hard to detect. What to do?
- Stronger Field
  - Gives electrons more energy
  - If the electrons have enough energy to ionize along their path
- Constant E-field so avalanche everywhere

P P A C

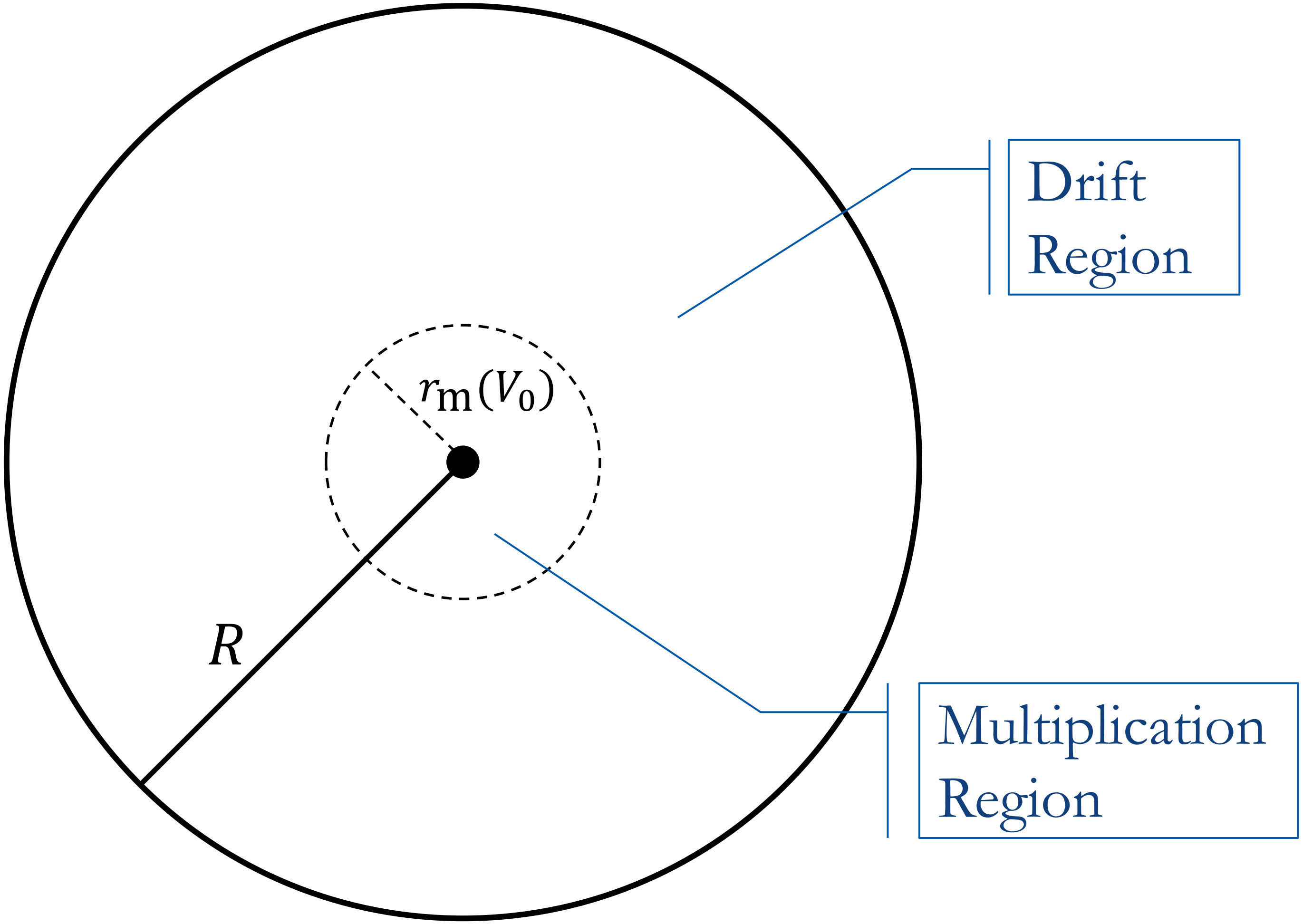
Parallel Plate Avalanche Counter

The Geiger-Müller tube

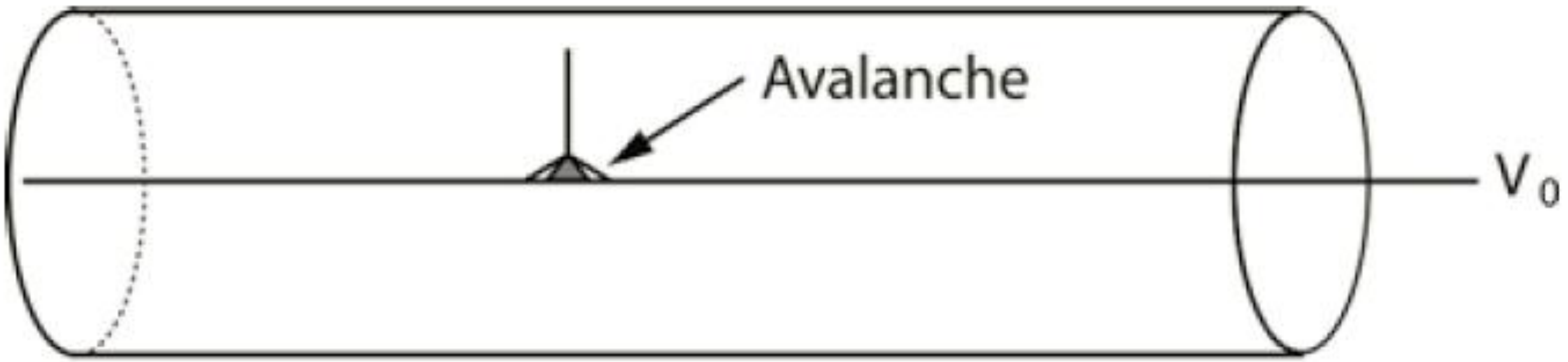


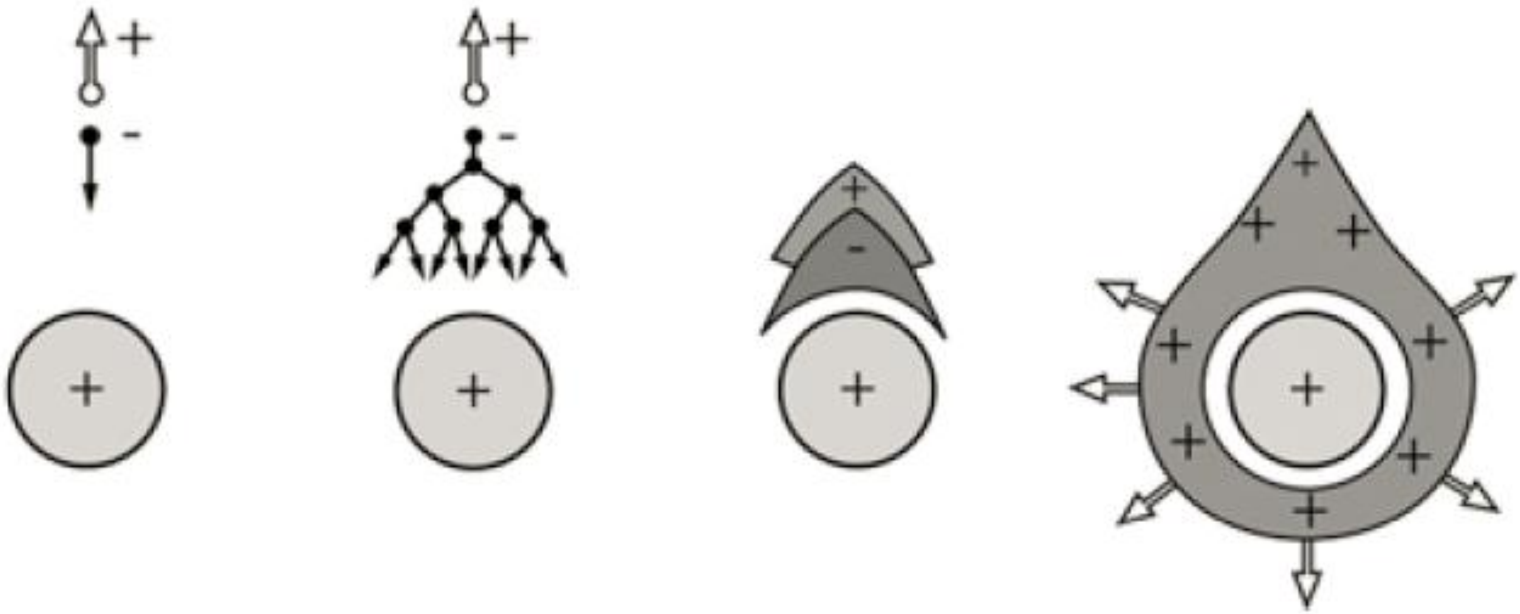
- Cylinder filled with gas
- Inner surface of the cylinder is conductive
- If V_0 is applied to the wire: $E(\rho) = \frac{V_0}{\rho \ln\left(\frac{R}{r}\right)}$

The Geiger-Müller tube

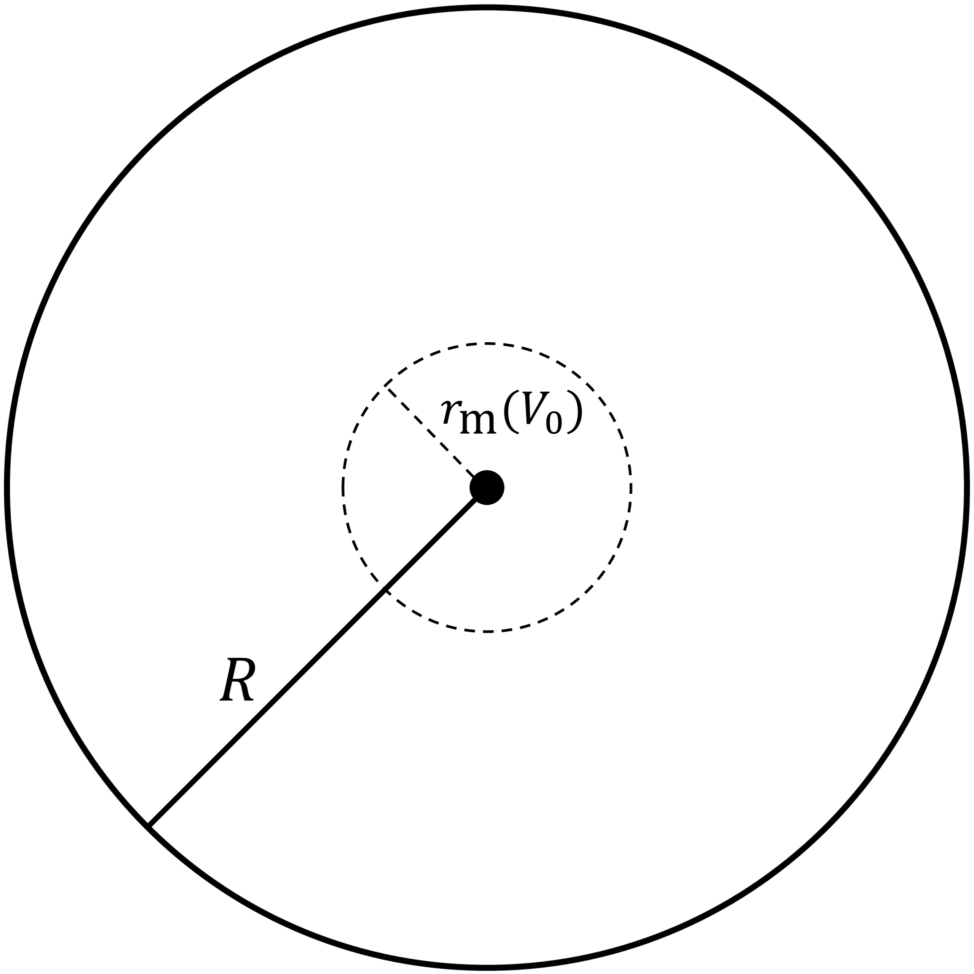


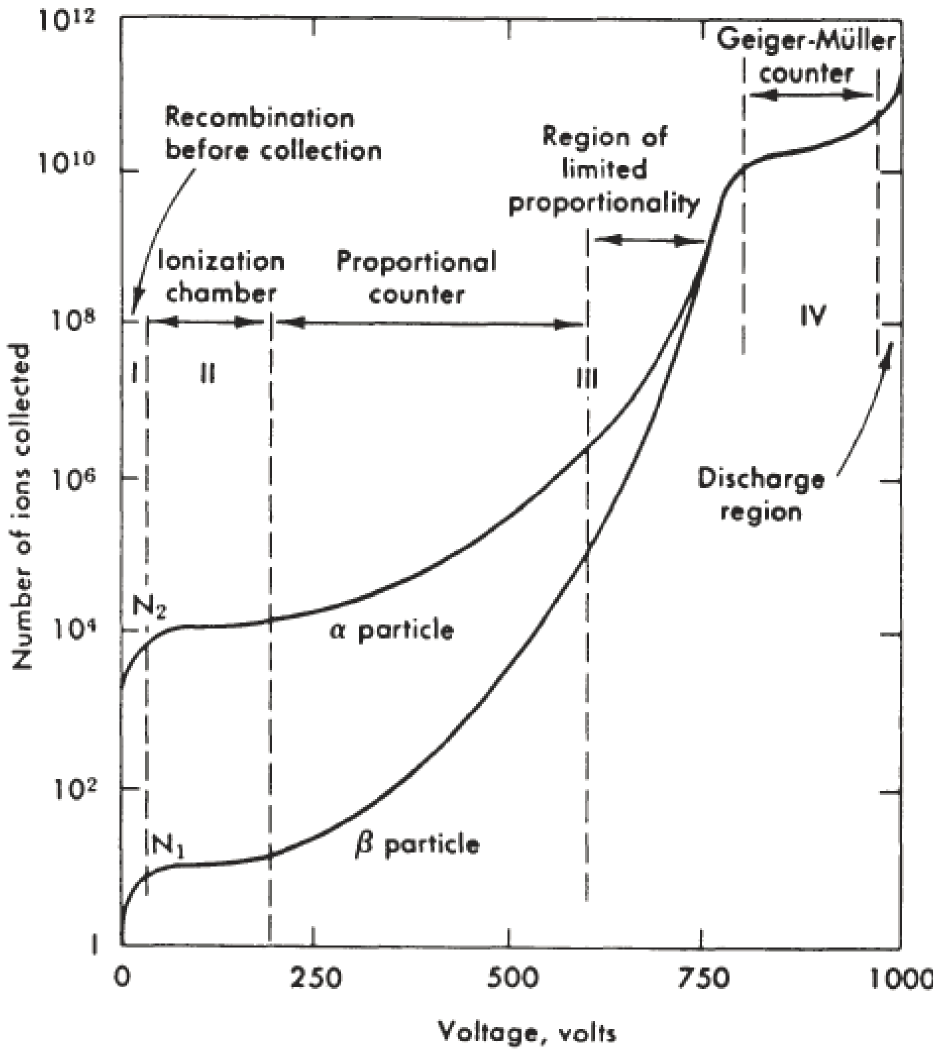
The Geiger-Müller tube





The Geiger-Müller tube

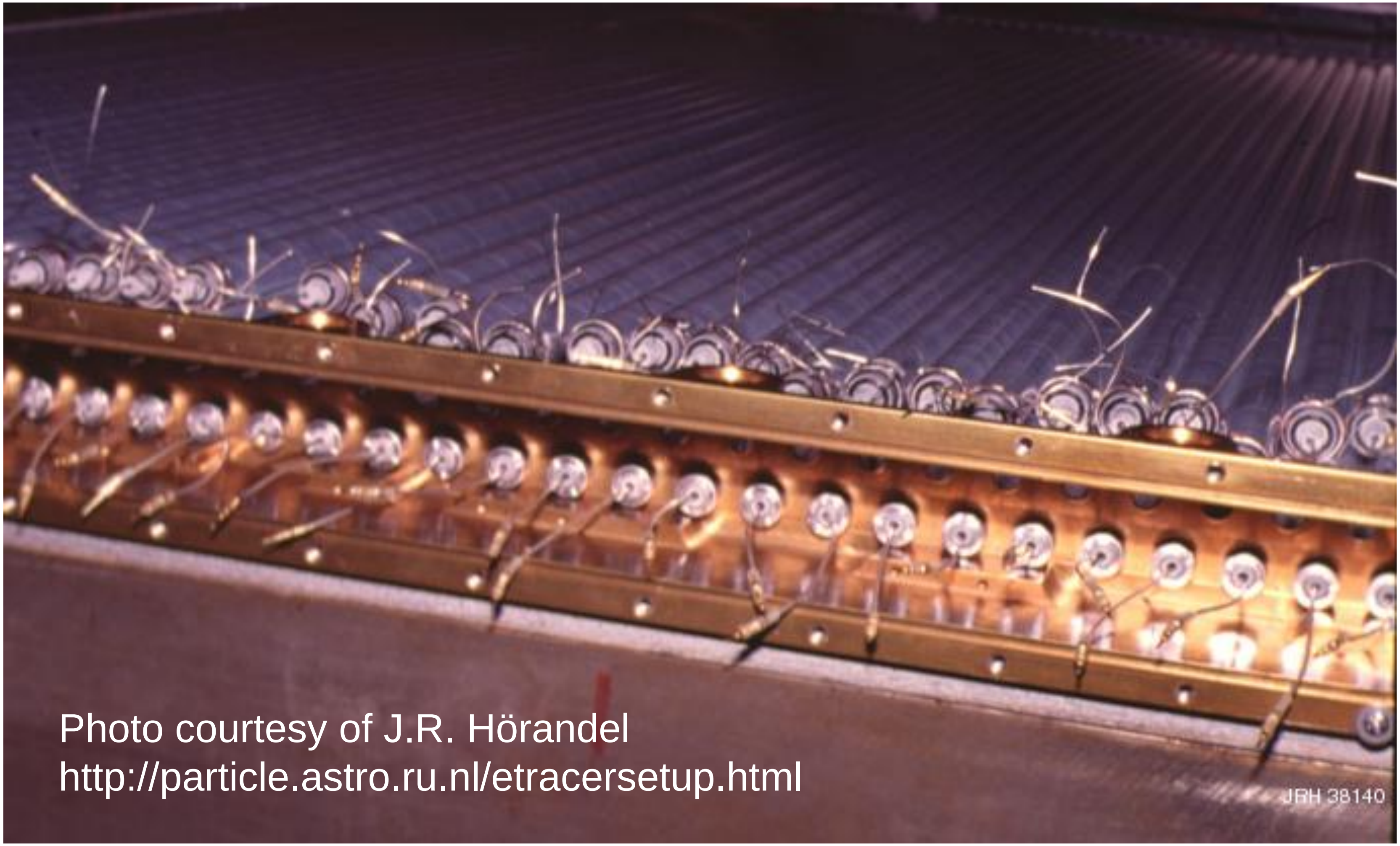




The Geiger-Müller tube

- What you gain:
  - Energy sensitivity that is scalable with voltage
  - Position sensitivity in x **or y**
  - Portability
- What you lose:
  - Position sensitivity in x and y
    or
  - Money – get position back with an array.

Proportional Tube Array



TRACER

Photo courtesy of stratocat.com

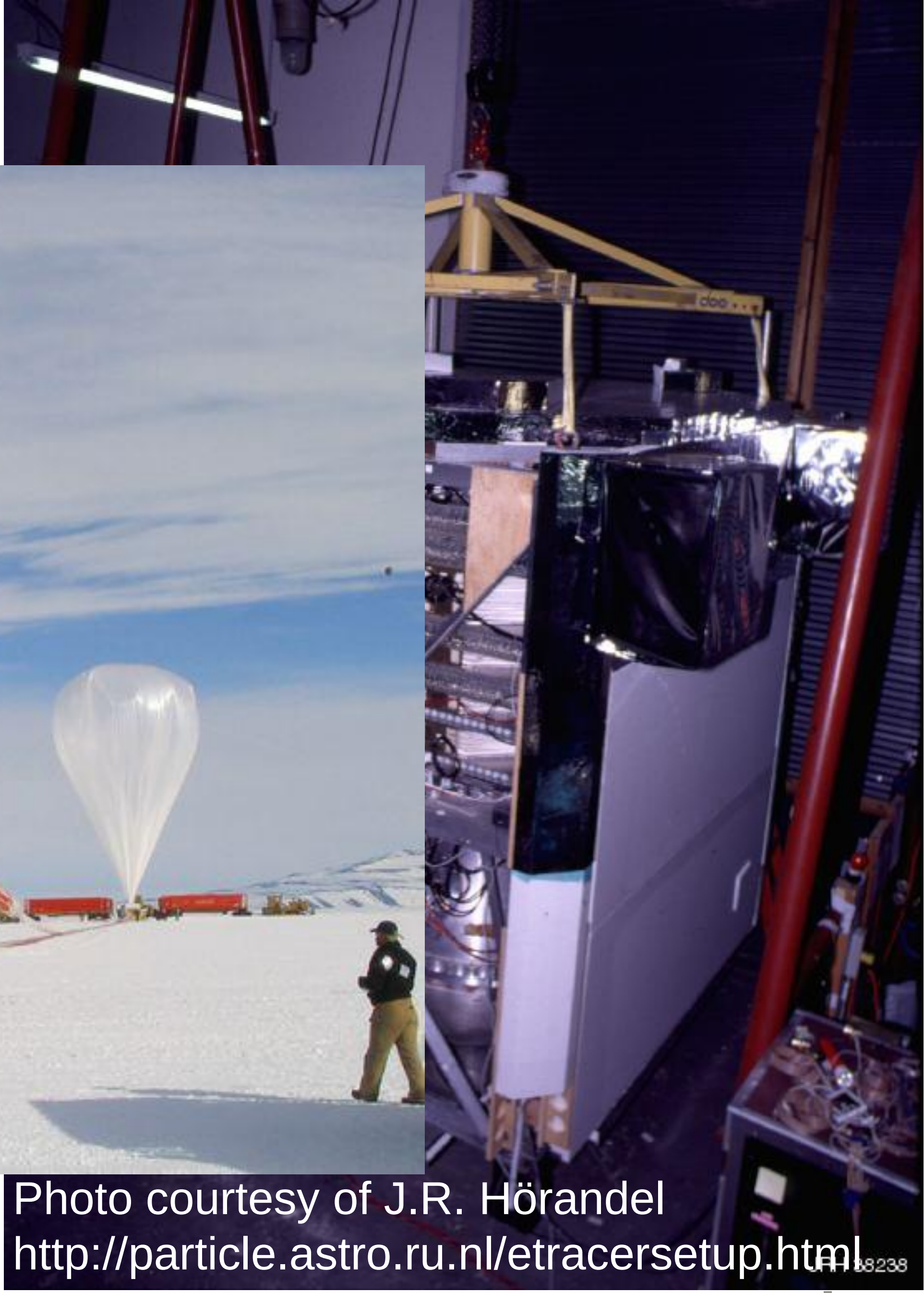


Photo courtesy of J.R. Hörandel
http://particle.astro.ru.nl/etracersetup.html

TRACER

Photo courtesy of stratocat.com

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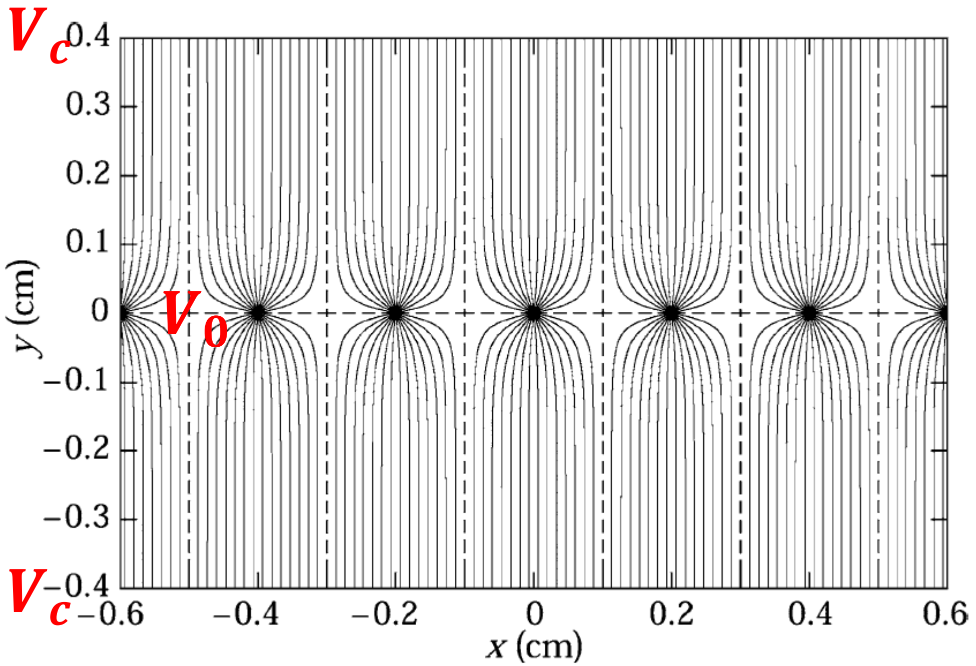
Multiwire Proportional Chamber (MWPC)

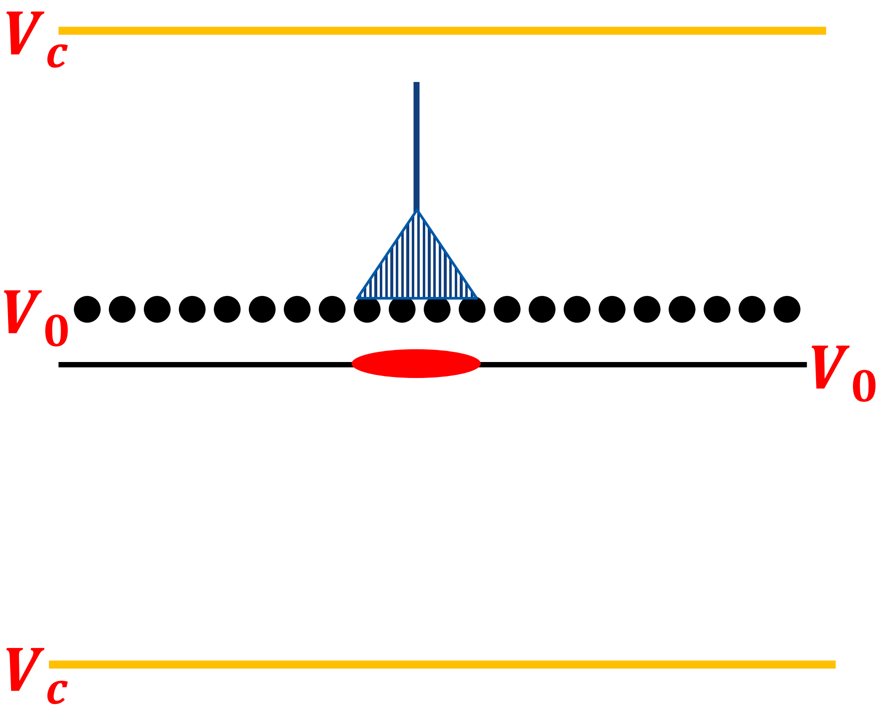
- What if you don't want a plethora of independent gas volumes?
- Each wire acts as its own proportional counter.
- Could snake the wire and use a delay line.

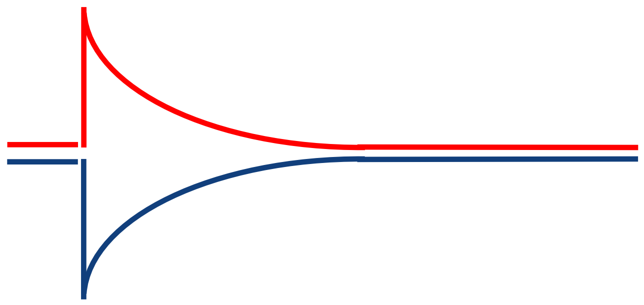


MWPC X-Y sensitivity

What if you want 2D sensitivity?

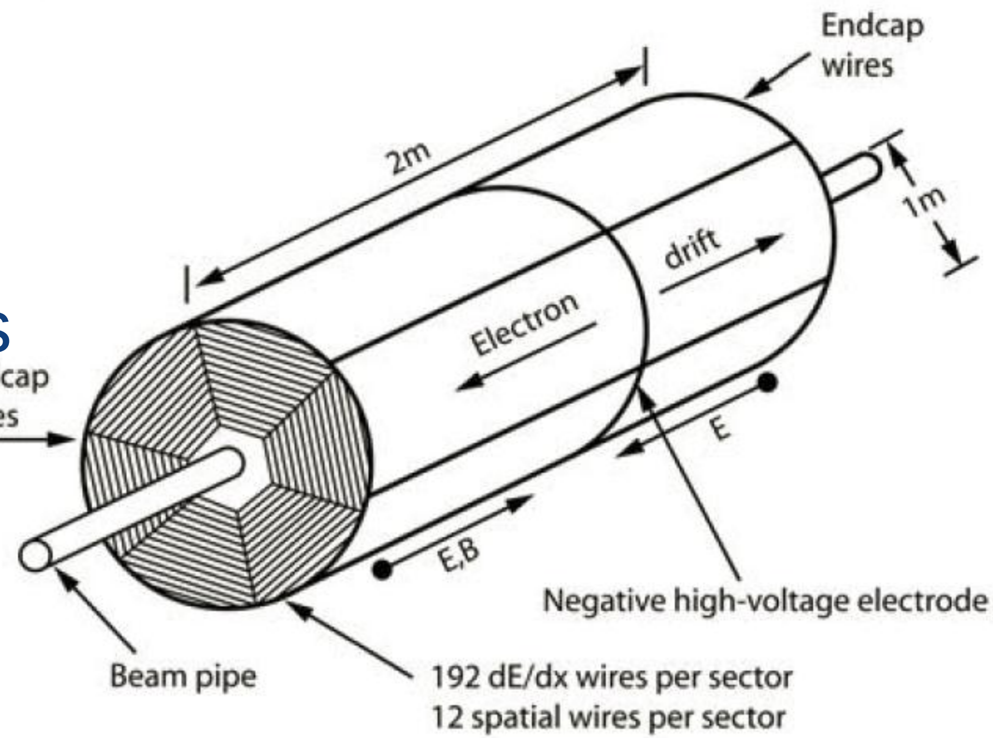
- Create an array in X and an array in Y below.
- Charge deposited above goes to the top array
  and
- Signal induces an image charge on the opposite array



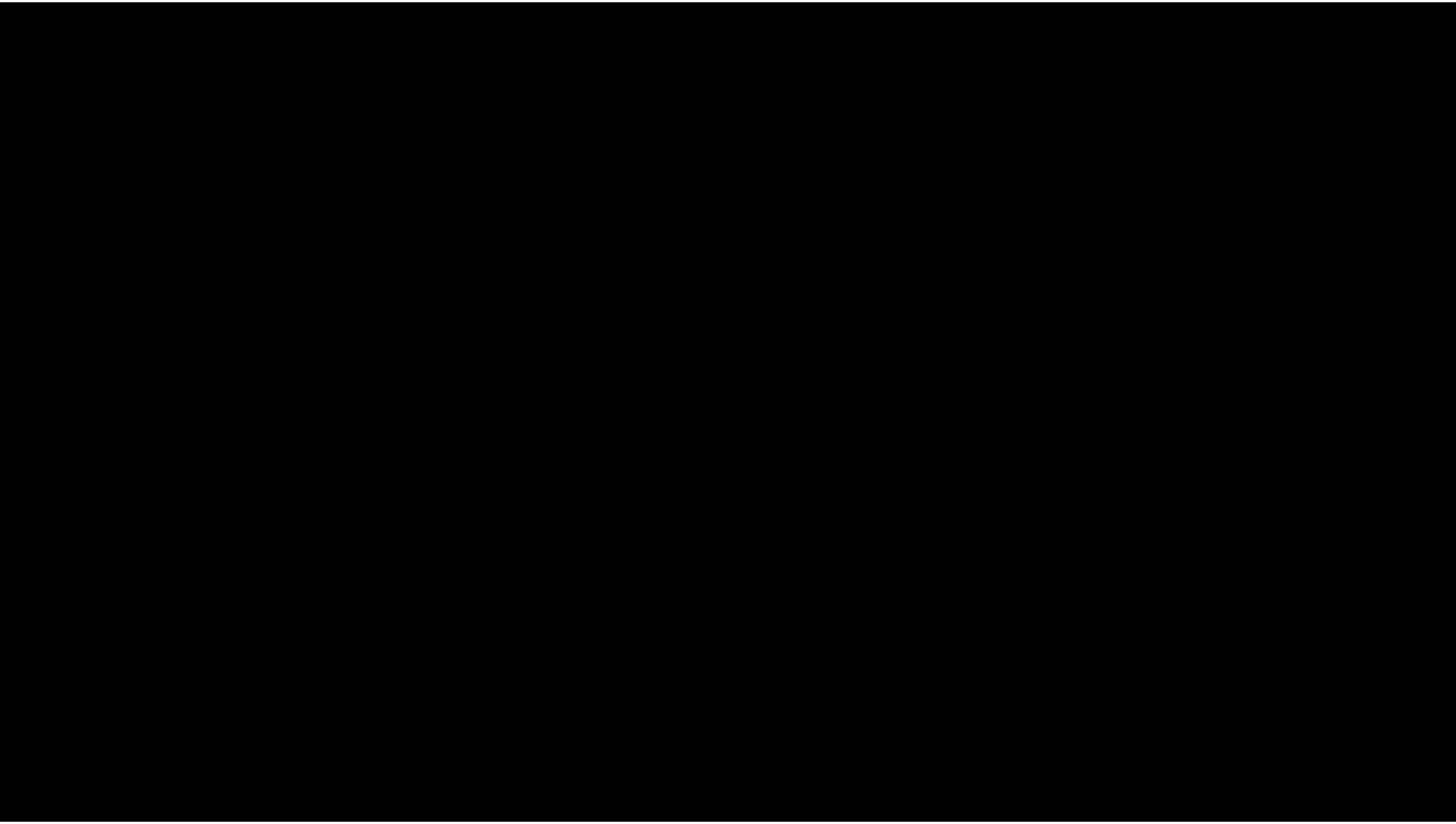


E.G. The Time Projection Chamber (TPC)

- If you know where and when an event starts, you have a trigger.
- Most of the detector is a drift chamber.
- Endcaps are MWPCs
- $\vec{p}$ determined via curvature in $\vec{B}$



TPC movie

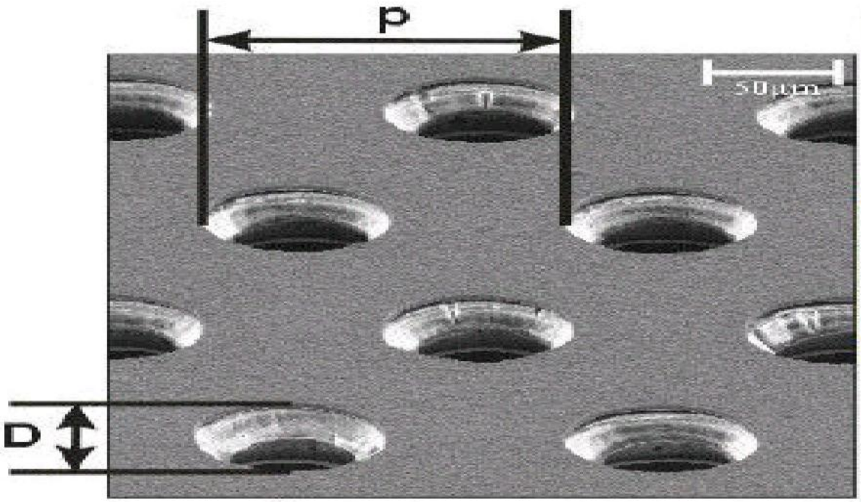


What if you need more gain?

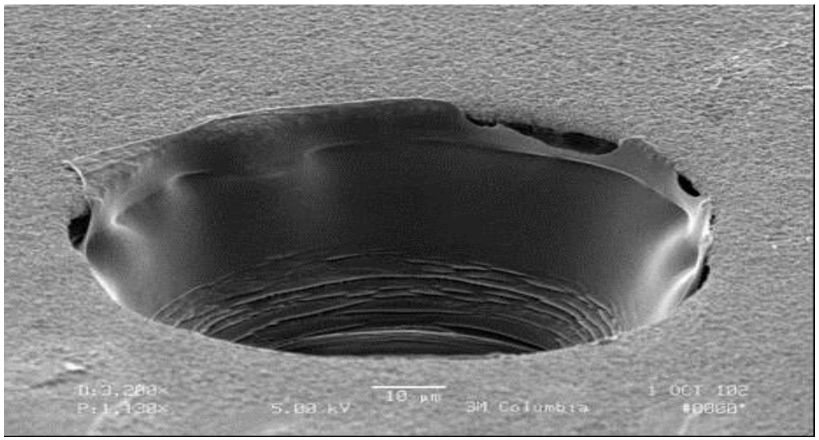
- It's still hard to detect low energy events.
- Proportional tubes/MWPCs have only one stage of charge multiplication.
- Proportional tubes arrays & MWPCs are labor-intensive to assemble.
- What is needed is an array of discreet charge multiplication regions.

What is a GEM?

- **A Gas Electron Multiplier (GEM) is essentially a thin layer of kapton insulation sandwiched between two layers of copper.**
- **Holes are then etched into the assembly.**

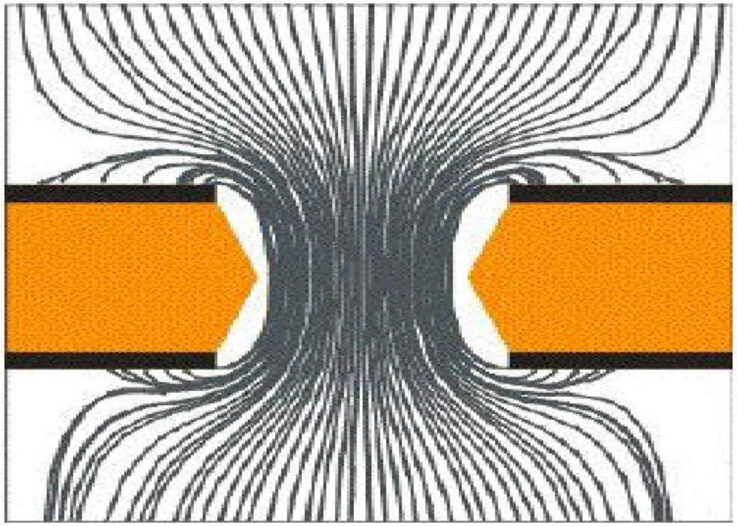


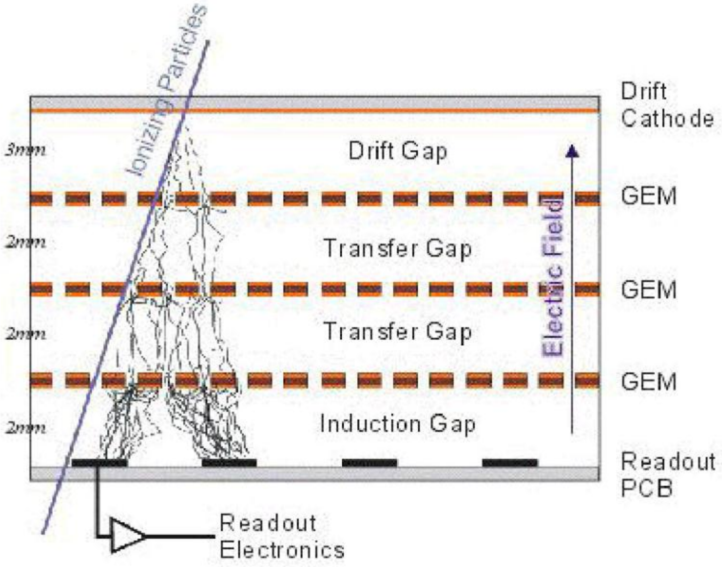
Many holes



A close-up of a single hole

How does it work?

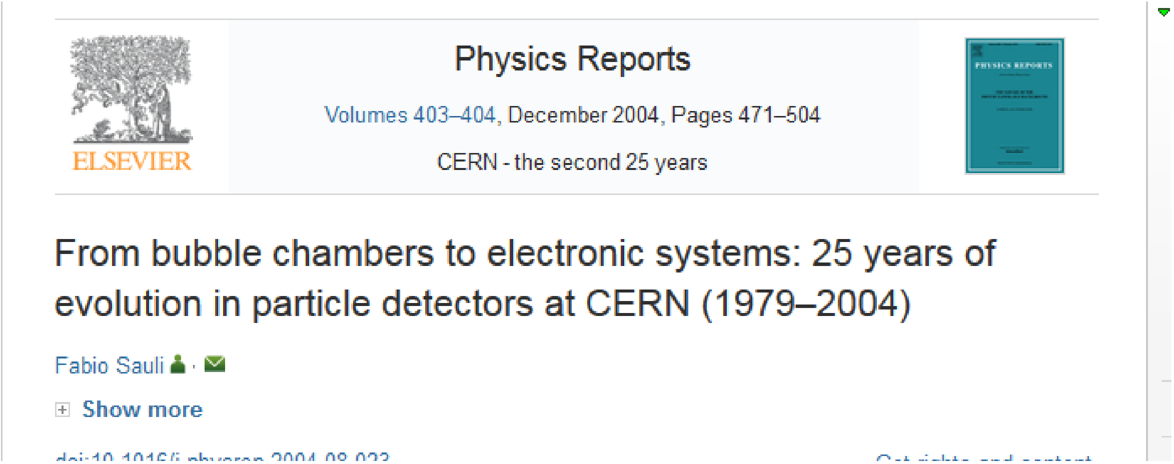




- Behaves like a parallel plate capacitor.
- e^- channeled through holes
- Fields in holes can reach ~120 kV/cm.
- Charge multiplication inside the holes only.
- GEMs can be stacked so multiplication can be done in stages

Additional Material

- The two textbooks
- http://lhcb-muon.web.cern.ch/lhcb-muon/documents/Sauli_77-09.pdf
- http://www.sciencedirect.com/science/article/pii/S0370157304003345#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Fabio Sauli

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Thank you!
Merci

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