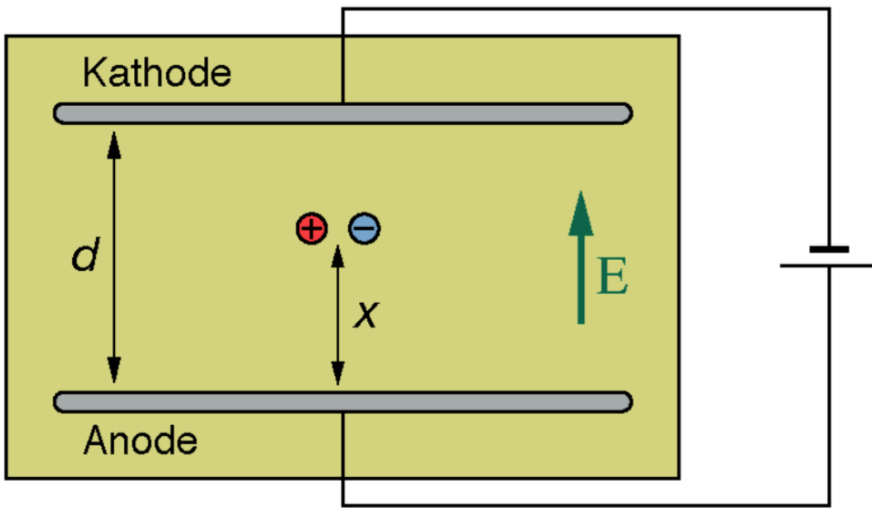
Gas Detectors Overview

Ionization Chambers
Proportional Counters
MWPC
MPGD

Ionization Chambers

Ionization chamber

- An ionization chamber is operated at a voltage which allows full collection of charges, however **below the threshold of secondary ionization** (no amplification).
- When gas between the electrodes is ionized by incident ionizing radiation, e-ion-pairs are created and the resultant positive ions and dissociated electrons move to the electrodes of the opposite polarity under the influence of the electric field.
- For a typical field strength 500 V/cm and typical drift velocities the collection time for 10 cm drift is about 2 µs for e– and 2 ms for the ions.
  - Remember: $\mu^{Ion} = 10^{-3} \ldots 10^{-2}\,\mu^{electrons}$



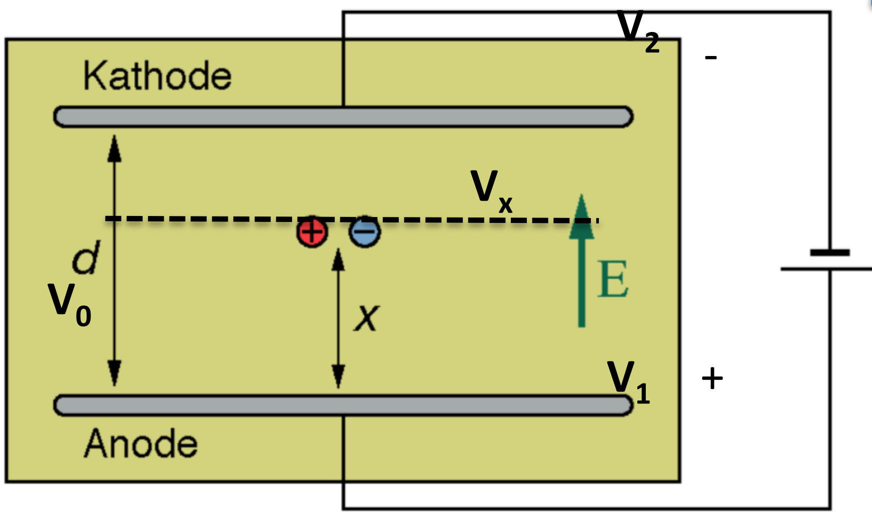
- Ionization charges move in electric field and induce a signal on the electrodes
- Here: planar geometry
  2 electrodes → parallel plate capacitor
- Free charge q moves: electric field does work → capacitor is charged

- It can be computed by considering the system as a capacitor →is energy source to move the charges

Signal Shape

(single e-ion pair)

Q=N*e, N=number of electron-ion pairs



$$dq = Q\frac{dV}{V_0} = Q\frac{dx}{d}$$

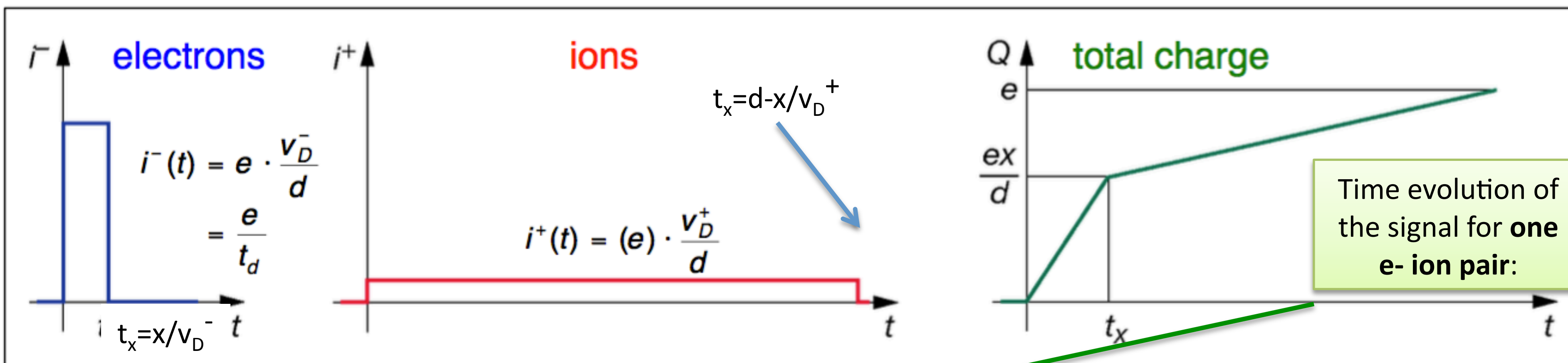
$$i = \frac{dq}{dt} = \frac{Q}{d}\frac{dx}{dt} = \frac{Q}{d}v_D$$

$$q(t) = \frac{Q}{d}v_D t$$

$$q(t) = \frac{Q}{d}v_D^- t^- + \frac{Q}{d}v_D^+ t^+$$

$$q_{Tot} = \frac{Q}{d}v_D^- T^- + \frac{Q}{d}v_D^+ T^+$$

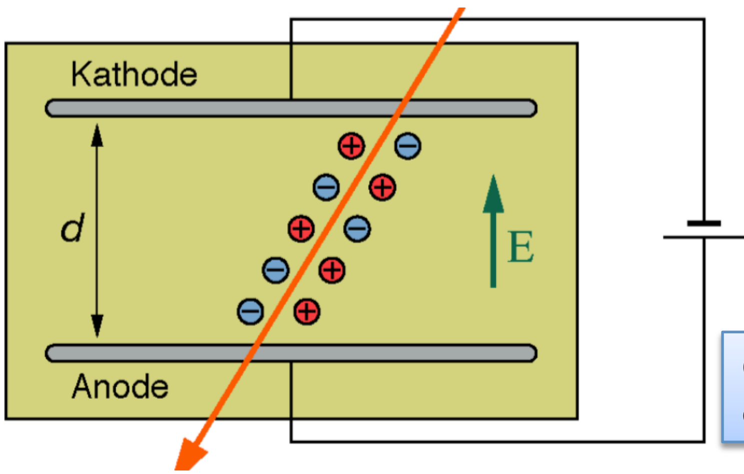
$$q_{Tot} = \frac{Q}{d}v_D^- \frac{x}{d} + \frac{Q}{d}v_D^+ \frac{d-x}{d} = Q$$



Total induced signal (charge) is independent on x

Signal Shape (incoming particle)

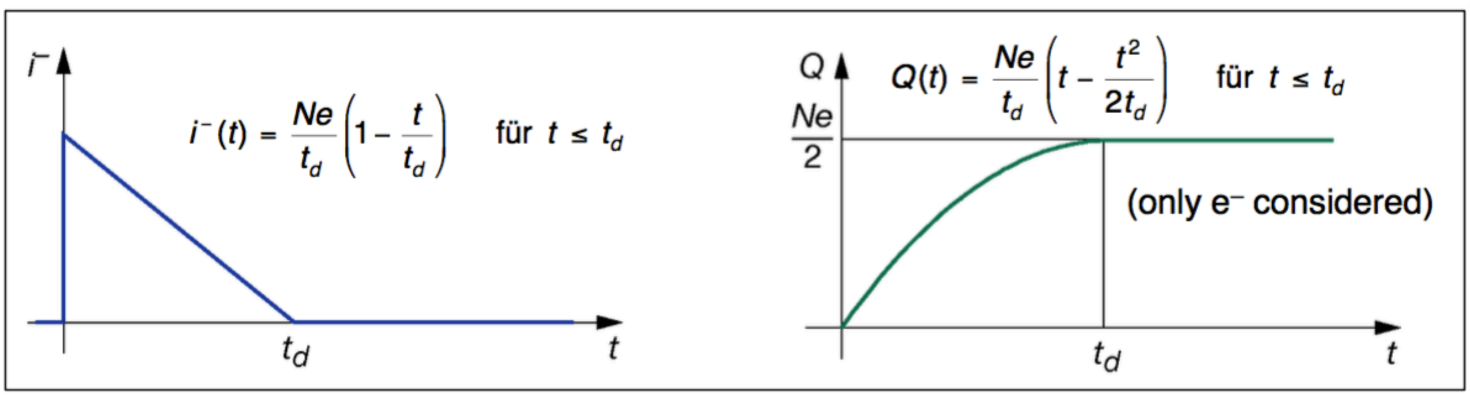
- Planar ionization chambers, continuous charge generation
- Remember:
  - The signal is induced by the movement of e- and ions in the electric field.
  - The fast drifting e- cause a short pulse, whereas the slow moving ions cause a long running current pulse.



$$i = \frac{v_D}{d}\int_0^{x-v_d t} \rho ds = \frac{v_D Q}{d}(1 - \frac{v_D t}{d})$$

$$q(t) = \int_0^t i dt = \frac{v_D Q}{d} t(1 - \frac{v_D t}{2d})$$

Q=N*e, N=number of electron-ion pairs



Time evolution of the signal for **continuous charge generation** (only drift of e- considered):

Limit of ionization chamber

- Output signal is a current that is read by an electrometer
- This current is proportional to the charge collected, given by the primary ionization of the incident radiation into the filling gas
- **Signals in ionization chambers are generally VERY SMALL**
- Example: 1 MeV particle stops in gas

$$
\begin{aligned}
N_e &\simeq \frac{10^6 \text{ eV}}{35 \text{ eV}} \simeq 3 \cdot 10^4 \\
C &\simeq 100 \text{ pF} \\
\Rightarrow \Delta U_{max} &= \frac{3 \cdot 10^4 \cdot 1.6 \cdot 10^{-19} \text{ C}}{10^{-10} \text{ F}} \\
&= 4.6 \cdot 10^{-5} \text{ V}
\end{aligned}
$$

- They need very sensitive, low-noise pre-amplifiers
- The electrometer must be capable of measuring the very small output current which is in the region of femtoamperes to picoamperes, depending on the chamber design, radiation dose and applied voltage.

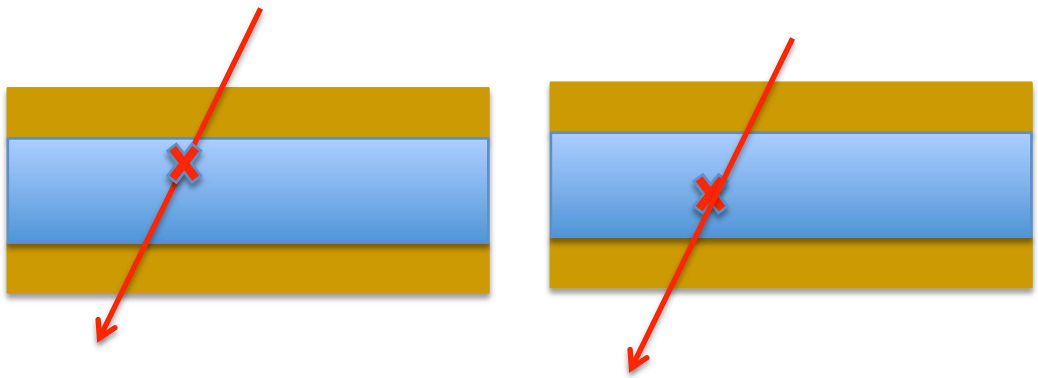
Usage

- An ionization chamber measures the charge from the number of ion pairs created within a gas caused by incident radiation.
- Each ion pair created deposits or removes a small electric charge to or from an electrode, such that the accumulated charge is proportional to the number of ion pairs created, and hence the radiation dose. This continual generation of charge produces an ionization current, which is a measure of the *total* ionizing dose entering the chamber.
  - However, the chamber cannot discriminate between radiation types (beta or gamma) and cannot produce an energy spectrum of radiation.
- Applications:
  - nuclear industry as they provide an output that is proportional to radiation dose
  - Smoke detectors
  - **Medical radiation measurement (radiotherapy)** ensure that the dose delivered from a therapy unit or radiopharmaceutical is what is intended

Proportional counter

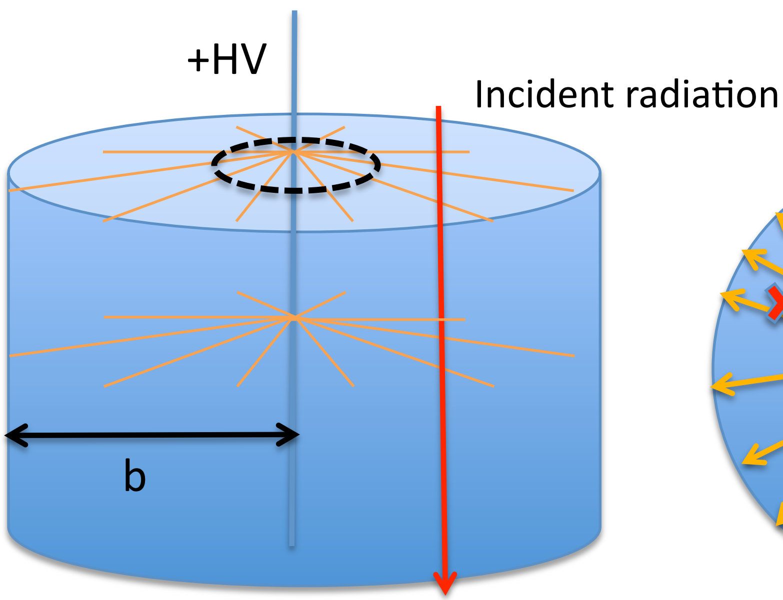
Proportional Counter

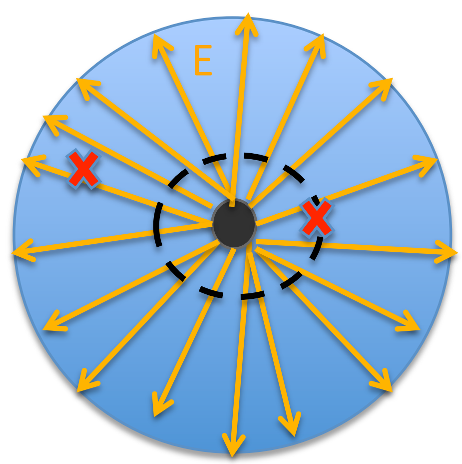
- Plane electrodes configuration



The avalanche starting can happen at different position (depending on the position of the first ionization) → not an optimal configuration if one wants perform energy loss measurement (lack of proportionality with the collected charge)

- Cylindrical configuration

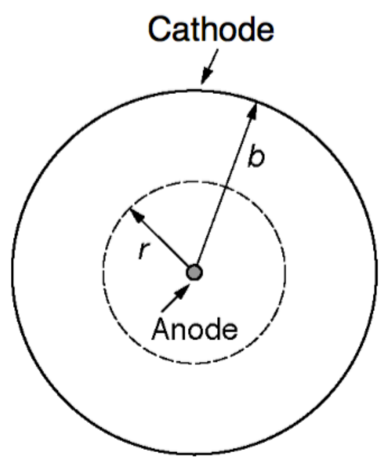




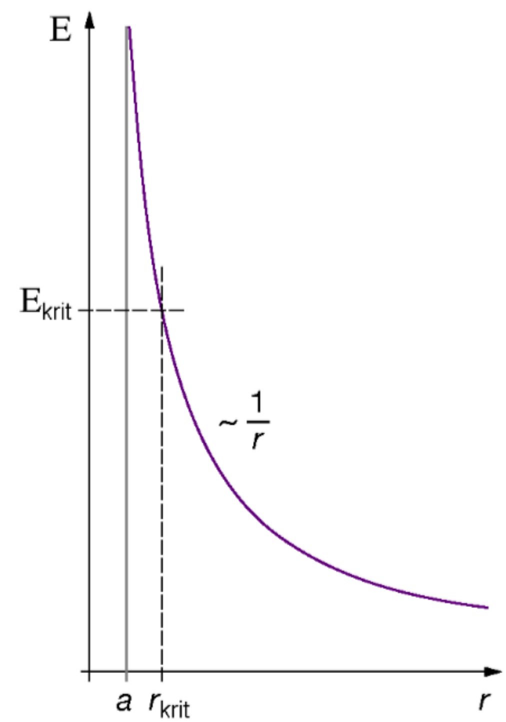
Take cylindrical geometry with anode represented by a very thin wire:
E close to wire is very large ($E \propto 1/r$)
All the avalanche will start at the same distance r from the anode wire→ this will avoid energy fluactuation with the position and preserve the proportionality with the energy loss

Gas Proportional Counter Operation

- Operates at **very high voltage,** in the second ionization or “avalanche” region
- Signal amplification **through secondary ionization**
- The amplification factor in gas detectors operating in the proportional mode is constant → signal is proportional to the primary ionization
- Amplification factors in proportional mode of 10^4–10^6
- Limit of the proportional mode is reached when electrons produced by the photo effect are no longer negligible
  - Second Townsend coefficient, effects driven by the electrons extract from the wall of the counter
- The effect of photons is reduced with admixtures of a “quenching” gas (e.g. $CH4$, $CO2$). These gases absorb UV photons.
- Typical geometry: cylindrical cathode with thin central anode wire.
  - Electric field in vicinity of the wire ~$1/r$, at $r \leq r_c$ field strength high enough to cause secondary ionization,
  - wire diameter 20 - 100 µm.

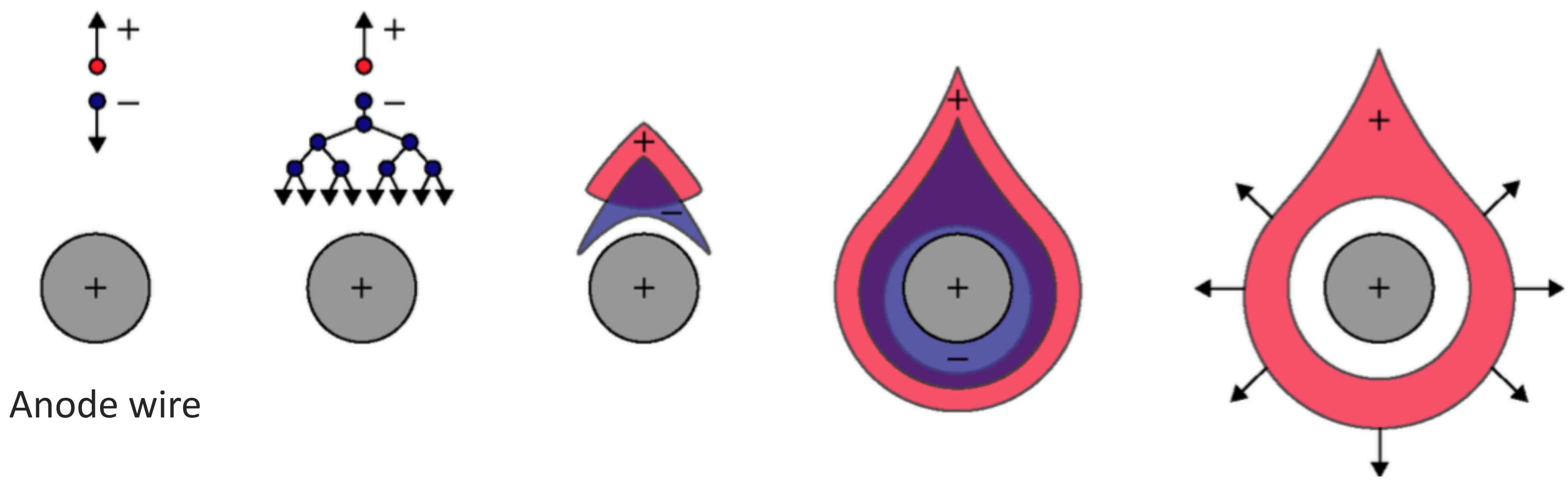


a … radius anode wire
b … radius cathode



Amplification process around a wire

- Electrons produced by the primary particle drift towards the anode wire. They reach the area of high fields.
- As soon as the field is larger than E_c secondary ionization starts. A charge avalanche develops in the vicinity of the anode wire.
- The electrons drift quickly to the anode wire, whereas the positive ions slowly drift away towards the cathode.
- Notice→drop shape perpendiculare to the anode wire, with the ions in the back of the avalanche



Avalanche development

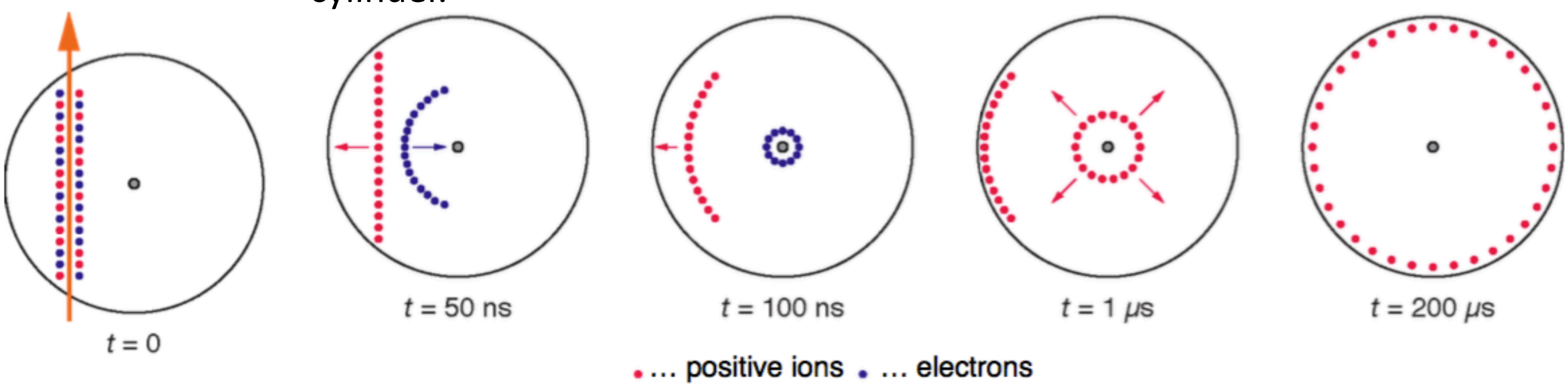
Charged particle produces pri-mary ionization along the track

Primary e- drift quickly to the anode wire. Ions drift much slower to the cathode cylinder.

The primary e- reach the region of high field and produce secondary ionization charge carrier avalanche around the wire. The primary ions continue to drift to the cathode.

The ions produced in the secondary ionization drift also to the cathode. The secondary e- are generated close to the anode.

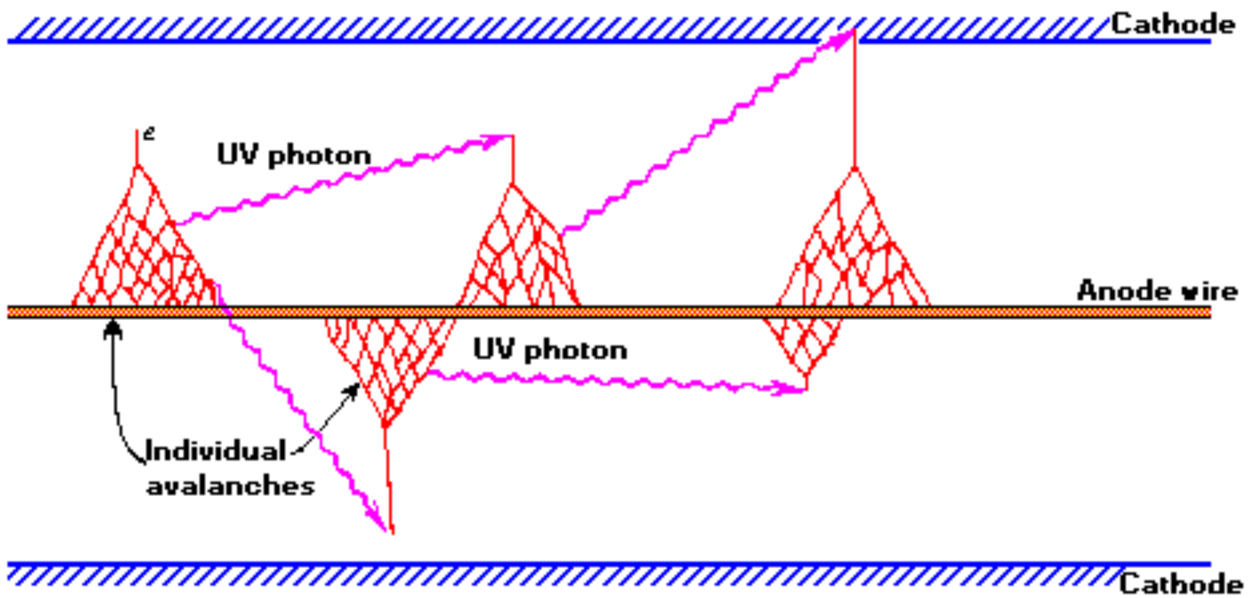
Finally also the secondary ions reach the cathode.



The induced signal is by far dominated by the movement of the ions!

Geiger-Müller Counter

- Is the electric field large enough that $\gamma A \approx 1$ the detector is operating in the Geiger-Müller mode.
- The UV photons are spreading transversal to the field and create photoelectrons in the whole gas volume. The discharge is no longer localized.
- The produced total charge is independent from the primary ionization
  - The charge depends only on the capacitance of the counter and the applied voltage.
- Gas amplification in Geiger-Müller mode is between 10^8 und 10^{10}



Discharge quenching

- Some UV photons can be created by de-exciting gas atoms→ can extract photo-electrons from the walls→Avalanches are created everywhere.
- The e- disappear quickly, whereas the **positive ions create a plasma** tube (space charge) along the anode wire
- The space charge **reduce field around the wire** and prevent e- from secondary ionisation
  - E field decrease, the gain decrease→this effect increse with increasing incident particle rates
- ions drift slowly to the cathode (~ 1 ms), where they may create secondary e- avalanche production continues.
- **Discharge has to be stopped, various methods are used:**
  - Charging resistor *R* reducing the high voltage to *U0–IR*. Time constant *RC* .must be long enough to allow all ions to reach the cathode detector → dead time of ~10 ms.
  - Change of polarity for a short time ions created close to the anode wire are then absorbed quickly by the negative polarity of the wire.
  - Self clearing using admixture of quencher gas, e.g. methane (CH_4), ethane (C_2H_6), isobutane (iC_4H_{10}), ethanol (C_2H_5OH) methylal ($CH_2(OCH_3)_2$). The absorption of UV photons reduces their range to few hundred µm close to the anode wire lower *R* possible shorter dead time ~ 1 µs

Signal in proportional counters

- A simple wire chamber:
  Gas filled cylinder with an anode wire. The cylinder surface is the cathode.
- The applied voltage *V* creates
  an electric field E. For this geometry the field is:

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

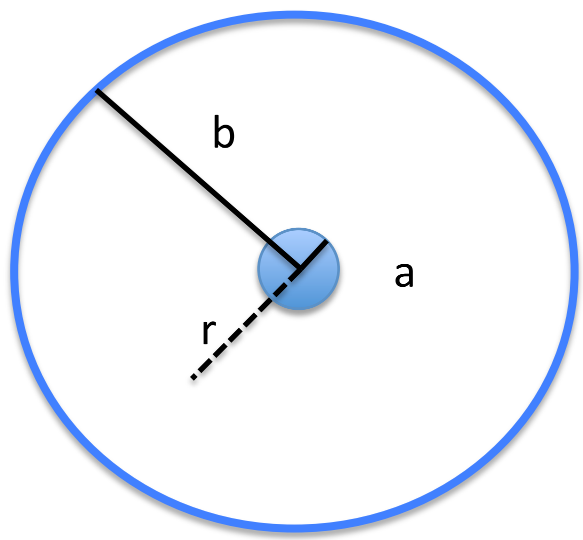
r … distance from the wire
a … radius of anode wire
b … radius of cathode cylinder

$$C = \frac{2\pi\varepsilon}{\lg\left(\frac{b}{a}\right)}$$

Capacitance per unit lenght

$$E(r) = \frac{CV_0}{2\pi\varepsilon}\frac{1}{r}$$

$$\varphi(r) = -\frac{CV_0}{2\pi\varepsilon}\log\left(\frac{r}{a}\right)$$



Signal in proportional counters

- U = qϕ(r) → dU = q(dϕ(r)/dr)dr **Energy of a charge moved in a electric potential**
- U = 1/2 LCV_0^2 **Total energy accumulated in a capacitor of lenght L**

If the power supply reaction is slow

$$dU = LCV_0 dV = q\frac{d\varphi(r)}{dr}dr \rightarrow dV = \frac{q}{LCV_0}\frac{d\varphi(r)}{dr}dr$$

Signal induced by electrons drift toward the anode wire

$$V^- = \frac{-q}{LCV_0}\int_{a+r'}^{a}\frac{d\varphi}{dr}dr = \frac{-q}{2\pi\varepsilon L}\lg\left(\frac{a+r'}{a}\right)$$

Signal induced by Ions drift toward the cathode walls

$$V^+ = \frac{q}{LCV_0}\int_{a+r'}^{b}\frac{d\varphi}{dr}dr = \frac{-q}{2\pi\varepsilon L}\lg\left(\frac{b}{a+r'}\right)$$

$$\frac{V^-}{V^+} = \frac{\lg\frac{a+r'}{a}}{\lg\frac{b}{a+r'}}$$

a = 10 µm,
b = 10 mm
r' = 10 µm

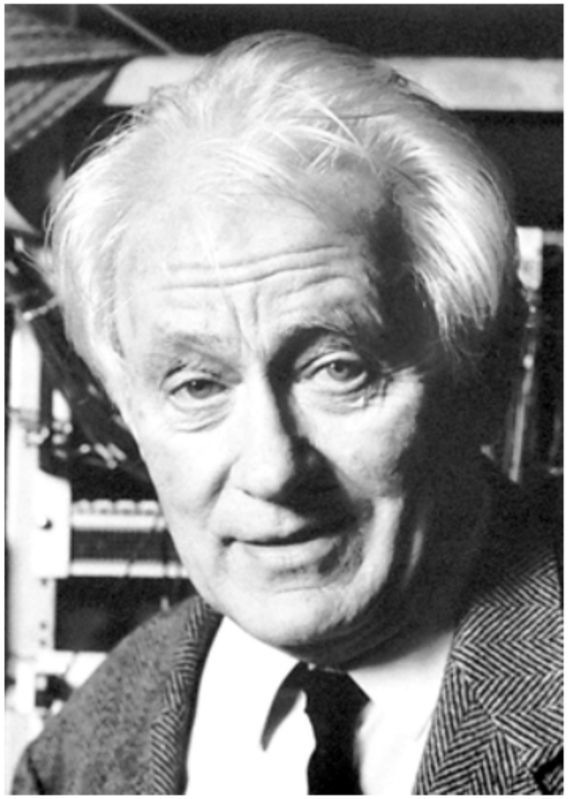
$V^- \sim 1\% V^+$

Multiwire Proportional Chambers MWPC

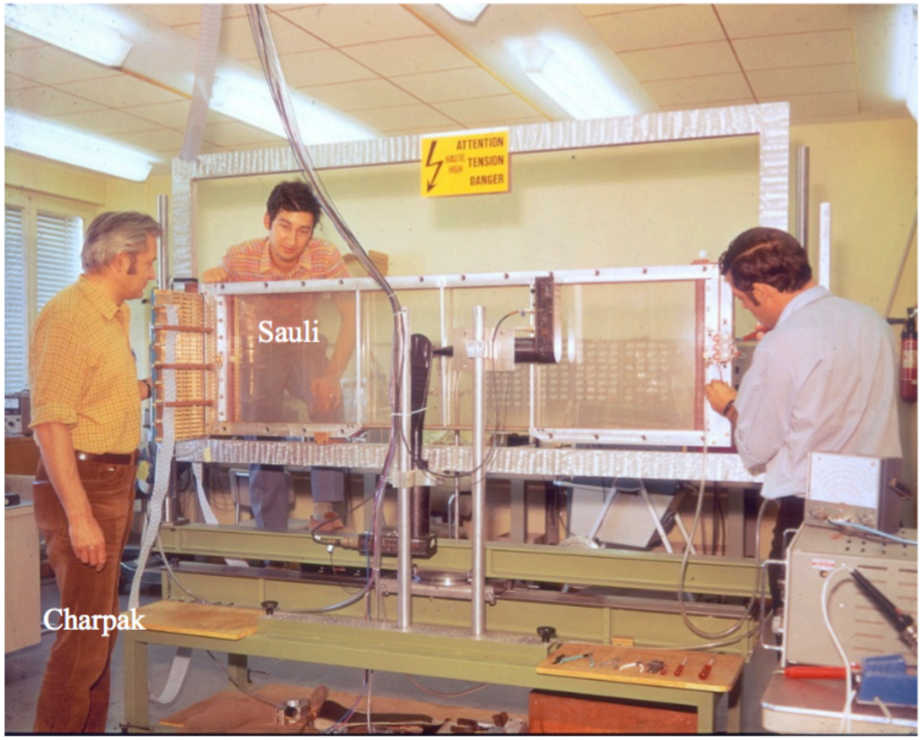
A breakthrough in the technique for exploring the innermost parts of matter

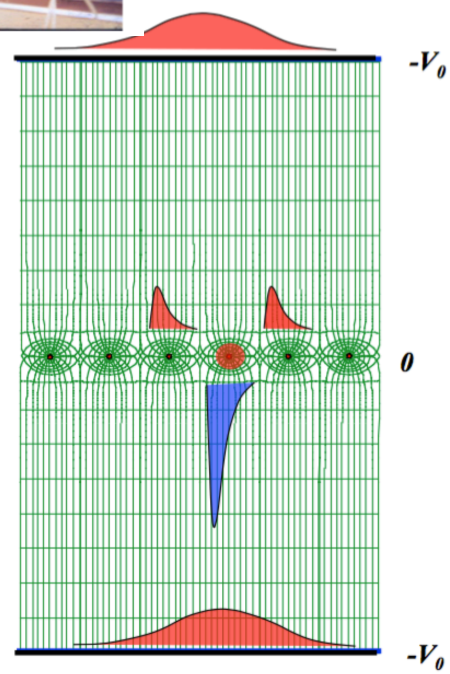
Press release of the Nobel Prize in Physics 1992

- Particle detectors in the first half of the 20th century:
  - cloud chambers, scintillation counters, photo multiplier tubes, flash tubes, proportional counters, Geiger-Müller tubes, ...
  - optical and (later) electronic read-out of detectors
  - in the 1950s and ’60s: mainly bubble and spark chambers
    - Difficult for reading and storing data, long dead-time, small rate capability



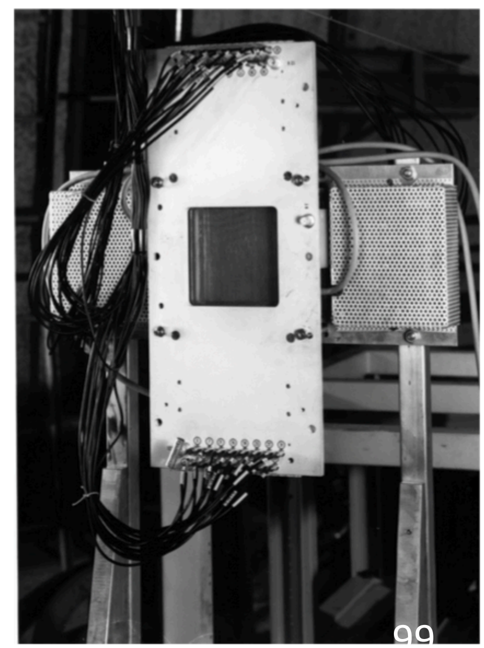
- MWPC was the first full electronic detector!
- MWPC developed 1968 by Georges Charpak and others (R. Bouclier, F. Sauli, ...).
- The Nobel Prize in Physics 1992 was awarded to Georges Charpak *"for his invention and development of particle detectors, in particular the multiwire proportional chamber"*.
- Charpak published the paper in 1968:
  - “The use of multiwire proportional counters to select and localize charged particles”
- in the following years, > 200 papers, many on multiwire proportional chambers and their developments





G. Charpak et al, Nucl. Instr. and Meth. 62(1968)262

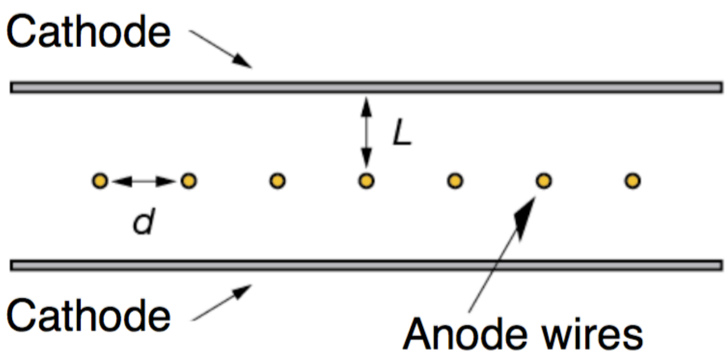
FIRST MWPC (1968)

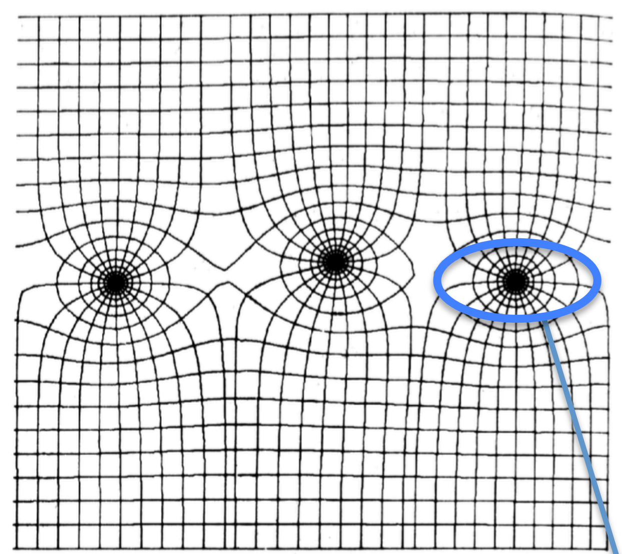


FABIO SAULI - XVII SEMINARIO NAZIONALE di FISICA NUCLEARE E SUBNUCLEARE – OTRANTO 4-11 GIUGNO 2015

The basic concept

- Geometry of a MWPC: planar arrangement of proportional counters without walls
  - parallel anode wires (usually gold-plated tungsten) stretched between two cathode planes
  - cathodes can either be made of wire planes or conducting foil



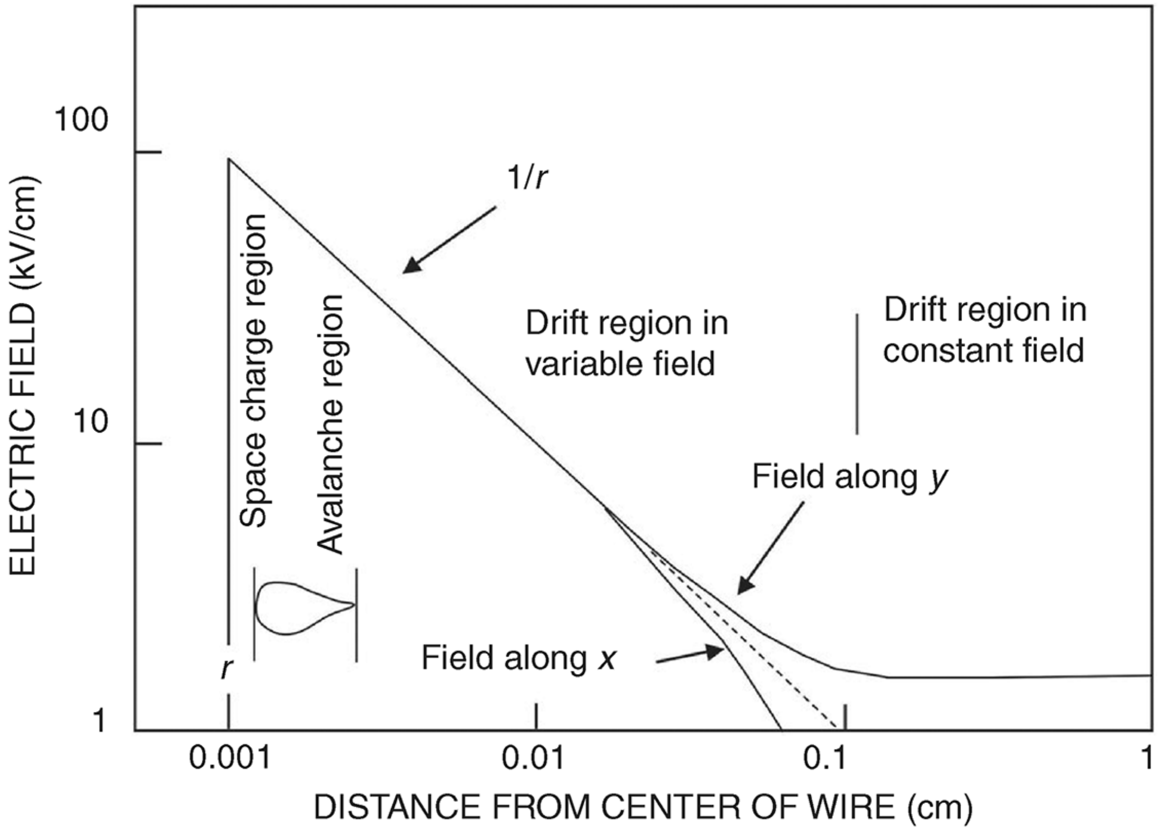


- Diameter of anode wires 10 – 50 µm
- Distances between wires 2 – 5 mm
- HV ~1-5kV
- Each wire connected to an amplifier
- Typical gas amplification in MWPC is 10^5
- Max. particle rate ~10 kHz/mm2

Radial electric field as in cylindrical proportional chambers in the vicinity of the anode wire

Every wire acts as an independent proportional counter!
→This opens up the possibility to build larger volumes and perform the tracking

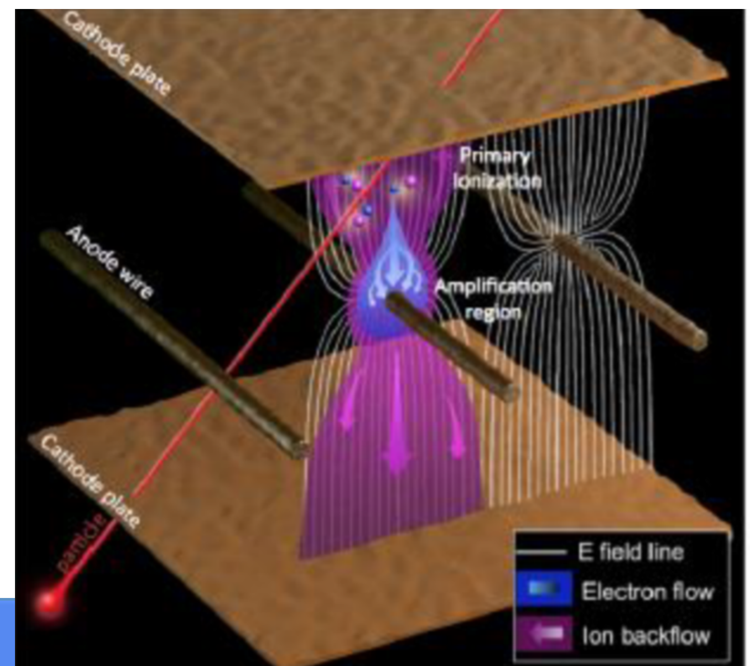
Electric field and avalanche development



$$V(x,y) = -\frac{CV}{4\pi\varepsilon}\lg\left[4\left(\sin^2\frac{\pi x}{s} + \sinh^2\frac{\pi y}{s}\right)\right]$$

$$C = \frac{2\pi\varepsilon}{\frac{\pi L}{s} - \lg\frac{\pi d}{s}}$$

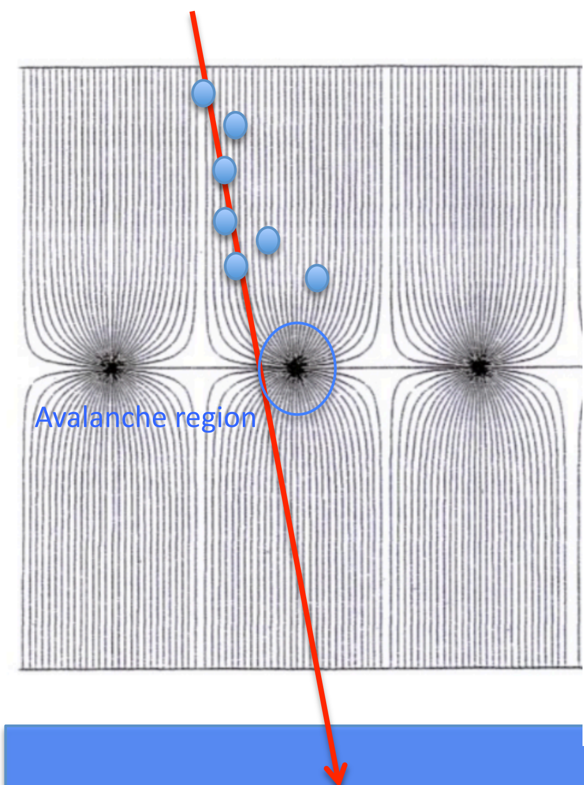
Note that since a<<s, the capacitance is always smaller than the one of the double layer condeser with the same surfate

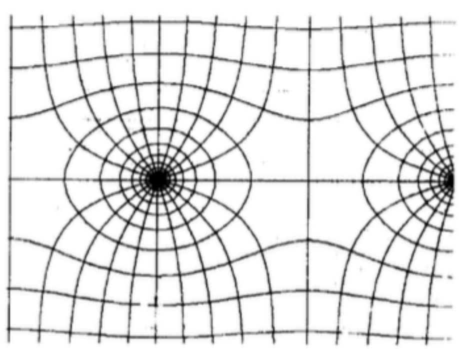


MWPC: The basic concept

The signal formation on a single wire of a MWPC is essentially the same as in a proportional counter:

- electrons from gas ionisation drift to anode wires
- gas amplification close to wire (E~1/r) → avalanche formation
- only ends when electrons reach wire, or when space charge from positive ions "counters" electric field
- drift of electrons and mainly ions induces signal on both anode and cathodes
- **→ position measurement possible**

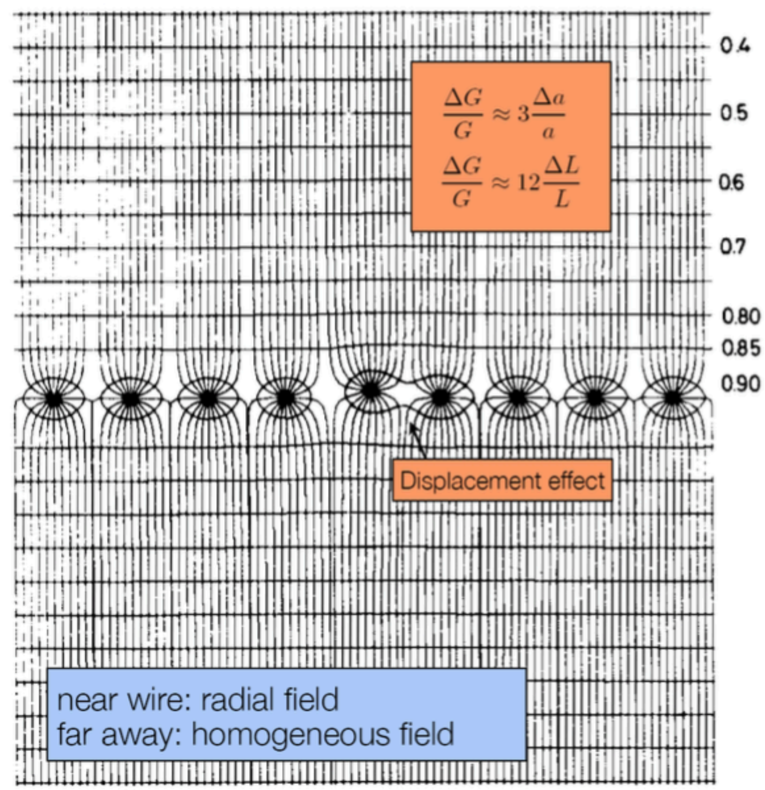




Small wire displacements reduce field quality ...

Need high mechanical precision both for geometry and wire tension ...

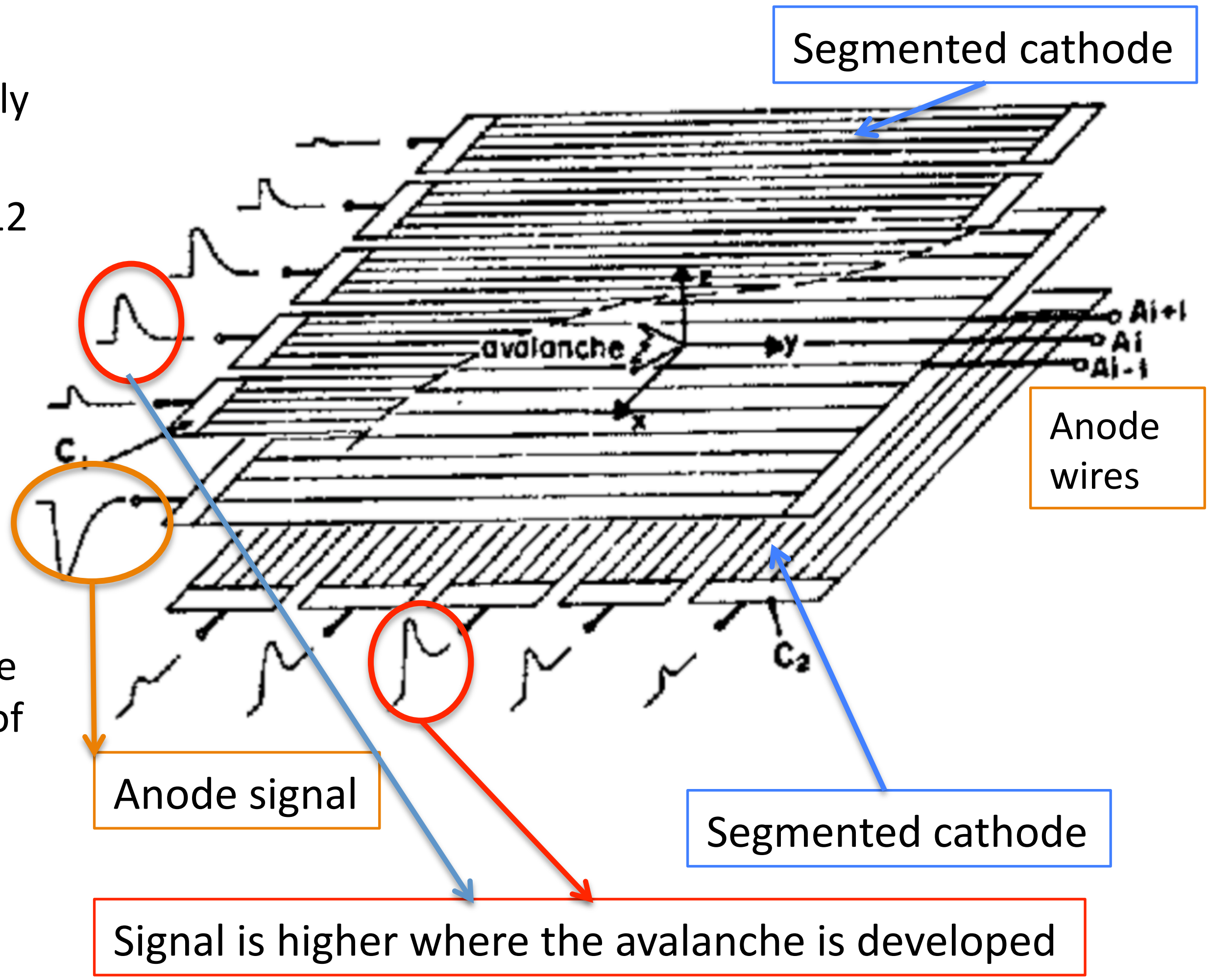
[electrostatics and gravitation; wire sag]



Readout and spatial resolution

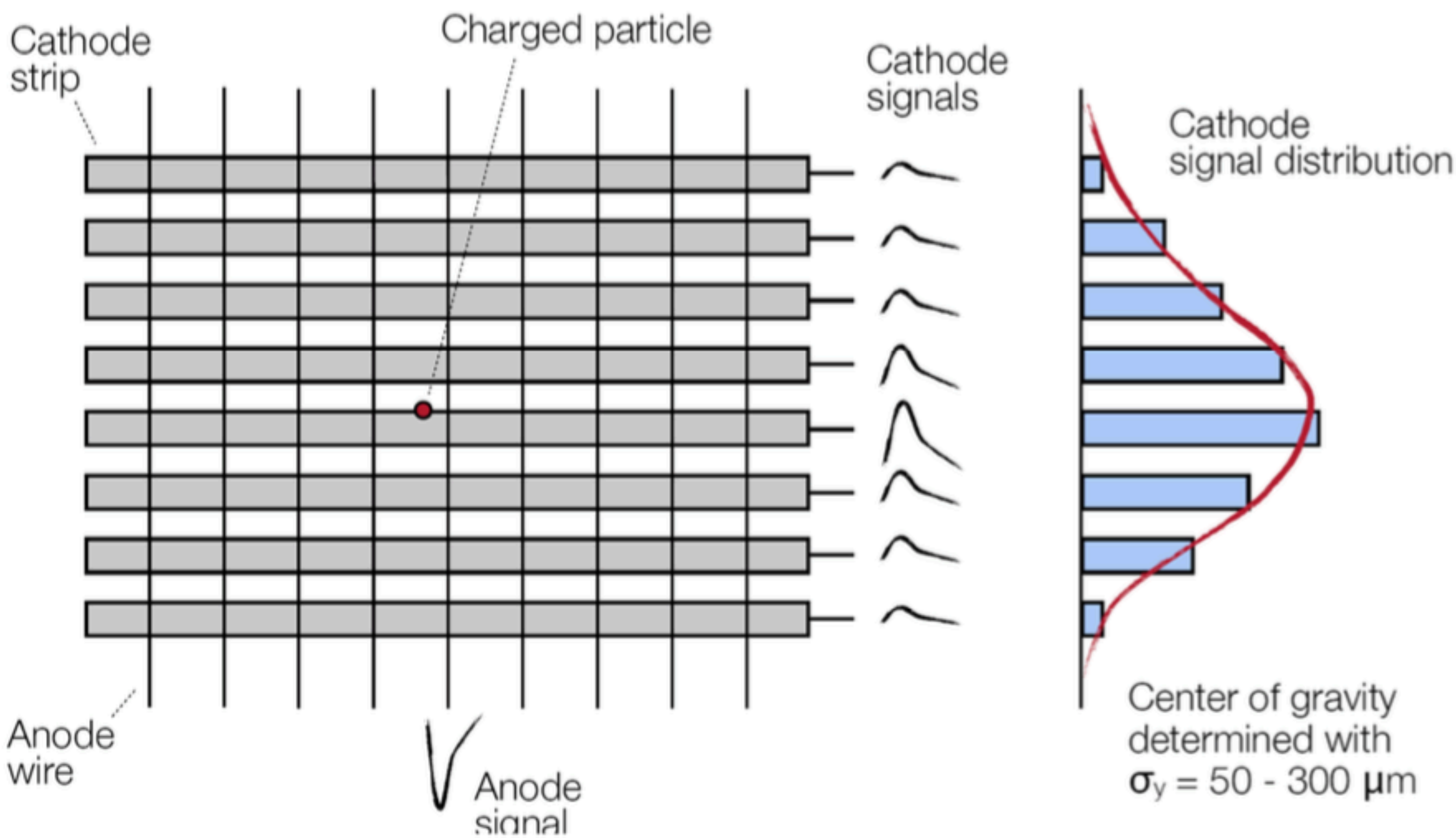
- Each wire is read indepentently with preamp integrated in the chamber frame
- Signal on wire closest to avalanche is negative, signals on neighbouring wires are positive

- Electronics read out only anode wire with negative signal but: only information about closest wire
- Resolution is limited to $\delta x = d/\sqrt{12}$
  - for d =2mm: δx =577 m
  - only 1-dimensional and rather imprecise
- **→ also use cathode read-out**
  - read-out not only on anode wires, but also on cathodes
  - segementation of cathodes
- → charge sharing allows for more precise measurement of centre of gravity
- resolution of y coordinate (along the wire) of ≥ 50 µm possible



Readout and spatial resolution

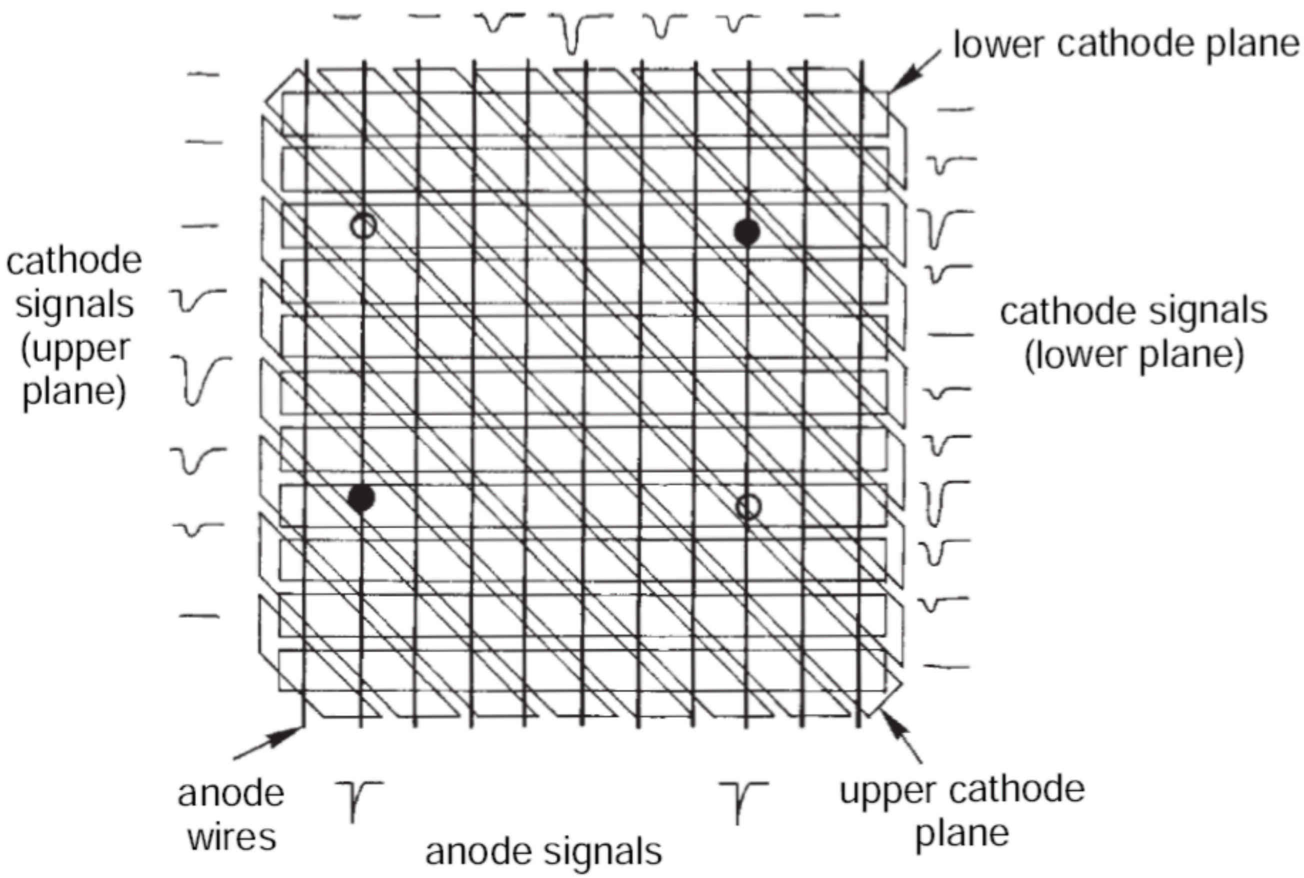
- Perpendicular to wire: since information comes only from closest wire → $\delta x = \mathbf{d/\sqrt{12}}$ = e.g. 577 μm for d = 2 mm not quite so precise!
- Then: segment the cathode in strips: the induced signal is spread over more strips. Using the **center of gravity** of the signal (charge sharing), high precision of 50 – 300 μm can be reached



2D-MWPC

- ● true hit
- ○ ghost hit

When 2 particles cross the MWPC, with only one orientation of the cathode strips we are left with the ambiguity of the combinations of signals
→ 4 possibilities: 2 real, 2 ghosts



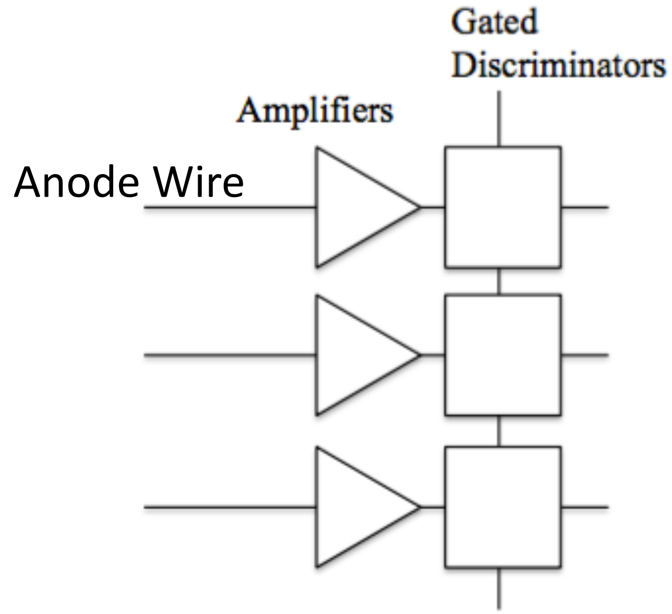
Possible solution: use different orientation of strips on the second cathode plane

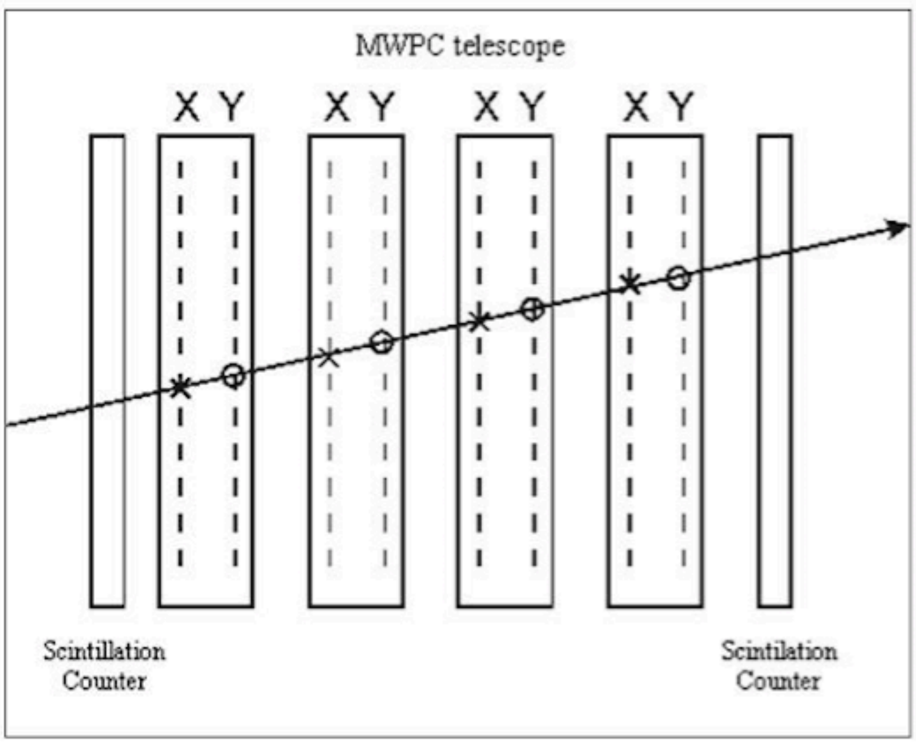
For high multiplicities and high hit density: segment the **cathode in pads for a 2-dimensional measurement**

Disadvantage: number of readout channels grows quadratically (expensive!)

Tracking with MWPC

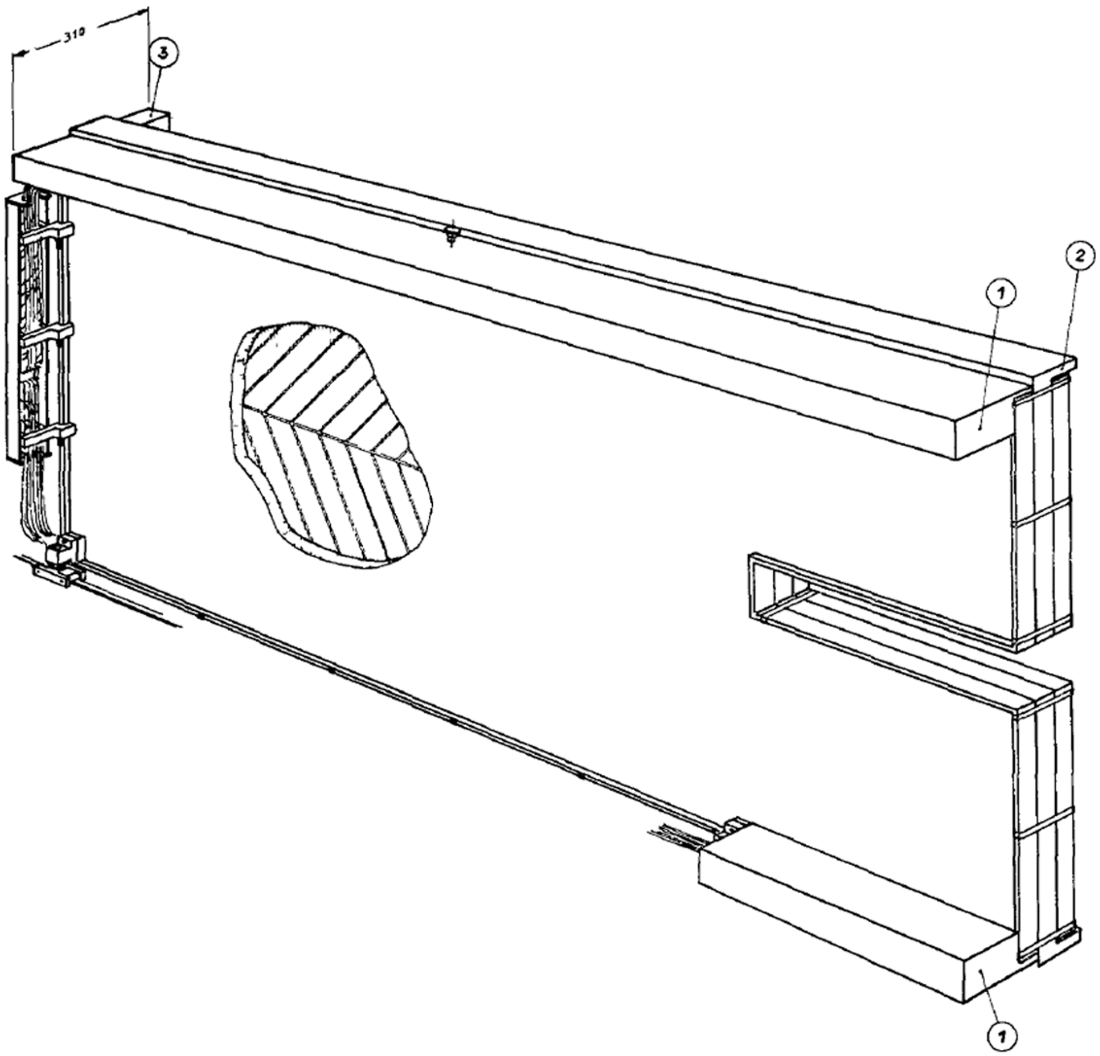
- Read each channel independetly with amplifier + discriminator with a time gate

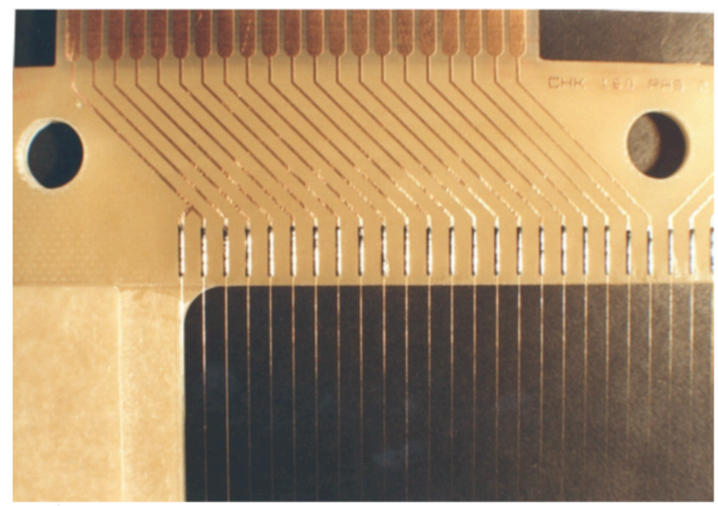




- One can use a second MWPC, whose anode are oriented perpendicularly to the first one, to build a telescope.
- Reading the position of the wires allow the reconstruction of the track

The MWPC mechanics





Wire stability

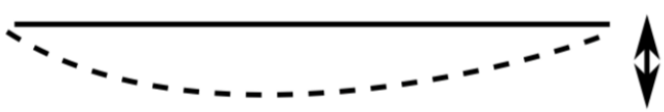
Can the resolution be improved by mounting the wires closer to each other? Practical difficulty in stretching wires precisely, closer than 1 mm:

- Electrostatic repulsion between anode wires (particularly for long wires) taht must be compensated by the mechanical tension tension
  - → can lead to "staggering" → puts limit on *d* and wire length *l*
- To achieve stability, tension on wires must be larger than a given value

$$T \geq \left(\frac{U_0 \cdot l}{d}\right)^2 \cdot 4\pi\epsilon_0 \left[\frac{1}{2\left(\frac{\pi L}{d} - \frac{2\pi r_i}{d}\right)}\right]^2$$

- l =1m,d =2mm, ri =15µm, L=10mm, U0 =5kV →T ≈0.5N

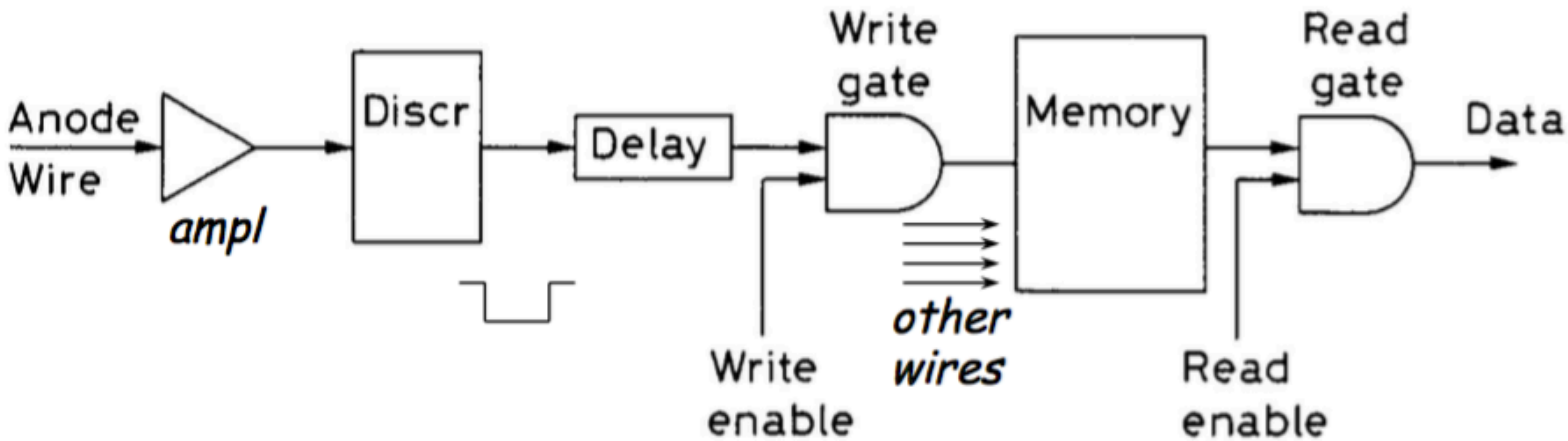
- → need a stable framework!
- **Gravitational sagging→attarction of the cathode toward the anoide**
- horizontal wires will show a sag f under their weight



$$f = \frac{\pi r_i^2}{8} \rho g \frac{l^2}{T} = \frac{mlg}{8T}$$

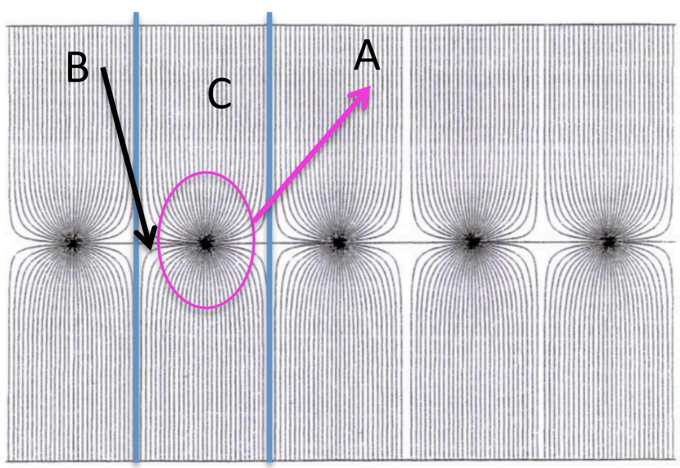
- same example as before: → f ≈ 34 µm → the electric field change → the gain change

Readout


Anode
Wire
ampl
Discr
Delay
Write
gate
Memory
Read
gate
Data
other
wires
Write
enable
Read
enable

Gas Choice and Signal timing

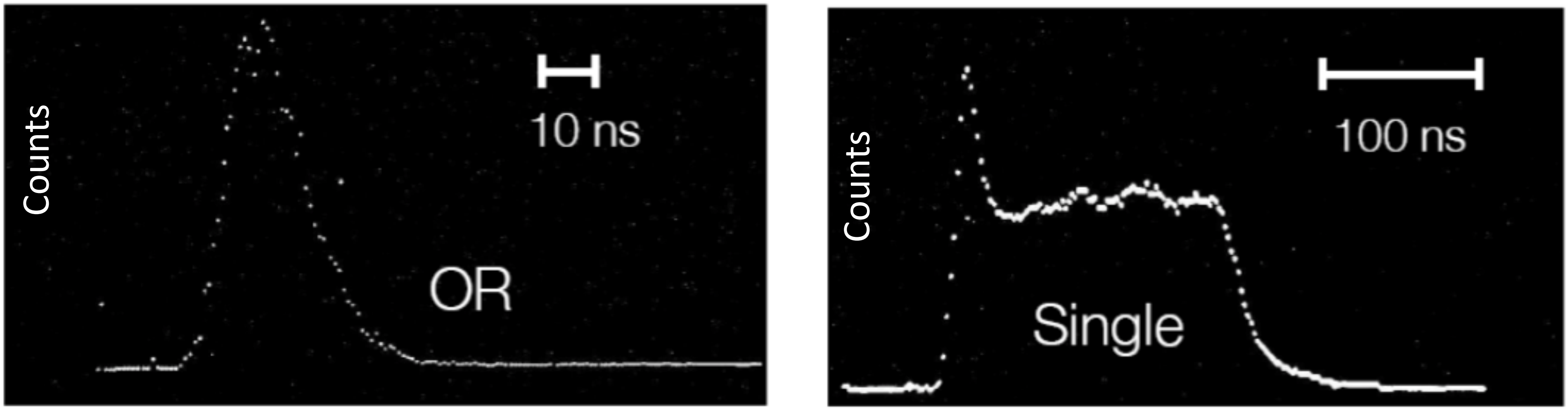
- The suitable gas for a MWPC is identical to those used for the proportional counters
  - Magic Gas: Ar/Isobutane/Freon (75/24.5/0.5) →Gain 10^7
  - Signal is independent to the particle energy! → The large signal amplitude simplifies the readout electronics
  - The gas gain is so high that the avalanche can start before the vicinity of the anode wire→ the electrons produced have longer path to be covered→ the contribution of the electrons to the signal shape become important
  - The electrons are faster than ions → the signal can be faster



- The timing properties of proportional chambers are determined by the collection time of the electrons produced by the ionizing tracks
- The structure of the electric field allow the separation of 3 regions
  - Electrons released in region A are quickly collected
  - Electrons created in region B create a tail in the time distribution
  - Electrons created in region C drift to the anode where they are amplified and collected with a delay correnspondent to the drift time.

Signal timing

Time Resolution of the chamber: gate width necessary for the electronics to record efficiently the signal



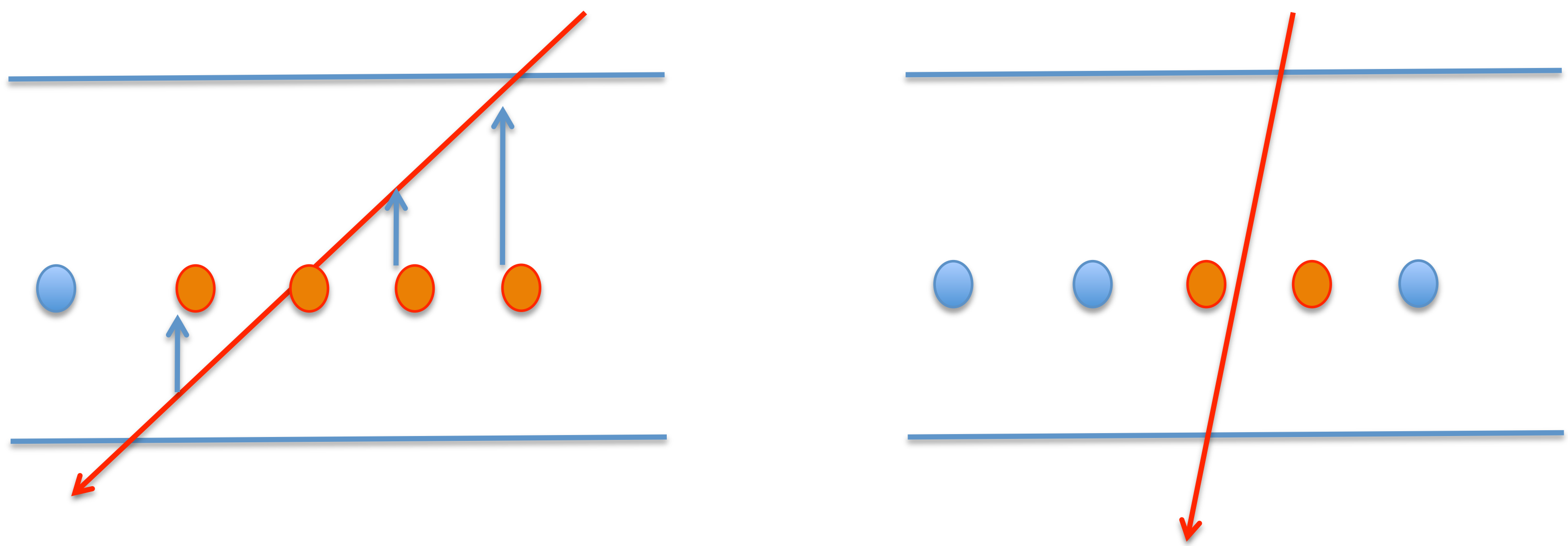
Time

- Left: Time distribution measured for the OR of all channels→ aech track crosses region A or B of at least one wire → it correnspond to the intrinsec time resolution of the detector
  - Around 10 ns (for 2mm wire spacing→ 1mmamplitude for region B)

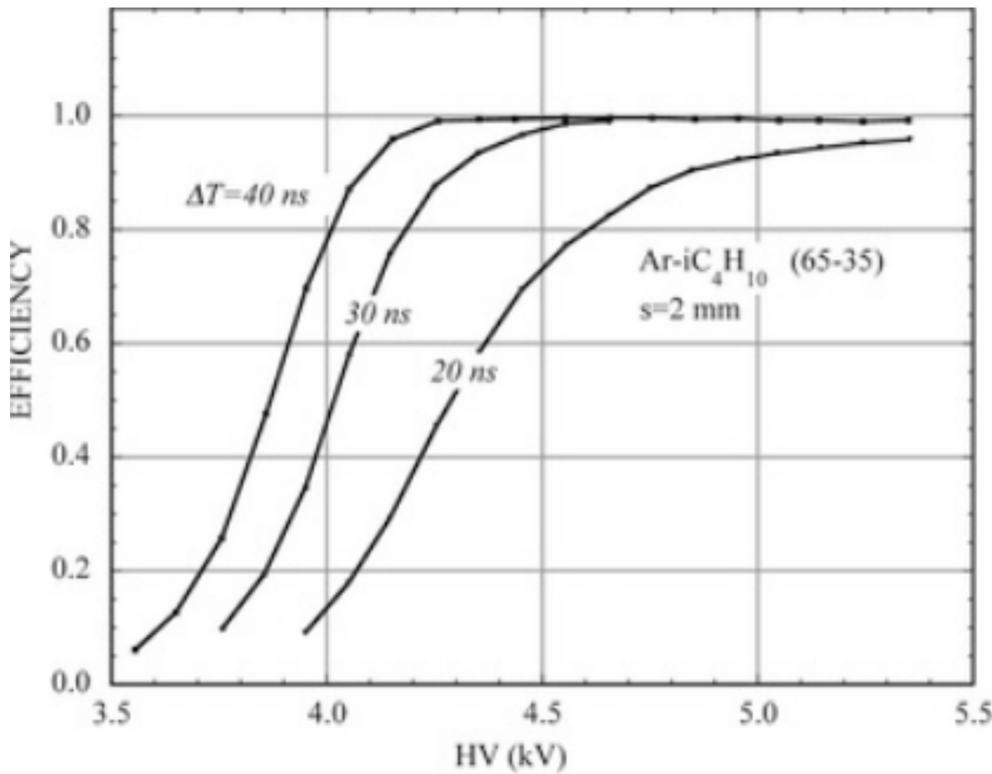
- Right: Time spectrum recorded by a single wire for an inclined beam: the tail correnspond to the trrack in region C of this wire

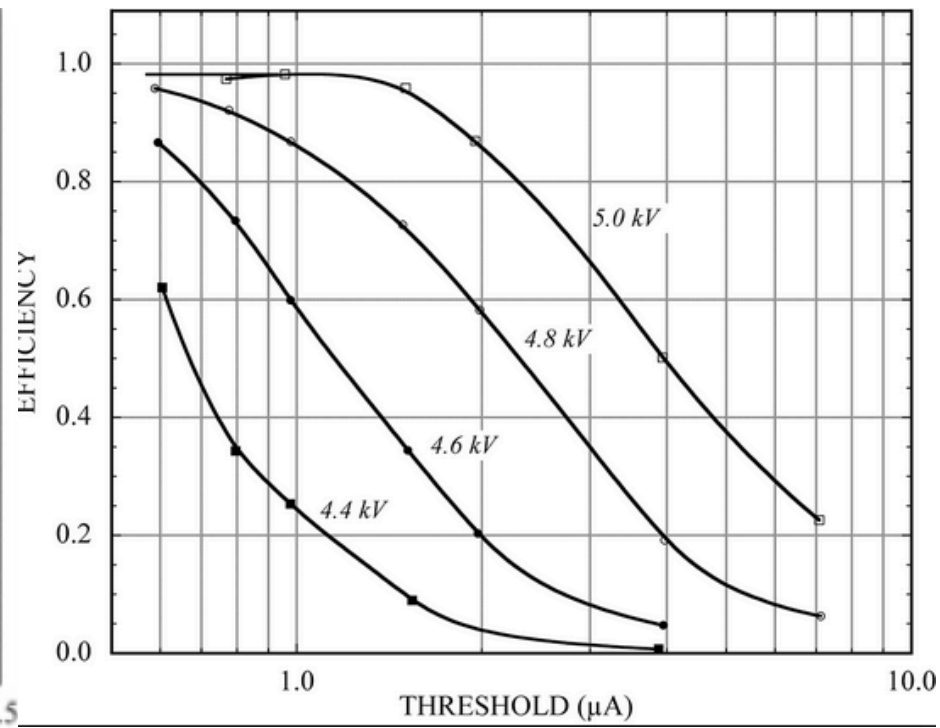
Clusters

- When detecting tracks not pependicular to the chamber, the number of wires fired by each track (cluster size) depends on the timing gate of the electronics:
- if the gate lenght is the minimum required for full efficiency the cluster size ~ 1-2 wires
  - It depend on track crossing angle
  - Typical value of the time gate for full eff. ~ 30ns
- If the gate lenght correnspont to the max drift time off region C, the cls size depends just on the crossing angle



Efficiency of a MWPC





Efficiency vs HV for several time gate

Efficiency vs the thresold of the readout circuit for several HV values

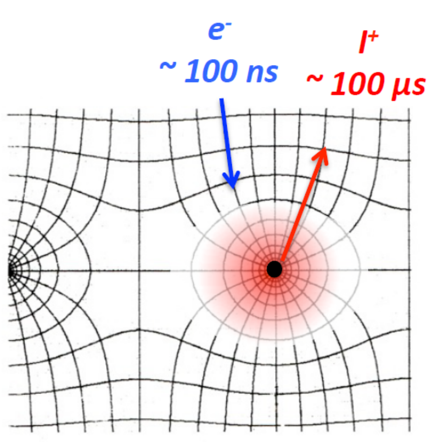
Limitation factors of MWPC: effects on the rate capability

- Despite their successful use in particle physics experiments and other fields, MWPCs have several limitations,intrinsic in their conception.

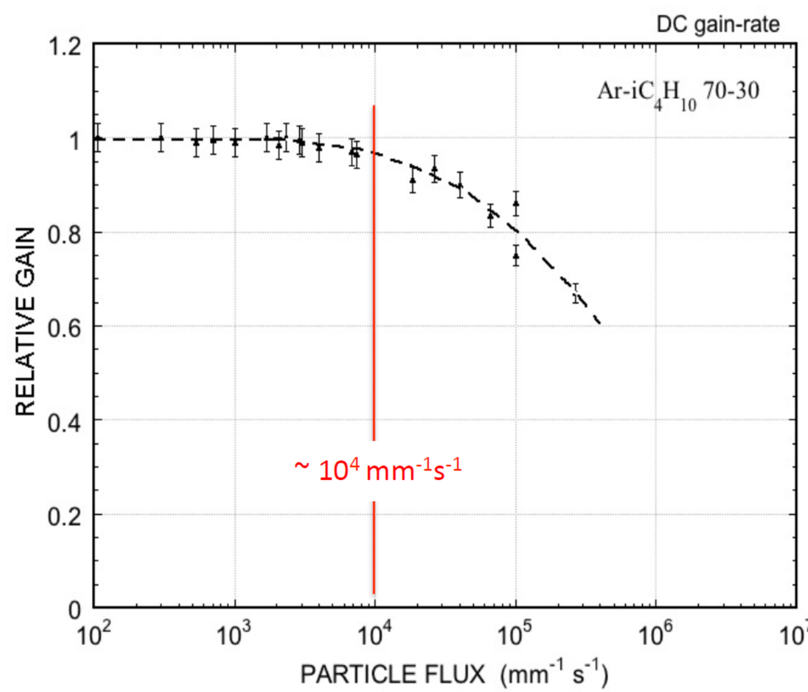
RATE-DEPENDENT GAIN REDUCTION

SPACE CHARGE

SPACE CHARGE NEAR THE ANODE: BUILDUP OF SLOW POSITIVE IONS MODIFIES THE ELECTRIC FIELD



RELATIVE GAIN AS A FUNCTION OF RATE:



A. Breskin et al, Nucl. Instr. and Meth. 124(1974)189

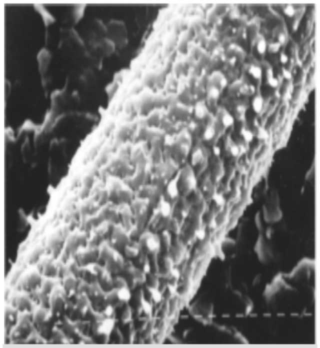
- The creation in the multiplication process of large amounts of positive ions, slowly receding towards the cathodes, causes a modification of the applied electric field, and results in a drop of gain and efficiency at particle fluxes above ~$10^4 mm^{-1}s^{-1}$.
- The discrete wire spacing is itself a limitation to the multi-track resolution, essential at high particle rates and multiplicities.

Limitation: the ageing and discharge

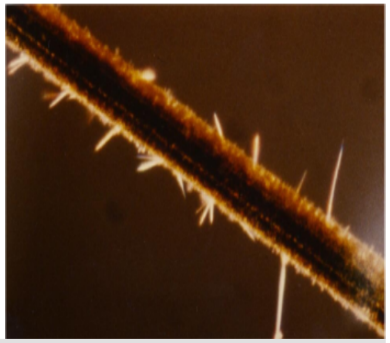
AGING

SECONDARY PROCESSES

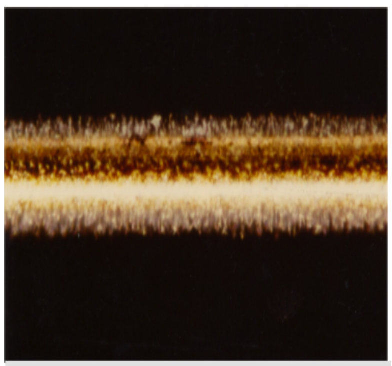
Polymerization of organic compounds with formation of deposits on thin wires:



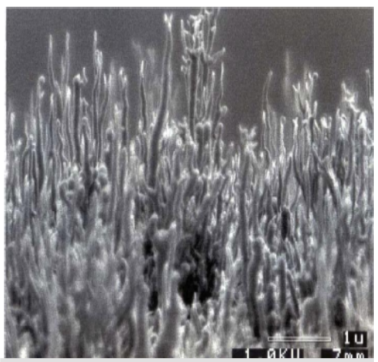
O. Ullaland, LBL-21170 (1986)107



I. Juric and J. Kadyk, LBL-21170 (1986)141



I. Juric and J. Kadyk, LBL-21170 (1986)141



M. Binkley et al,
Nucl. Instr. and Meth. A515(2003)53

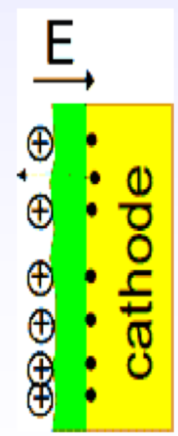
Even more detrimental, the creation and deposit on the anode wires of thin insulating layers caused by the polymerization of organic gases or pollutants may result in an amazingly short operating life span

Classical ageing

Avalanche region → plasma formation (complicated plasma chemistry)

- Dissociation of detector gas and pollutants
- Highly active radicals formation
- Polymerization (organic quenchers)
- Insulating deposits on anodes and cathodes

Anode: increase of the wire diameter, reduced and variable field, variable gain and energy resolution.



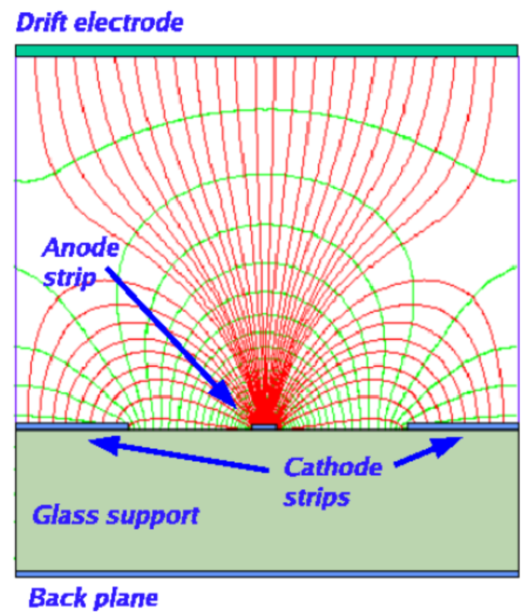
Cathode: formation of strong dipoles, field emmision and microdischarges (Malter effect).

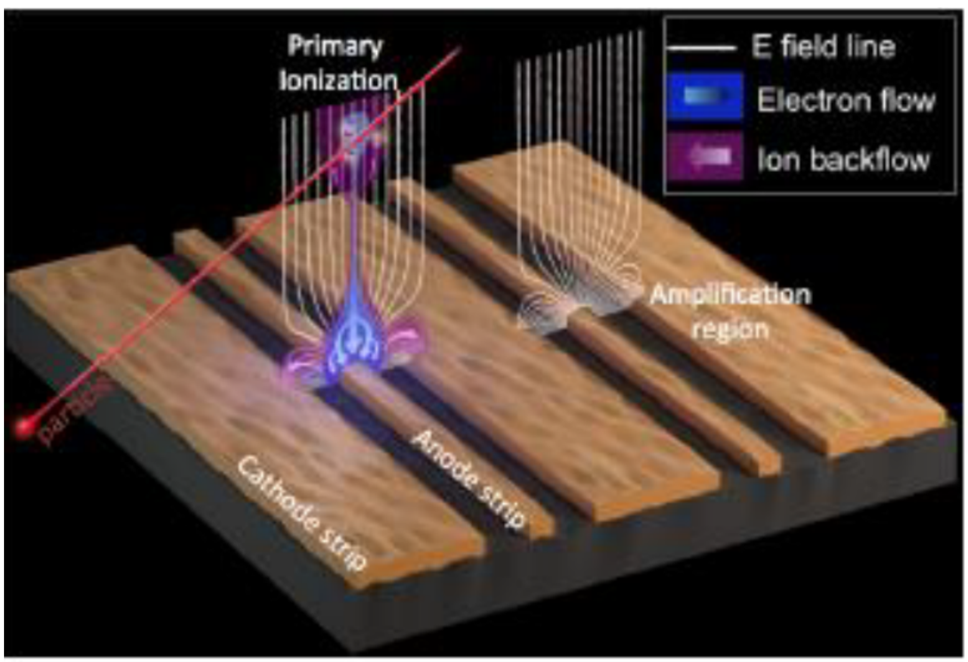
Micro-strip gas chambers

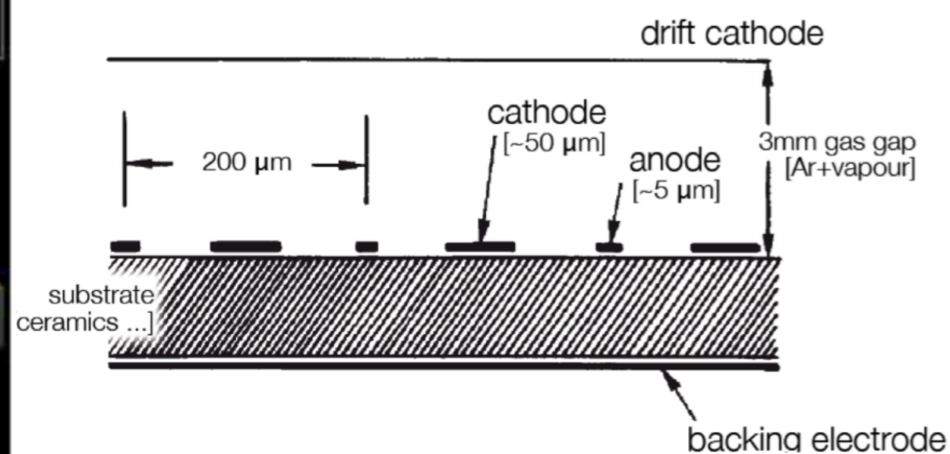
Anton Oed in 1988

- Same working principle of MWPC but
- Anodes can be realized via microstructures on dielectrics (material with high resistivity)
  - Metallic strips coated on a resitivie sub-strate
  - This allows to reduce the discharge damages
- Simple construction (today thanks to the litographique technique)
- Enhanced stability and flexibility

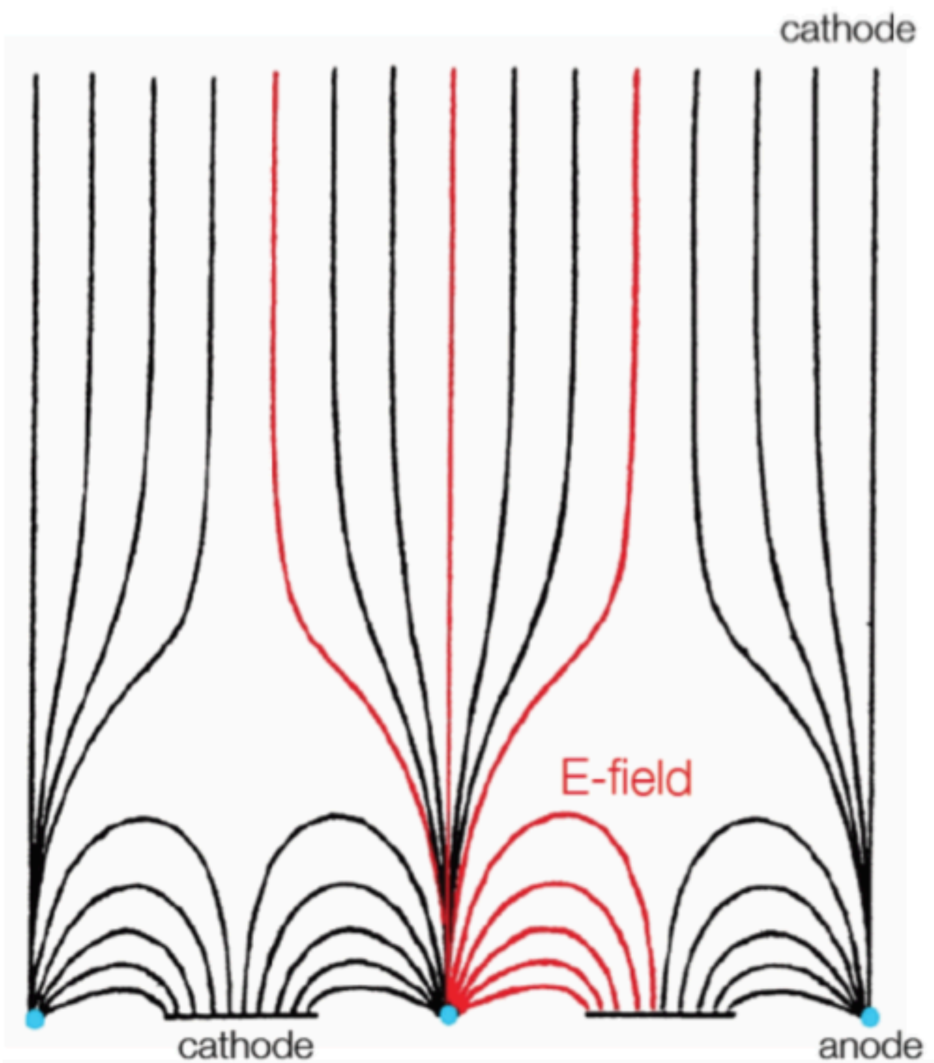
  → insulating material avoid the problem of electrostatic repulsion among wires and field modifications
- Improved rate capabilities







MSGC Electric Field



Advantages:

- High field directly above anode
- Ions drift only 100 µm → low dead time, high rate capability without build-up of space charge
- Resolution: fine structures can be fabricated by electron lithography on ceramics, glass or plastic foils on which a metal film was previously evaporated

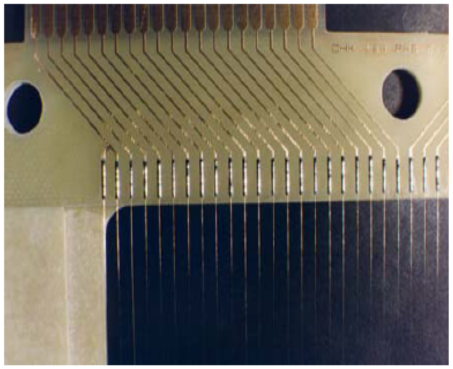
Problems:

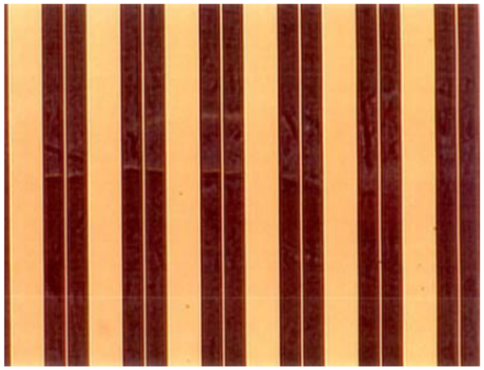
- Charging of insulating structures
- Time dependent gain, sparks, anode destruction, corrosion of insulator
- Lifetime of detector too limited
- the device appeared to be rather susceptible to irreversible degradation due to occasional but destructive discharges.

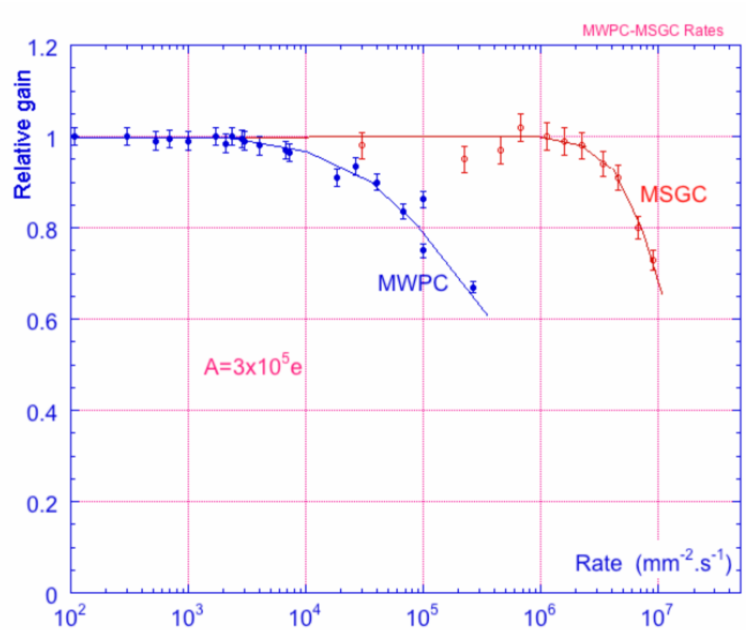
Not quite a success!

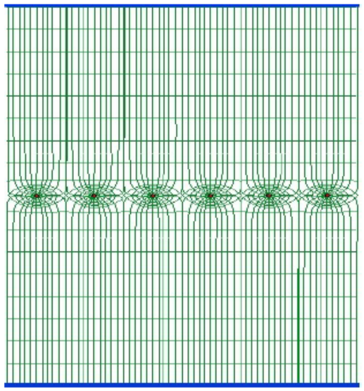
Comparison MWPC vs MSGC

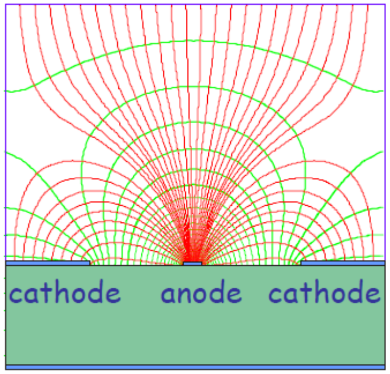
MWPC **MSGC**











Typical distance between wires limited to 1 mm due to mechanical and electrostatic forces

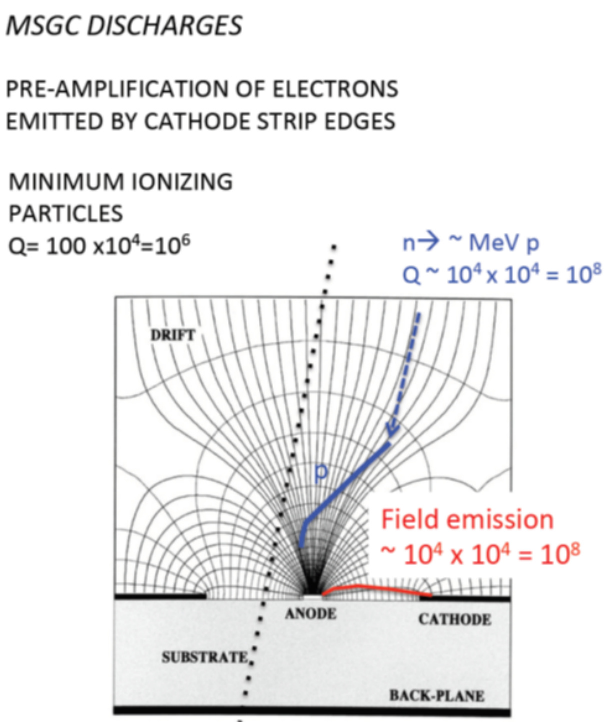
Typical distance between anodes 200 μm thanks to semiconductor etching technology

Rate capability limit due to space charge overcome by increased amplifying cell granularity

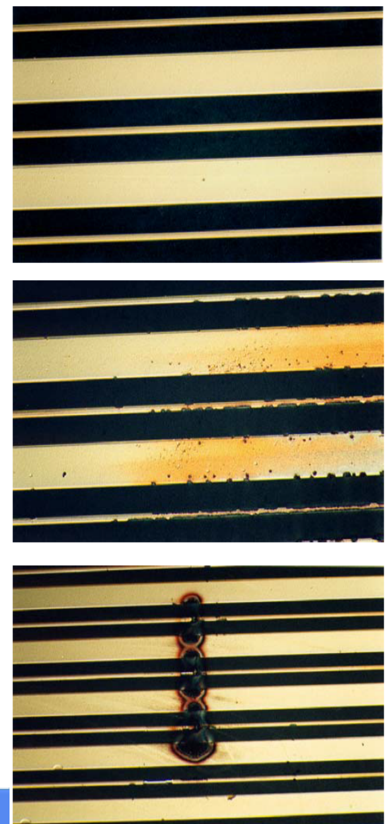
A. Oed
Nucl. Instr. and Meth. A263 (1988) 351.

Problem with MSGC: discharge issue

- Many of the problems encountered with MSGCs are connected to the use of fragile electrodes exposed to the high electric fields needed to achieve the gains, typically around 10^4, needed for detection of small ionization yields.
- Under these condition,the occurrence in the gas of rare but highly ionizing events, due for example to neutron or gamma conversions, may lead to the creation of a local charge density exceeding the Raether limit (10^7 electron–ion pairs) leading to the formation of a streamer, and eventually to a discharge.



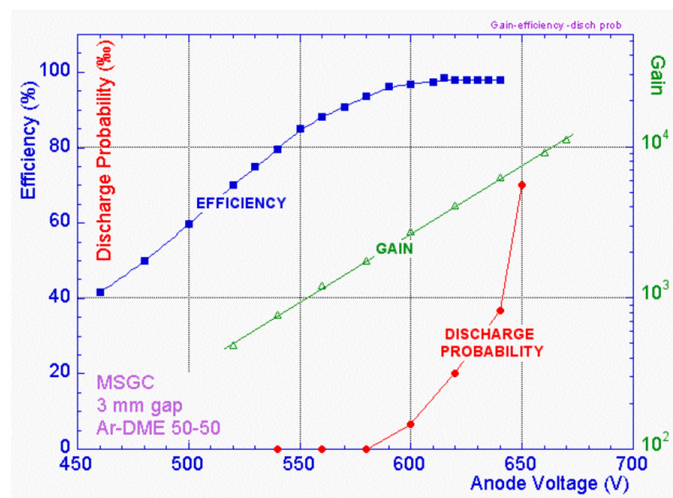
T. Beckers et al, Nucl. Instr. and Meth. A346(1994)95



Surface charging
Bulk resistivity of the support material
Surface modification by doping or deposition

Ageing
Gas, Gas system, MSGC support, Construction material

Discharges

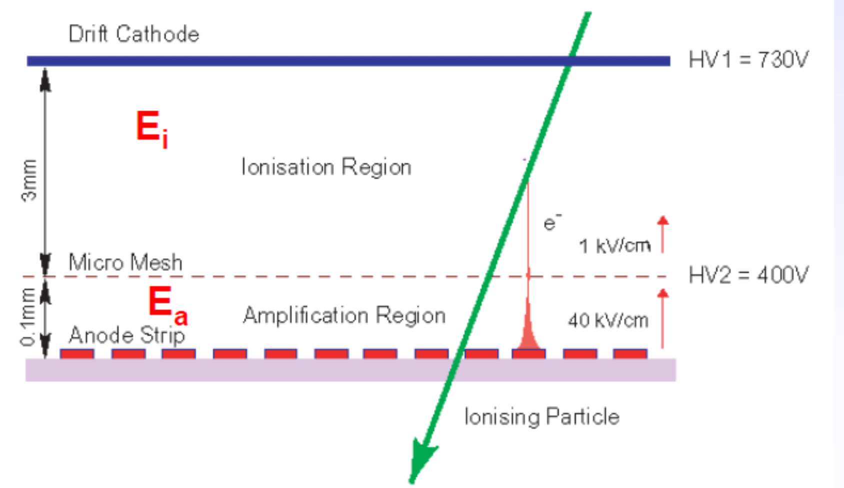


Two very solid, fully established MPGD technologies

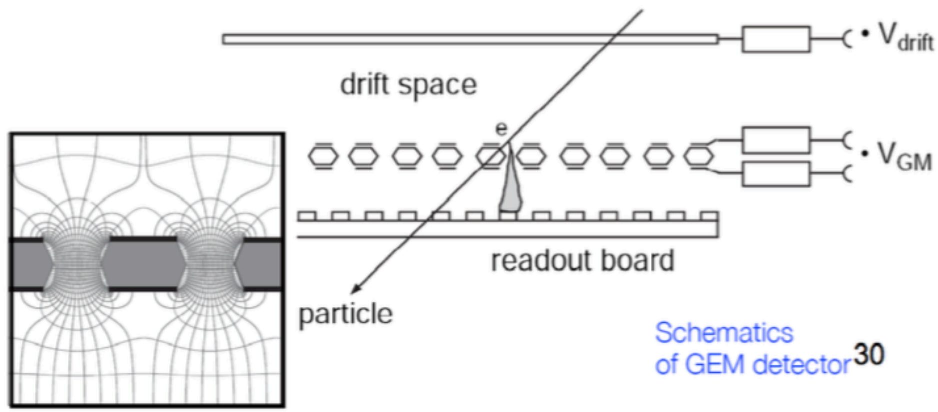
- Mitigation of problems: add an intermediate structure

Micromegas (MICRO MEsh GAseous Structure**)**

- fine cathode mesh collects ions. Still fast. No wires
- Thin gap Parallel Plate Chamber: micromesh stretched over readout electrode.
- ***Y. Giomataris-G. Charpack et al., Nucl. Instr. and Meth. A376(1996)29***



- **Gas Electron Multiplier** (GEM)
- Thin, metal-coated polymer foil with high density of holes, each hole acting as an individual proportional counter.
- Offers a pre-amplification and allows reduced electric field in the vicinity of the node structures.
- Ease of construction again partly eliminated, risk of discharge on foil (huge capacitance)
- F. Sauli, CERN, ~1997

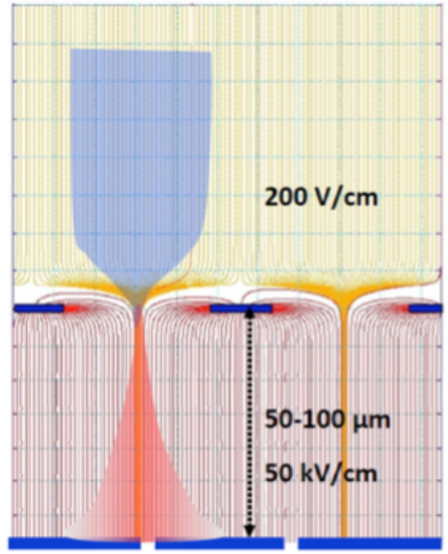


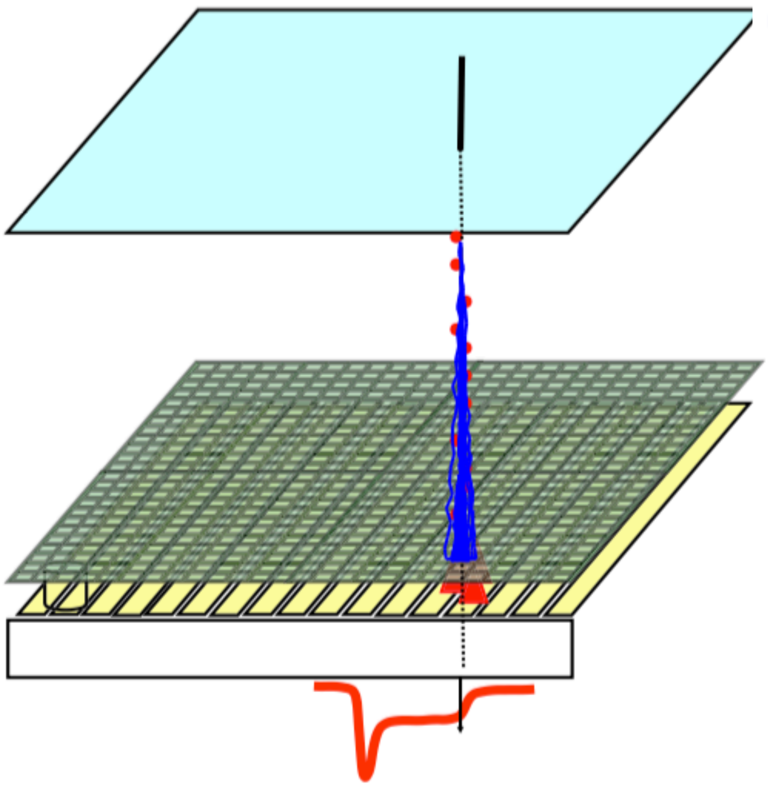
Schematics of GEM detector[30]

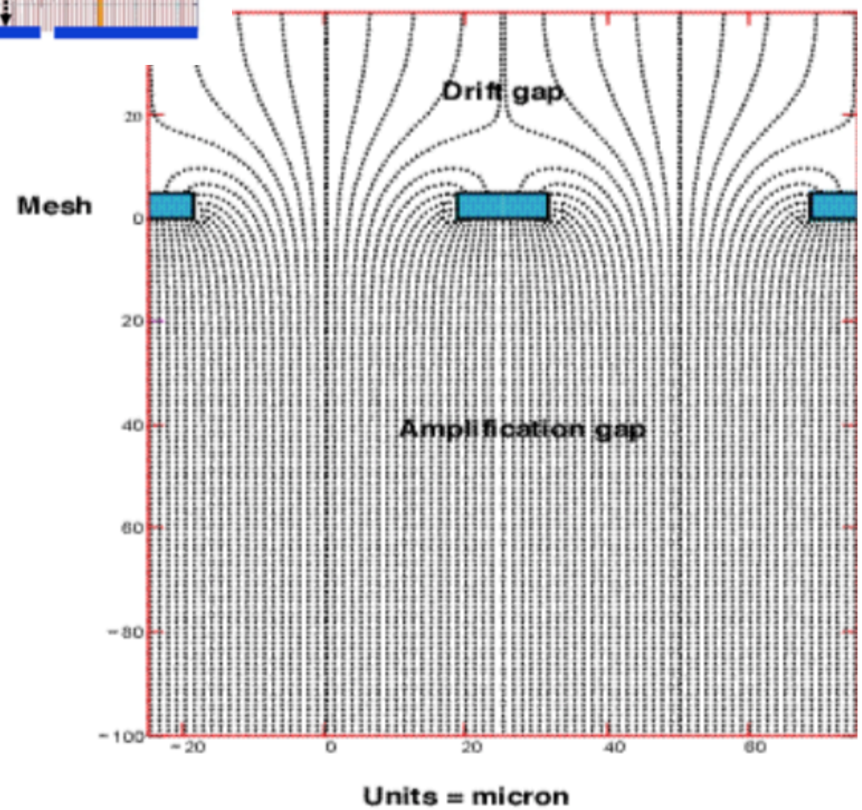
HIGHER LUMINOSITIES, HIGHER PRECISION EXPERIMENTS →MPGDs allow for
• High rates (granularity & occupancy, signal formation time)
• Fine space resolution
2. Technological maturity and accurate engineering FUNDAMENTAL for successful MPGDs

MICROMEGAS

The working principle



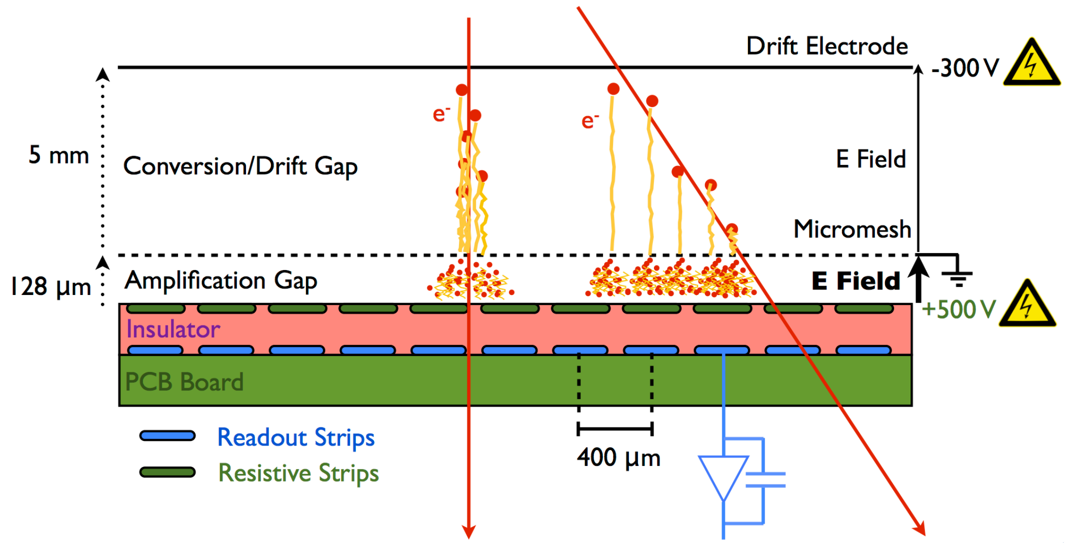




MICROMEGAS

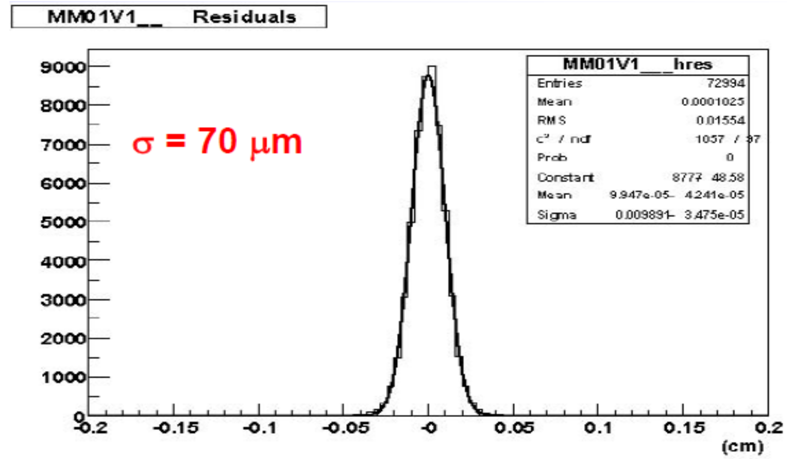
- MICROMEGAS is a very asymmetric double structure detector
  - two well distinguished regions no longer separated by a plane of wires, but by a micromesh.
- The first part a particle will have to cross is the drift electrode.
- Then it is inside the conversion region, which stretches up to some mm until the grid.
  - weak electric field (200 V/cm)
  - is the place where the ion-electron pair production takes place.
- The role of the grid (or else micromesh) is multiple. It is made out of copper (5 μm) with photolithograhy technique that allows to print on it 25 μm openings and a pitch of 50 μm
- The voltage applied to it (up to 5 kV/cm) is such that the ratio of the electric field in the amplification gap over the field of the conversion gap is very big.
  - The bigger the ratio the bigger the electron transmission (ratio 20→full transmission).
- Once in the amplification gap, the process of avalanche is started; the gap is so small (of the order of 100 μm) that the electric field achieved is very high (up to 50 kV/cm).

- The micromesh prevents the ions produced by the avalanche to enter the conversion gap.
  - the ions are collected by the micromesh with a high efficiency and speed,
  - the electrons continue in the amplification gap and end their travel on the anode electrode.
- The anode electrode consists of copper strips with a typical width of 150 μm and a pitch of 200 μm, grounded through low-noise charge preamplifiers of high gain to an isolating layer (usually kapton).



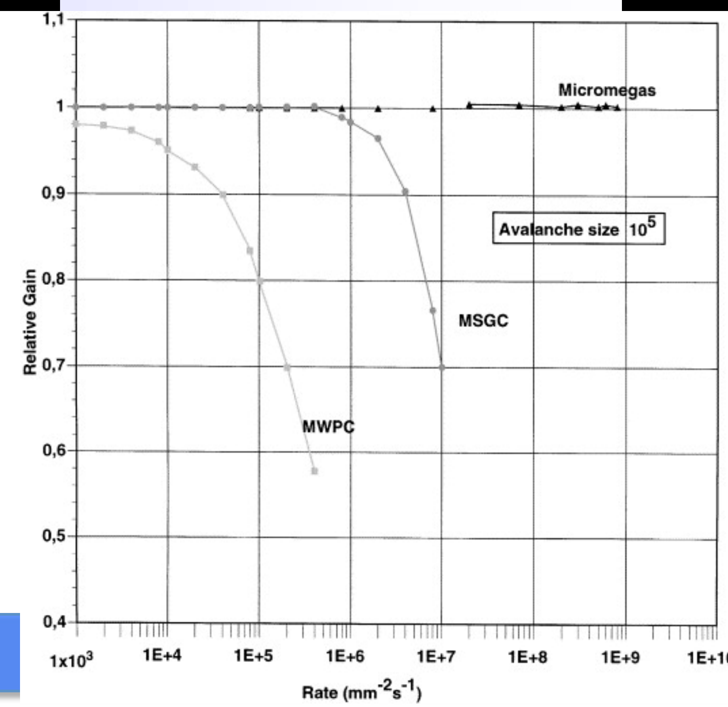
Advantages

- The fast response: because of the very small path the ions need to travel (amplifi- cation gap length ~ 100 µm) and of the very strong field, the ions are very rapidly collected, suppressing any space-charge effects.
- Any mechanical imperfection on the stretching of the micromesh above the strips is compensated, leading to essentially steady gain;
- Because of the constant field along the amplification region, the signal detected in the anode is equally due to the ions and the electrons, contrary to the wire chambers.
- An excellent spatial resolution.
- Counting capability of the order of 10^6 counts mm^2 s^{-1} due to the fast evacuation of the ions and the high granularity of the mesh.



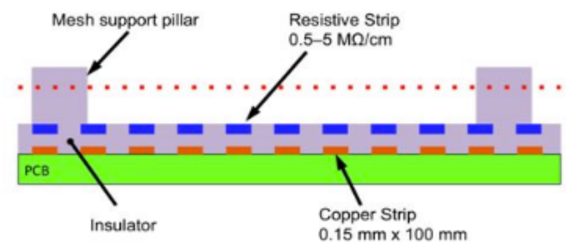
Space resolution

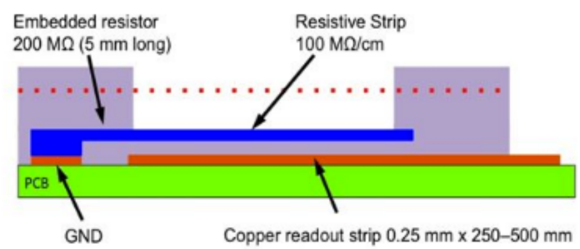
E field similar to parallel plate detector.
E_a/E_i ~ 50 to secure electron transparency and positive ion flowback supression.

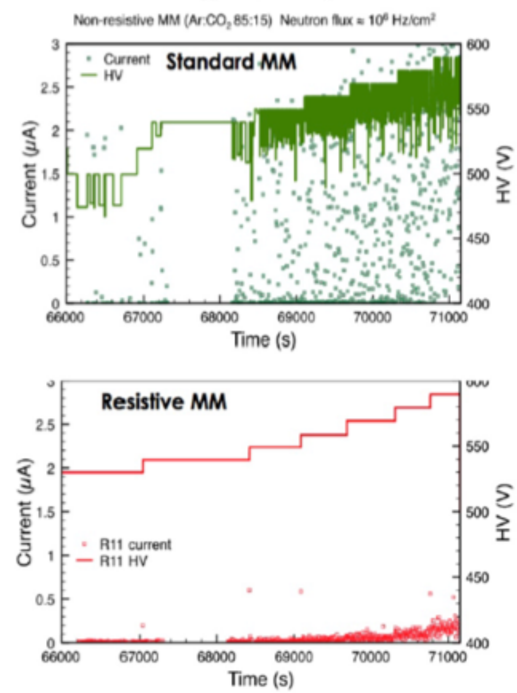


Discharge mitigation technique in MMEGAS

- It has been noticed that during operation with hadrons irradiation (COMPASS experiment), a large discharge occurs, proportional to the hadron rate
- It is due to large charge deposit in the drift space from recoil nuclei produced by hadrons traversing the detector
  - In the case of muons this process has a lower cross section
- Solution: A protective resistive structure is laid on the readout electrodes to prevent the development of a discharge between the micro-mesh and readout strips.
- Several designs have been considered whereas the discharge quenching mechanism principle remains the same
  - When a discharge is igniting, the potential on the resistive surface increases toward the mesh potential, canceling the electric field and quenching the discharge.
  - Physics signals are read by capacitive effect in hundreds of nanoseconds before charges flow out of the layer in microseconds,.
- The challenge of resistive technologies is to obtain a robust design that allows a fast evacuationof the charges in order to avoid local charge space.

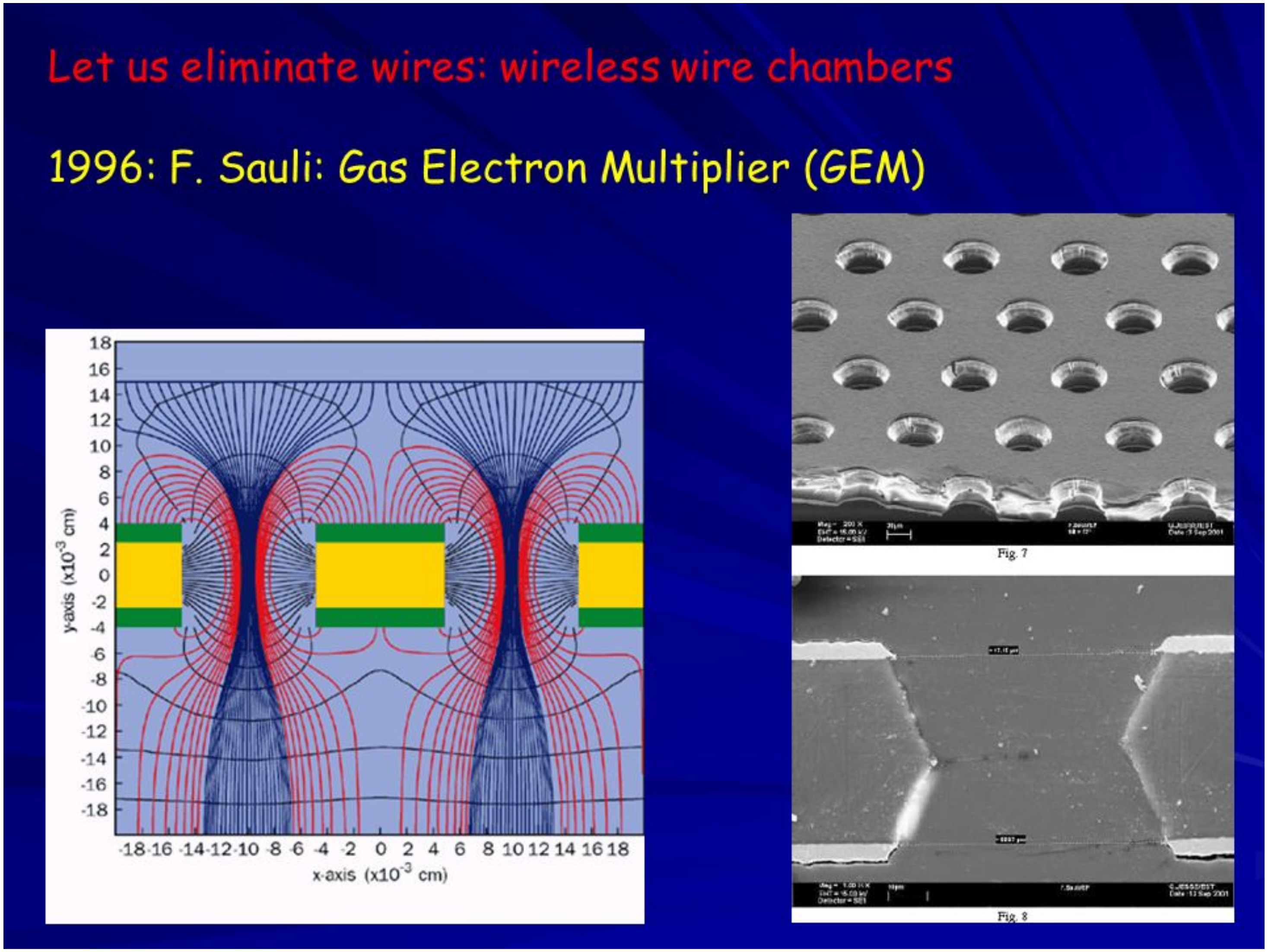






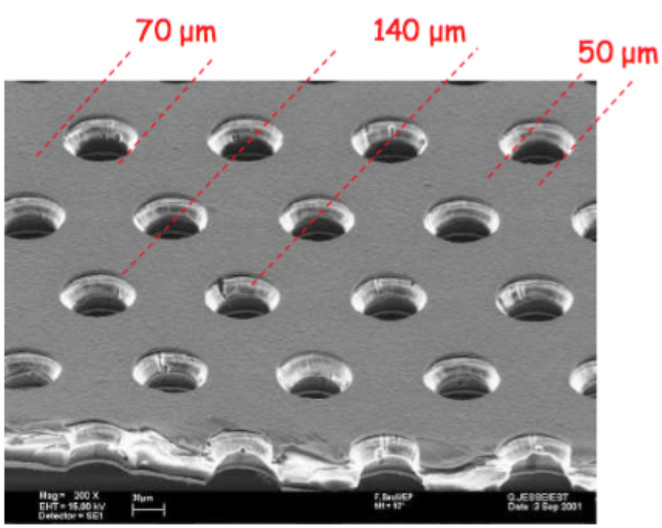
Spark rate in neutron flux

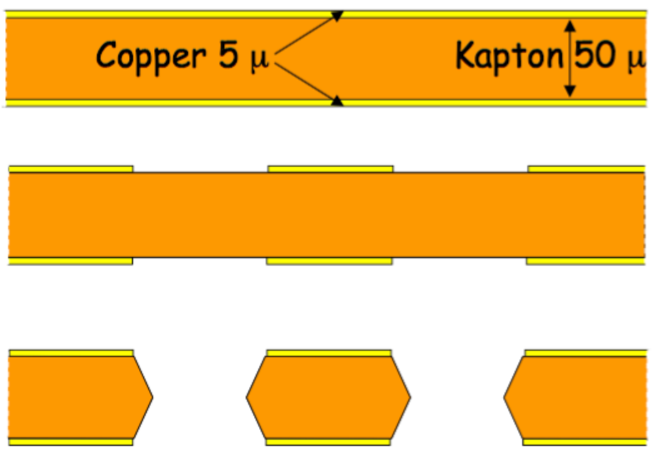
The GEM detectors

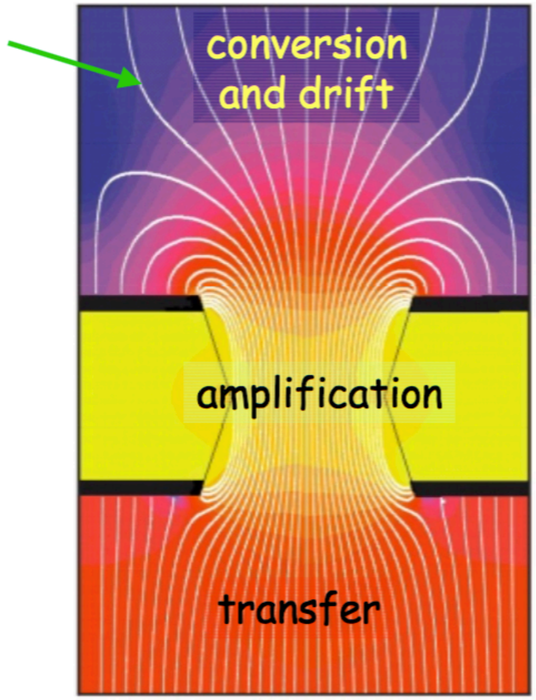


The GEM working principle

- 50 µm thick kapton foil, copper clad on each side and perforated by an high surface-density of bi-conical channels;
  - Kapton is a high-resistivity material
- Copper etching by chemical solution
- kapton etching using the copper mask
- By applying a potential difference between the two copper sides an electric field as high as 100 kV/cm is produced in the holes acting as multiplication channels.
- Potential difference ranging between 400 - 500 V

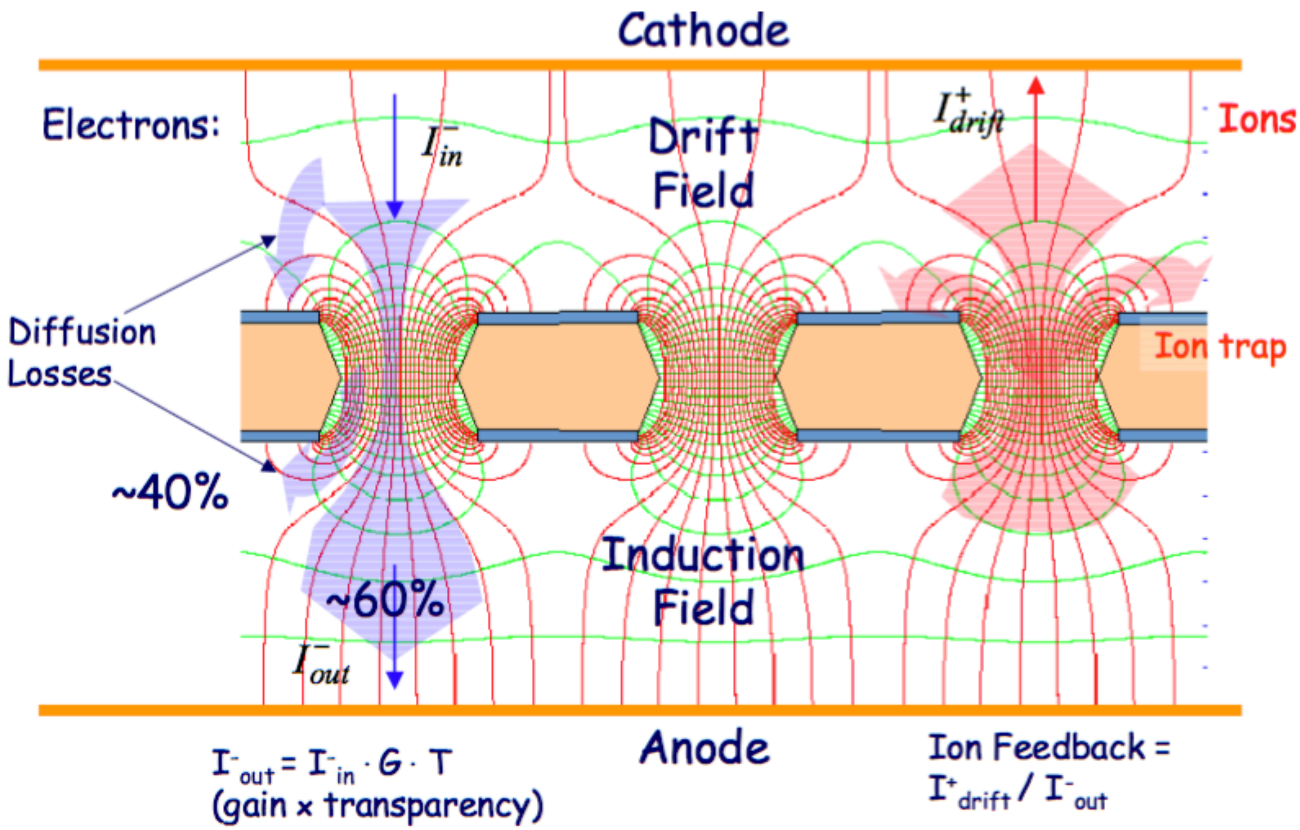






The Single GEM working principle

1. Electrons are collected on patterned readout board.
2. A fast signal can be dected on the lower GEM electrode for triggering or energy discrimination.
3. All readout electrodes are at ground potential.
4. Positive ions partially collected on the GEM electrode

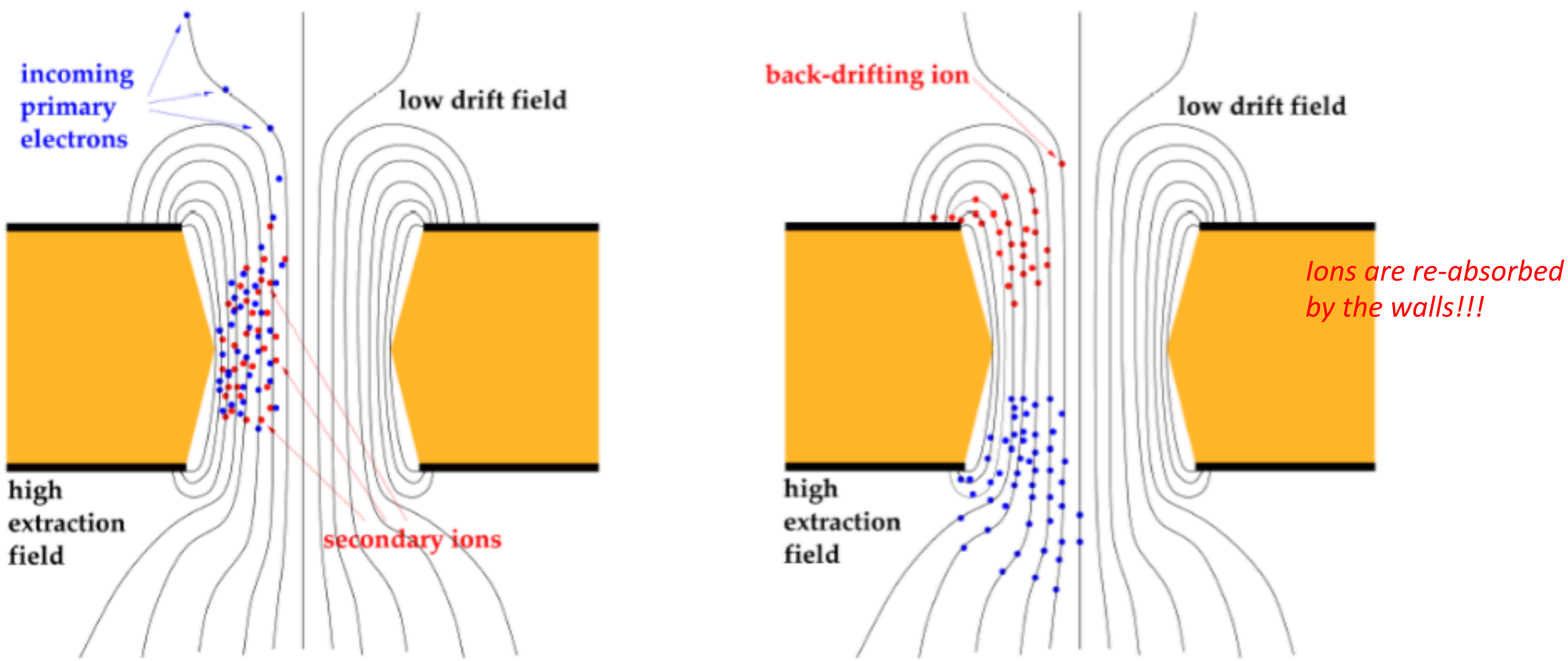


- To study gain in GEM we have to analyze which are the mechanisms of charge amplification
- We identify three electric fields: *drift field, moltiplication field, induction field*

Ion Backflow suppression

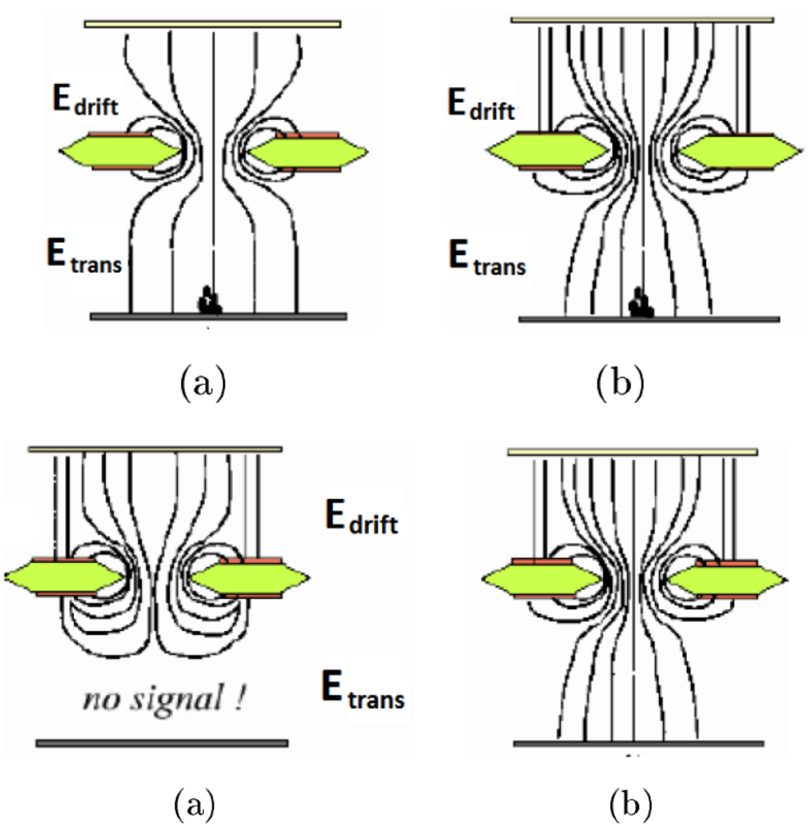
Ion backflow=ratio of positive ions reaching the drift electrode to the electron charge detected at the anode

- Natural IBF suppression:
  - Asymmetric mobility [low for ions – high for electrons]
    - Electrons move to larger fields in the amplification channel
    - More ions are produced at the edges → trajectory ends on top electrode
  - Asymmetric field [drift – induction]
    - Many field lines end on top electrons (ion capture)
    - Transfer region allows for good electron extraction



Ions are re-absorbed by the walls!!!

The electron Transparency



1. The electric fields (drift and induction) play a crucial role to define the so called *Transparency*
2. Another important parameter is the geometry of holes

Focusing (a) or undefocusing (b) effect on electron determines the *sticking* ε_{coll} and the *transfering* ε_{extr} efficiencies

Intrinsic gain of GEM foil

$$G_{intr} \propto e^{<\alpha> V_{GEM}}$$

effective gain

$$G_{eff} = G_{intr} \bullet \varepsilon_{coll} \bullet \varepsilon_{extr}$$

Rigorous formula of Gain

$$G = \exp\left(\int (\alpha(x) - \eta(x))\delta x\right),$$

Gain Determination

$$\epsilon^{coll} = \frac{electrons\ collected\ in\ the\ holes}{electrons\ produced\ above\ the\ holes}$$

Collection efficiency

$$\epsilon^{extr} = \frac{electrons\ extracted\ from\ the\ holes}{electrons\ produced\ in\ the\ holes}$$

Extraction efficiency

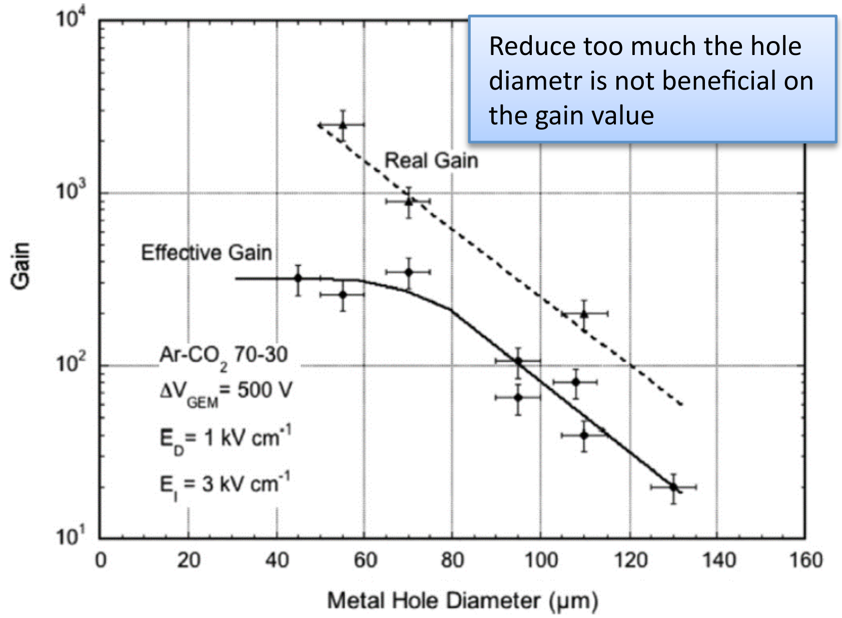
$$G_{int} \propto e^{\overline{\alpha}\Sigma V_{GEM}}$$

Intrinsic gain

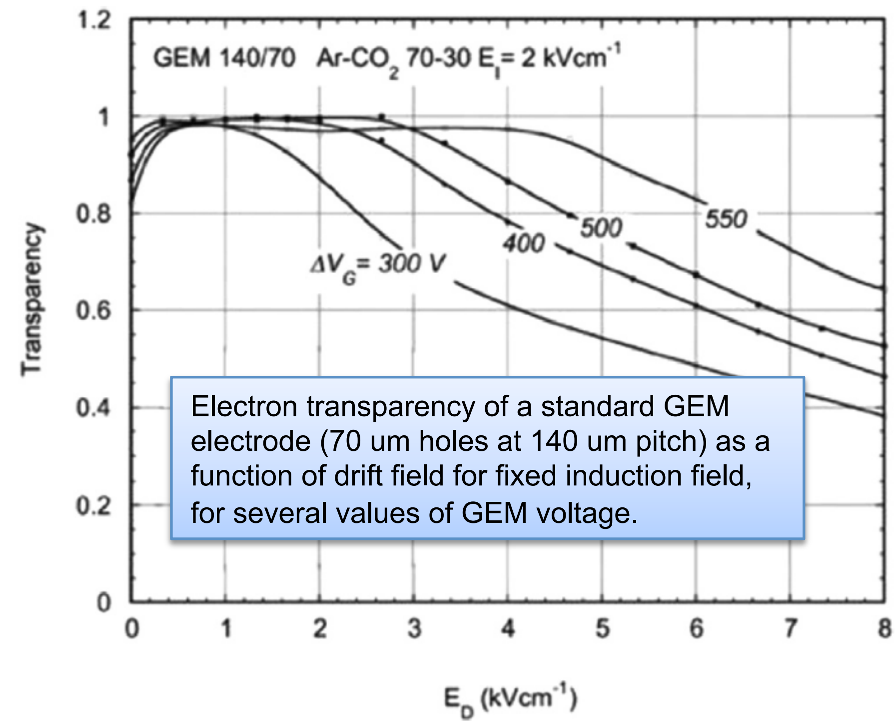
$$G_{eff} = G_{intr} * \varepsilon^{coll} * \varepsilon^{extr} = G_{intr} * T$$

Effective gain

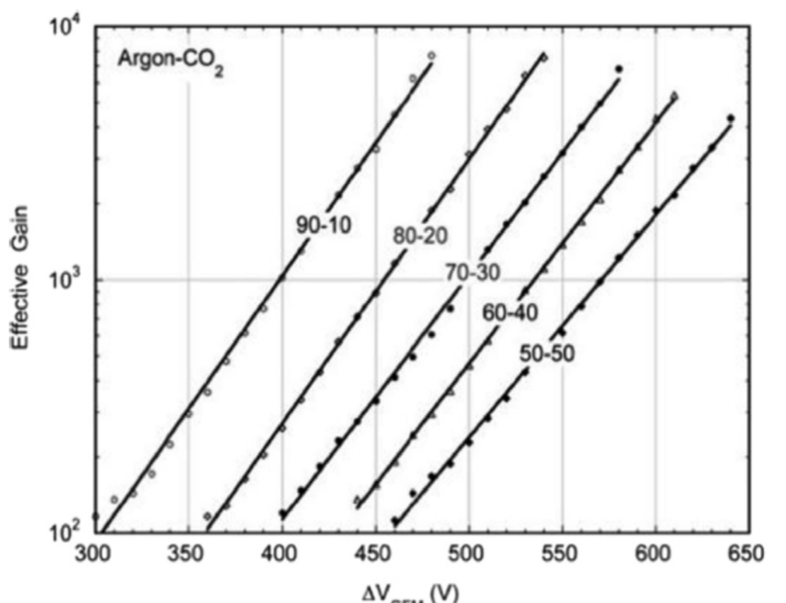
Since a field-dependent fraction of the multiplying electrons is lost on the lower face of the GEM electrode, the useful or effective gain, defined as ratio of the detected to the primary ionization charge, is always lower than the real gain of the multiplier.



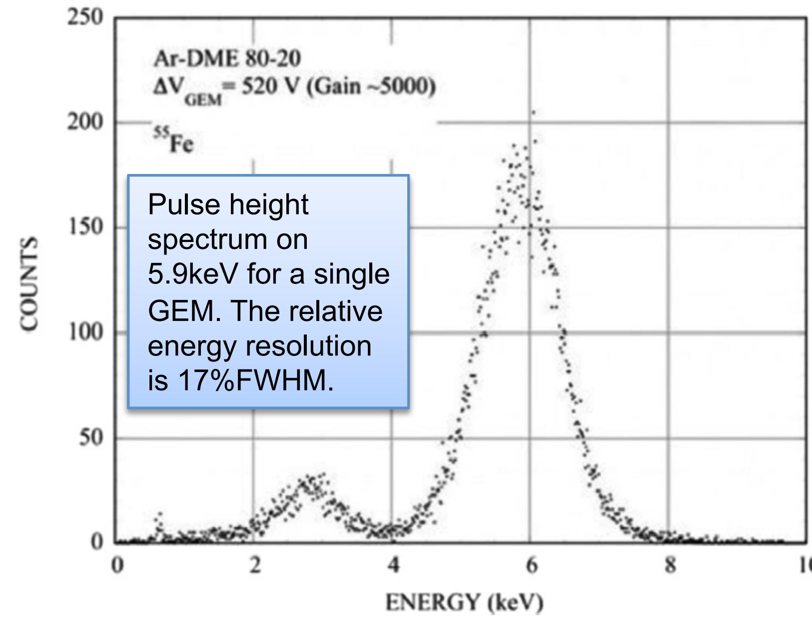
Reduce too much the hole diametr is not beneficial on the gain value



Electron transparency of a standard GEM electrode (70 um holes at 140 um pitch) as a function of drift field for fixed induction field, for several values of GEM voltage.



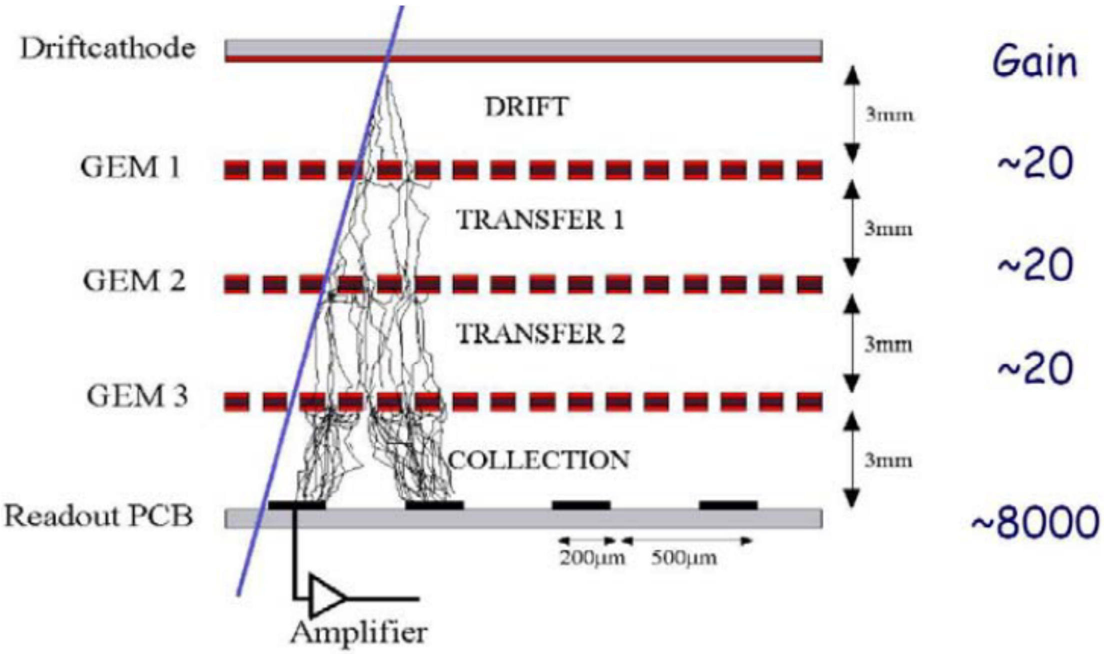
Single GEM effective gain as a function of voltage in Ar–CO_2 mixtures at atmospheric pressure as a function of HV



Pulse height spectrum on 5.9keV for a single GEM. The relative energy resolution is 17%FWHM.

The triple GEM detector

With an appropriate choice of the fields, the fraction of amplified electrons transferring to the gas gap following a first electrode can be injected and multiplied in a second foil, and yet again in a cascade of GEM electrodes



- Multiple structures provides equal gain at lower voltage
- Discharge probability on exposures to α particles is strongly reduced

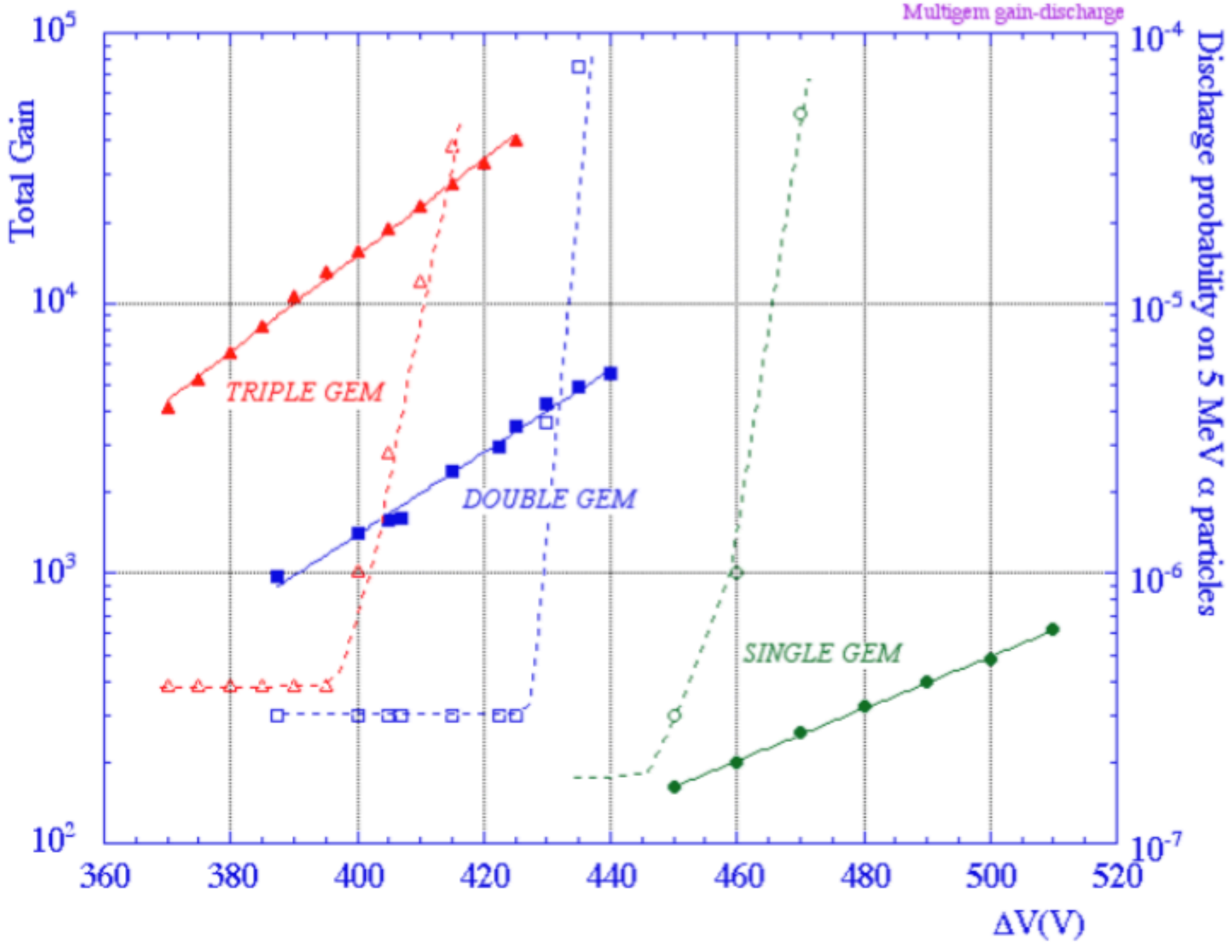
$$G_{intr} \propto e^{<\alpha> V_{GEM_{TOT}}}$$

$$G_{eff} = \prod_{i=1}^{3} G^i_{intr} \cdot \epsilon^i_{infil} \cdot \epsilon^i_{estr}$$

$$\epsilon^i_{infil} \cdot \epsilon^i_{estr} = T^i$$

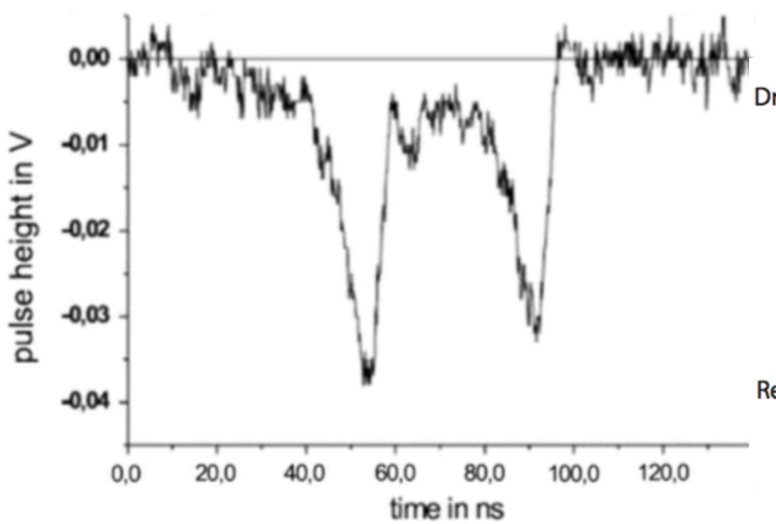
Single vs Triple GEM

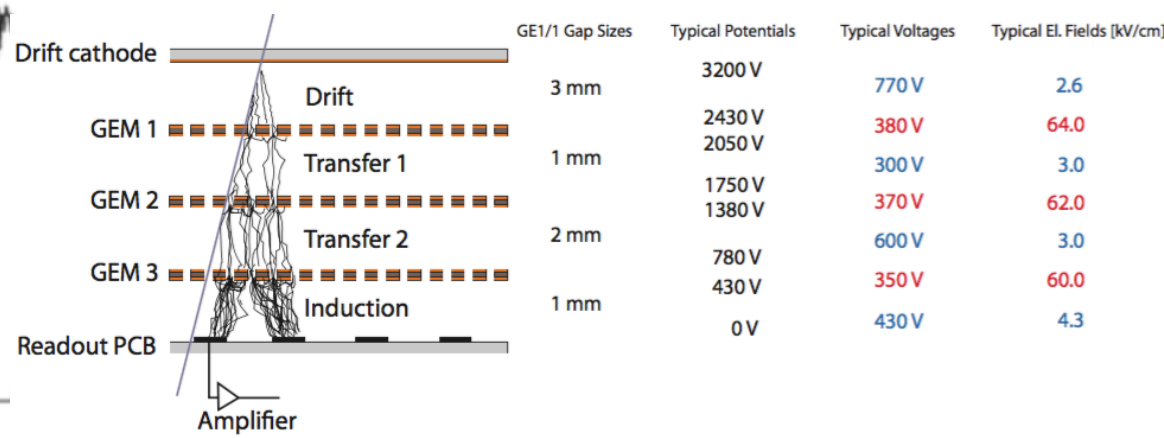
Measurements with alfa particle



Signal formation

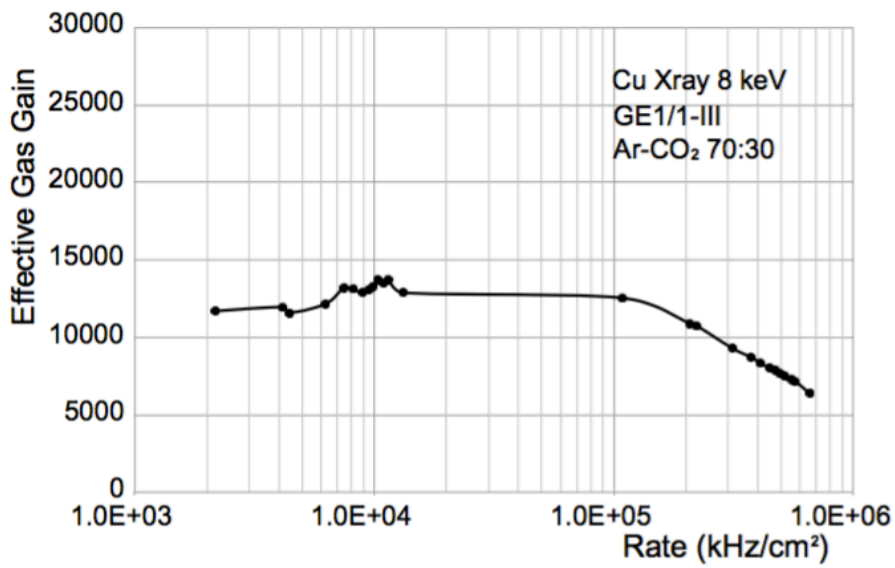
- The amplified charges (electrons and ions) resulting from the multiplication process are collected on the various electrodes;
- The anode (readout), only gathers the electrons leaving the last GEM;
- the induced negative signal is therefore very fast
  - it corresponds to the drift of the high mobility electrons over a few mm.
  - the anode can be patterned with one- or two-dimensional projective readout strips to perform localization.
- the signal induction is caused by the motion of the electrons towards the electrode;
  - while the strips facing the event collect a charge proportional to the avalanche spread, strips on the side detect a positive signal but no integral charge
- A signal identical but of opposite polarity is induced by the electrons collection on the bottom GEM electrode, facing the anode, and can be used to generate an energy trigger



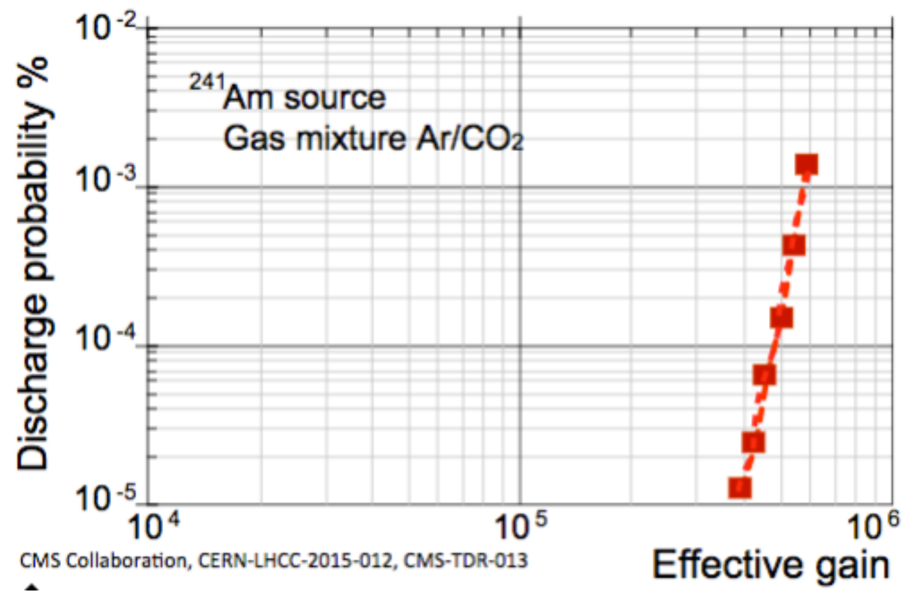


Rate capability and discharge probability

- A systematic study of rate dependence of gain in multi-GEM devices in a range of operating conditions and geometry has shown the gas gain to keep constant wrt to the rate;



Gas gain is observed to be constant over four orders of magnitude of incident particle rate up to 100 MHz/cm2. In HEP experiment a maximum rate on the order of 10 kHz/cm2 is expected



Discharge probability for typical operating conditions ($G=10^4$) is around 10^{-9} → the charge is spread over many different holes

Time Resolution

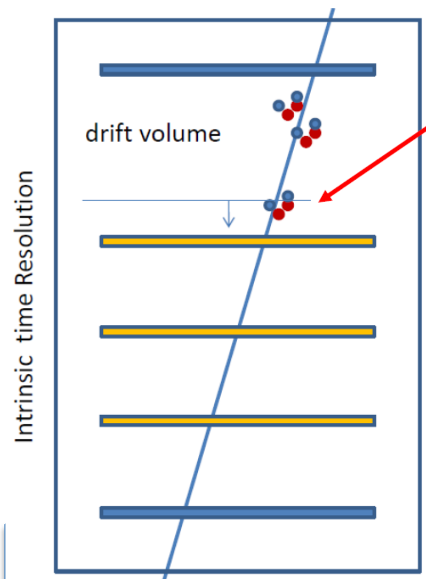
- The time resolution is dominated by fluctuations of the nearest distance of the primary ionisation processes to the region where the gain is acquired, d_{near}.
- Defining N as the average number of primary clusters generated by an ionising particle inside the gas, this distance follows a classical exponential distribution

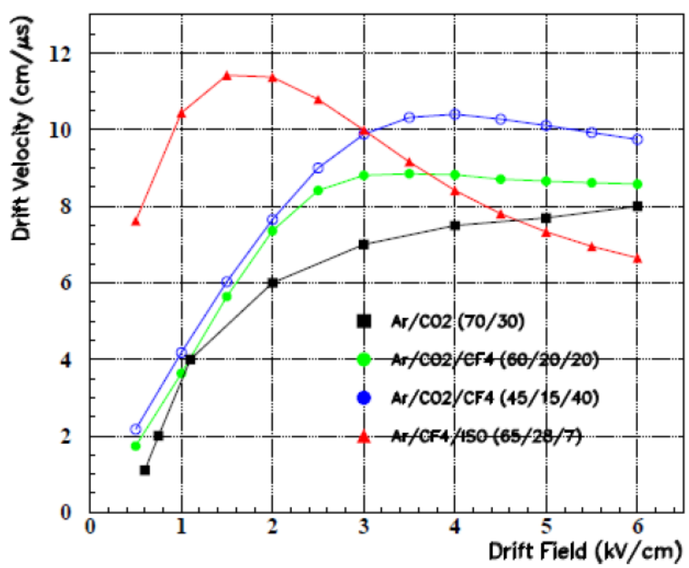
$$d = exp(-Nx)/N$$

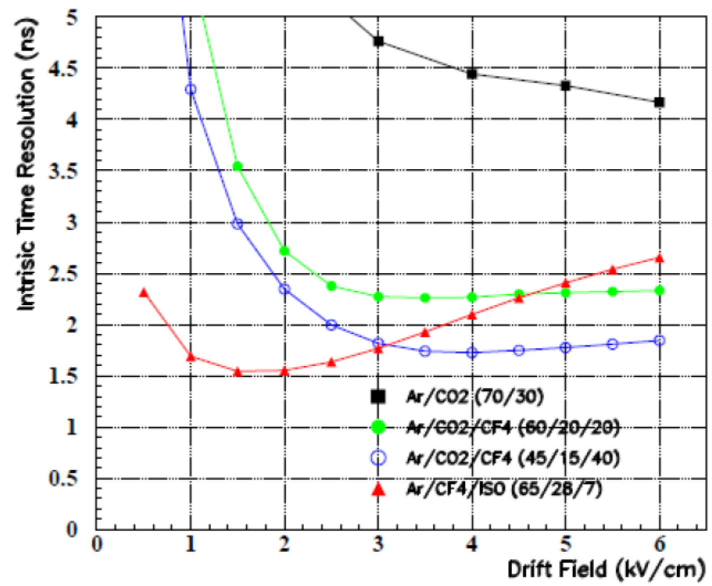
- The contribution of the time resolution to the drift velocity is

$$\sigma_t = 1/N * v_D$$

- Typical values for gases employed in MPGDs are N = 3(electrons-ion)/mm and $v_d \sim$ 0.12 mm/ns leading to **few-10 ns time resolution** with the best choice of gas mixtures and operating voltages







The Lab measurement