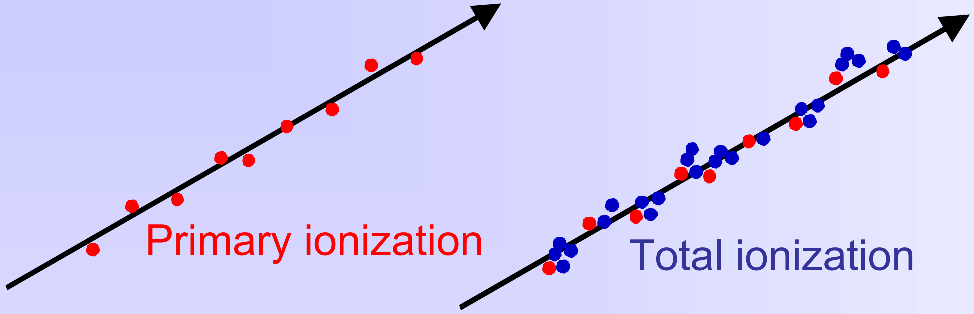
Outline

- **Lecture 1 - Introduction** C. Joram, L. Ropelewski
- **Lecture 2a - Gas Detectors** L. Ropelewski
  - Ionization of Gases
  - Gas Amplification
  - Single Wire Proportional Chamber
  - Drift Chamber
  - Drift and Diffusion of Charge Carriers in Gases
  - Examples of Detectors (CSC, RPC, TPC)
  - New Technologies – Micropattern Detectors
  - Limitations of Gas Detectors
  - Gas Detectors Simulations
  - Applications
- **Lecture 2b – Silicon Detectors** M. Moll
- **Lecture 3 - Scintillation and Photodetection** C. D'Ambrosio, T. Gys
- **Lecture 4 - Calorimetry, Particle ID** C. Joram
- **Lecture 5 - Particle ID, Detector Systems** C. Joram, C. D'Ambrosio

Ionization of Gases



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

Fast charged particles ionize atoms of gas. Often resulting primary electron will have enough kinetic energy to ionize other atoms.

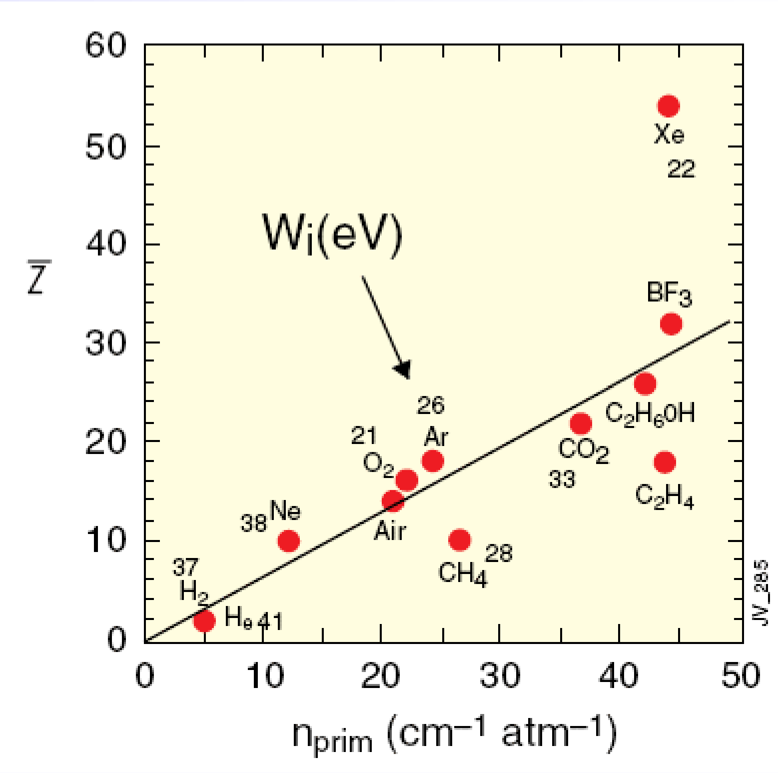
$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

n_{total} - number of created electron-ion pairs

Δ_E = total energy loss

W_i = effective <energy loss>/pair



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

Ionization of Gases

- The actual number of primary electron/ion pairs is Poisson distributed.

$$P(m) = \frac{\bar{n}^m e^{-\bar{n}}}{m!} \qquad \bar{n} = \frac{L}{\lambda} = LN\sigma_i$$

The detection efficiency is therefore limited to :

$$\varepsilon_{\text{det}} = 1 - P(0) = 1 - e^{-\bar{n}}$$

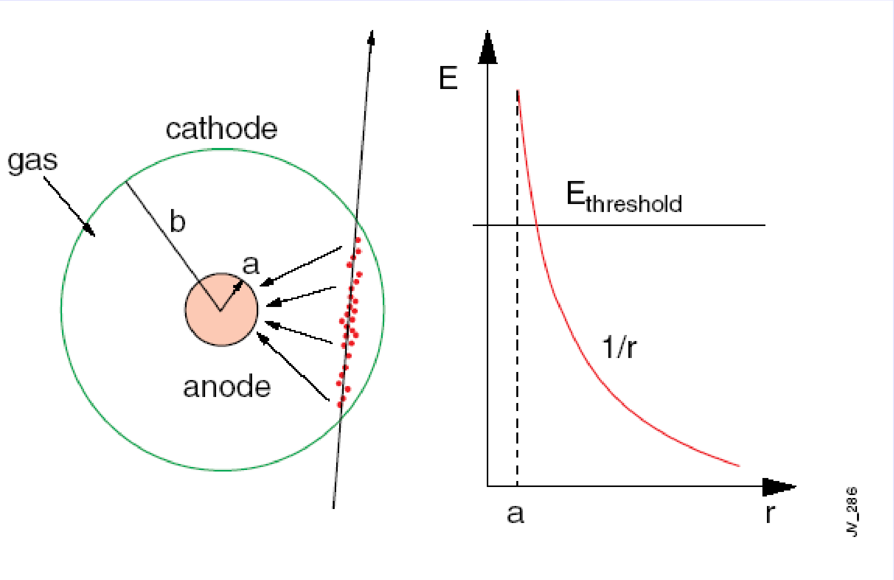
For thin layers ε_{det} can be significantly lower than 1**.**

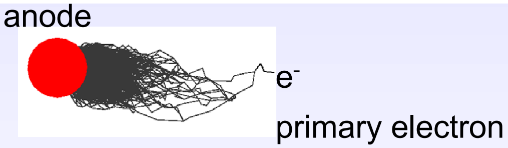
For example for 1 mm layer of Ar $n_{primary} = 2.5 \rightarrow \varepsilon_{det} = 0.92$.

- 100 electron/ion pairs created during ionization process is not easy to detect.

  Typical noise of the amplifier ≈ 1000 e^- (ENC) → gas amplification .

Single Wire Proportional Chamber





Electrons liberated by ionization drift towards the anode wire.

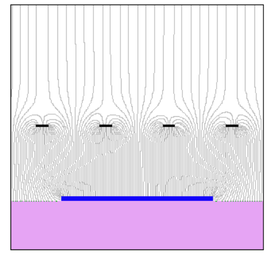
Electrical field close to the wire (typical wire Ø ~few tens of μm) is sufficiently high for electrons (above 10 kV/cm) to gain enough energy to ionize further → avalanche – exponential increase of number of electron ion pairs.

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

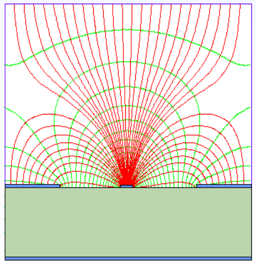
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C – capacitance/unit length

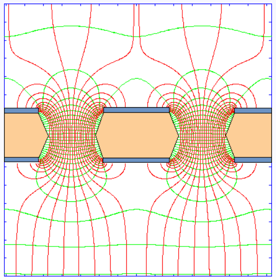
Cylindrical geometry is not the only one able to generate strong electric field:



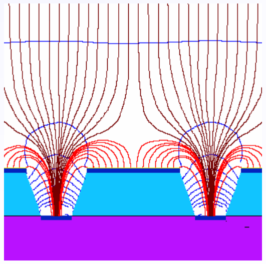
parallel plate



strip



hole



groove

Single Wire Proportional Chamber

Multiplication of ionization is described by the first Townsend coefficient $\alpha(E)$

$$dn = n\alpha dx \qquad \alpha = \frac{1}{\lambda}$$

λ – mean free path

$$n = n_0 e^{\alpha(E)x} \quad \text{or} \quad n = n_0 e^{\alpha(r)x}$$

$\alpha(E)$ is determined by the excitation and ionization cross sections of the electrons in the gas.

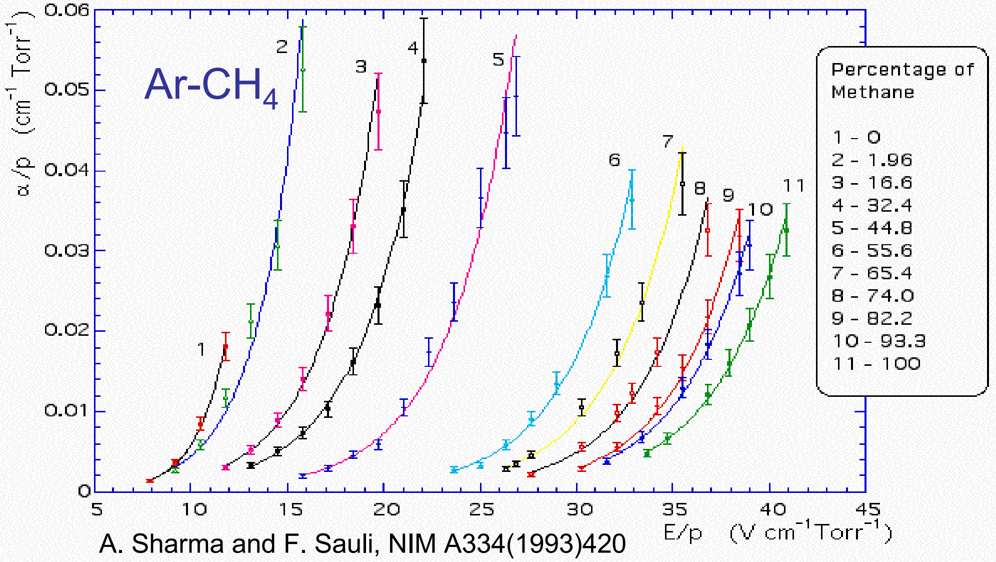
It depends also on various and complex energy transfer mechanisms between gas molecules.

There is no fundamental expression for $\alpha(E)$ → it has to be measured for every gas mixture.

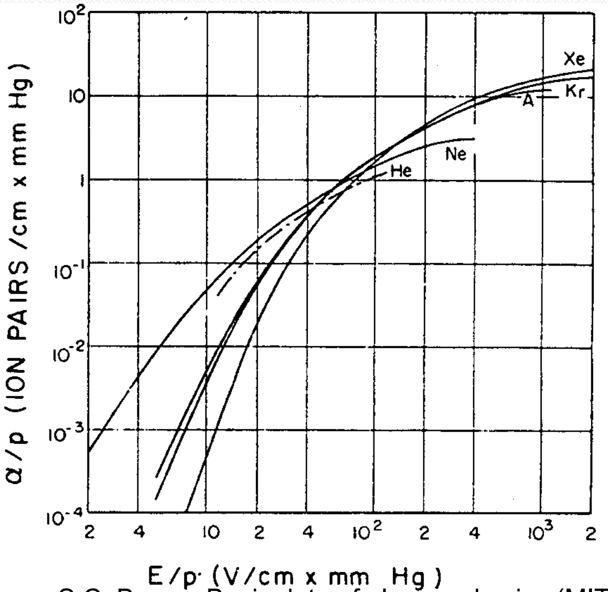
$$M = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)dr\right]$$

Amplification factor or

Gain



A. Sharma and F. Sauli, NIM A334(1993)420

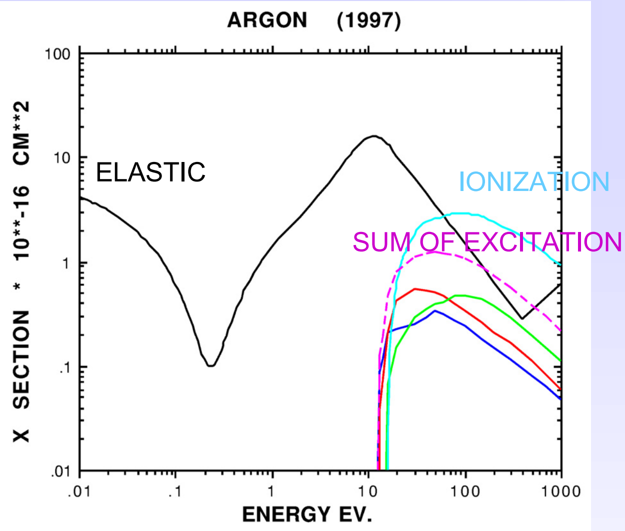


S.C. Brown, Basic data of plasma physics (MIT Press, 1959)

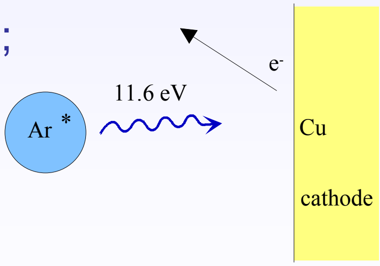
SWPC – Choice of Gas

In the avalanche process molecules of the gas can be brought to excited states.

S. Biagi, NIM A421 (1999) 234



De-excitation of noble gases only via emission of photons;
e.g. 11.6 eV for Ar.
This is above ionization threshold of metals;
e.g. Cu 7.7 eV.



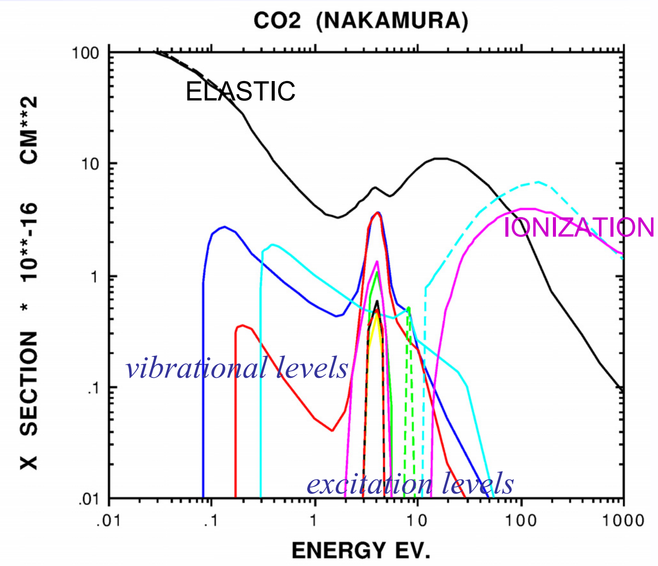
new avalanches → permanent discharges

Solution: addition of polyatomic gas as a quencher

Absorption of photons in a large energy range (many vibrational and rotational energy levels).

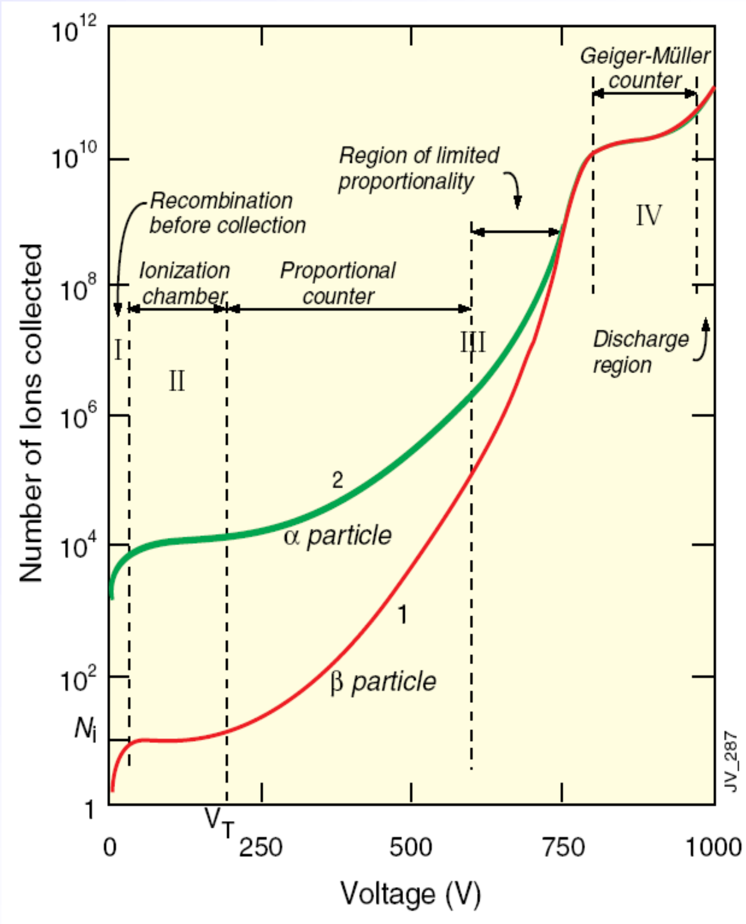
Energy dissipation by collisions or dissociation into smaller molecules.

S. Biagi, NIM A421 (1999) 234

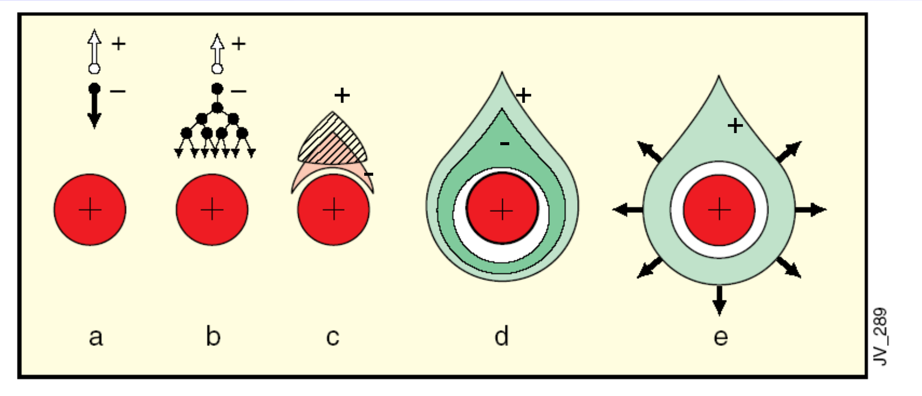


SWPC – Operation Modes

- ionization mode – full charge collection, but no charge multiplication;
  gain ~ 1
- proportional mode – multiplication of ionization starts; detected signal proportional to original ionization → possible energy measurement (dE/dx); secondary avalanches have to be quenched;
  gain ~ $10^4 – 10^5$
- limited proportional mode (saturated, streamer) – strong photoemission; secondary avalanches merging with original avalanche; requires strong quenchers or pulsed HV; large signals → simple electronics;
  gain ~ 10^{10}
- Geiger mode – massive photoemission; full length of the anode wire affected; discharge stopped by HV cut; strong quenchers needed as well



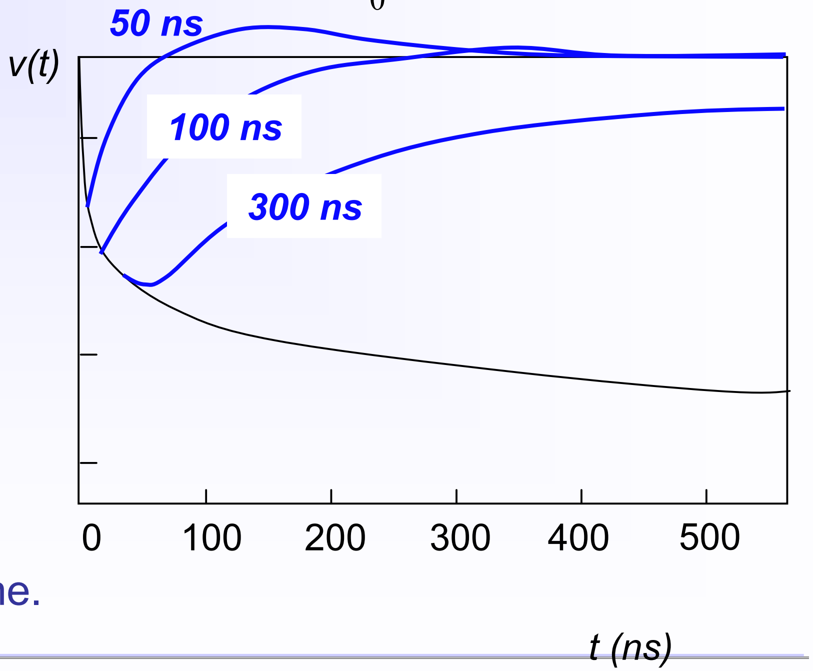
SWPC – Signal Formation



Avalanche formation within a few wire radii and within t < 1 ns.

Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

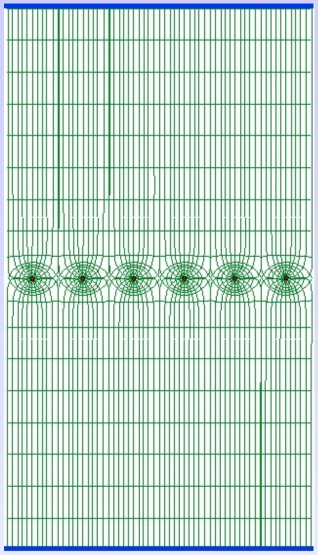


Electrons collected by the anode wire i.e. dr is very small (few μm). Electrons contribute only very little to detected signal (few %).

Ions have to drift back to cathode i.e. dr is large (few mm). Signal duration limited by total ion drift time.

Need electronic signal differentiation to limit dead time.

Multiwire Proportional Chamber



Simple idea to multiply SWPC cell : Nobel Prize 1992

First electronic device allowing high statistics experiments !!

Typical geometry

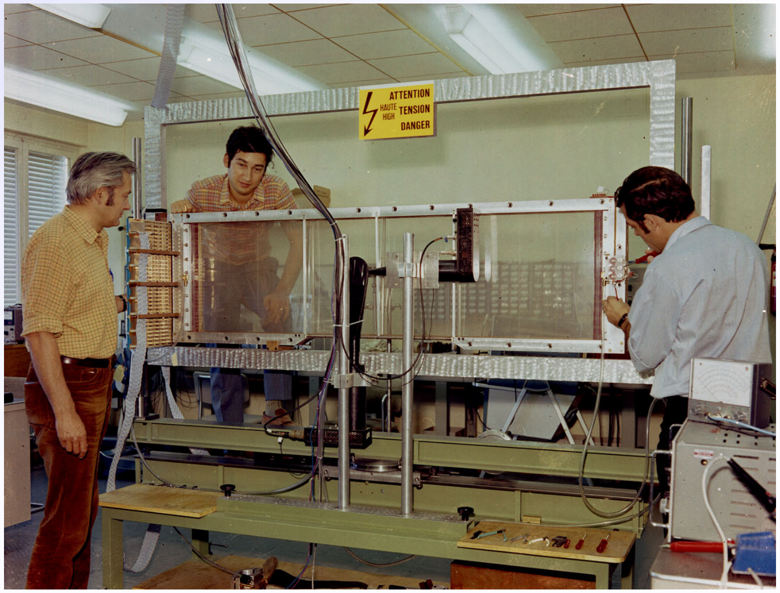
5mm, 1mm, 20 μm

Normally digital readout :

spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

for d = 1 mm σ_x = 300 μm

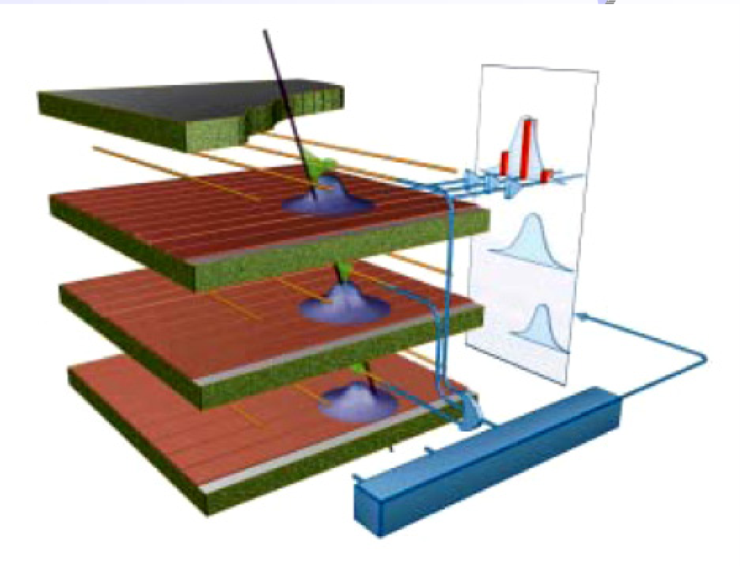


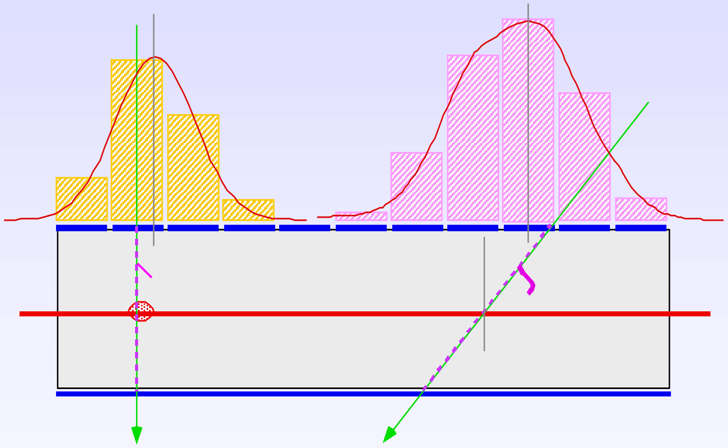
G. Charpak, F. Sauli and J.C. Santiard

CSC – Cathode Strip Chamber

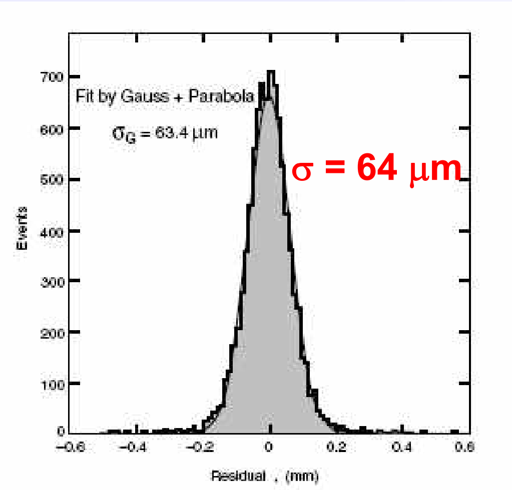
Precise measurement of the second coordinate by interpolation of the signal induced on pads.

Closely spaced wires makes CSC fast detector.

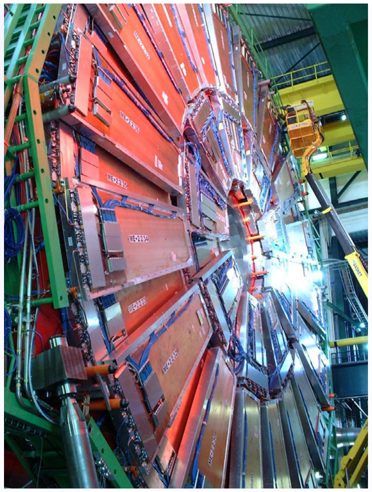




Center of gravity of induced signal method.

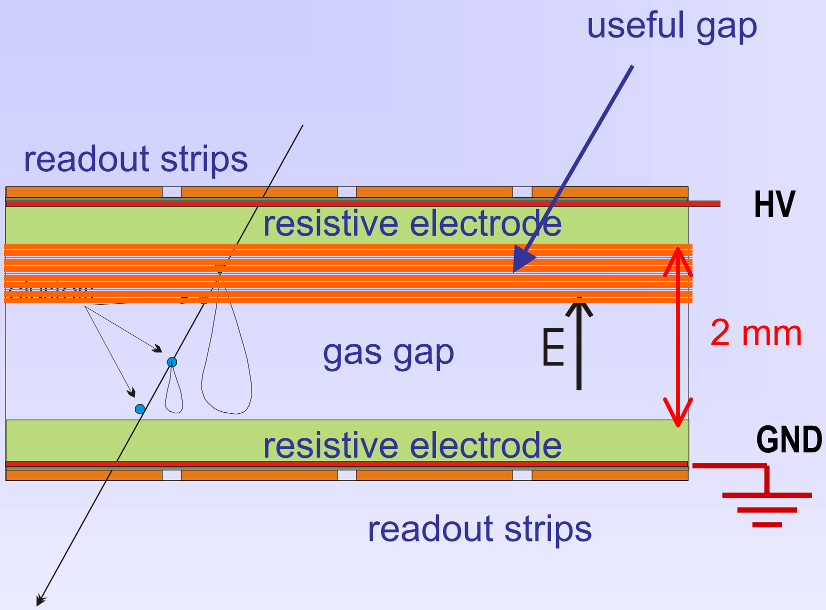


Space resolution

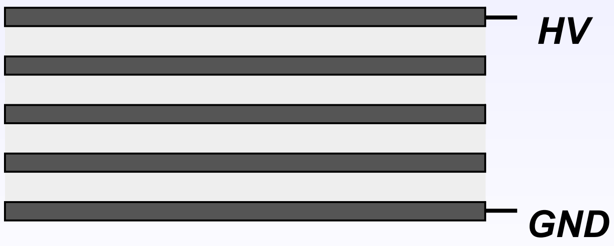


CMS

RPC – Resistive Plate Chamber



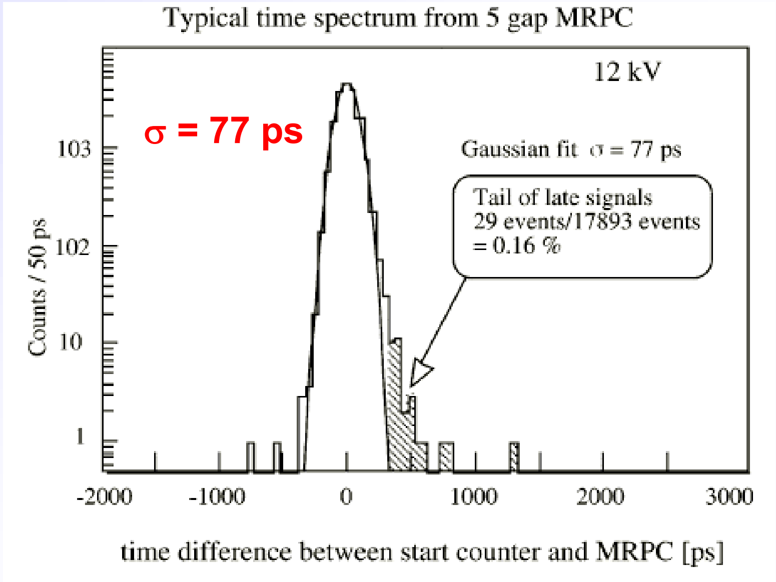
MRPC



Multigap RPC - exceptional time resolution suited for the trigger applications

Rate capability strong function of the resistivity of electrodes in streamer mode.

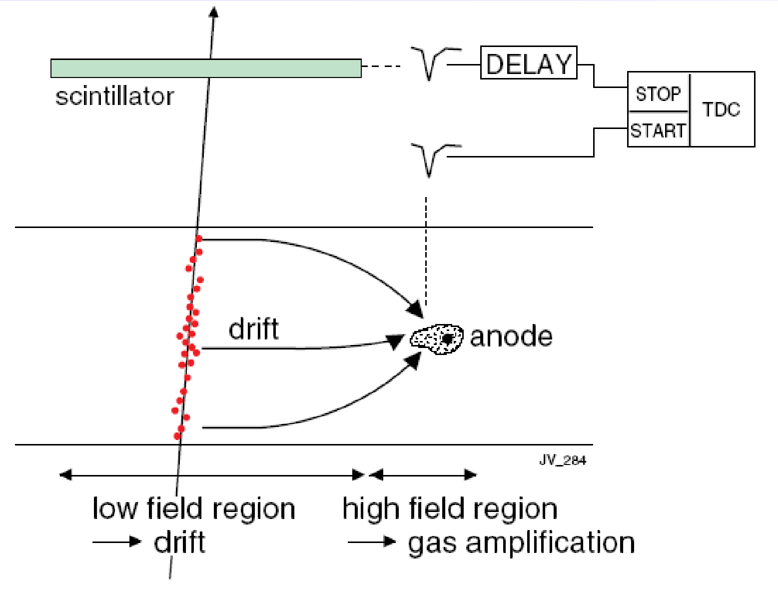
A. Akindinov et al., NIM A456(2000)16



Time resolution

Drift Chambers

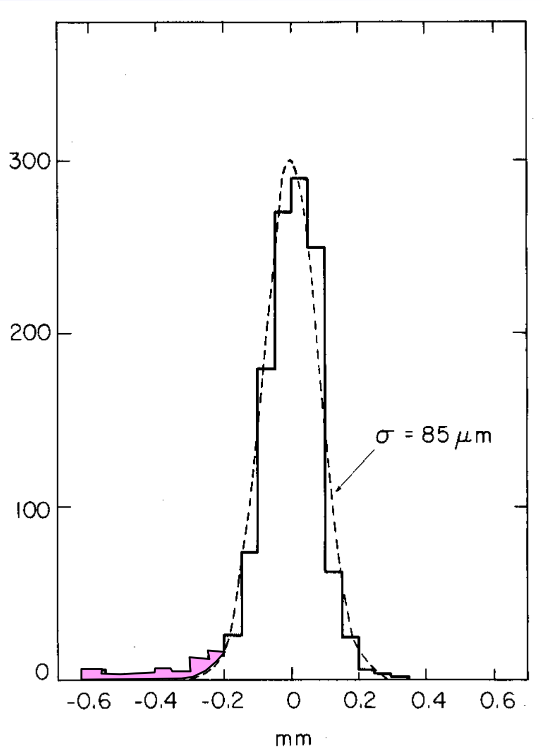
Spatial information obtained by measuring time of drift of electrons



Measure arrival time of electrons at sense wire relative to a time t_0.

Need a trigger (bunch crossing or scintillator).

Drift velocity independent from E.



F. Sauli, NIM 156(1978)147

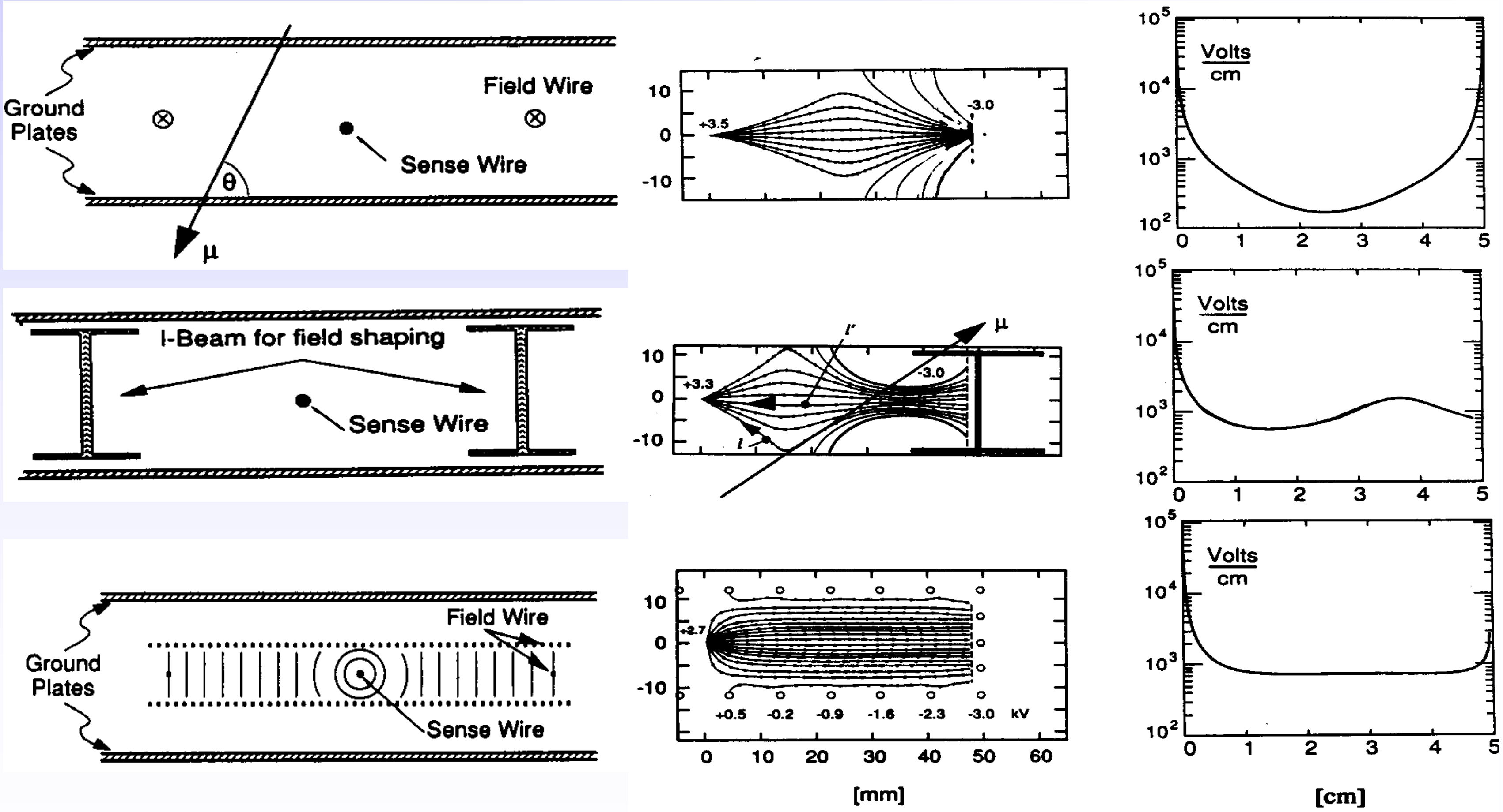
Advantages: smaller number of electronics channels.

Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics.

Drift Chambers

Planar drift chamber designs

Essential: linear space-time relation; constant E-field; little dpendence of v_D on E.



U. Becker in Instrumentation in High Energy Physics, World Scientific

Diffusion of Free Charges

Free ionization charges lose energy in collisions with gas atoms and molecules (thermalization).

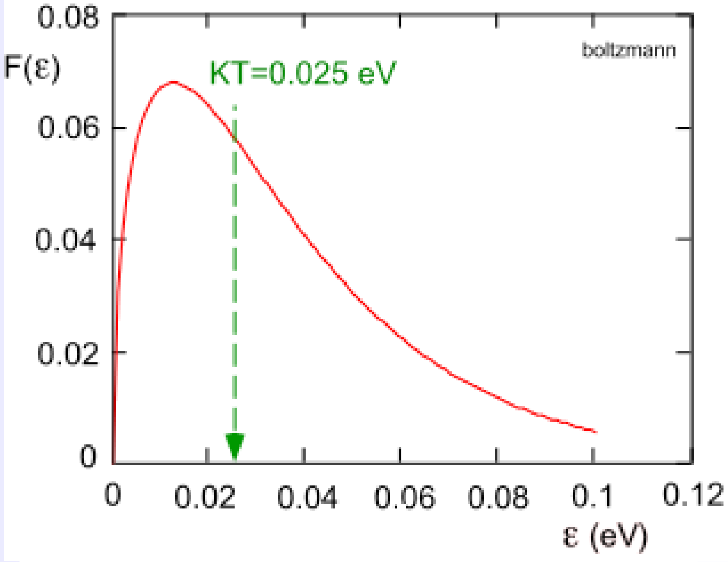
Maxwell - Boltzmann energy distribution:

$$F(\varepsilon) = const\sqrt{\varepsilon}e^{-\frac{\varepsilon}{kT}}$$

Average (thermal) energy:

$$\varepsilon_T = \frac{3}{2}kT \approx 0.040eV$$

F. Sauli, IEEE Short Course on Radiation Detection and Measurement, Norfolk (Virginia) November 10-11, 2002



Diffusion equation:

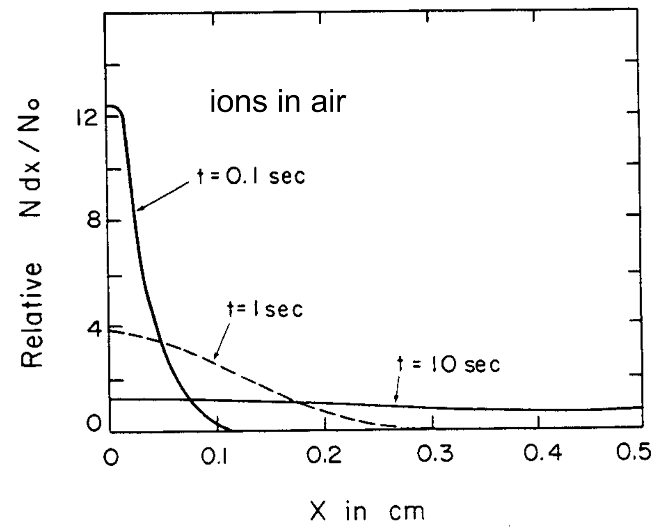
Fraction of free charges at distance x after time t.

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}}e^{-\frac{x^2}{4Dt}}dt$$

D: diffusion coefficient

RMS of linear diffusion:

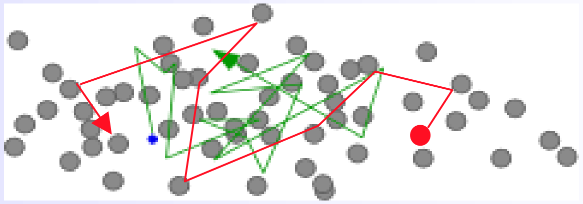
$$\sigma_x = \sqrt{2Dt}$$



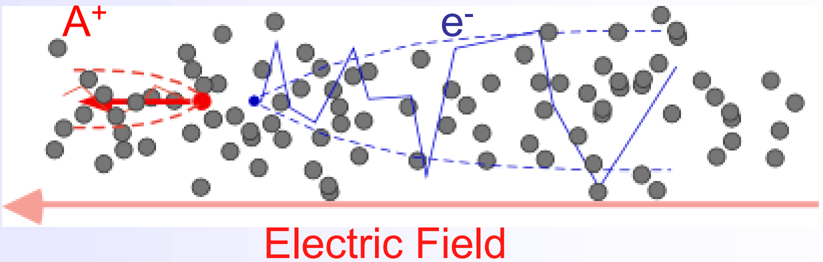
L.B. Loeb, Basic processes of gaseous electronics
Univ. of California Press, Berkeley, 1961

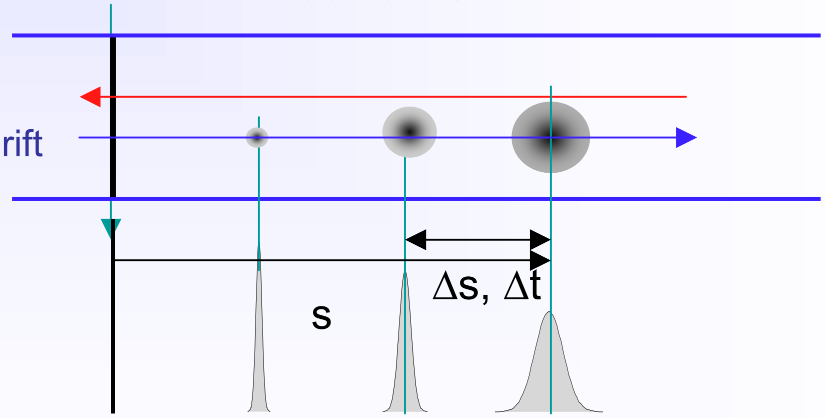
Drift and Diffusion in Presence of E field

E=0 thermal diffusion $\langle v \rangle_t = 0$



E>0 charge transport and diffusion $\langle v \rangle_t = v_D$





Electron swarm drift

Drift velocity

$$v_D = \frac{\Delta s}{\Delta t}$$

Diffusion

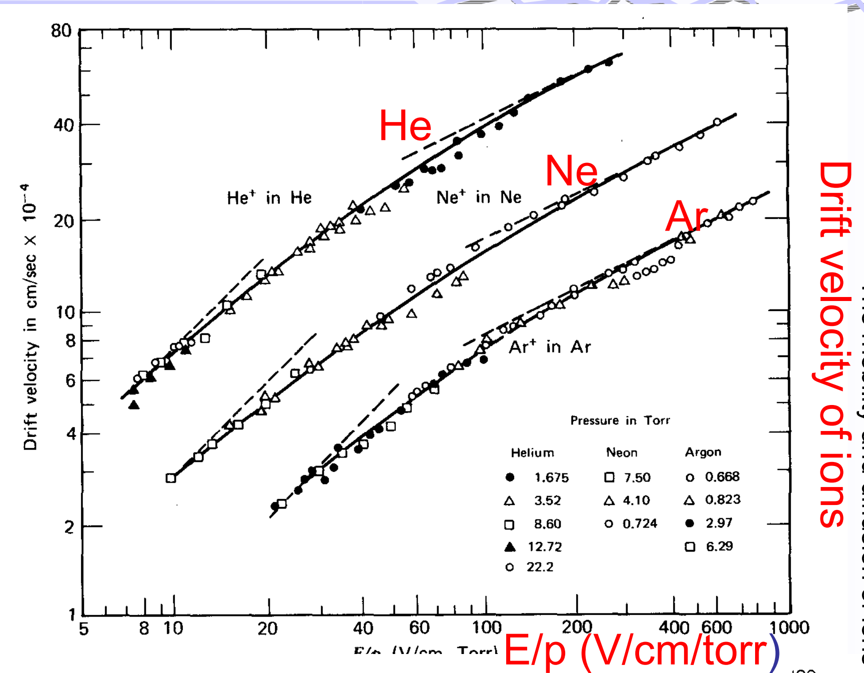
$$\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$$

Drift and Diffusion of Ions in Presence of E Field

Drift velocity of ions

is almost linear function of E $v_D^{ion} = \mu^{ion} E$

Mobility: $\mu^{ion} = \frac{e\tau}{m}$ is constant for given gas at fixed P and T, direct consequence of the fact that average energy of ion is unchanged up to very high E fields.



E. McDaniel and E. Mason, The mobility and diffusion of ions in gases, Wiley 1973

Diffusion of ions

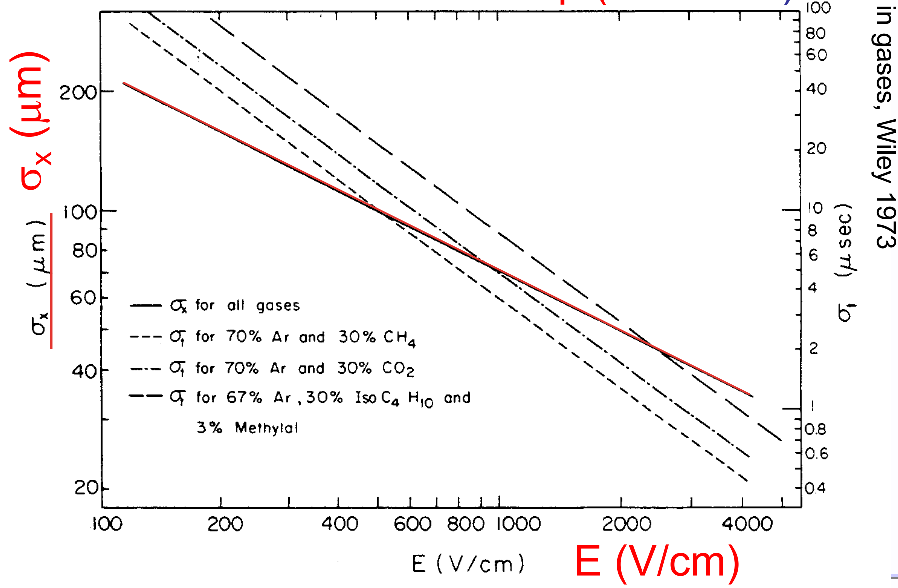
from microscopic picture can be shown:

$$\varepsilon = \frac{3}{2}\frac{De}{\mu}$$

$$\frac{D}{\mu^{ion}} = \frac{kT}{e} \quad \rightarrow \quad \sigma_x^{ion} = \sqrt{\frac{2kT}{e}\frac{x}{E}}$$

thermal limit

the same for all gases !!



Simplified Electron Transport Theory

$v_D = \mu E = \frac{eE}{m}\tau$ Townsend expression; acceleration in the field times time between collisions

$\frac{x}{v_D\tau}\lambda(\varepsilon)\varepsilon_E = eEx$ balance between energy acquired from the field and collision losses

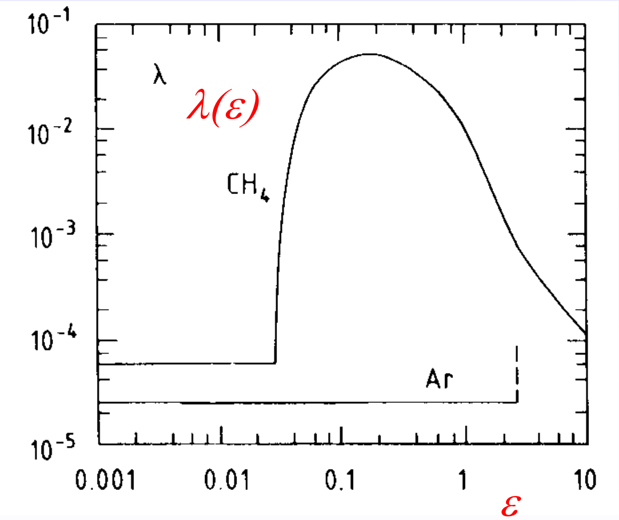
$\frac{x}{v_D\tau}$ number of collisions; $\lambda(\varepsilon)$ fractional energy loss per collision

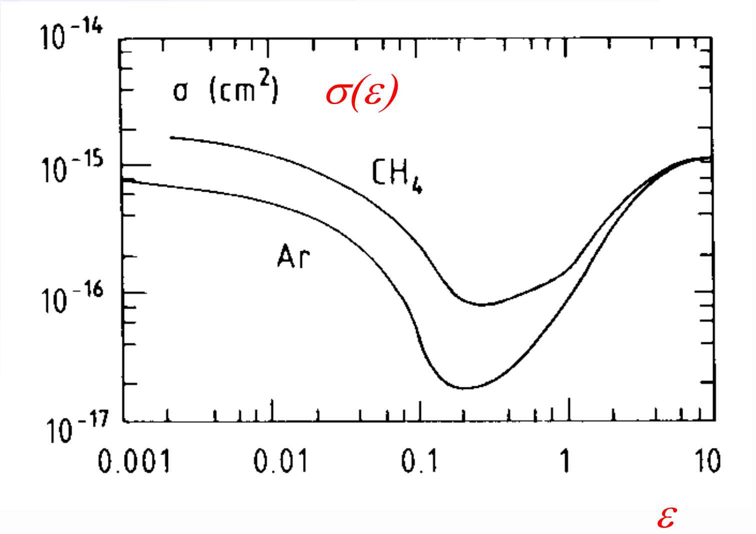
ε_E part of equilibrium energy not containing thermal motion

$\tau = \frac{1}{N\sigma(\varepsilon)v}$ time between collisions; v instantaneous velocity

$\varepsilon_E + \frac{3}{2}kT$ total energy

$$\boxed{v_D^2 = \frac{eE}{mN\sigma(\varepsilon)}\sqrt{\frac{\lambda(\varepsilon)}{2}}}$$

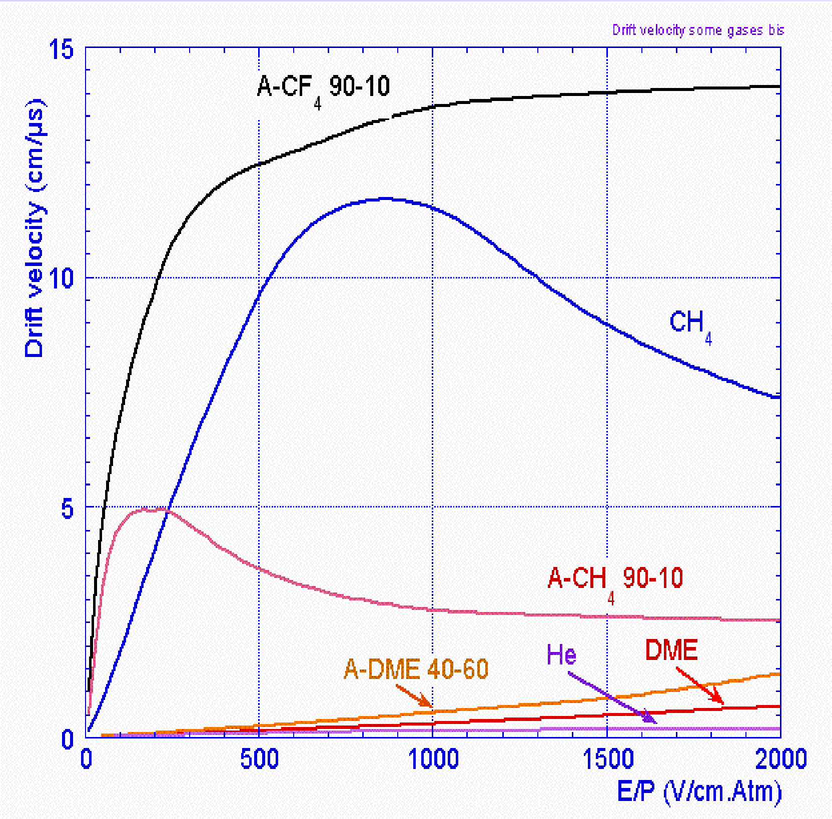


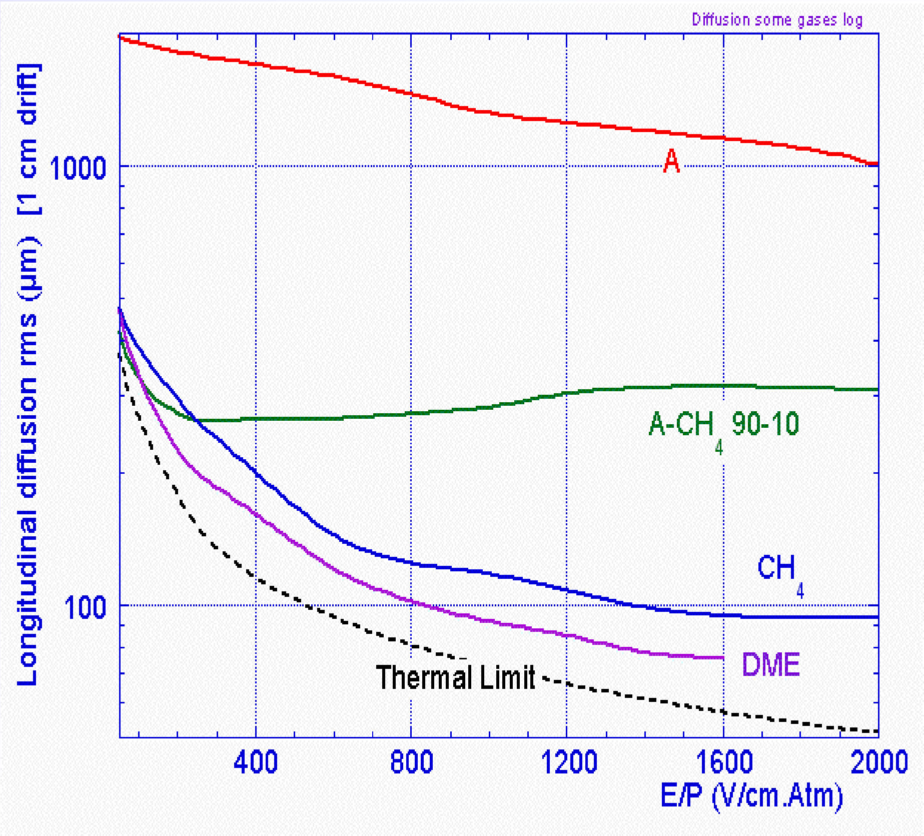


B. Schmidt, thesis, unpublished, 1986

Drift and Diffusion of Electrons in Gases

Large range of drift velocity and diffusion:





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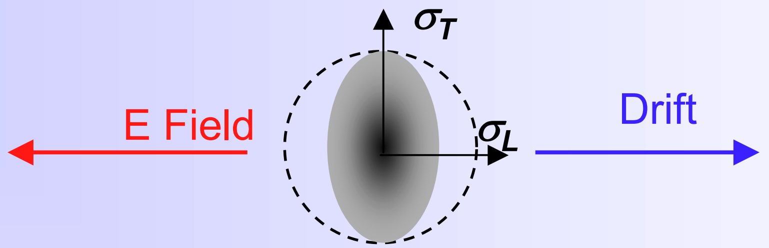
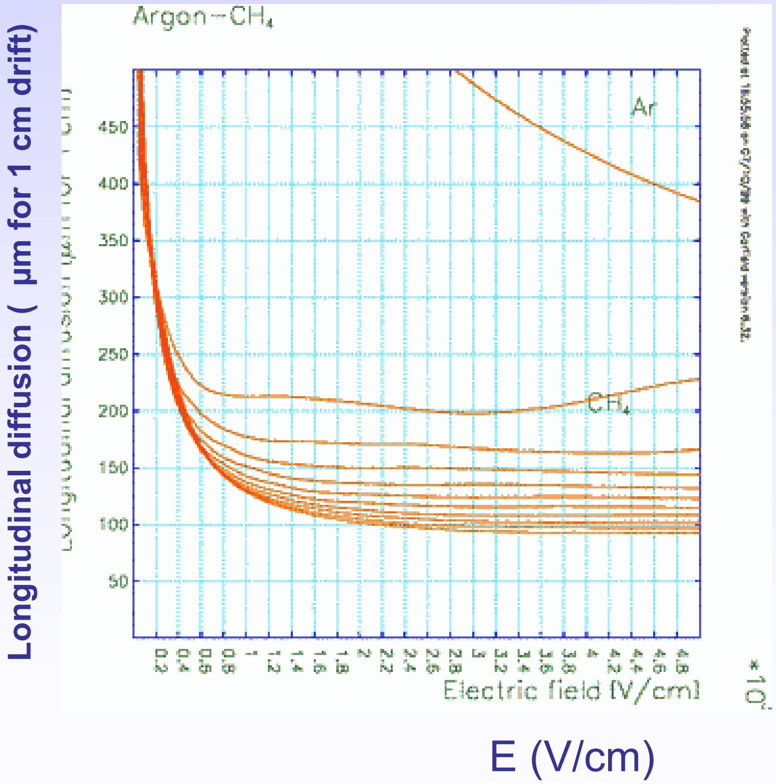
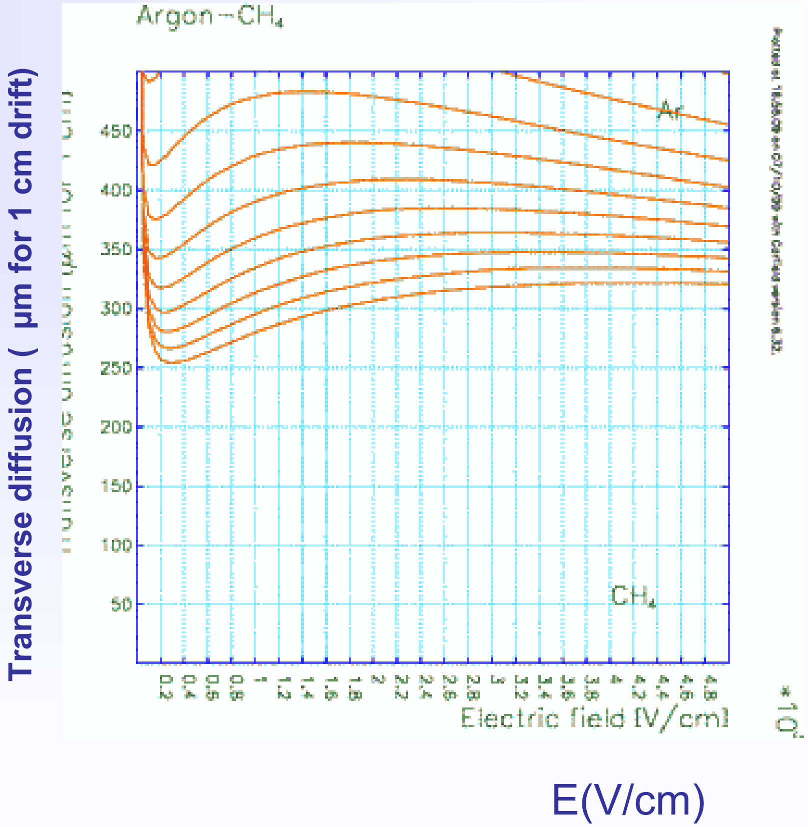
Diffusion Electric Anisotropy







S. Biagi http://consult.cern.ch/writeup/magboltz/

Drift in Presence of E and B Fields

Equation of motion of free charge carriers in presence of E and B fields:

$$m\frac{d\vec{v}}{dt} = e\vec{E} + e(\vec{v}\times\vec{B}) + \vec{Q}(t)$$ where $\vec{Q}(t)$ stochastic force resulting from collisions

Time averaged solutions with assumptions: $\vec{v}_D = \langle\vec{v}\rangle = const.$; $<\vec{Q}(t)> = \frac{m}{\tau}\vec{v}_D$ friction force

$$\left\langle\frac{d\vec{v}}{dt}\right\rangle = 0 = e\vec{E} + e(\vec{v}_D\times\vec{B}) - \frac{m}{\tau}\vec{v}_D$$ τ mean time between collisions

$$\boxed{\vec{v}_D = \frac{\mu|\vec{E}|}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau(\hat{E}\times\hat{B}) + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]}$$

$\mu = \frac{e\tau}{m}$ mobility $\omega = \frac{eB}{m}$ cyclotron frequency

$$B=0 \quad\rightarrow\quad \vec{v}_D^B = \vec{v}_D^0 = \mu\vec{E}$$

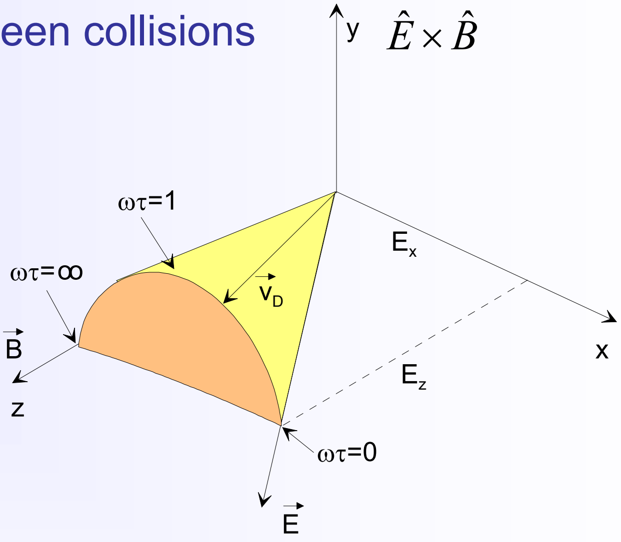
$$\vec{E}\parallel\vec{B} \quad\rightarrow\quad v_D^B = v_D^0$$

$$\vec{E}\perp\vec{B} \quad\rightarrow\quad v_D^B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

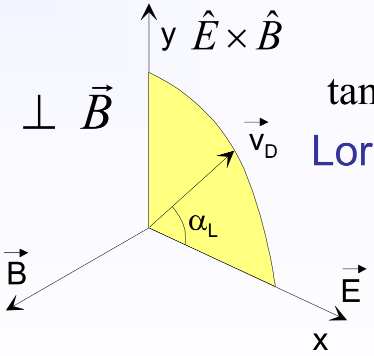
In general drift velocity has 3 components: $\parallel\vec{E};\parallel\vec{B};\parallel\vec{E}\times\vec{B}$

$\omega\tau << 1$ particles follow E-field

$\omega\tau >> 1$ particles follow B-field



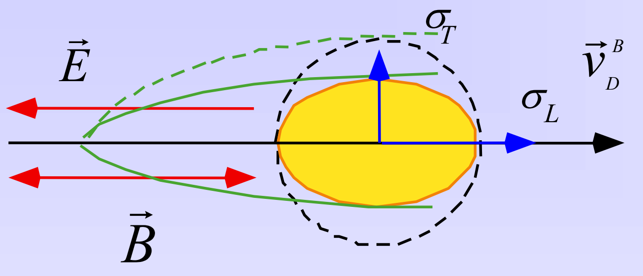
$\vec{E}\perp\vec{B}$



$\tan\alpha_L = \omega\tau$ Lorentz angle

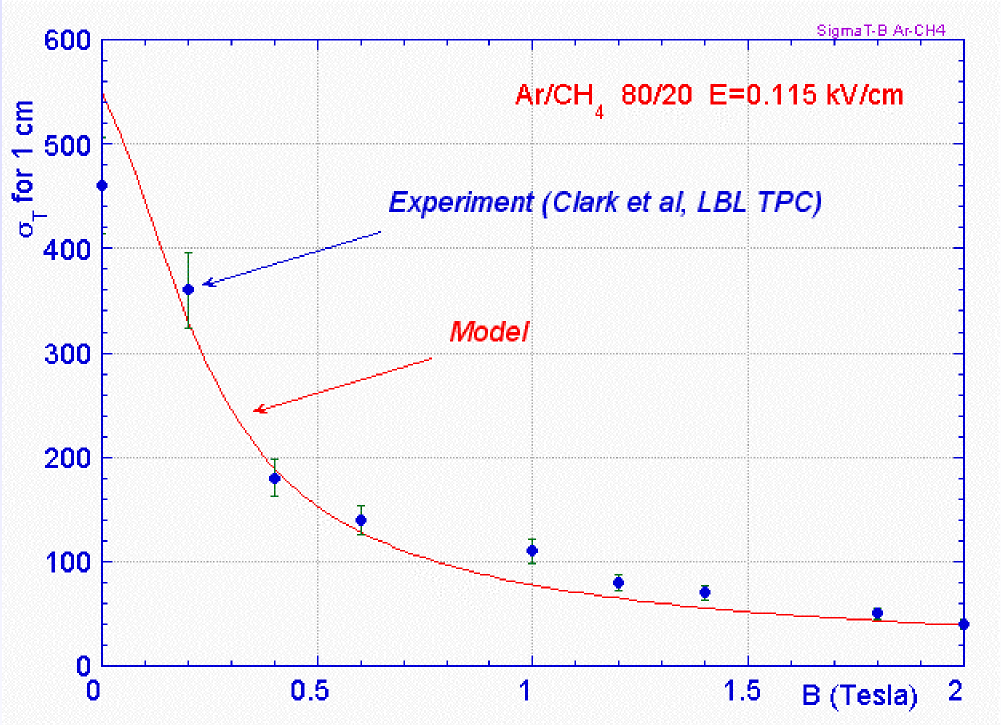
Diffusion Magnetic Anisotropy

$\vec{E} \parallel \vec{B}$



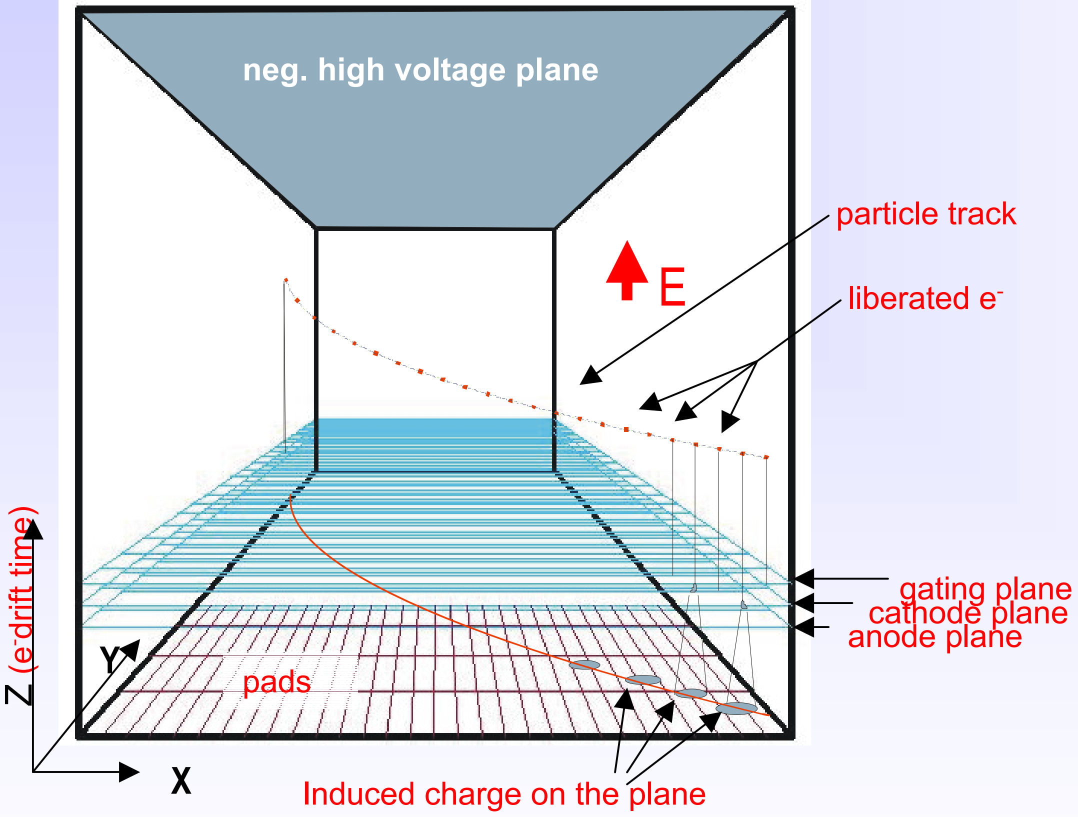
$$\sigma_L = \sigma_0$$

$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$



F. Sauli, IEEE Short Course on Radiation Detection and Measurement, Norfolk (Virginia) November 10-11, 2002

TPC – Time Projection Chamber



Time Projection Chamber

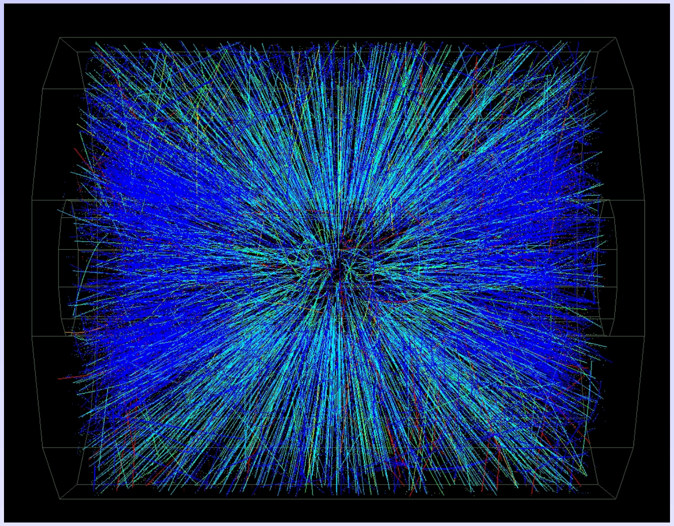
full 3D track reconstruction:

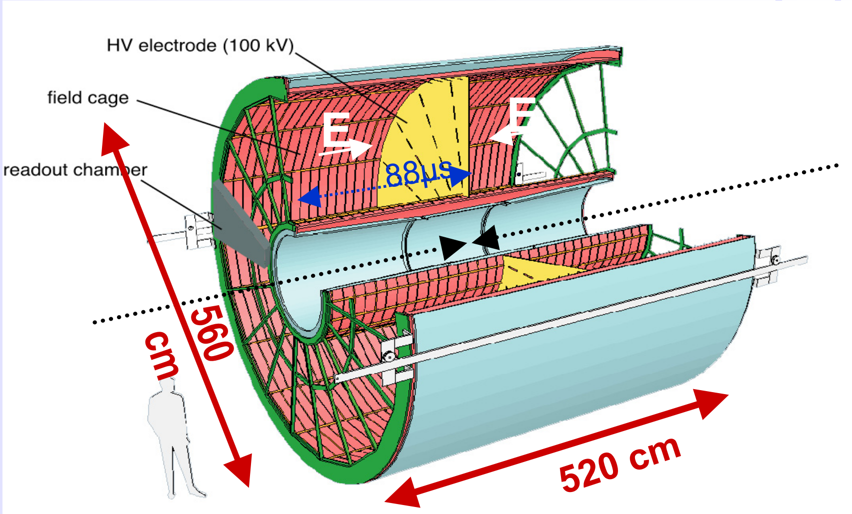
x-y from wires and segmented cathode of MWPC (or GEM)

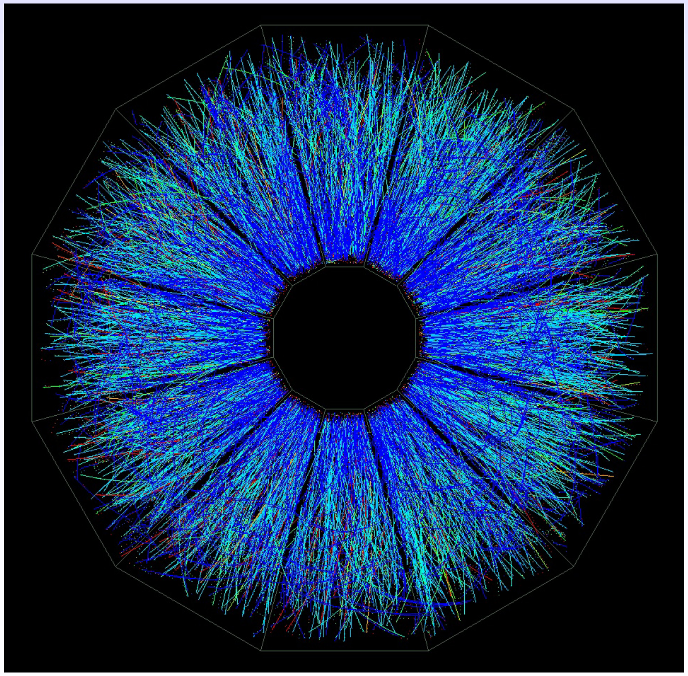
z from drift time

- momentum resolution
  space resolution + B field
  (multiple scattering)
- energy resolution
  measure of primary ionization

TPC – Time Projection Chamber







Alice TPC

HV central electrode at –100 kV

Drift lenght 250 cm at E=400 V/cm

Gas Ne-CO_2 90-10

Space point resolution ~500 μm

dp/p 2%@1GeV; 10%@10GeV

Events from STAR TPC at RHIC

Au-Au collisions at CM energy of 130 GeV/n

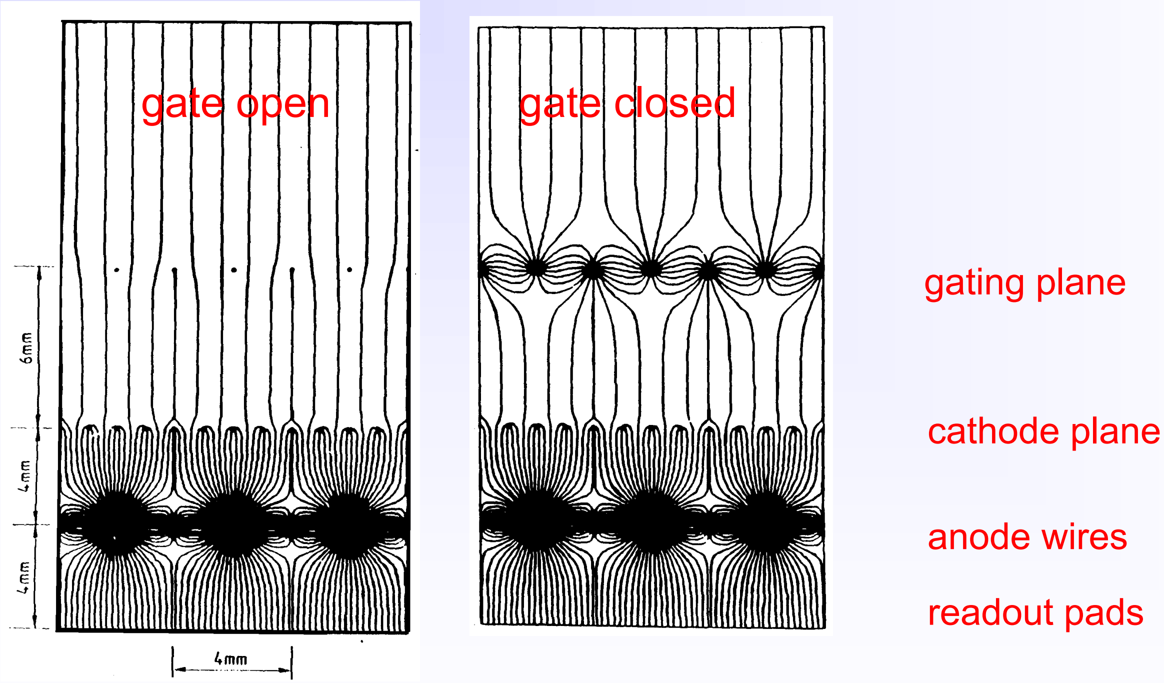
Typically ~2000 tracks/event

TPC – Time Projection Chamber

Positive ion backflow modifies electric field resulting in track distortion.

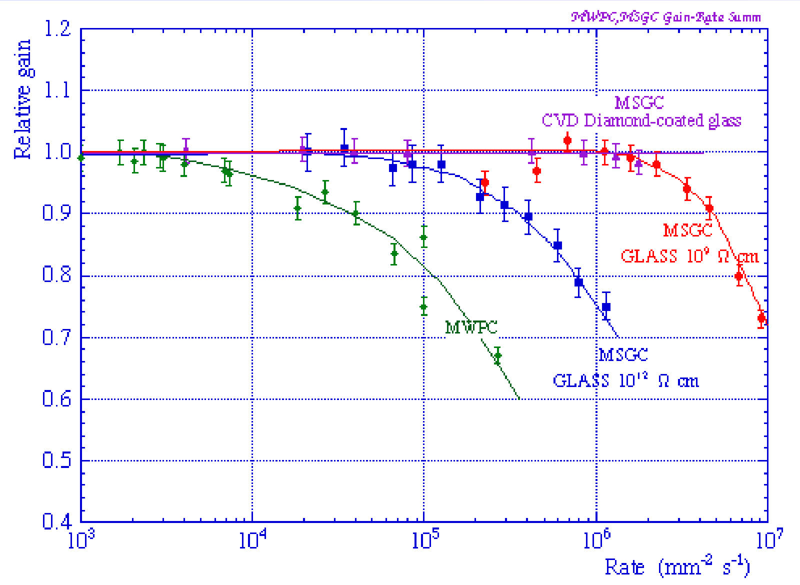
Solution : gating

Prevents electrons to enter amplification region in case of uninteresting event;
Prevents ions created in avalanches to flow back to drift region.



ALEPH coll., NIM A294(1990)121

Micropattern Gas Detectors



Advantages of gas detectors:

- low radiation length
- large areas at low price
- flexible geometry
- spatial, energy resolution …

Problem:

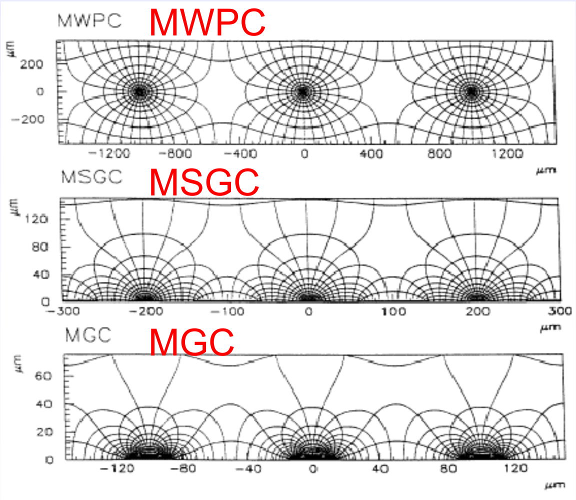
- rate capability limited by space charge defined by the time of evacuation of positive ions

scale factor

1

5

10

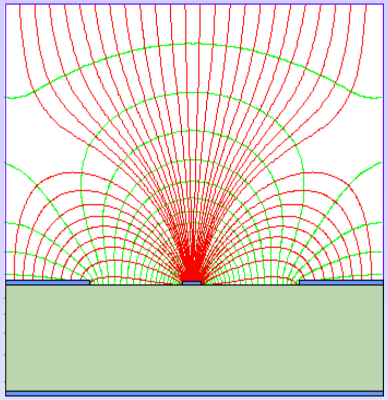


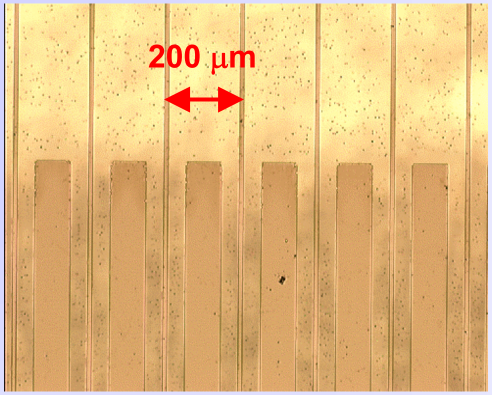
R. Bellazzini et al.

Solution:

- reduction of the size of the detecting cell (limitation of the length of the ion path) using chemical etching techniques developed for microelectronics and keeping at same time similar field shape.

MSGC – Microstrip Gas Chamber



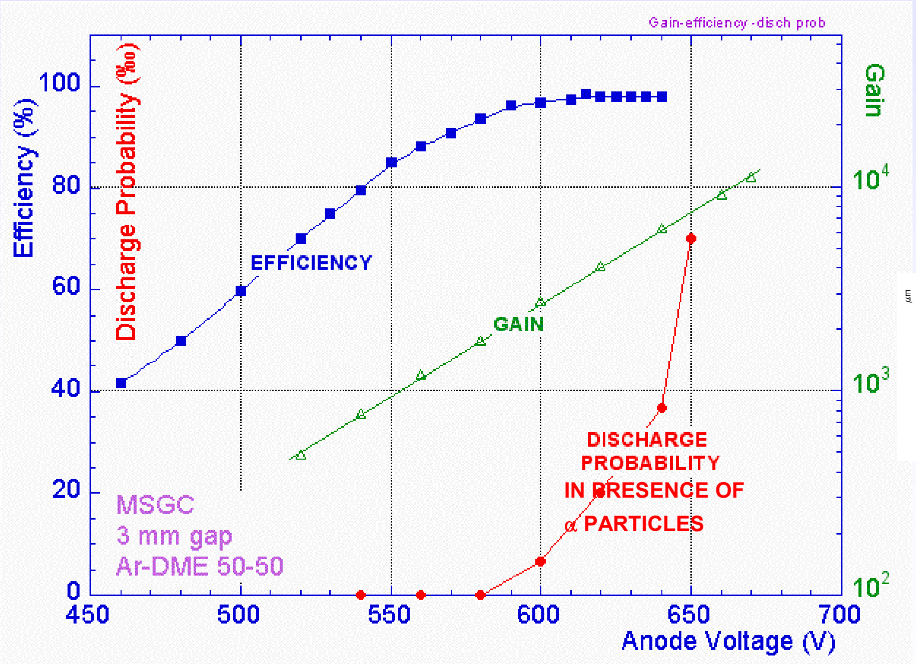


Thin metal anodes and cathodes on insulating support (glass, flexible polyimide ..)

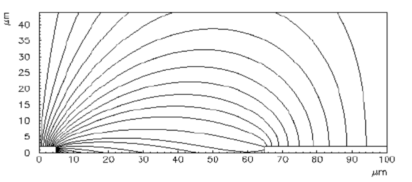
Problems:

High discharge probability under exposure to highly ionizing particles caused by the regions of very high E field on the border between conductor and insulator.

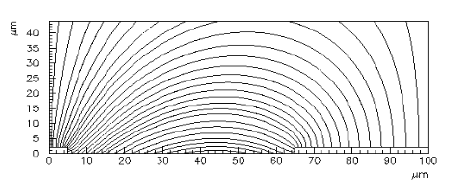
Charging up of the insulator and modification of the E field → time evolution of the gain.



insulating support



slightly conductive support



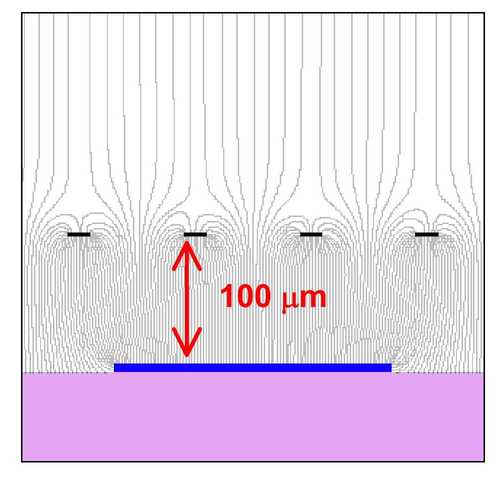
R. Bellazzini et al.

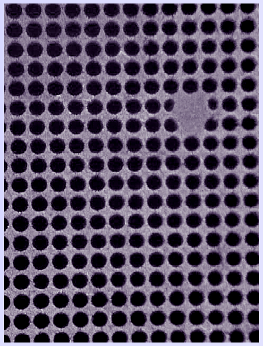
Solutions:

slightly conductive support

multistage amplification

Micromegas – Micromesh Gaseous Structure



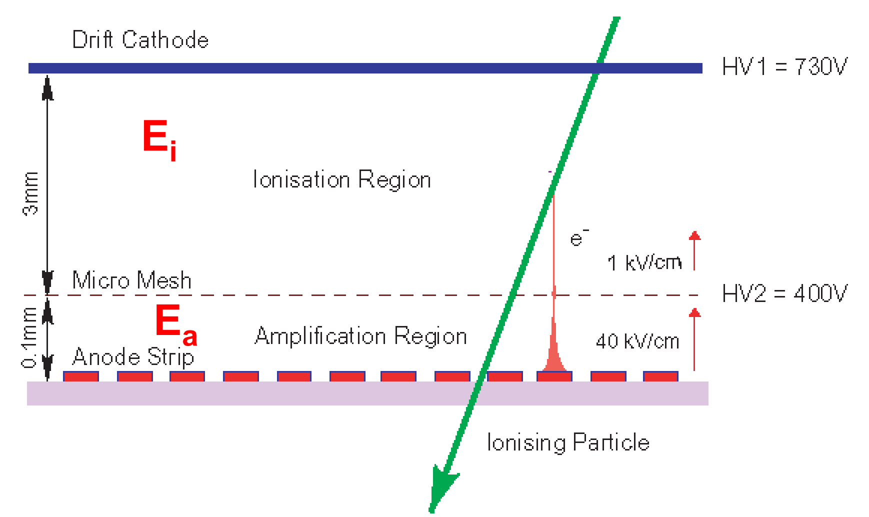


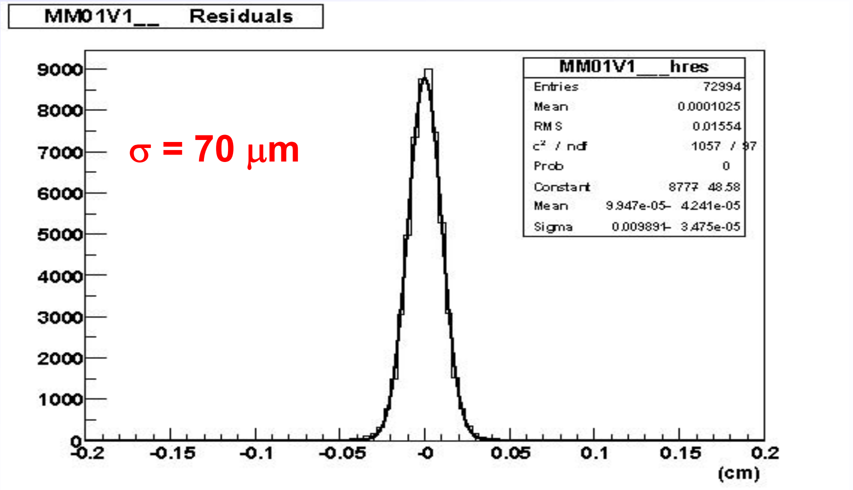
micromesh

Micromesh mounted above readout structure (typically strips).

E field similar to parallel plate detector.

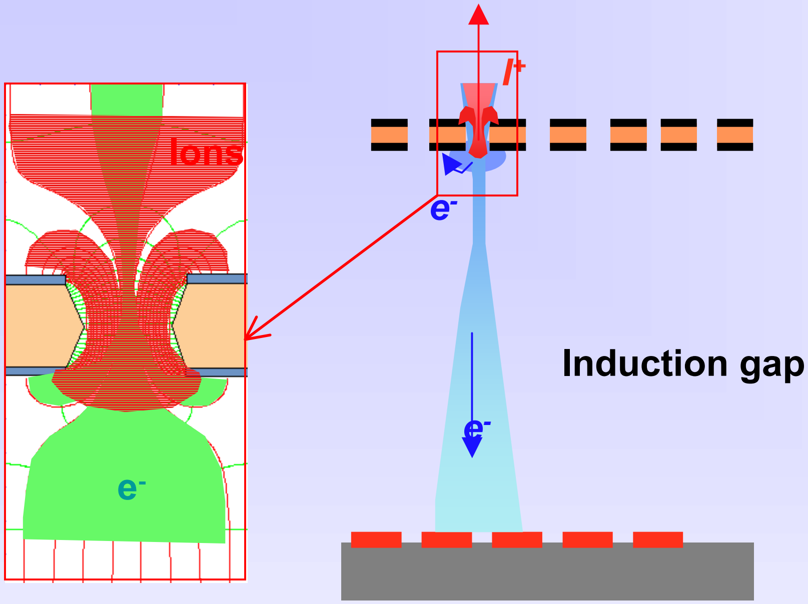
E_a/E_i ~ 50 to secure electron transparency and positive ion flowback supression.

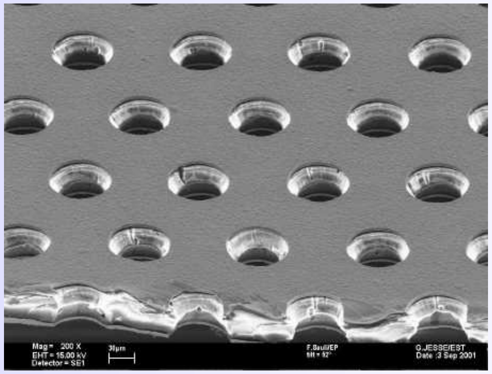


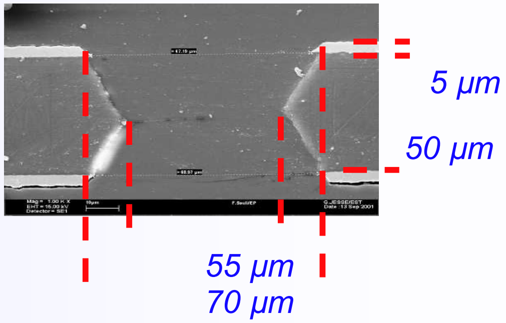


Space resolution

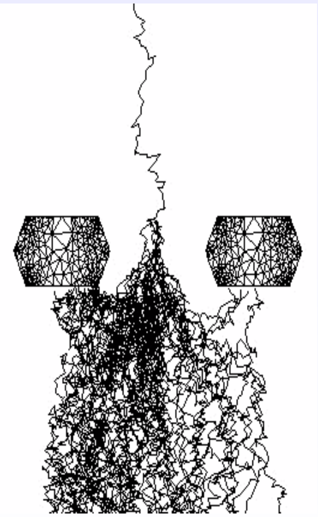
GEM – Gas Electron Multiplier





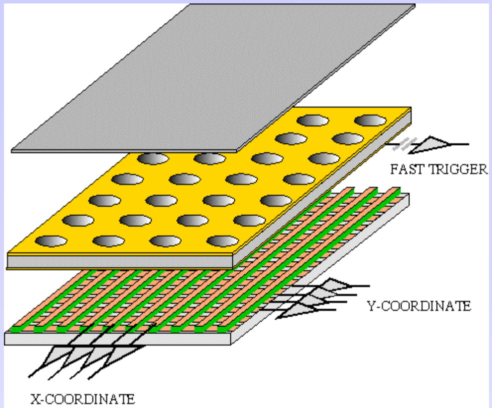


Thin, metal coated polyimide foil perforated with high density holes.



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

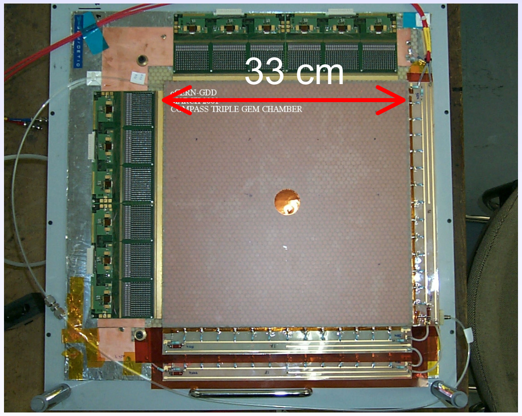
GEM – Gas Electron Multiplier

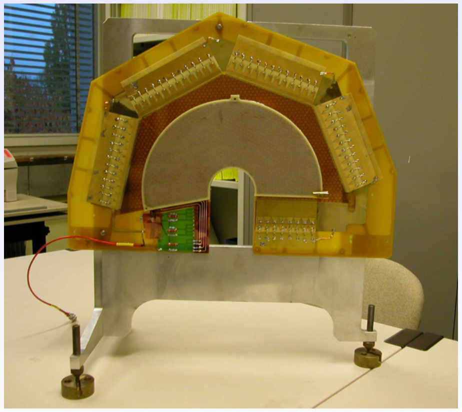


Full decupling of the charge ampification structure from the charge collection and readout structure.

Both structures can be optimized independently !

A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

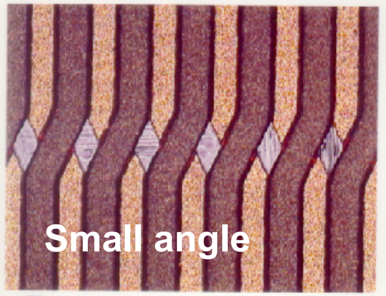


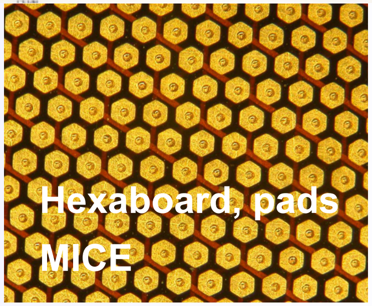


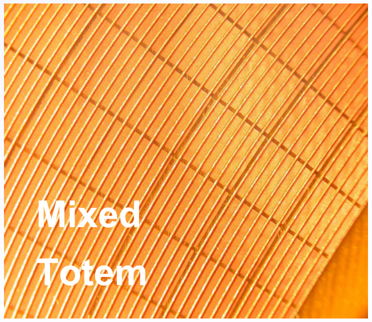
Compass

Totem

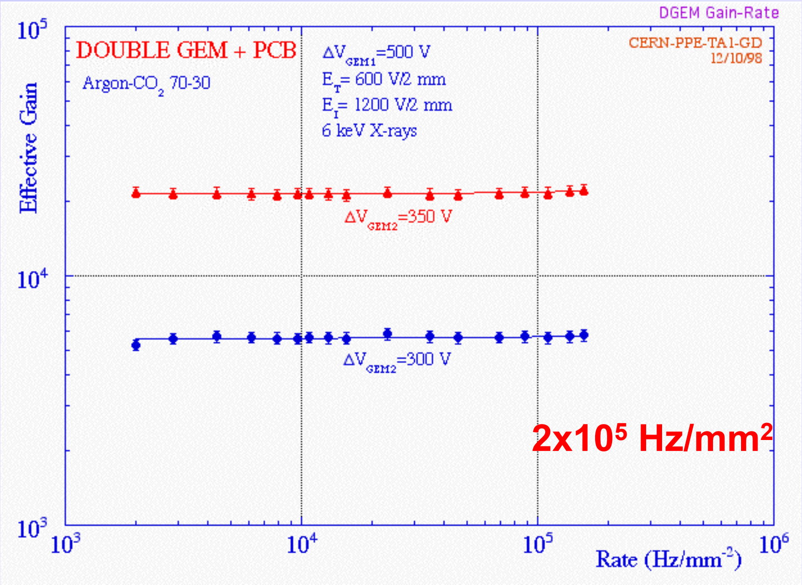
Both detectors use three GEM foils in cascade for amplification to reduce discharge probability by reducing field strenght.



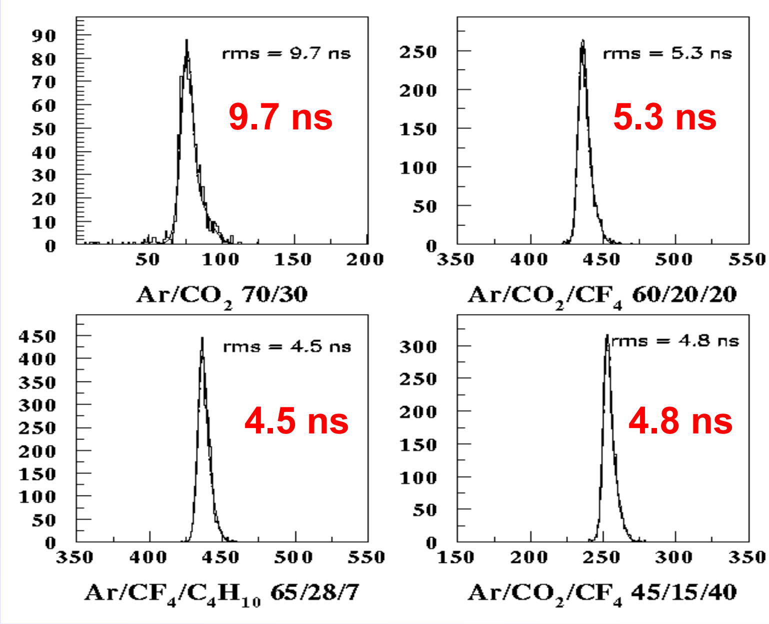




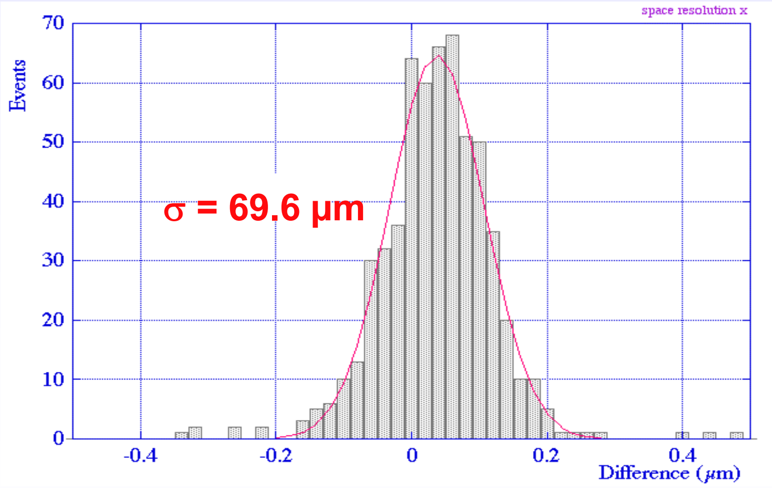
GEM – Gas Electron Multiplier



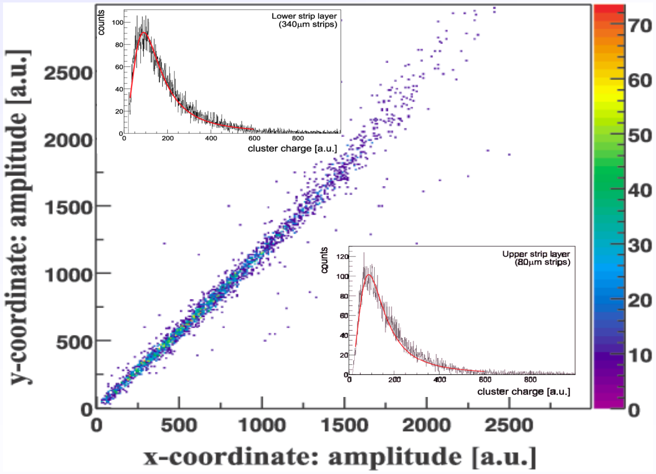
Rate capability



Time resolution



Space resolution



Charge corellation (cartesian readout)

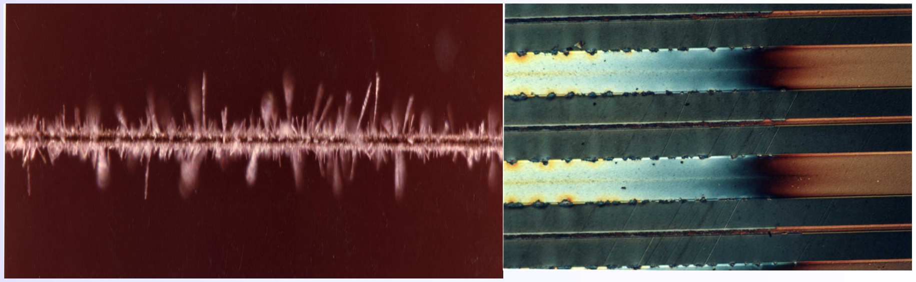
Limitations of Gas Detectors

Classical ageing

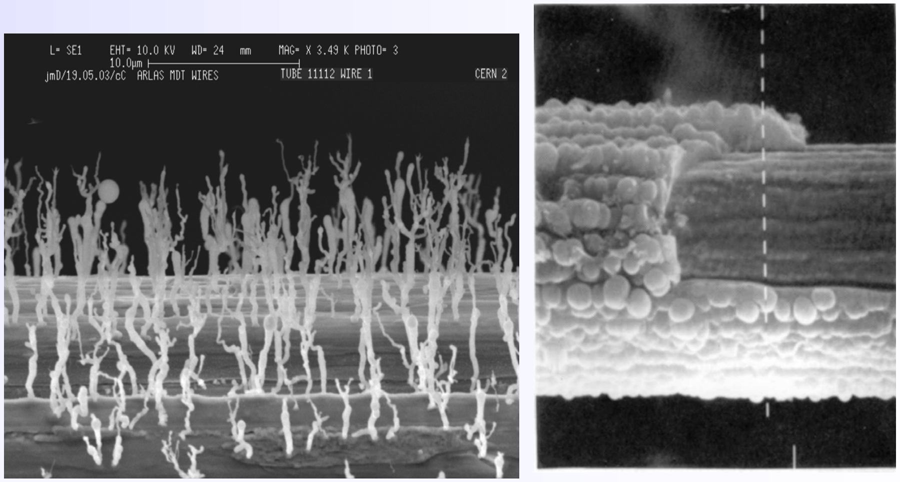
Avalanche region → plasma formation

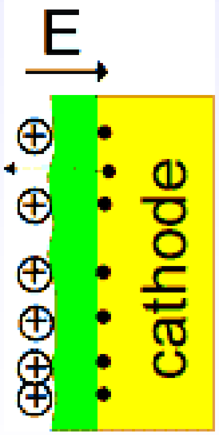
(complicated plasma chemistry)

- 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).

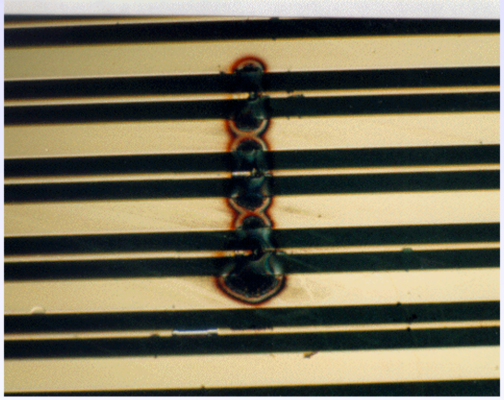
Limitations of Gas Detectors

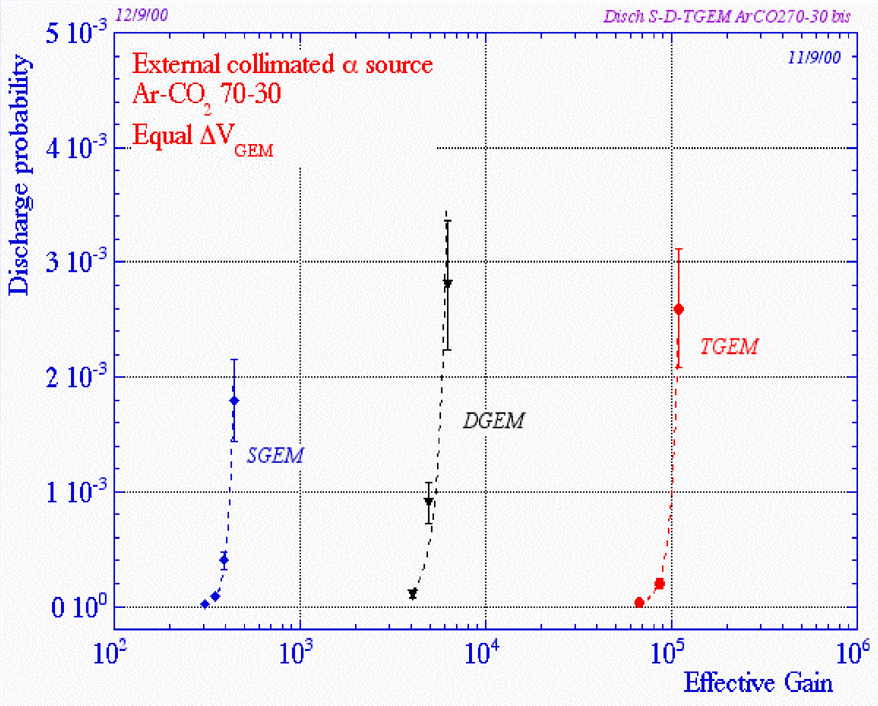
Solutions: carefull material selection for the detector construction and gas system, detector type (GEM is resitant to classical ageing), working point, non-polymerizing gases, additives supressing polymerization (alkohols, methylal), additives increasing surface conductivity (H_2O vapour), clening additives (CF_4).

Discharges

Field and charge density dependent effect.

Solution: multistep amplification





Space charge limiting rate capability

Solution: reduction of the lenght of the positive ion path

Insulator charging up resulting in gain variable with time and rate

Solution: slightly conductive materials

Computer Simulations

MAXWELL *(Ansoft)*

electrical field maps in 2D& 3D, finite element calculation for arbitrary electrodes & dielectrics

HEED *(I.Smirnov)*

energy loss, ionization

MAGBOLTZ *(S.Biagi)*

electron transport properties: drift, diffusion, multiplication, attachment

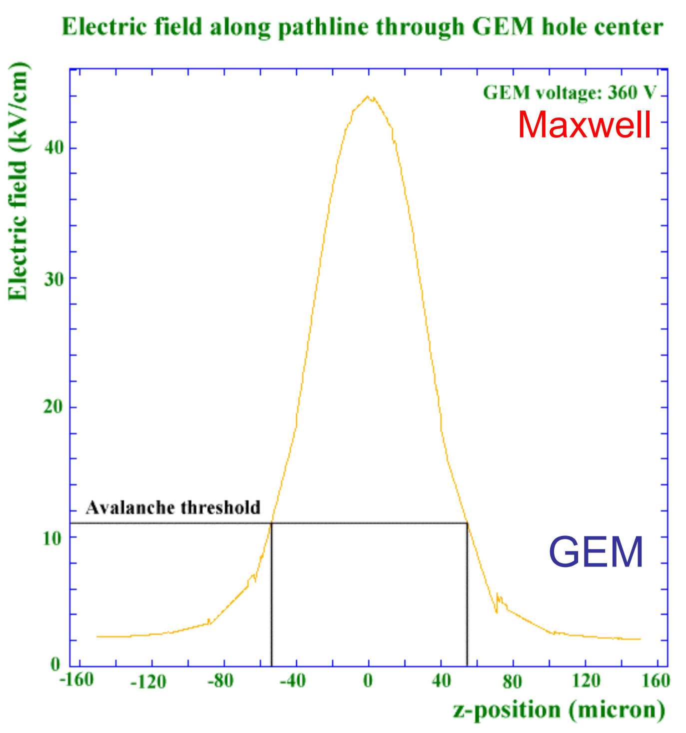
Garfield *(R.Veenhof)*

fields, drift properties, signals (interfaced to programs above)

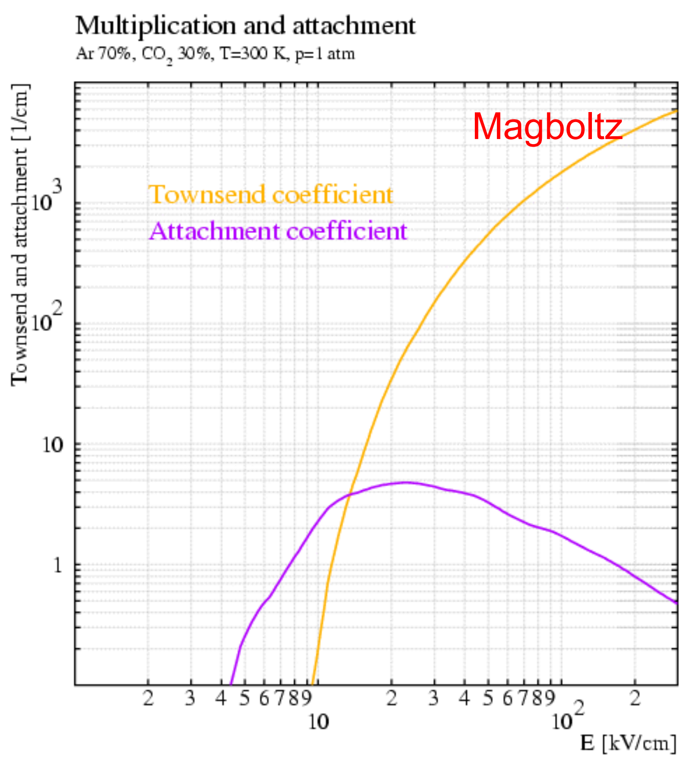
PSpice *(Cadence D.S.)* electronic signal

Computer Simulations

Input: detector geometry, materials and elctrodes potentials, gas cross sections.



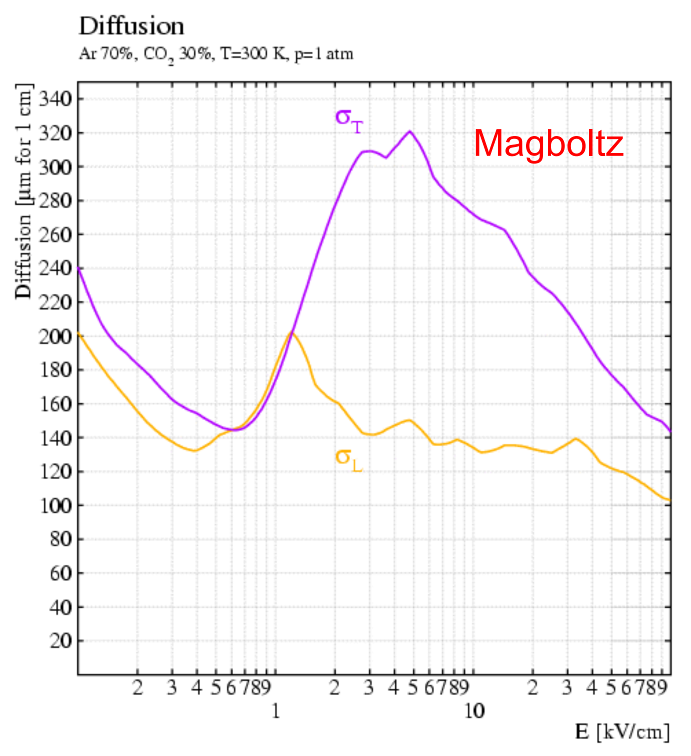
Field Strenght



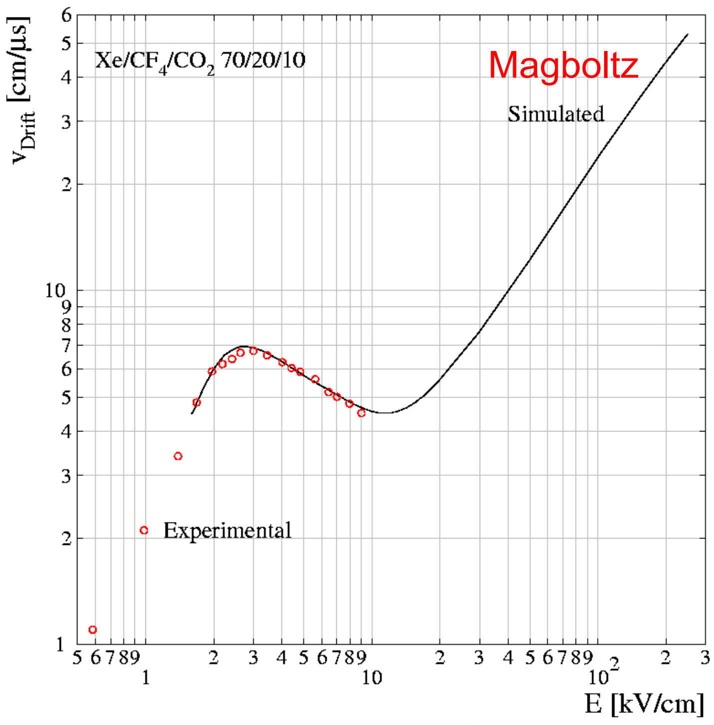
Townsend coefficient

P. Cwetanski, http://pcwetans.home.cern.ch/pcwetans/

Computer Simulations



Longitudinal, transverse diffusion



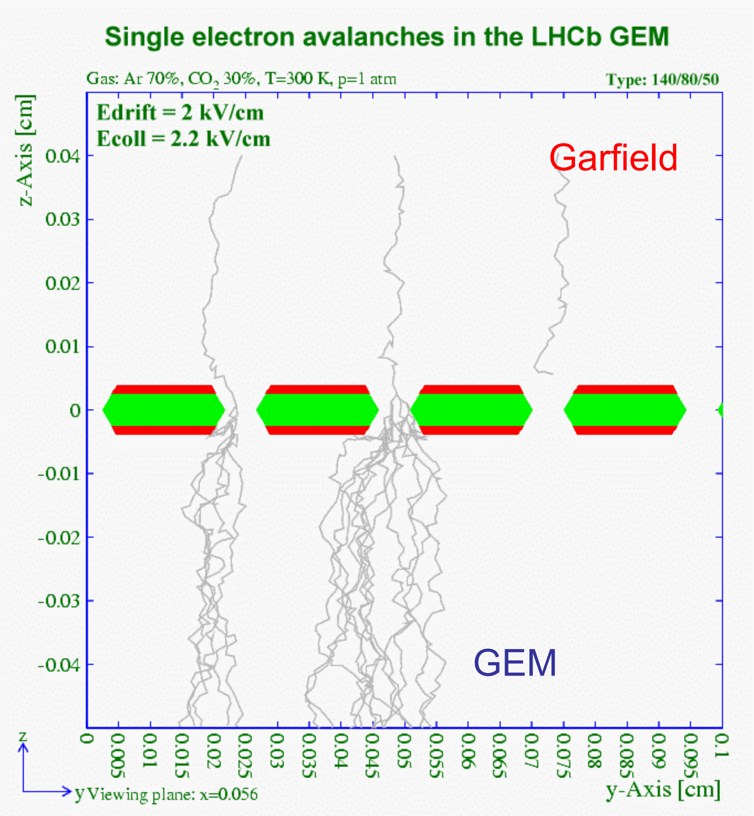
Drift velocity

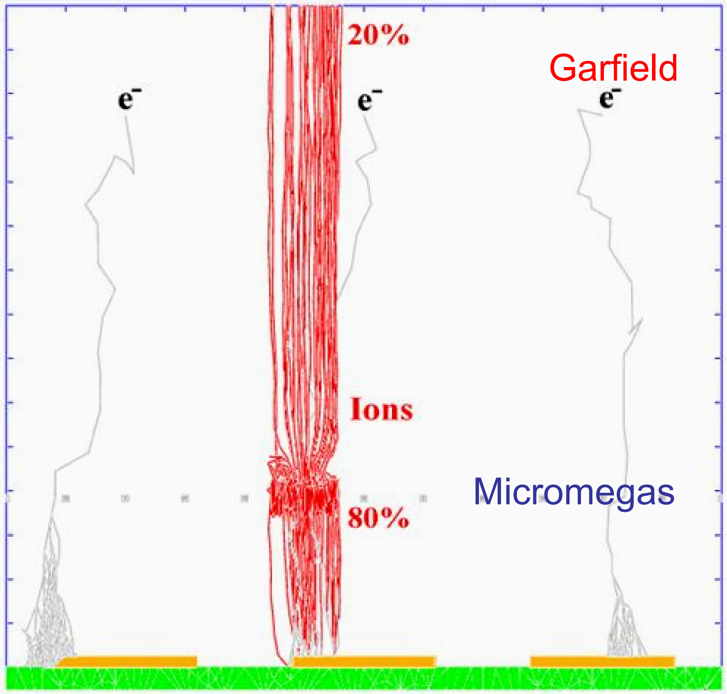
P. Cwetanski, http://pcwetans.home.cern.ch/pcwetans/

CERN Academic Training Programme 2004/2005

Computer Simulations

P. Cwetanski, http://pcwetans.home.cern.ch/pcwetans/





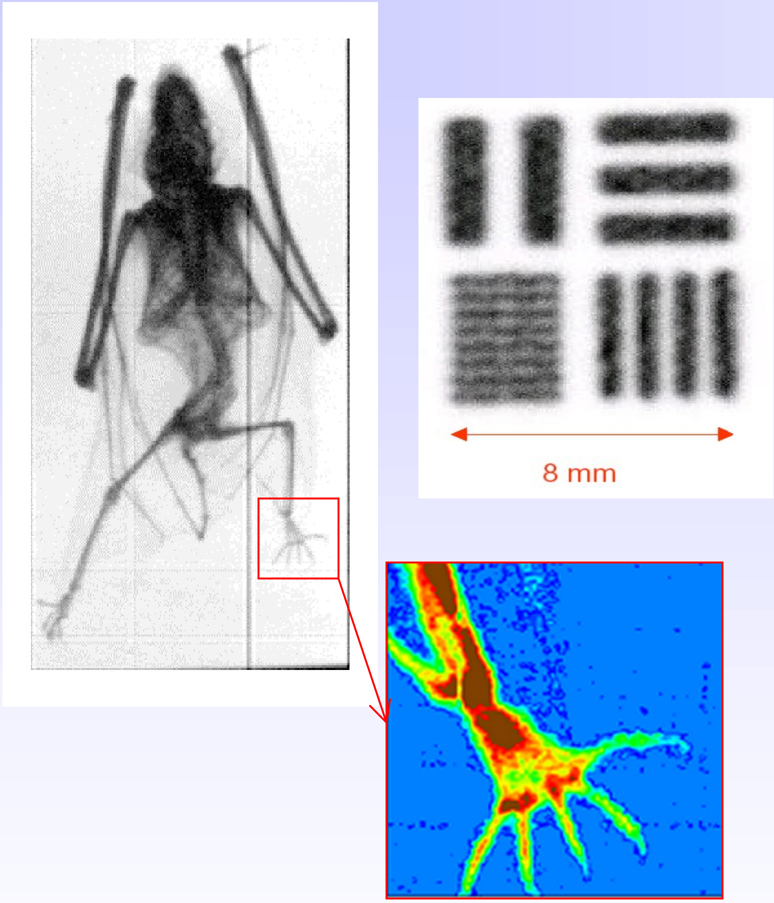
Electrons paths and multiplication

Positive ion backflow

Conclusion: we don't need to built detector to know its performance

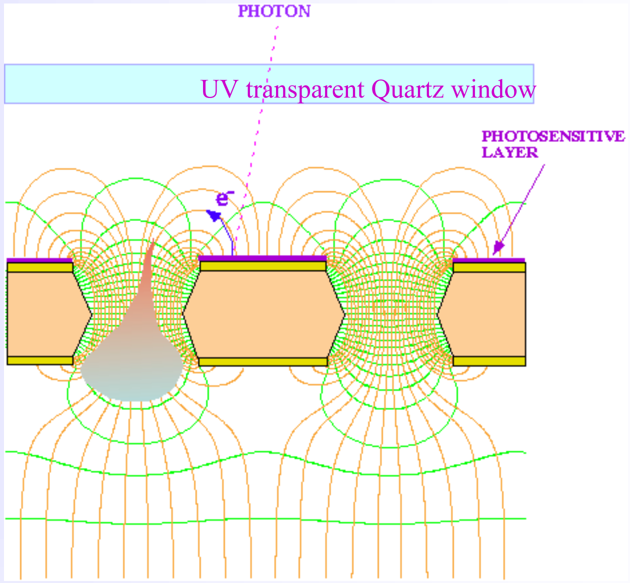
Other (than tracking) Applications

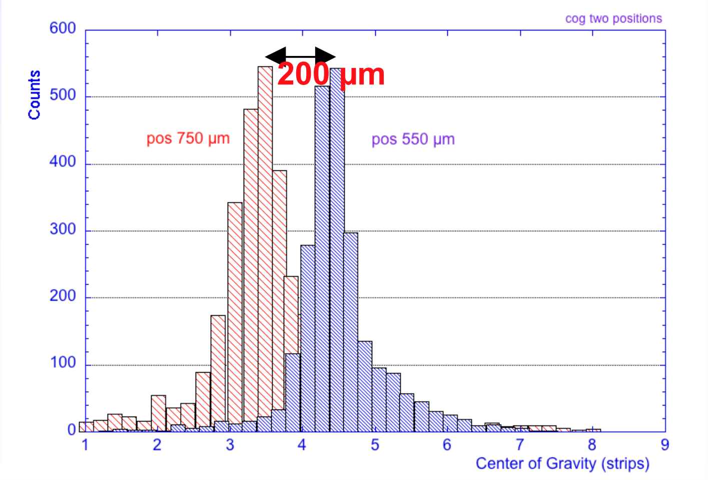
Radiography with GEM (X-rays)



Trigger from the bottom electrode of GEM.

UV light detection with GEM





Gas Detectors in LHC Experiments

ALICE:	TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)
ATLAS:	TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)
CMS:	Muon detector (drift tubes, CSC), RPC (muon trigger)
LHCb:	Tracker (straw tubes), Muon detector (MWPC, GEM)
TOTEM:	Tracker & trigger (CSC , GEM)

CERN Academic Training Programme 2004/2005

Acknowledgments

F. Sauli, IEEE Short Course on Radiation Detection and Measurement, Norfolk (Virginia) November 10-11, 2002

C. Joram, CERN Academic Training, Particle Detectors 1998

P. Cwetanski , http://pcwetans.home.cern.ch/pcwetans/

M. Hoch, Trends and new developments in gaseous detectors, NIM A535(2004)1-15

Literature:

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W. Blum and L. Rolandi, Particle Detection with Drift Chambers, Springer 1994

C. Grupen, Particle Detectors, Cambridge University Press, 1996

F. Sauli and A. Sharma, Micropattern Gaseous Detectors, Annu. Rev. Nucl. Part. Sci. 1999.49:341-88

http://gdd.web.cern.ch/GDD/