Tracking at LHC

M.. Vander Donckt, CERN

Outline

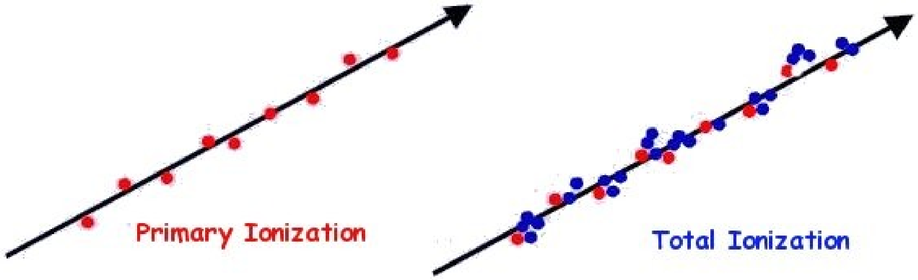
- Detector Requirements at LHC
- Semiconducting Detectors
  - Semiconductors for tracking
  - Solutions at LHC
  - Improvements for the future
- Gas Detectors
  - Gas detection technique & issues
  - Gas detectors at LHC

LHC Requirements

- High granularity for high track density
- Low material budget
- Speed : bunch crossings every 25ns, detectors and their electronics need to be fast.
- Radiation hardness :
  - Expected accumulated dose $=2\ 10^6$ Gy / r^2 / year (r in cm),
  - 70kGy of ionizing radiation
- Magnetic Field for high momentum precision

Gas Detectors

Ionization of Gases



Fast charged particles ionize atoms of gas.

Primary electrons will have enough kinetic energy to ionize other atoms.

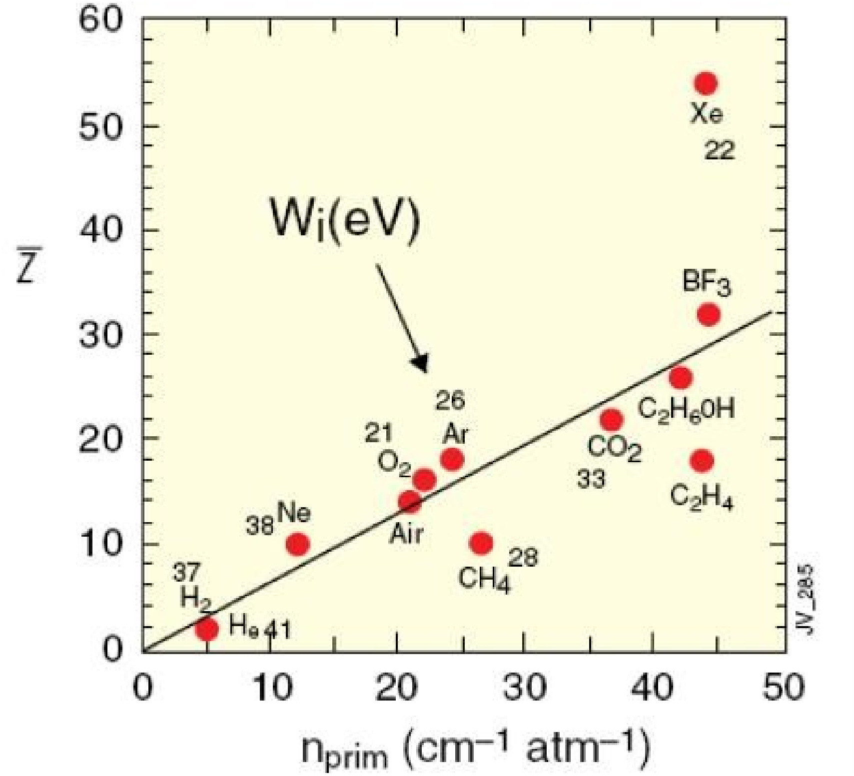
$$ntot = \frac{\Delta E}{Wi} = \frac{\frac{dE}{dx} \cdot \Delta x}{Wi}$$

ntot: number of created e^--ion pairs

≈ 3 to 4 time n_{prim}

ΔE = total energy loss

Wi = effective <energy loss>/pair



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

Ionization of Gases

- Primary ionization is Poisson Distributed

$$P(m)=\frac{\overline{n}^{m}\cdot e^{-\overline{n}}}{m!}$$

$$\overline{n}=\frac{L}{\lambda}=\ln\sigma_i$$

The detection efficiency can be much lower than 1 for thin layers

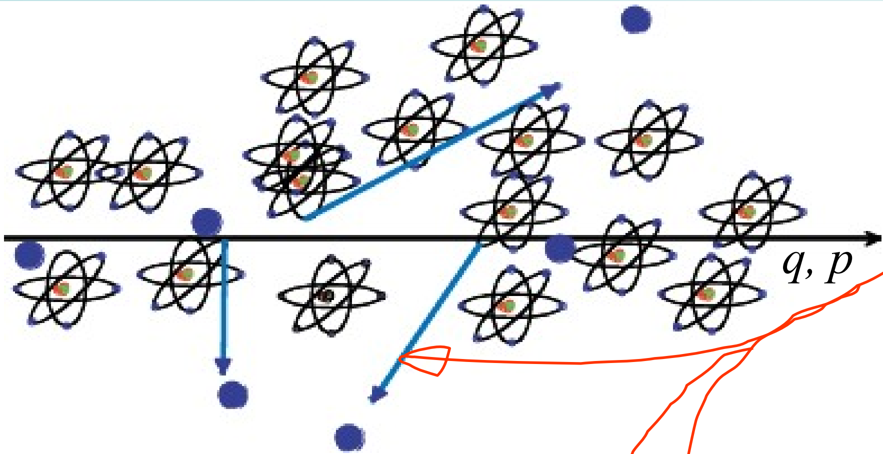
$$\varepsilon_{det}=1-P(0)=1-e^{-\overline{n}}$$

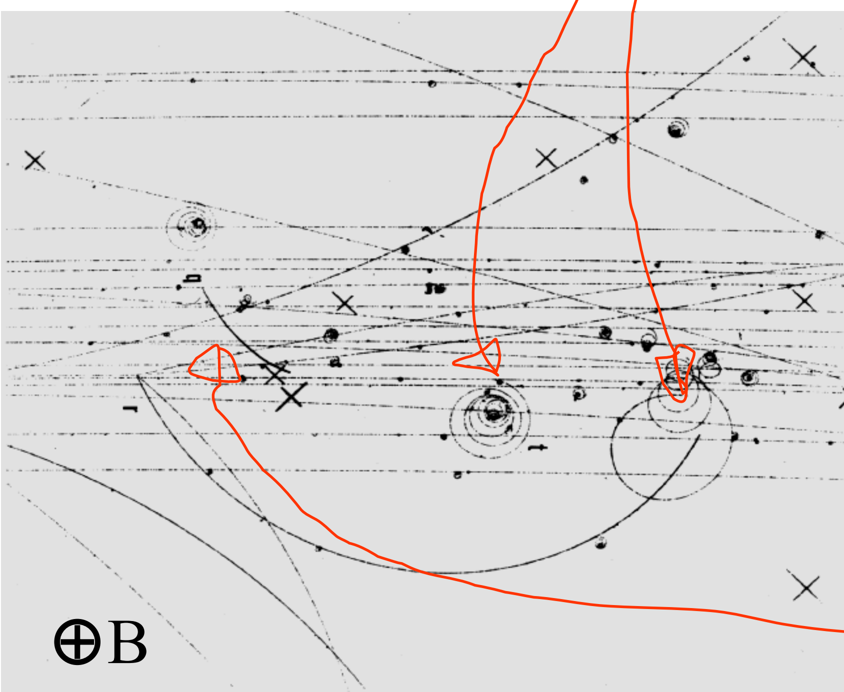
eg: 1mm of Ar n_{prim}=2.5 $\Longrightarrow$ e_{det}=0.92

- Impossible to detect ~100 e^-/ion pairs (amp noise ≈ 1000 e-)

$\Longrightarrow$ Needs amplification!!!

δ-electrons and other fluctuations.





http://www.ep.ph.bham.ac.uk/user/watkins/seeweb/Bubble.htm
Written by Peter Watkins of Birmingham University. The web pages were produced by Tom Adams of Cheltenham College

In the ionization, the ejected electron will have a kinetic energy: $0 \le T \le T_{max}$

A δ-ray with kinetic energy T_e and corresponding momentum p_e is produced at an angle Θ given by

$$\cos\Theta = \frac{T_e}{p_e}\frac{p_{\max}}{T_{\max}}$$

where p_{max} is the momentum of an electron with the maximum possible energy transfer T_{max}.

This (knock-on) electron can therefore have enough energy to ionize (far) away from the primary track.

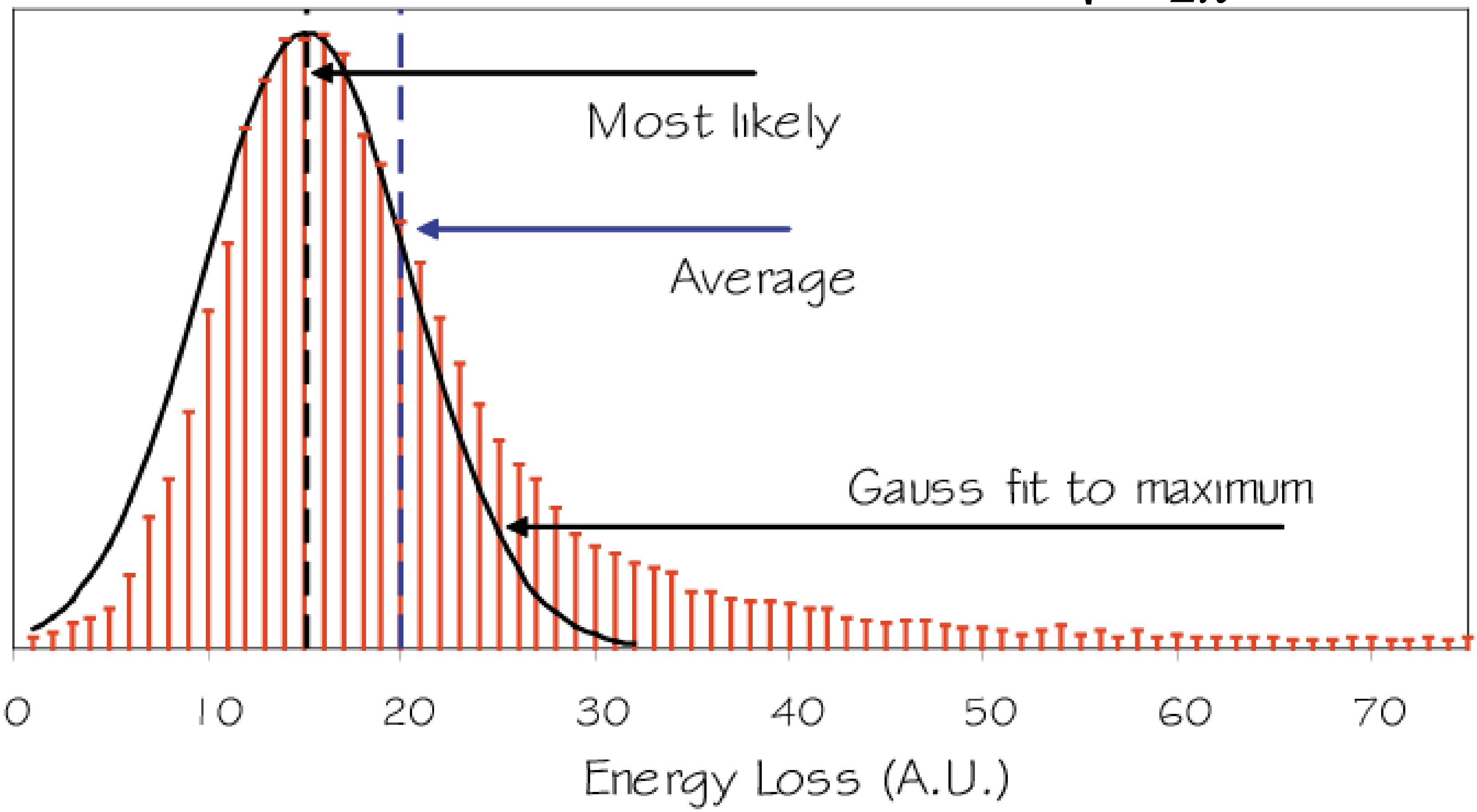
<u>Knock on:</u>

$K^- + p \rightarrow$ $K^- + p$, p slow, high ionisation

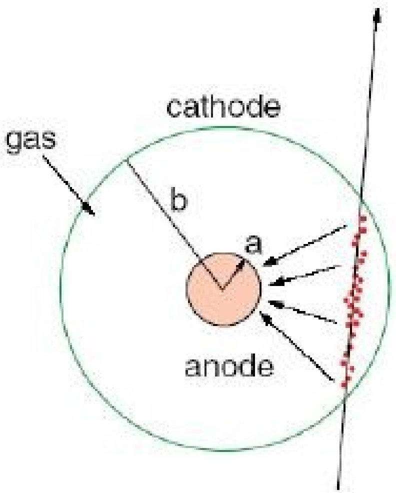
δ-electrons and other fluctuations (2).

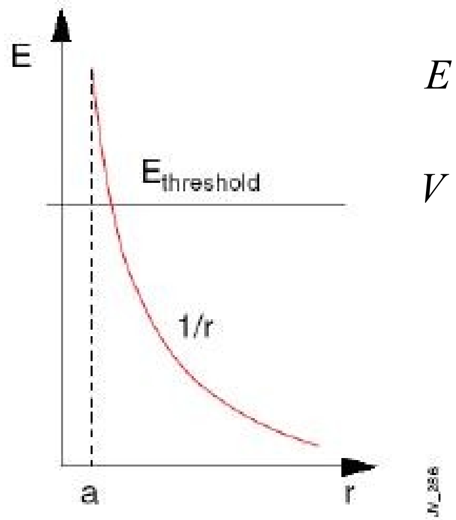
This leads to large fluctuations in the measurement of the deposited energy: Landau fluctuations.

(Normally) approximated by: $f(\lambda) = \sqrt{\frac{e^{-(\lambda + e^{-\lambda})}}{2\pi}}$



Amplification - SWPC



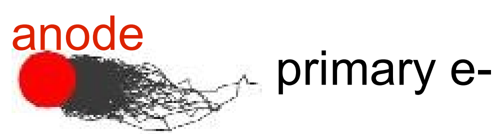


$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

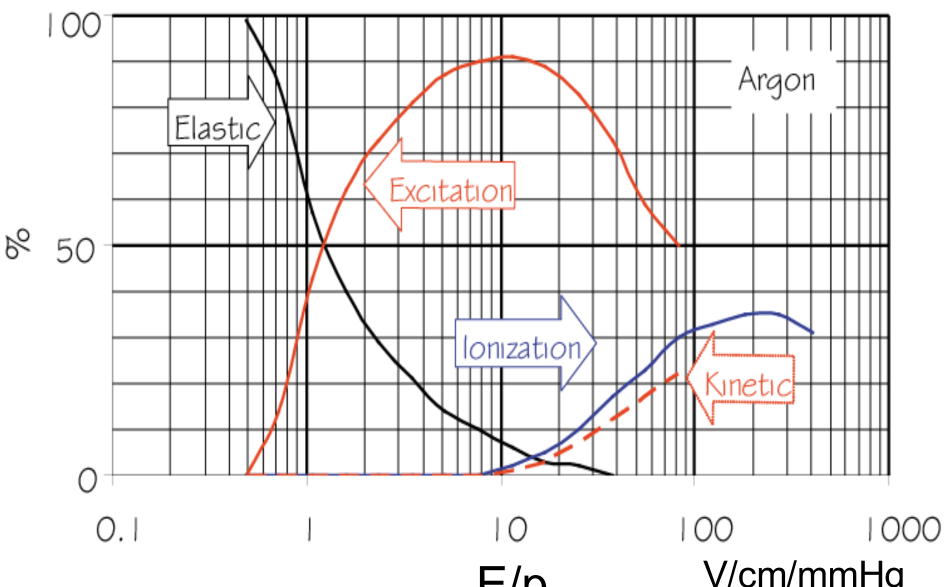
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C=capacitance/unit length

- The electrons from ionization drift towards the anode.
- E > 10kV/cm close to the wire (a~few 10s µm). Enough energy to ionize
  - And cause an *avalanche*

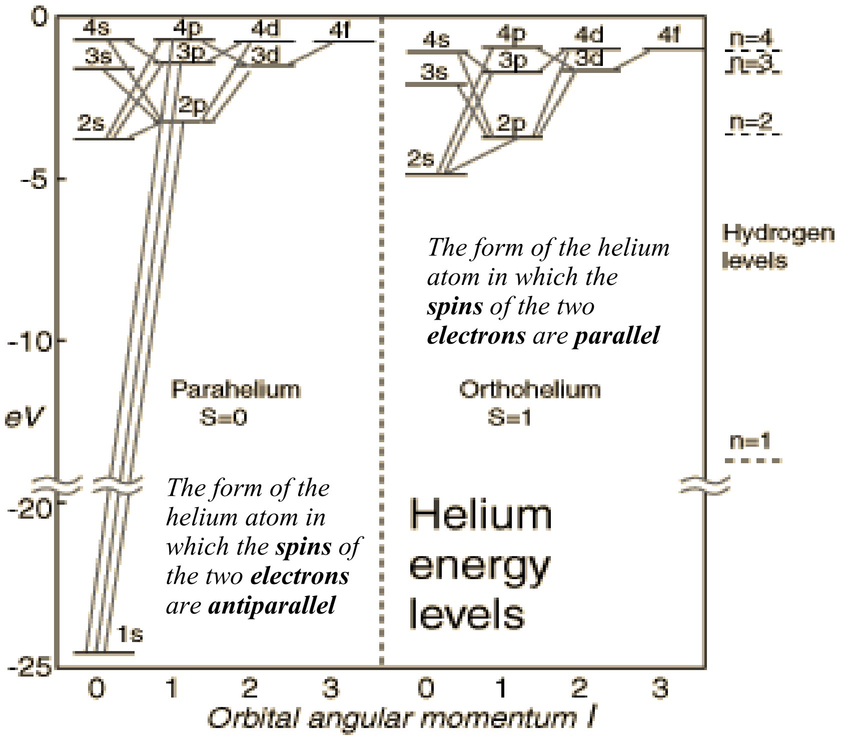


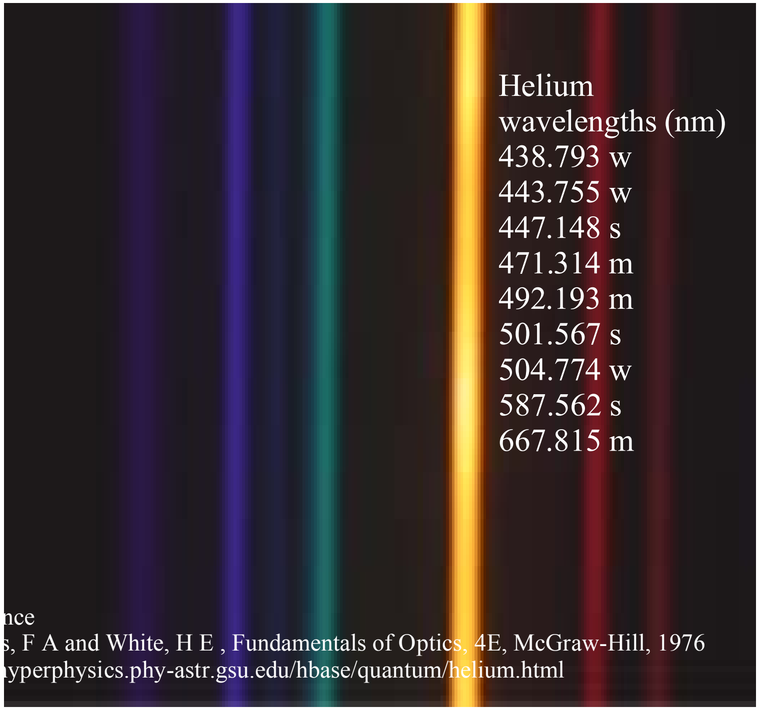
- The number of e^-/ion pairs increases exponentially close to the wire



L. B. Loeb, Basic Processes of Gaseous Electronics

Excitation....

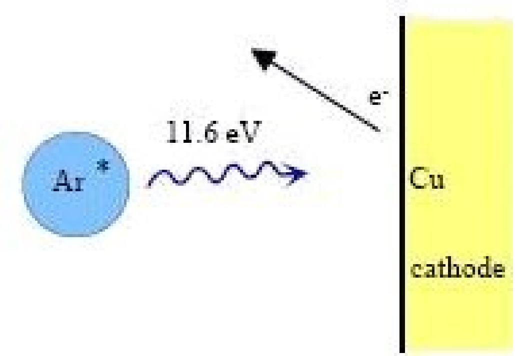




De-excitation of a noble gas is only possible via the emission of a photon.

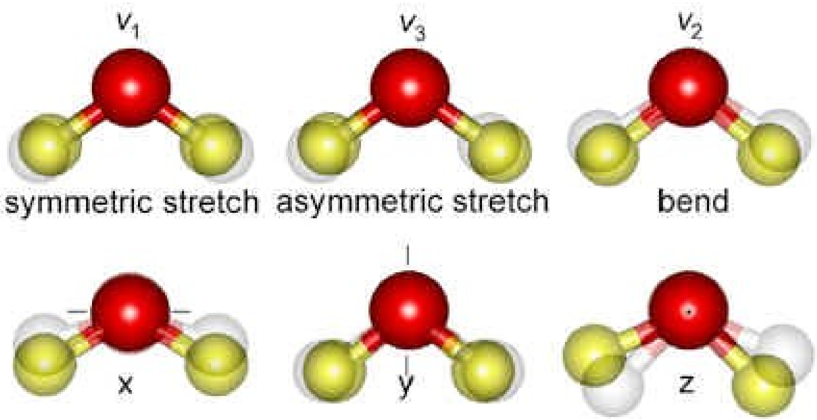
If the photon energy is above the ionization threshold for other molecules in the set-up, new avalanches will be created.

→ Permanent discharges

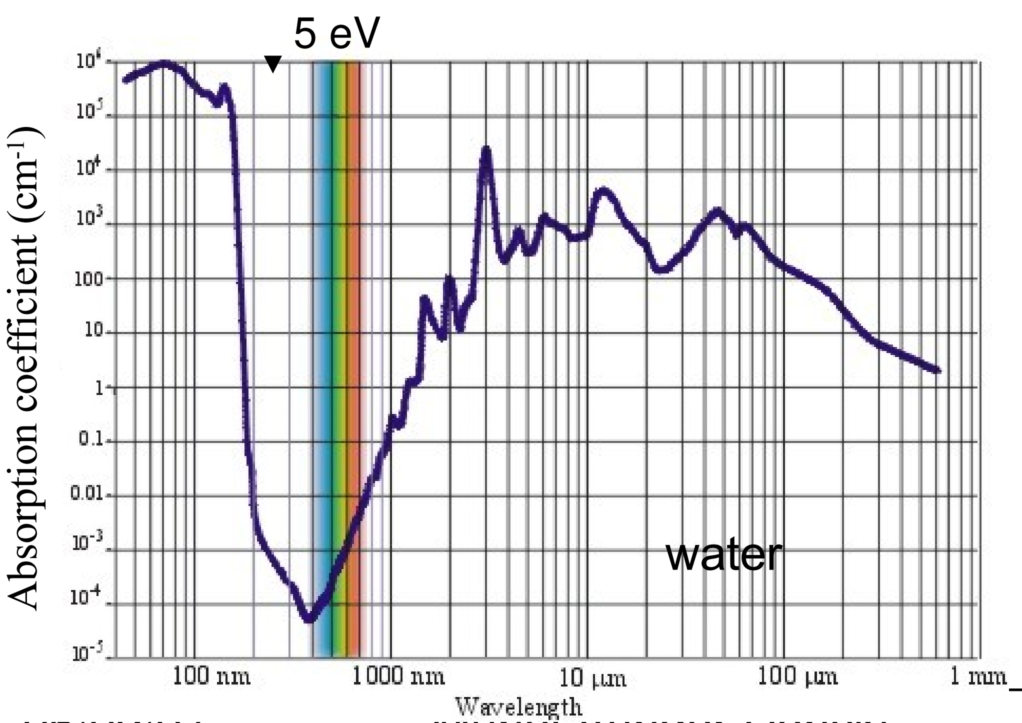


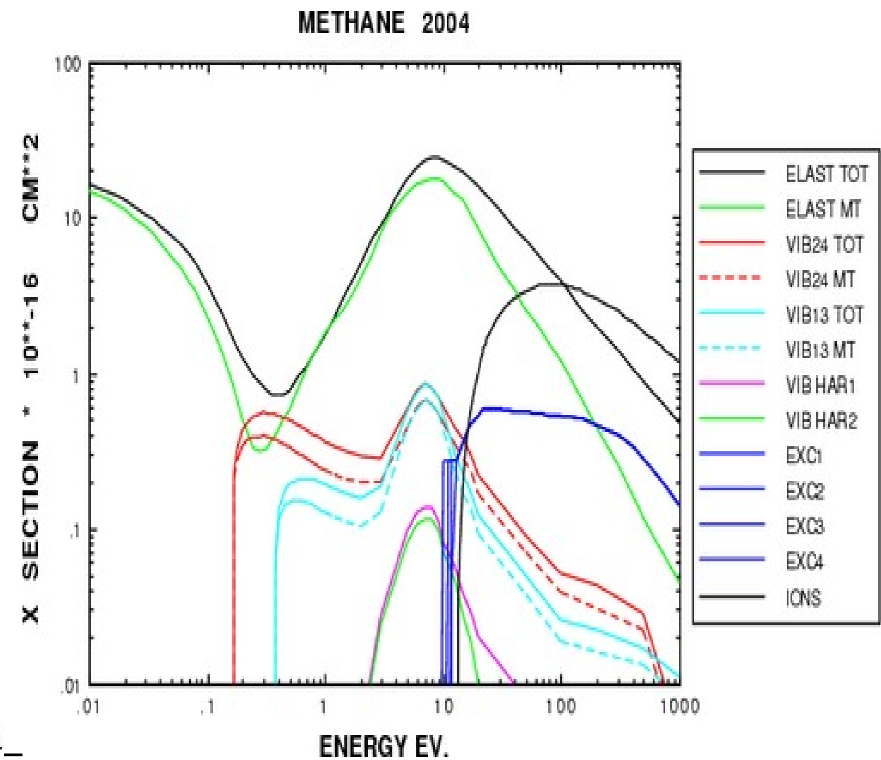
Quenching

- polyatomic quencher (H2O, CH4…).
- Absorbs the di-excitation photons into vibration, rotation, dissociation



vibrations



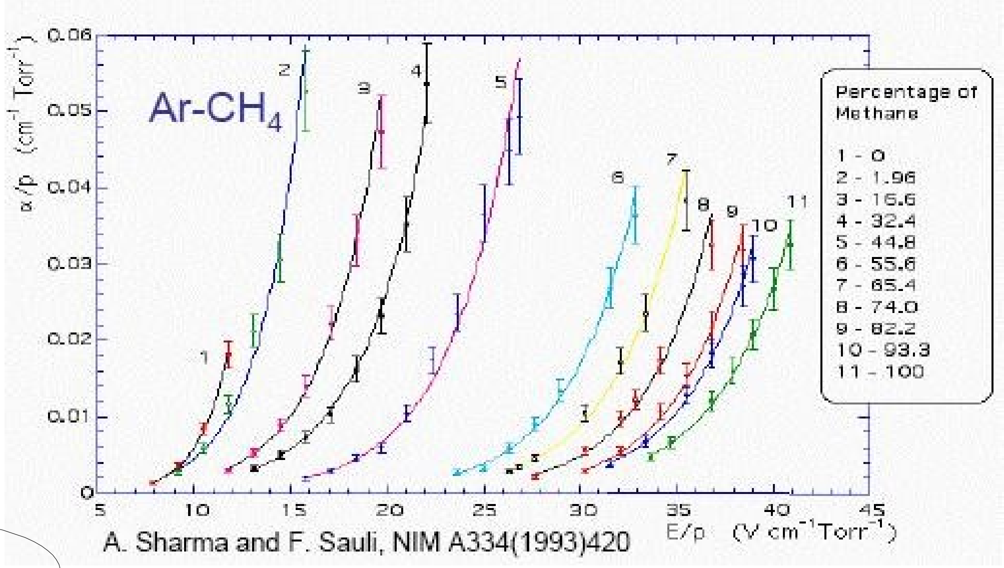


http://consult.cern.ch/writeup/magboltz/cross

What amplification to expect ?

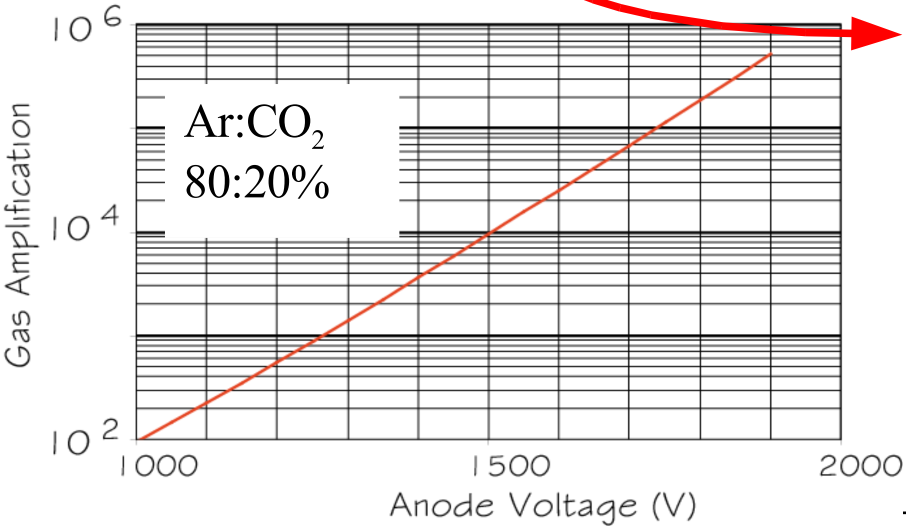
- $dn = n\alpha\, dx$ $\alpha = \frac{1}{\lambda}$ λ is the mean free path

  $n = n_0 e^{\alpha(E)x}$



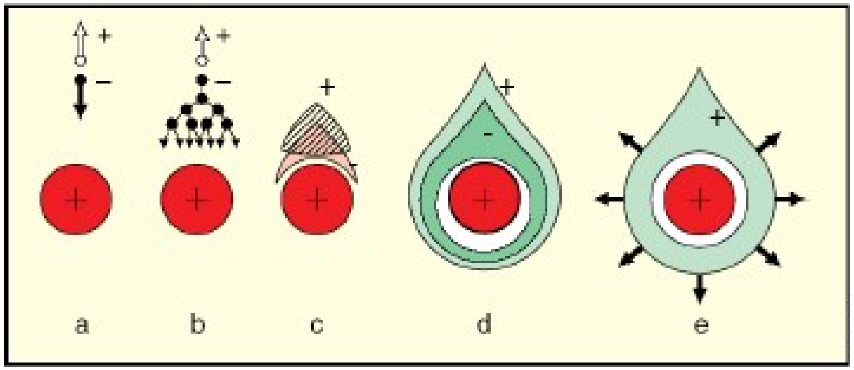
- α(E) or α(r) is f(σ_i,σ_e,transfer to molecules, pressure, density, T)
- Gain : $M = \frac{n}{n_0} = \exp[\int_a^{r_C} \alpha(r)\cdot dr]$
- Korff's approximation $\alpha = p \times A e^{-Bp}$

$$M = \exp\left[\frac{A}{B}\frac{V_0}{\ln\frac{R}{r_0}} e^{-\frac{Bpr_0 \ln\frac{R}{r_0}}{V_0}}\right]$$



	A	B
	Torr/cm	V/Torr/cm
He	3	34
Ne	4	100
Ar	14	180
Xe	26	350
CO_2	20	466

Signal formation



$$V_{electron}^{signal} = -\frac{Q}{lCV_0}\int_{r_0}^{r_0+\lambda}\frac{dV}{dr}dr = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{r_0+\lambda}{r_0}$$

$$V_{ion}^{signal} = +\frac{Q}{lCV_0}\int_{r_0+\lambda}^{R}\frac{dV}{dr}dr = +\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{R}{r_0+\lambda}$$

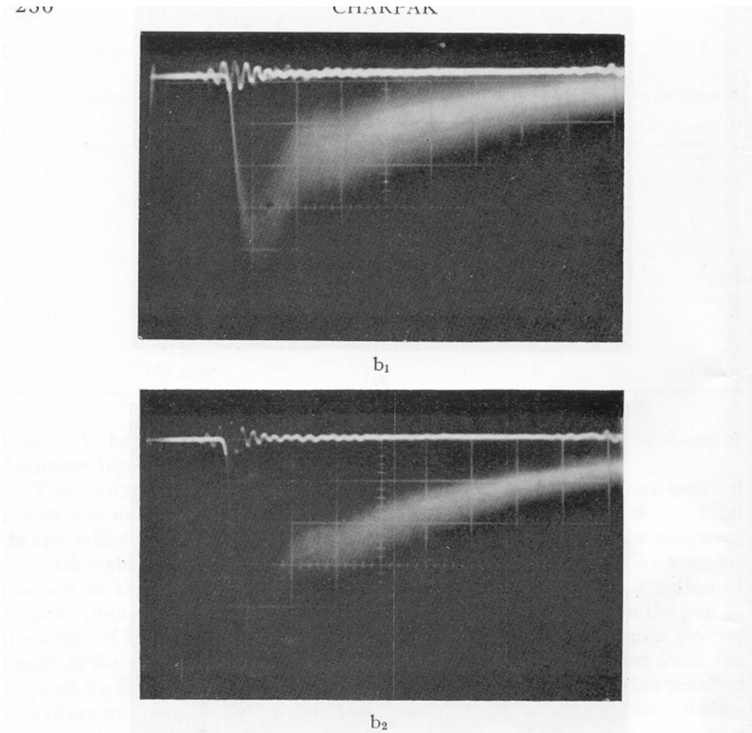
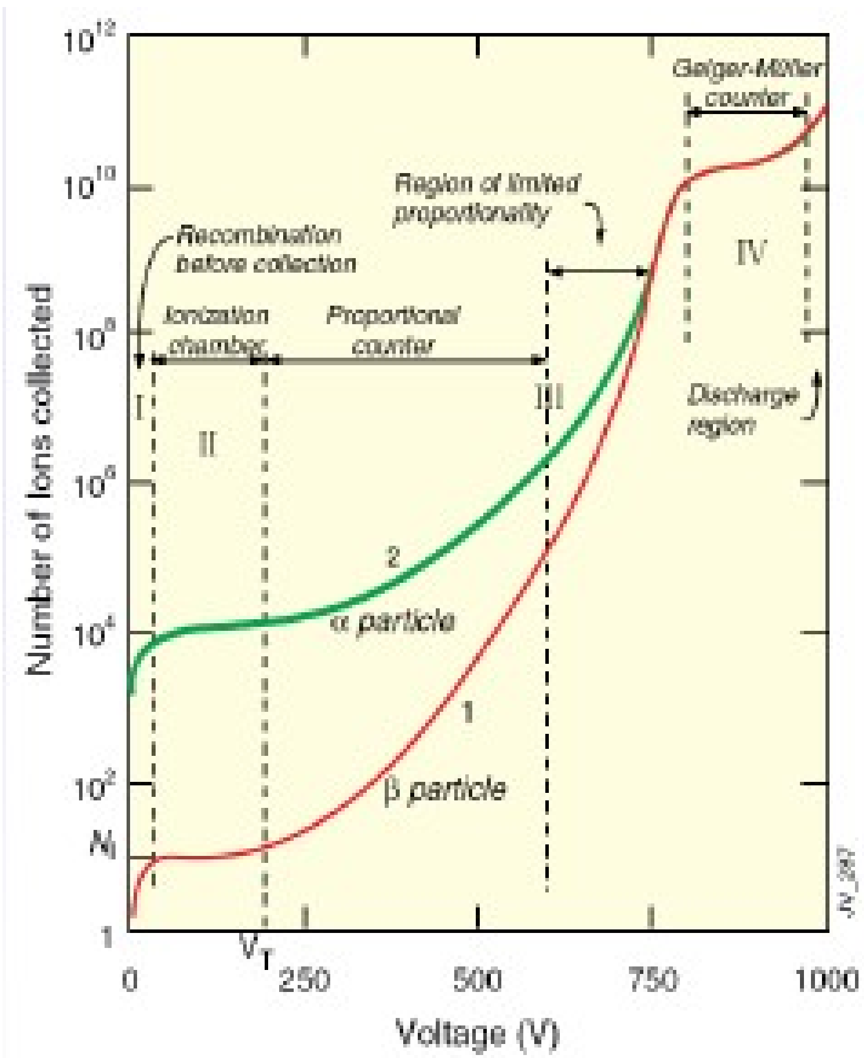


FIGURE 25. Proportional amplification at the limit of space charge saturation. Chamber with $L=8$ mm, $s=2$ mm, $d=20$ μm. "SFM magic mixture": argon+isobutane (80−20) and 0.4 percent freon 13 B1. 100 percent efficiency.

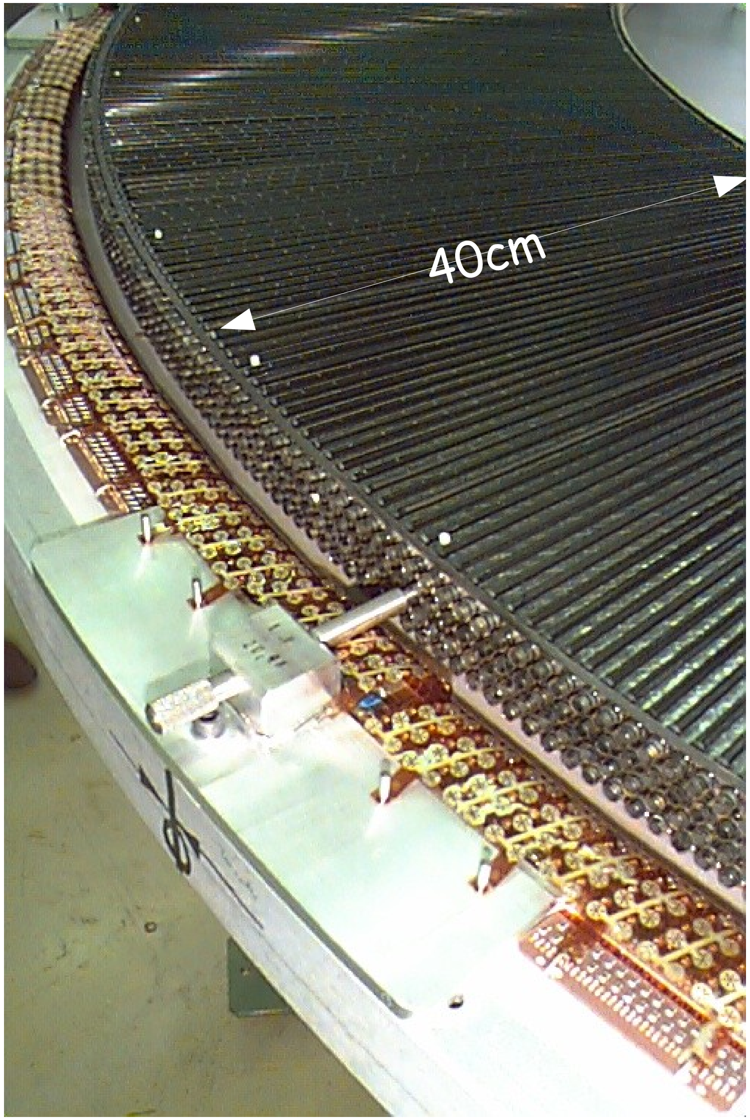
- The signal is the change of E field generated by the moving charges.
- If all charge is created at distance $\lambda \approx$ few μm from the wire
- $V_{ion}/V_{e-} \approx 100$
  - Signal duration depends on ion drift time
  - E field varies due ion drift – the gain, too.

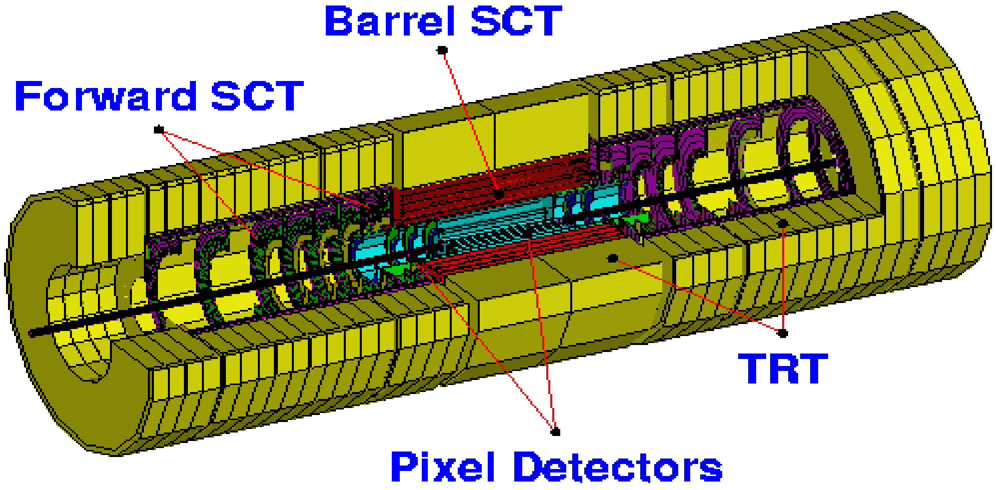
Operation Modes



- **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 photo-emission; 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 example ATLAS TRT





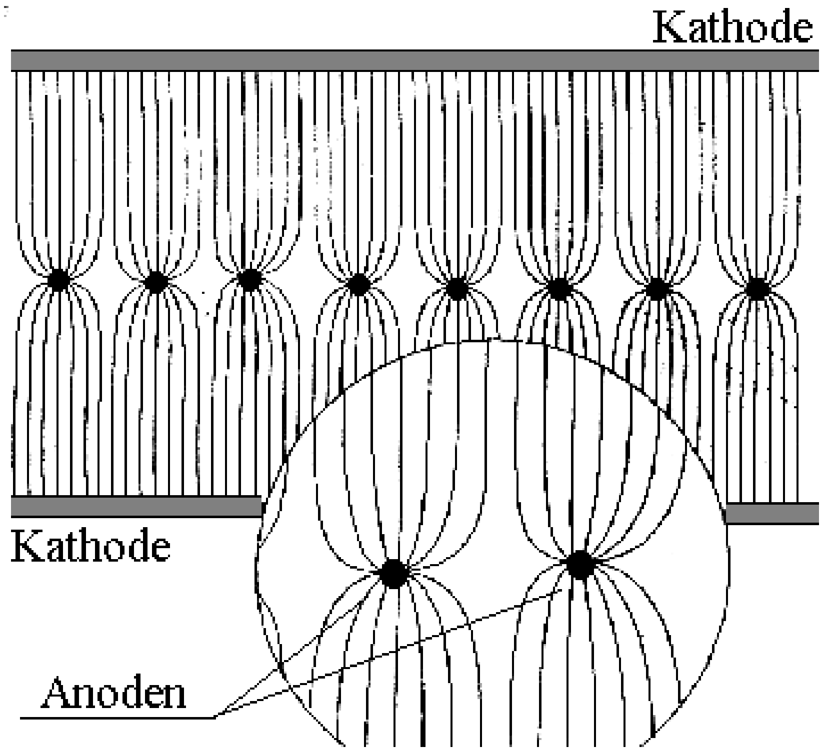
- 372000 straw proportional tubes
- $|\eta|<2.5$
- $Xe-CO_2-O_2$, 70%,27%, 3%
- Gain ~2.5-4 10^4
- 4ns e- collection time in B=2T

Beam test result:

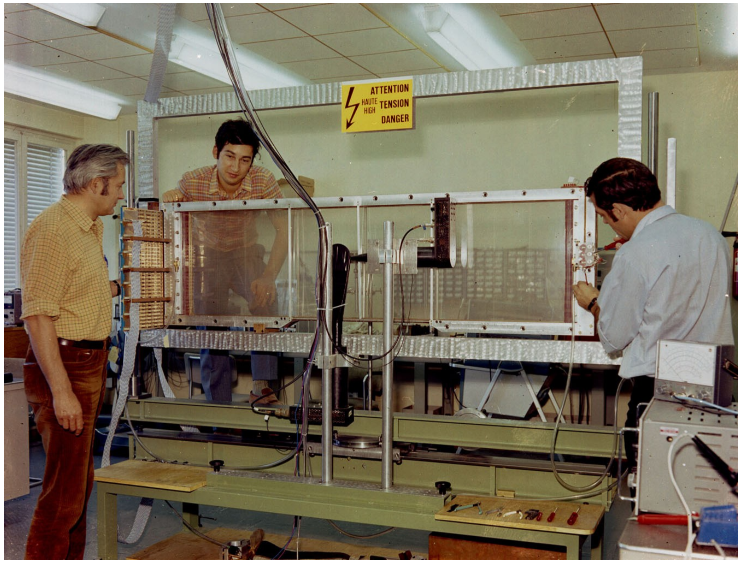
Hit efficiency: 96.7± 0.8%

Drift-time accuracy: 133 ± 4 μm

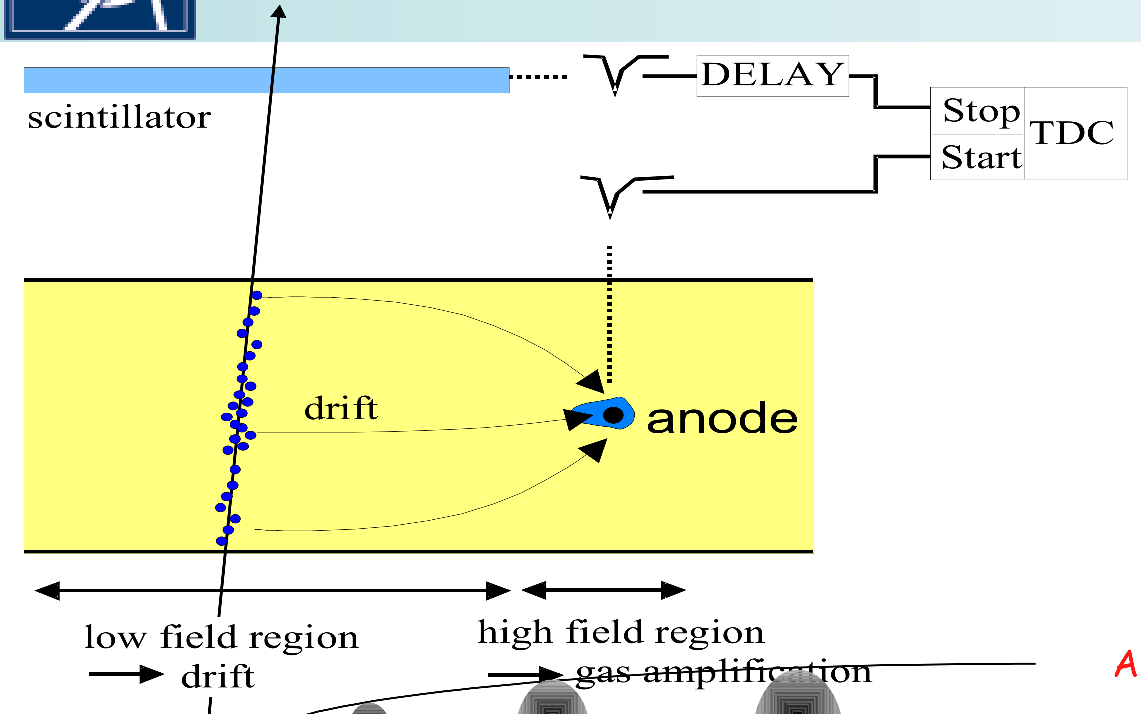
Multiwire proportional Chamber



- Nobel prize 1992 (Charpak)
- Normally digital readout :
- spatial resolution limited to
- $\sigma = \frac{d}{\sqrt{12}}$
- for d = 1 mm σ = 300 μm

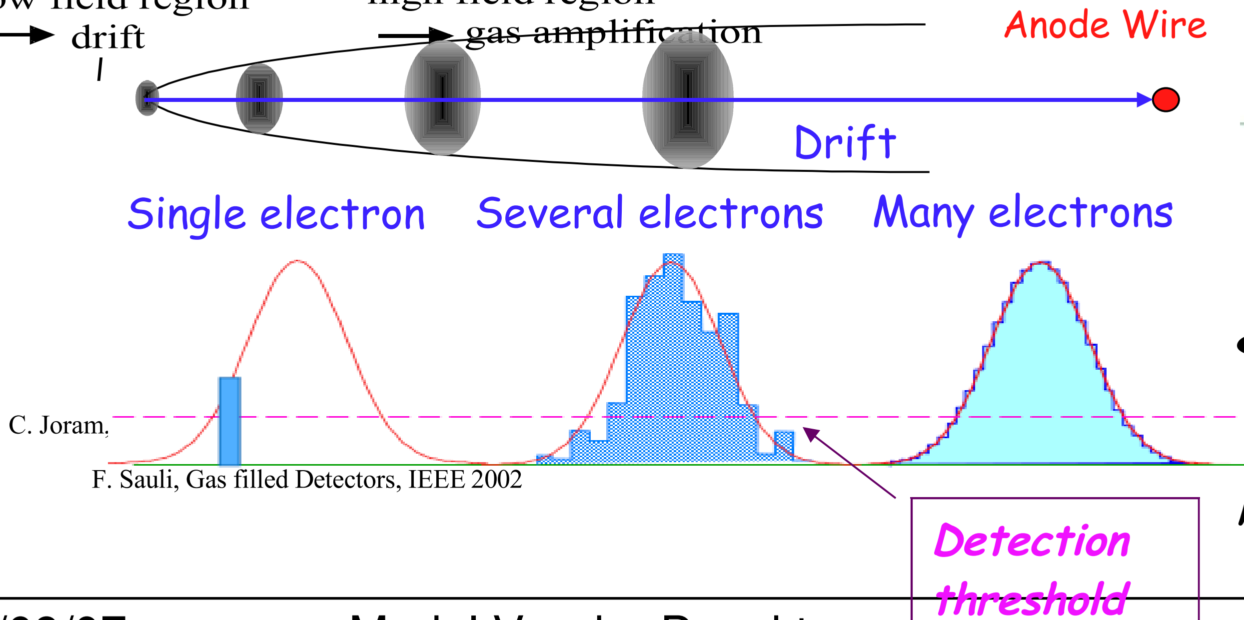


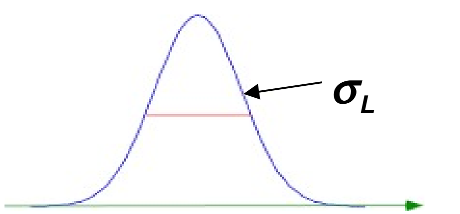
Drift Chambers



Measure the arrival time on wire.

$$x = v_d (t - t_0)$$



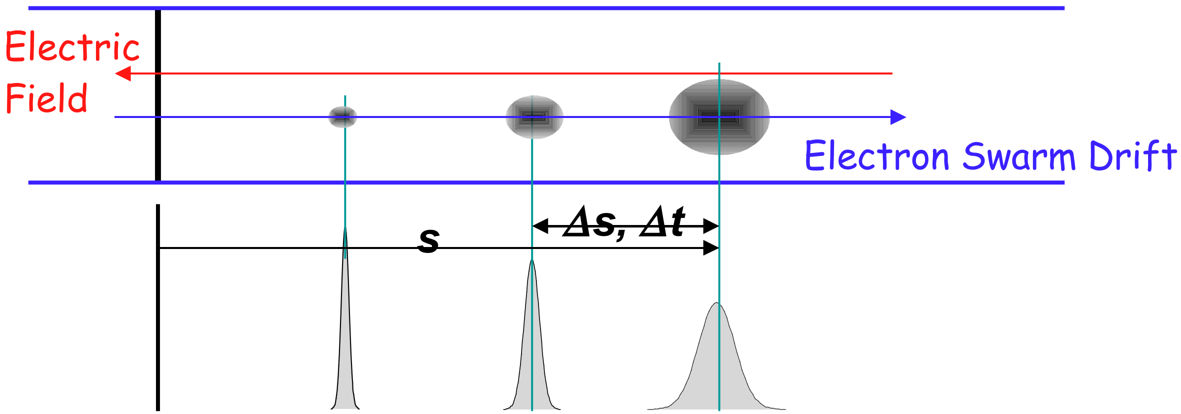


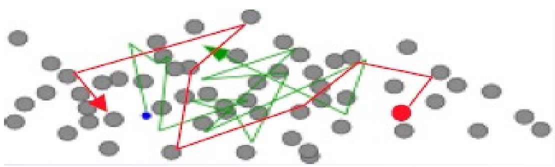
Error on first electron :

$$\sigma_1 = \frac{\pi}{2\sqrt{3 \ln N}} \sigma_L$$

$N=100$ $\sigma_1 \sim 0.4\, \sigma_L$

Electron drift and diffusion



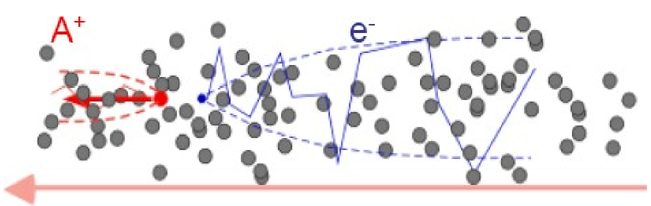


E=0

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

D= Diffusion coefficient

RMS $\sigma_i = \sqrt{2Dt}$



E>0

- $v_D = \frac{\Delta s}{\Delta t}$ $\sigma_i = \sqrt{2D\frac{s}{v_D}}$

Electron drift in E field

$$v_D = \mu E = \frac{eE}{m}\tau$$

$$\frac{x}{v_D \tau}\lambda(\varepsilon)\varepsilon_E = eEx$$

$$\tau = \frac{1}{N\sigma(\varepsilon)v}$$

$$\varepsilon = \varepsilon_E + \frac{3}{2}kT$$

- Acceleration in E field between the collisions
- Balance between loss in collisions and acquired energy

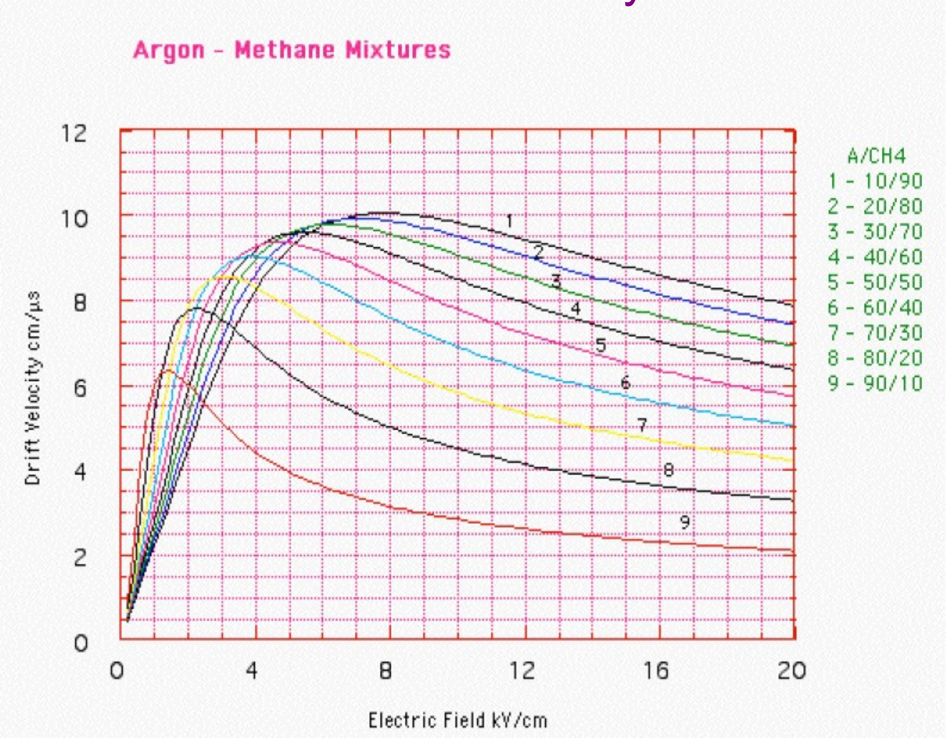
► Fractional Eloss

► Time between collisions

► Instantaneous velocity

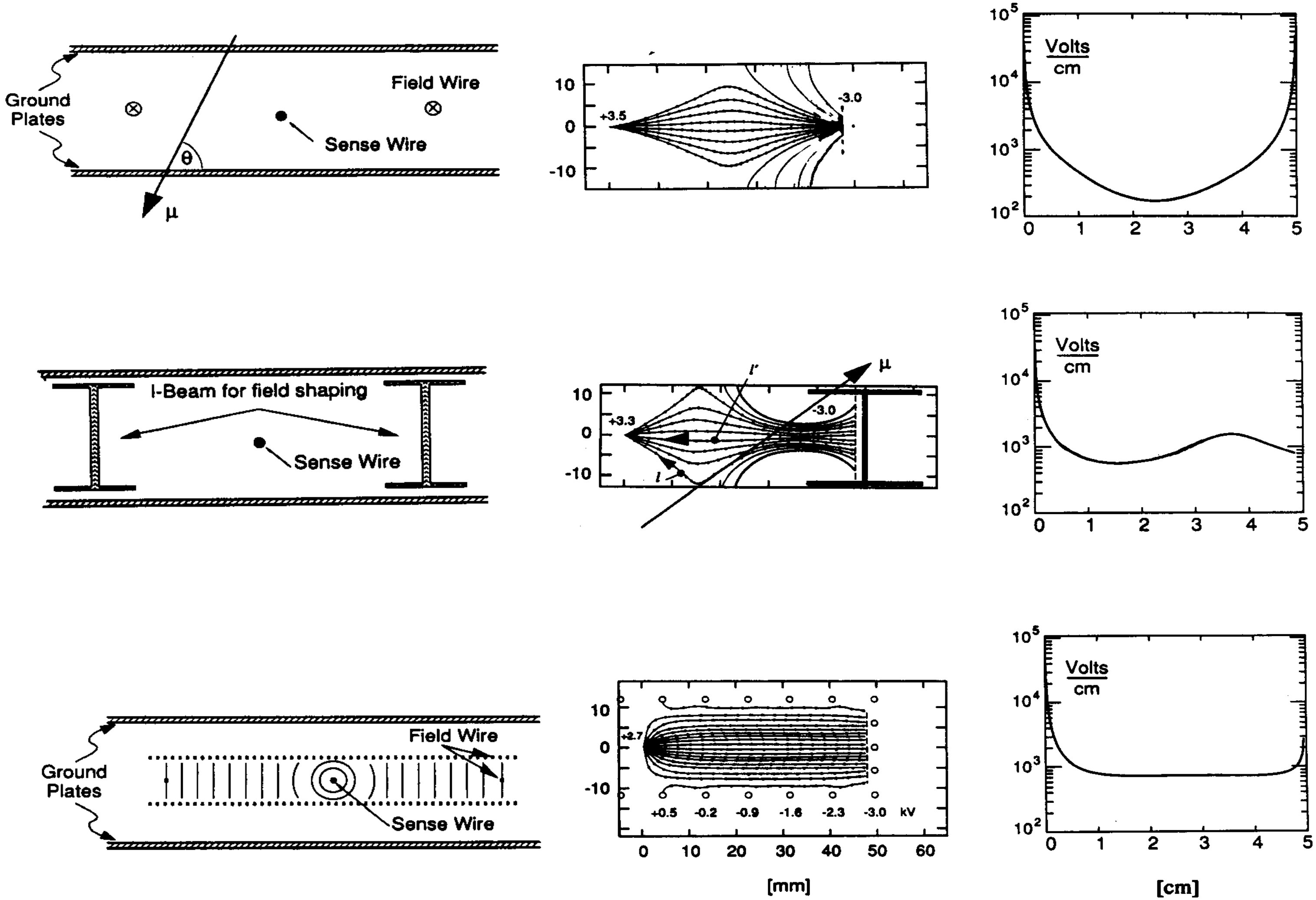
► Number of collisions

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



Some planar drift chamber designs ⟶Optimize geometry → constant E-field

Choose drift gases with little dependence $v_D(E)$→ linear space - time relation r(t)



Drift of ions with E field

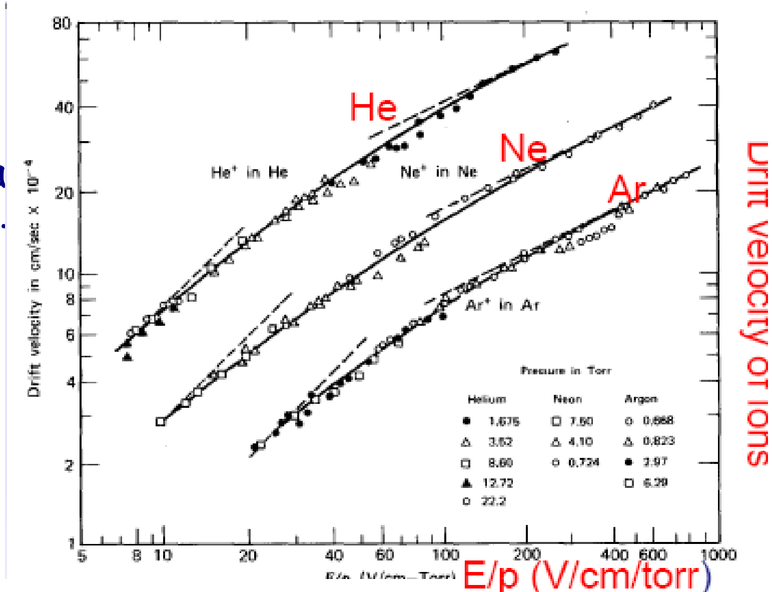
- Drift velocity of ions nearly∝E $v_D^{ion} = \mu^{ion} E$
- Mobility: $\mu^{ion} = \frac{e\tau}{m}$ constant for given gas fixed P and T, direct consequence of the fa that average energy of ion is unchanged up very high E fields.
- Diffusion of ions $\varepsilon = \frac{3}{2}\frac{De}{\mu}$

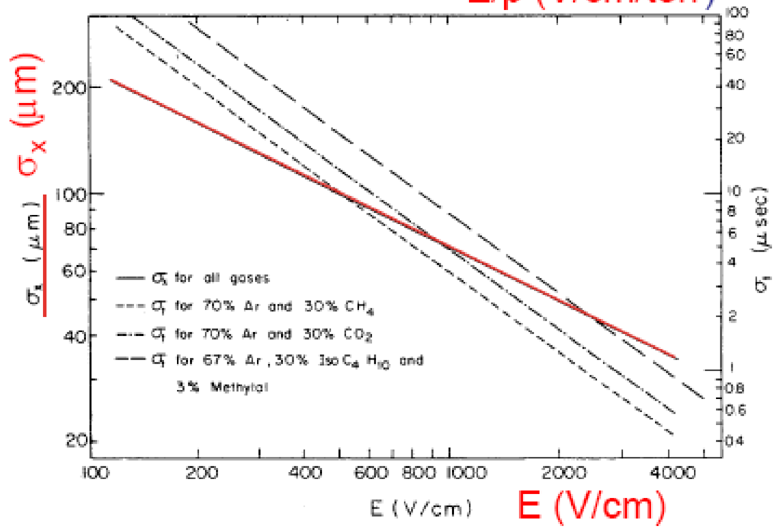
$$\frac{D}{\mu^{ion}} = \frac{kT}{e}$$

$$\sigma_x^{ion} = \sqrt{\frac{2kT}{e}\frac{x}{E}}$$

thermal limit

- the same for all gases !!





Electrons in E and B fields

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

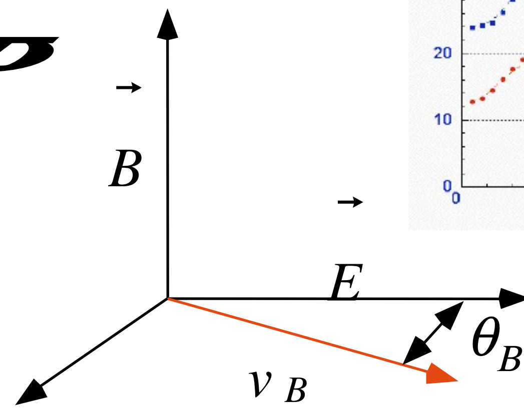
$\tan \theta_B = \omega\tau$

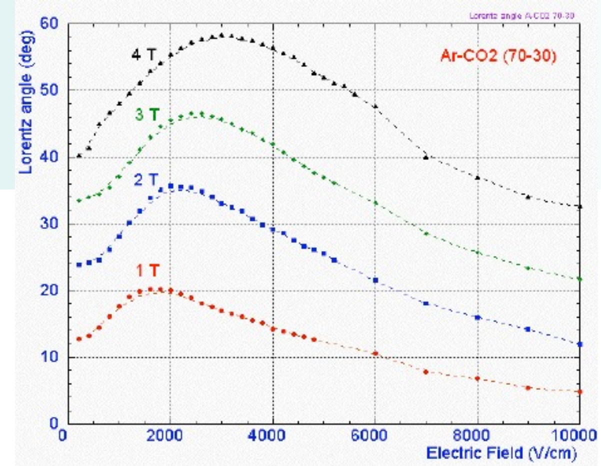
Lorentz angle

$$v_B = v_0 \frac{1+\omega\tau}{1+\omega^2\tau^2}$$

τ : mean collision time

$\omega = eB/m$ Larmor frequency



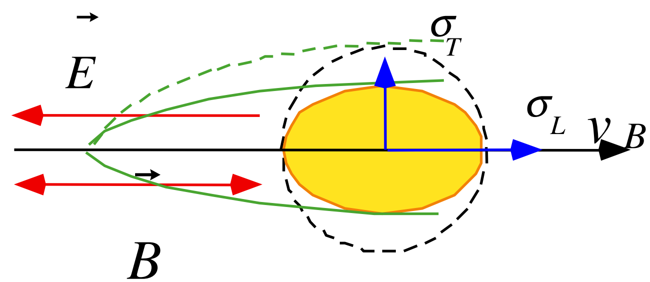


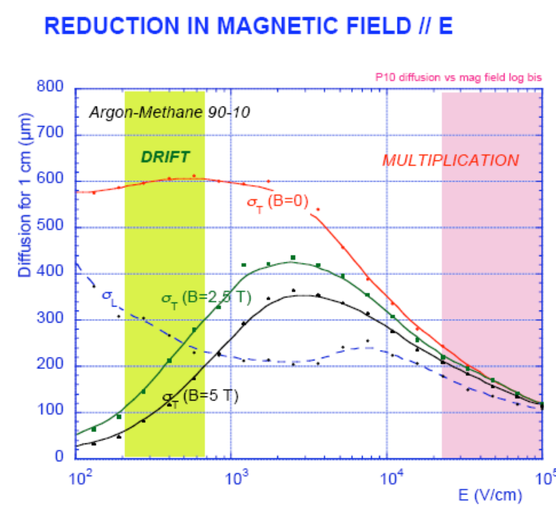
$\vec{E} \parallel \vec{B}$

$$v_B = v_0$$

$$\sigma_L = \sigma_0$$

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

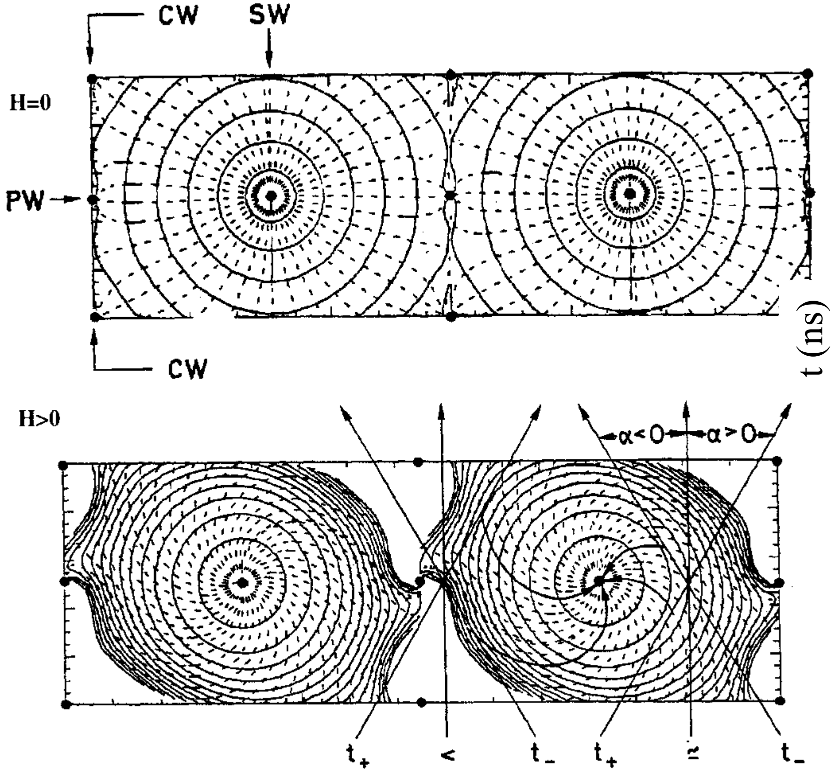




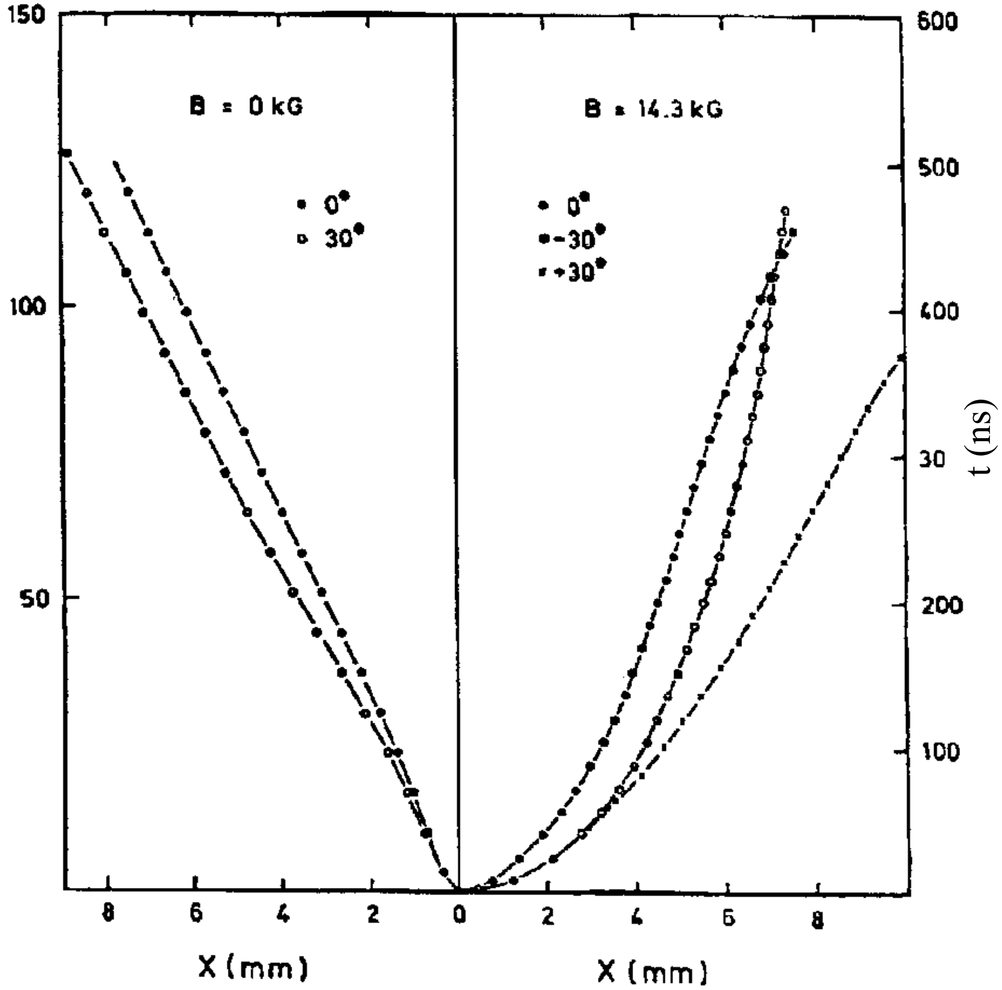
This reduces transverse diffusion.

F. Sauli, Gas filled Detectors, IEEE 2002

Magnetic field effects



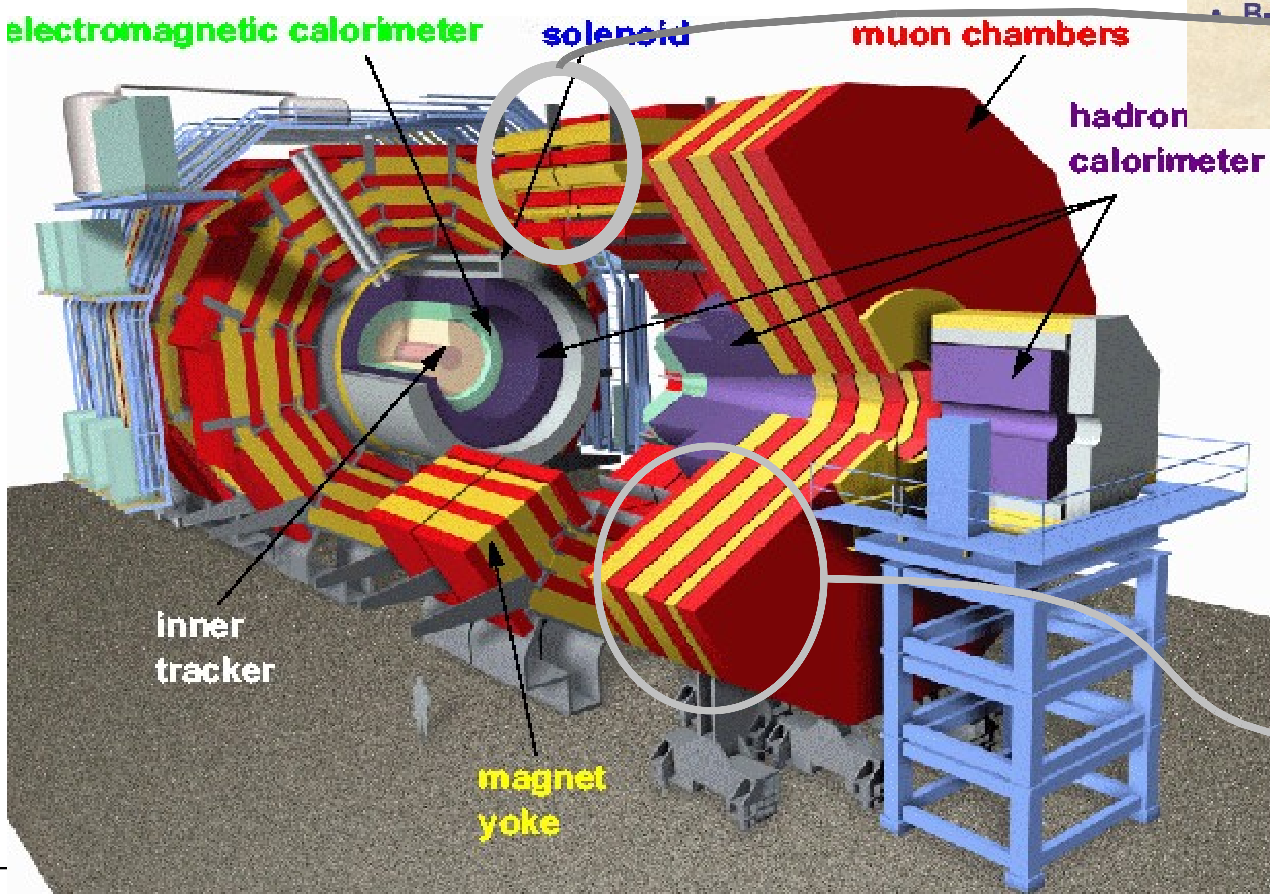
W. de Boer et al, Nucl. Instr. and Meth. 156(1978)249



The CMS muon system

Environment

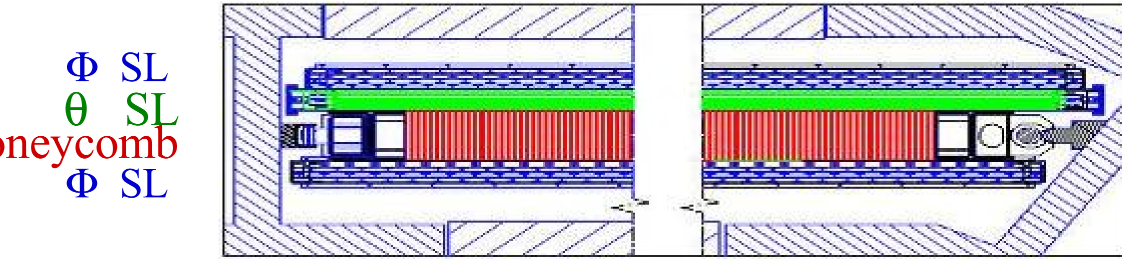
- random hit rates
  - up to 1000 Hz/cm^2
  - 20 kHz/channel
  - 4 times larger than mip signals
- punch-through rates
  - up to 100 Hz/cm^2
  - penetrate through all six planes of a chamber
- B-field
  - 3.5 T and uniform in ME1/1
  - 0-1 T and very non-uniform in some others



DT+RPC

CSC+RPC

Drift tubes



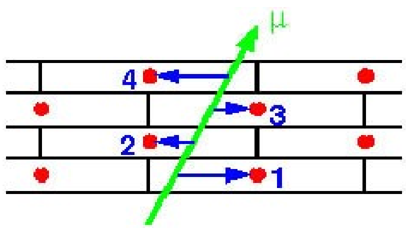
Cell designed to have electric field as uniform as possible

Gas mixture Ar/CO_2 (85/15 %)

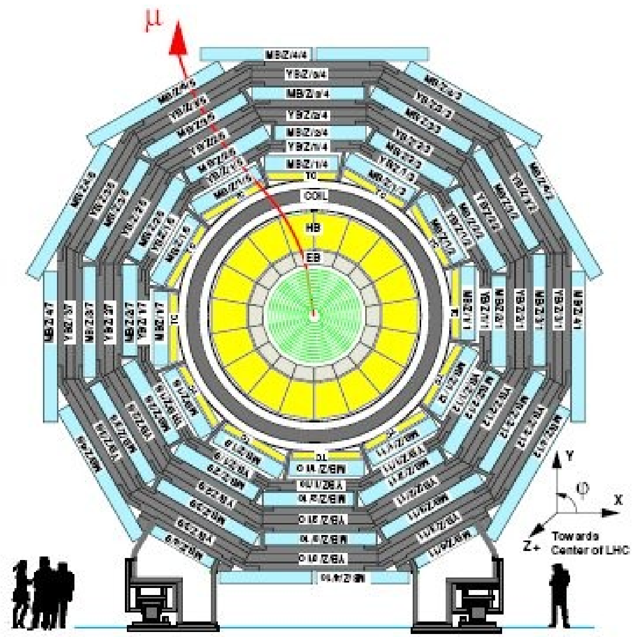
V_c / V_s / V_w = -1.2/+1.8/+3.6 (kV)

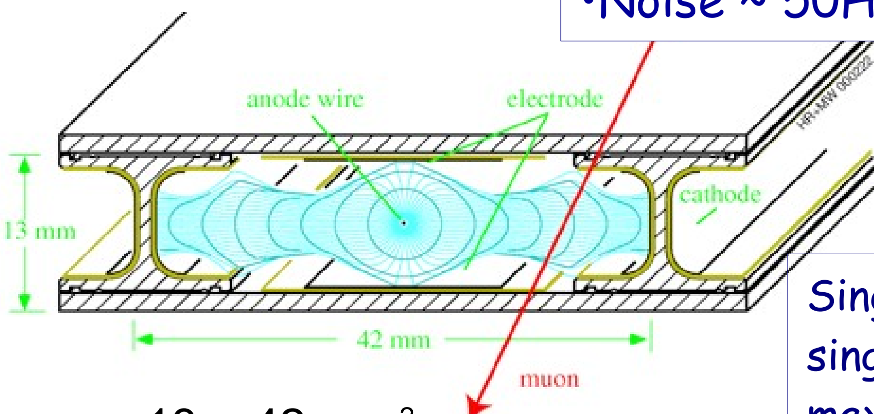
⇩

E = 1 - 2 kV/cm



- 5 Wheels - 250 DT's',
- 4 station (MB1, MB2, MB3, MB4) at least 3 track segments / muon
- Noise ~ 50Hz/cell

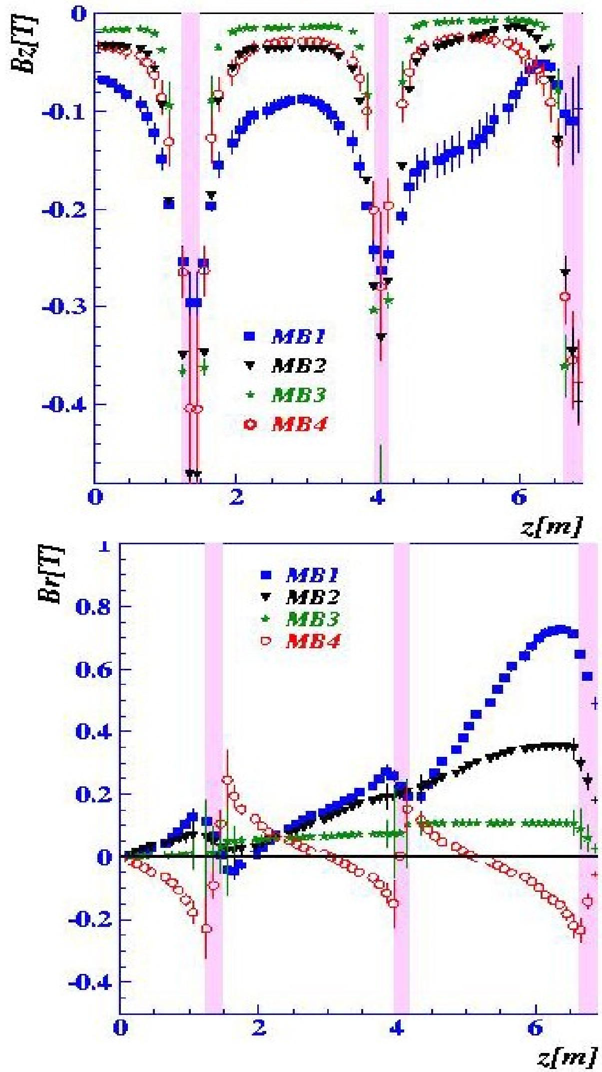


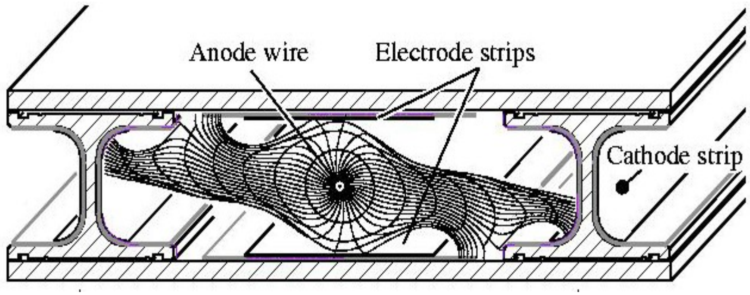


13 × 42 mm^2.

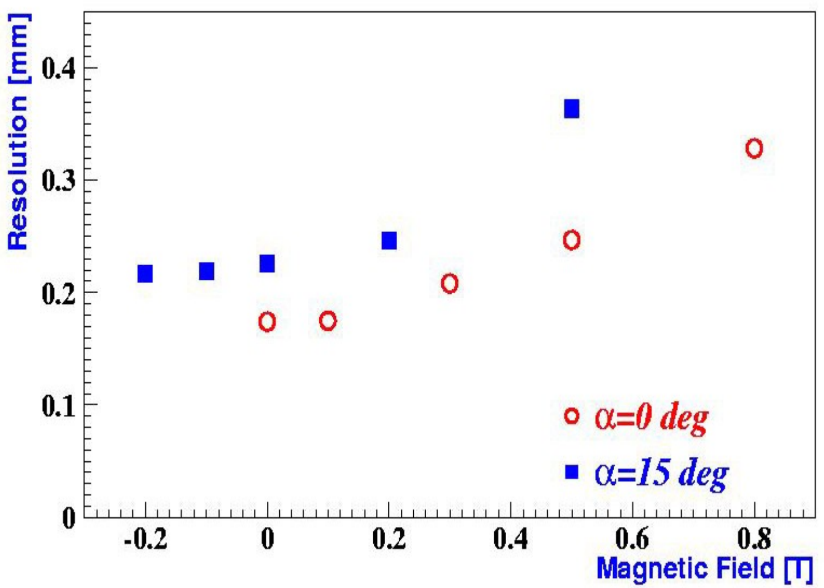
Single cell eff BX ID 99.8%
single cell σ=170μm
max drift time 380ns

Barrel Drift Tubes Chambers in Bfield

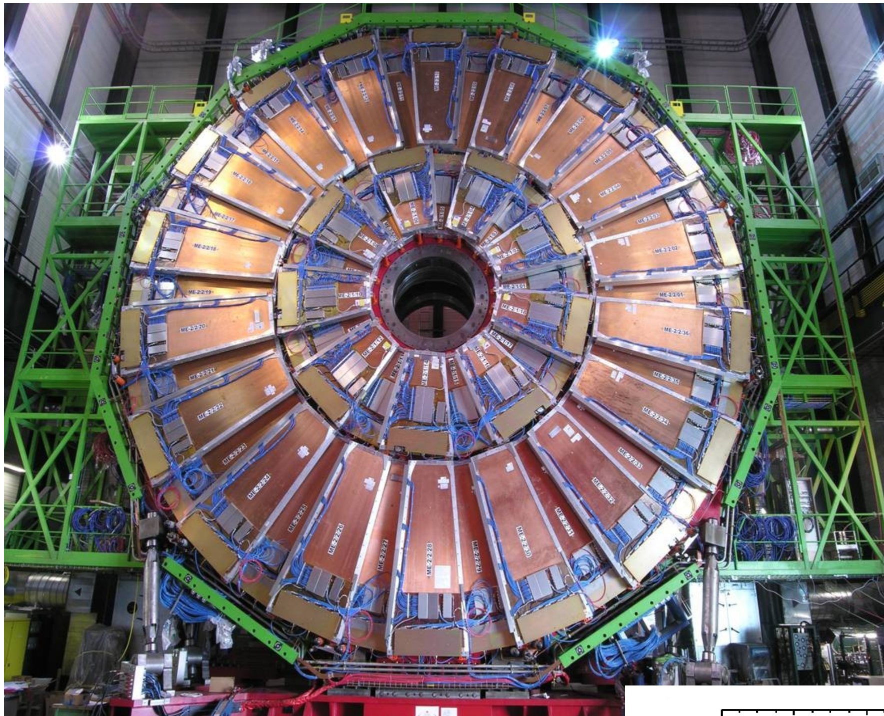




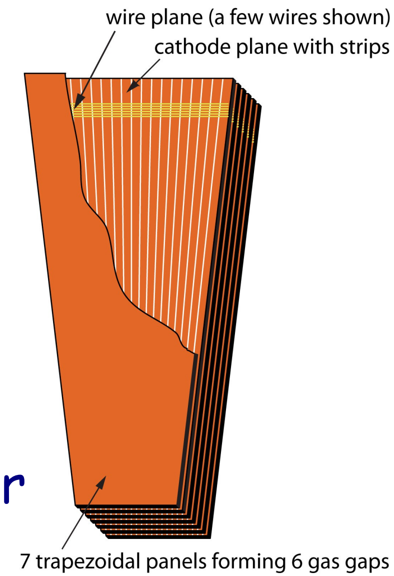
B_z

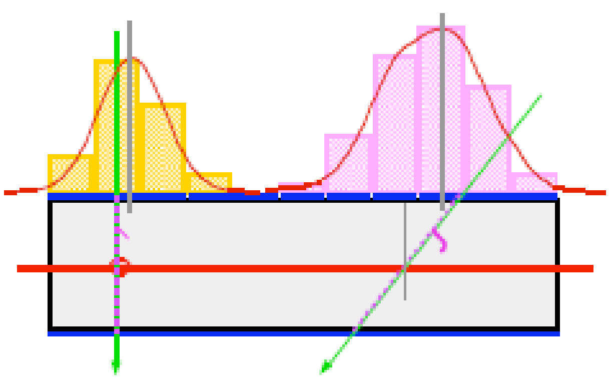


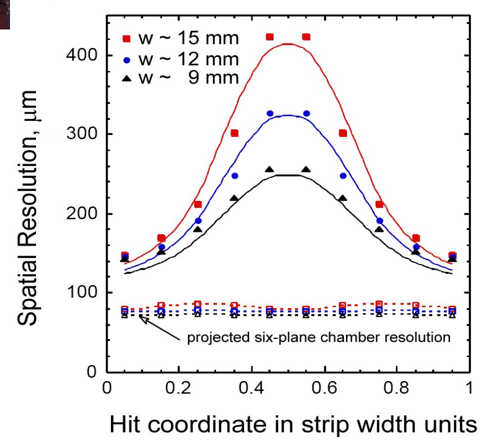
Cathode Strip chambers

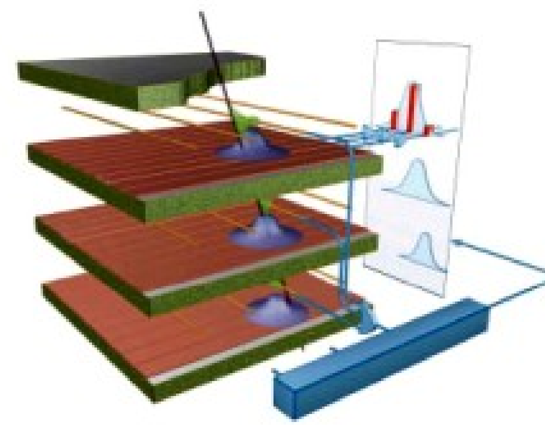


- $0.9 < |\eta| < 2.4$
- 3.6kV
- $G = 7.10^4$
- 1 kHz cm^{-2}.hit rate
- 99% efficiency
- 92% BX id/chamber
- σ=2mm rϕ @ L1
- 40%Ar + 50%CO_2 + 10%CF_4.





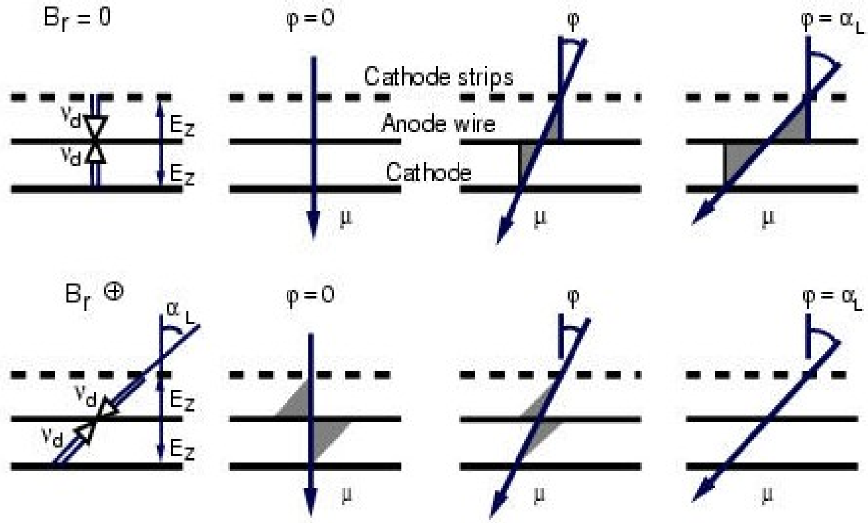


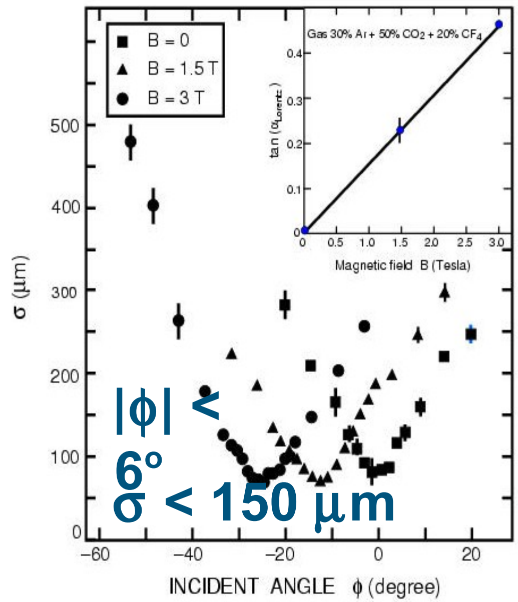


Endcap Cathode Strip Chambers

CSC performance in magnetic field

$B_r < 1$ T

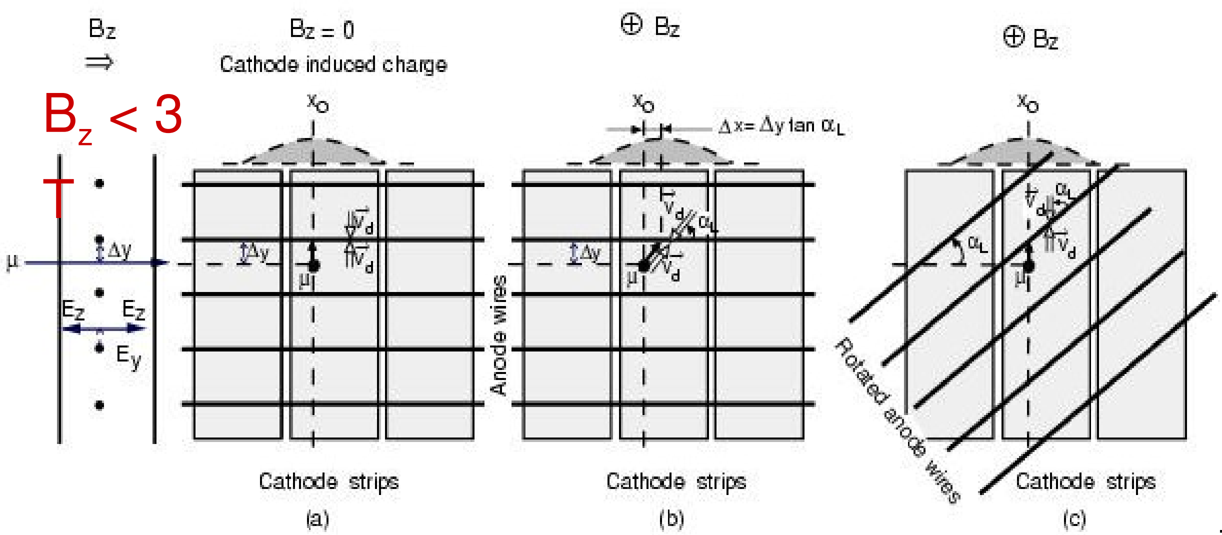




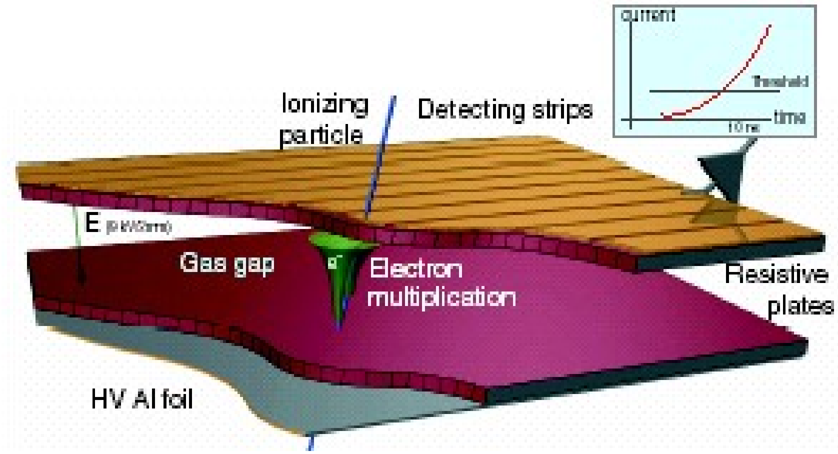
|ϕ| < 6°

σ < 150 µm

$B_z < 3$ T



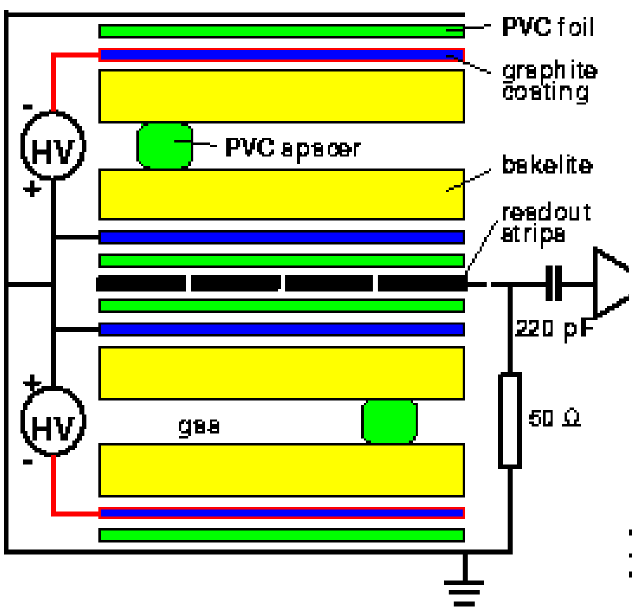
Resistive plate chambers

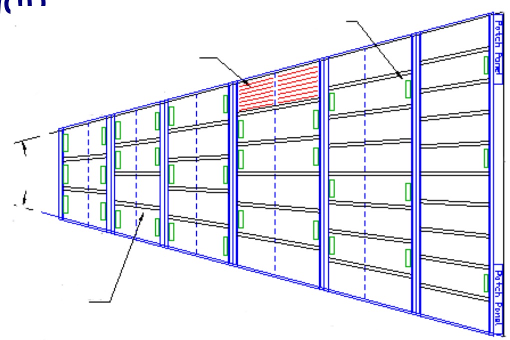


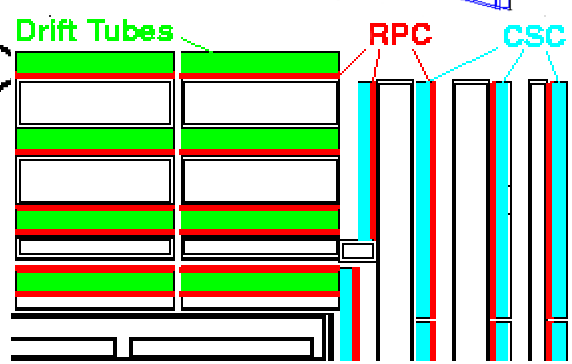
- Operating H.V. 8.5 - 9.0 kV
- Gap width 2 mm
- Bakelite bulk resistivity 1-2 1010 Ωcm
- Bakelite thickness 2 mm
- strip width ~ 35 mm
- Gas 95% $C_2H_2F_4$, 5% i-C_4H_{10}

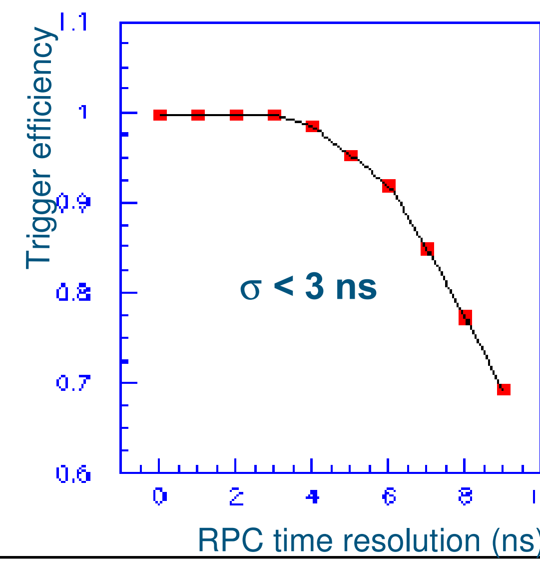
Avalanche created inside the gap

charge induced on strips









Time Projection Chambers (TPC)

Large volume active detector full 3-D track reconstruction

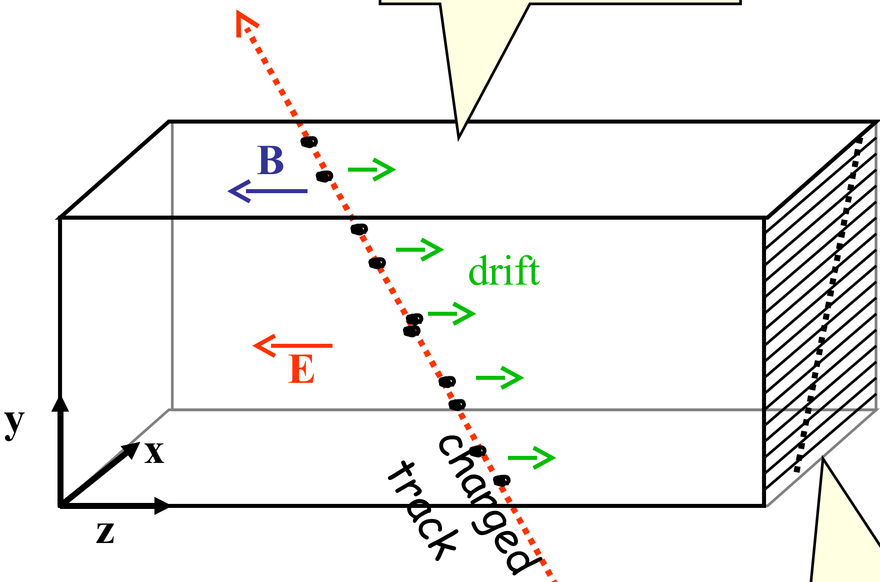
x-y from wires and segmented cathode of MWPC

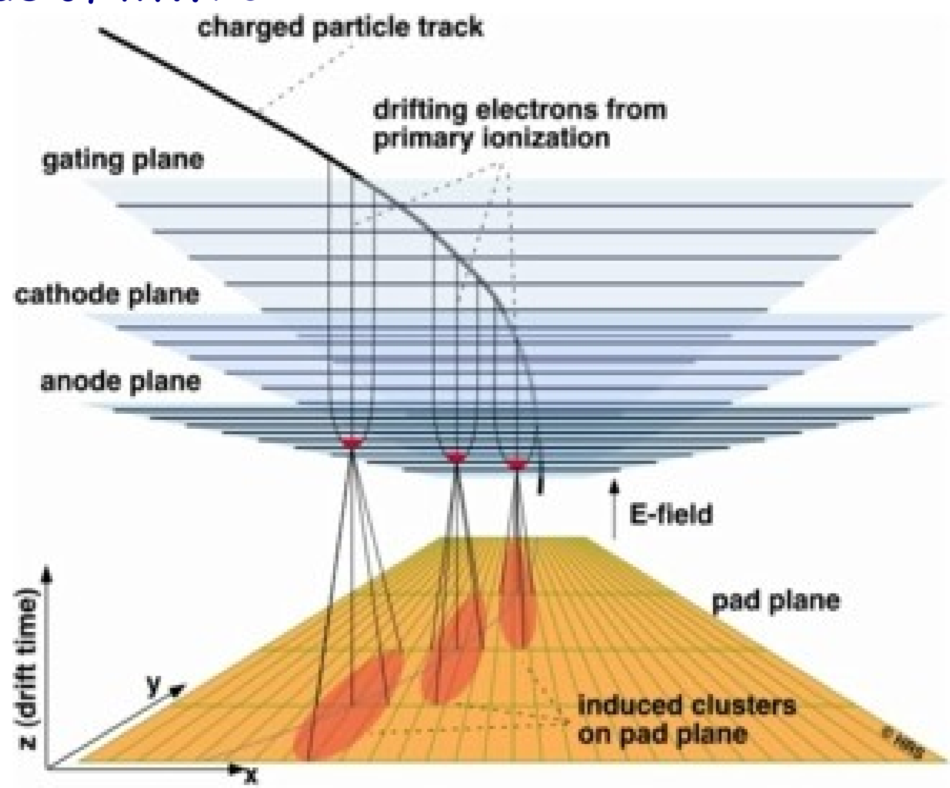
z from drift time

and

dE/dx

gas volume with **E** & **B** fields

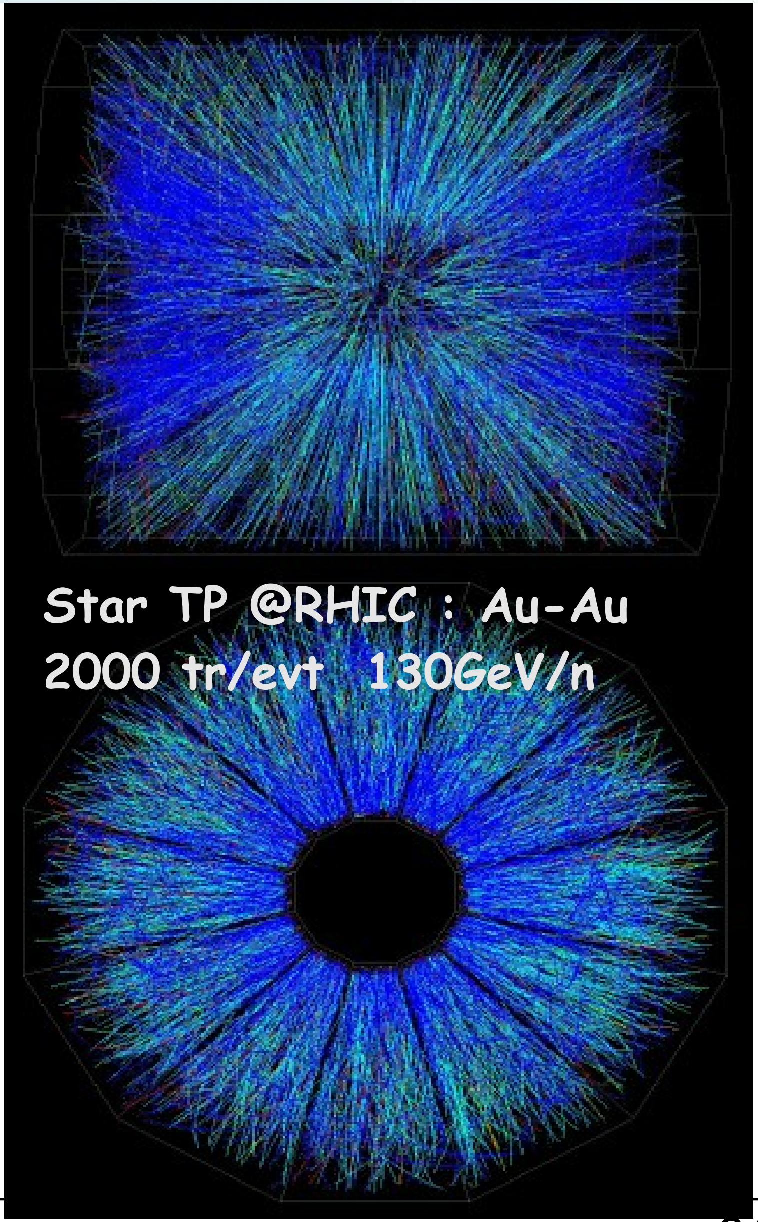




wire chamber to detect projected tracks

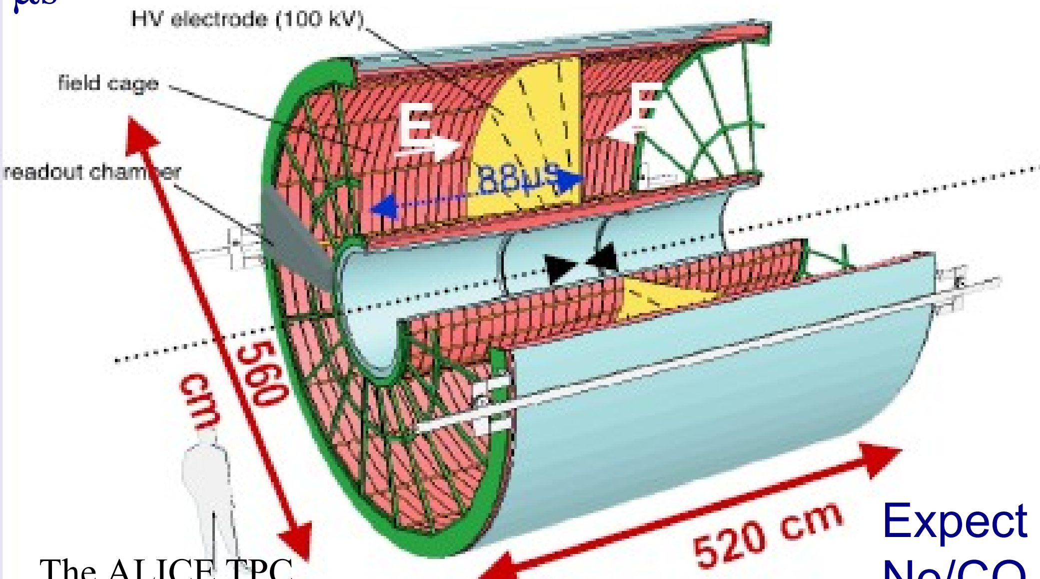
Time Projection Chamber

- TPC is a 3D detector
  - has no pulsed very high-voltage
  - is faster, its speed is determined by maximum drift time which for large chambers ~ 100 μs
- spatial resolution depends on many parameters
  - drift length and diffusion constant
  - track angle with respect readout plane and pad row
  - primary ionization (electron statistics)
  - a typical value is ~ 500 μm



The Alice on TPCs

- Usually $B \parallel E$ improvement of diffusion
- Drift length $\geq 1\text{m}$
- Rather (very) stringent requirement on homogeneity of E and B field
- Space charge by ions
- "Slow" detector $t_D \sim 10 \rightarrow 100$ μs



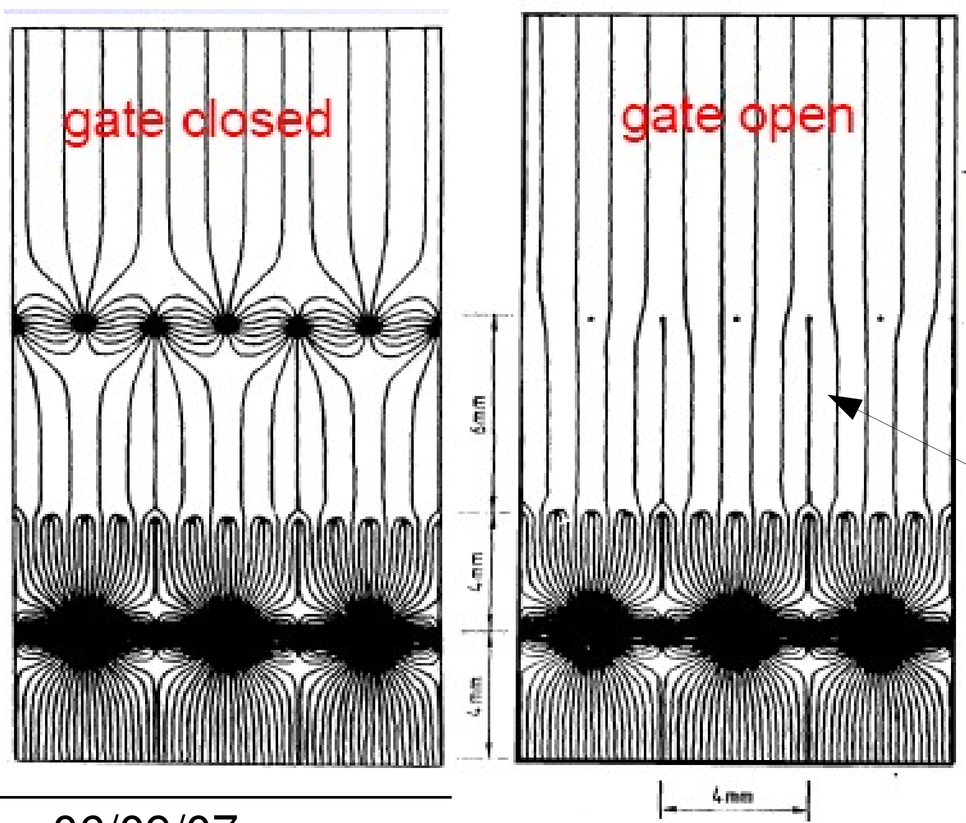
The ALICE TPC

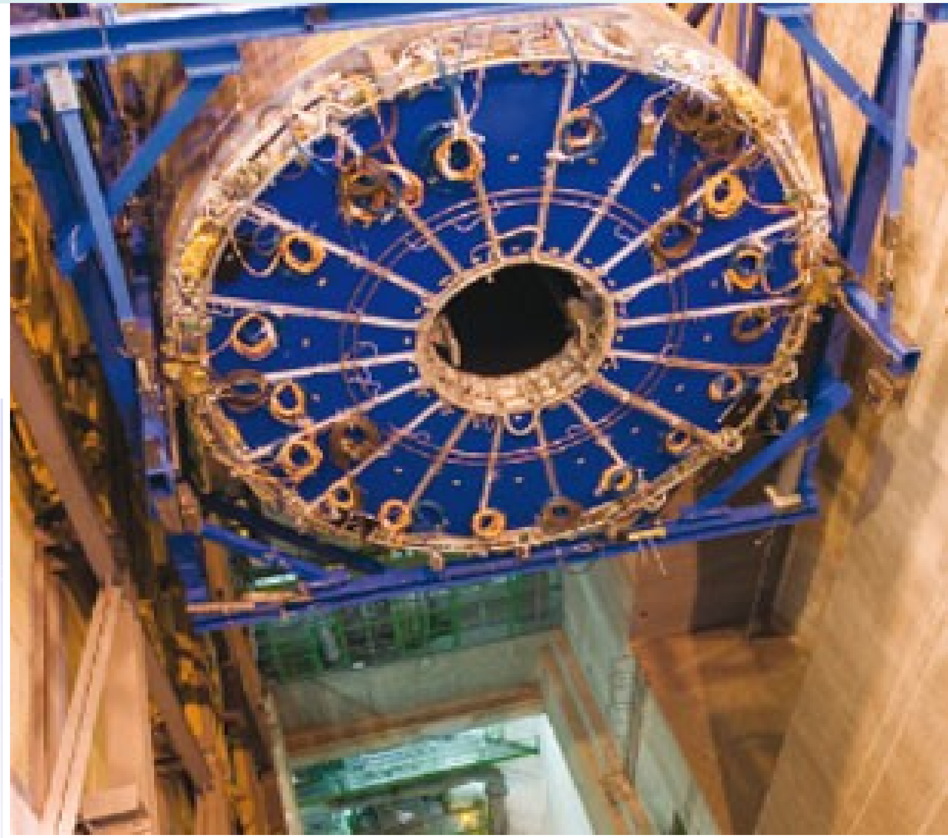
Expect dN/dη≤ 8000

$Ne/CO_2/N_e$ 90%-10%-5%

Positive ion back flow

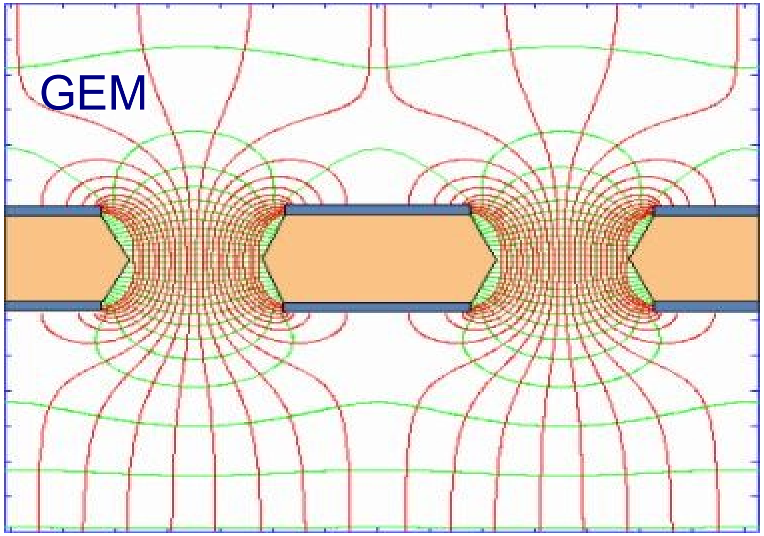
- Change of field during drift,
- Minimize dead time by gating
- (open gate on positive trigger)



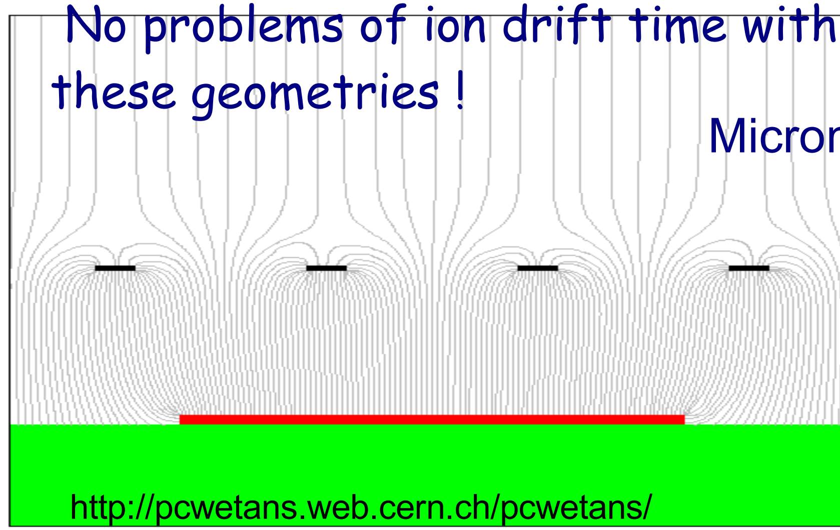


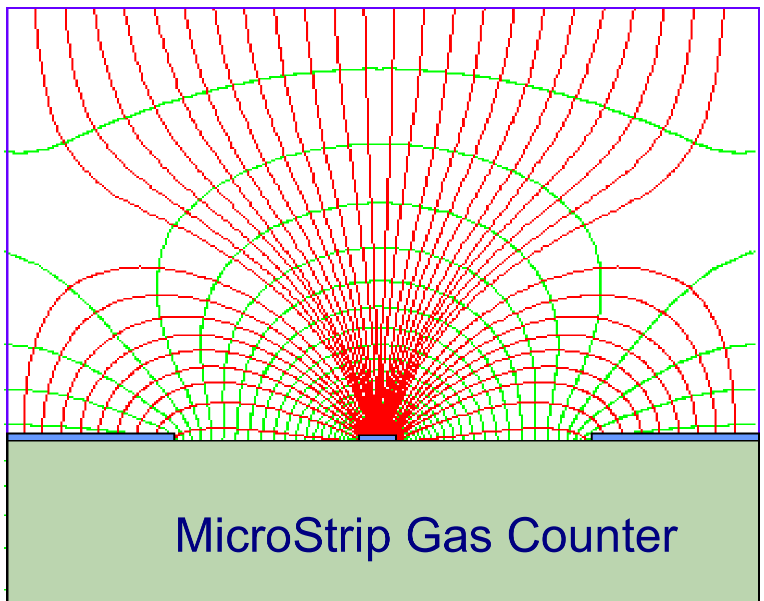
L1 trigger opens the gate
(6.5μs after BX)

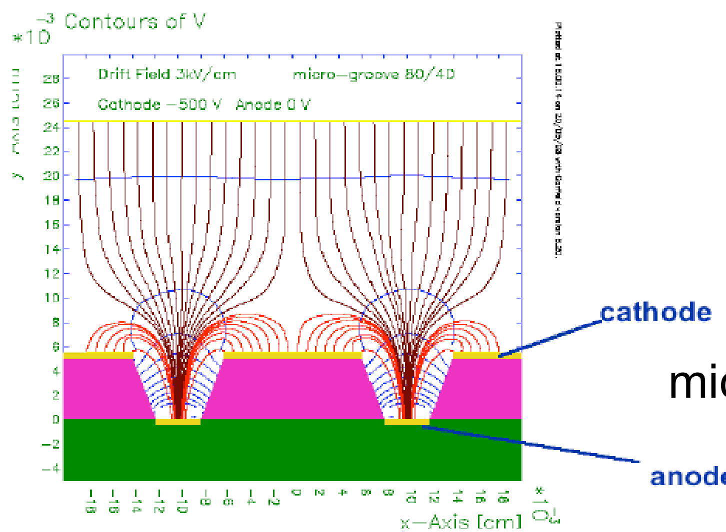
Other geometries generating strong E-field



No problems of ion drift time with these geometries !



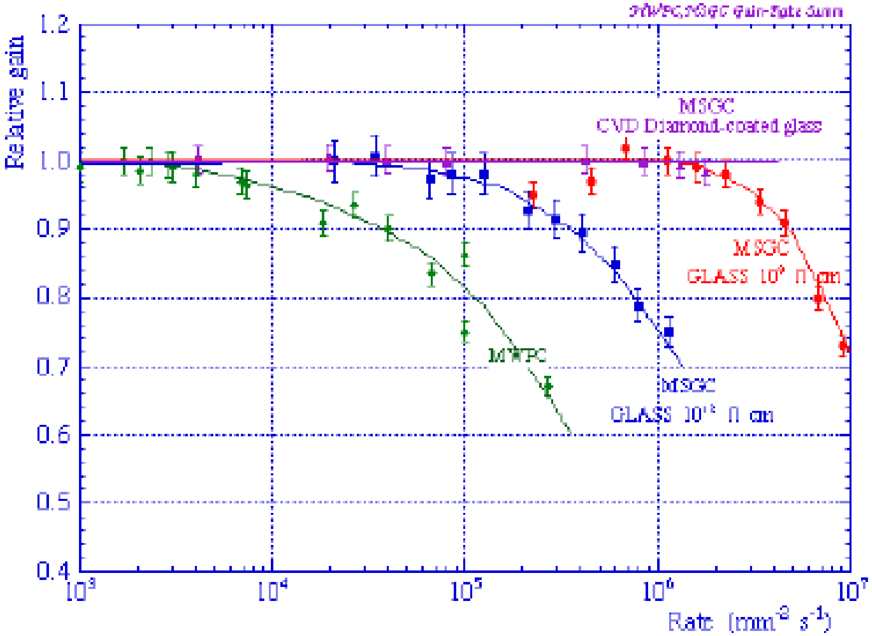




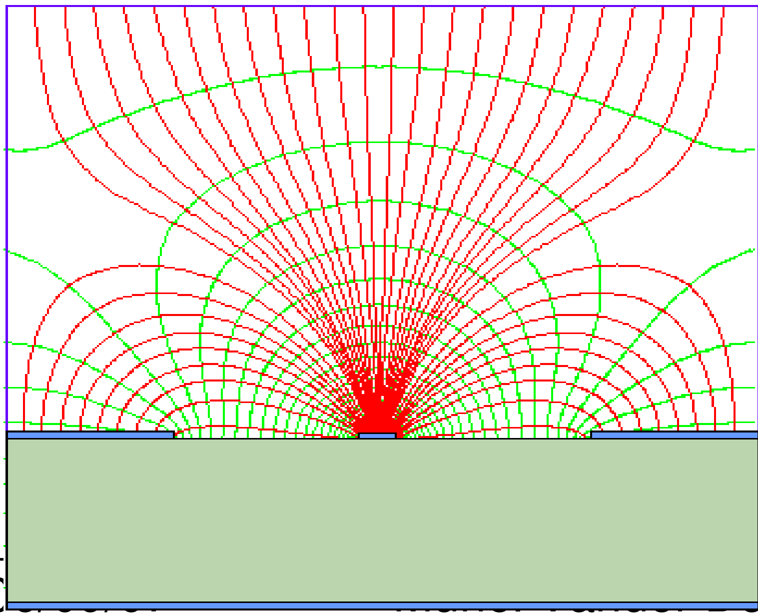
micrgroove

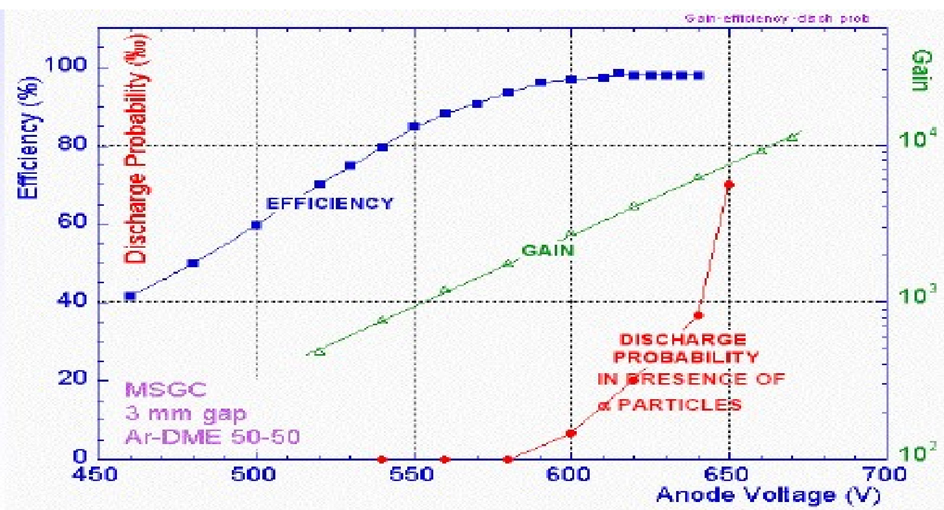
Equipotential and drift lines
(with zero diffusion)

Scaling down…

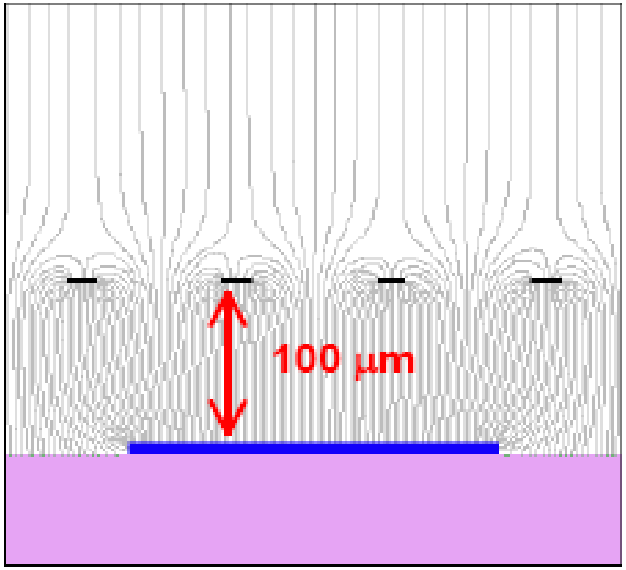


- Gas detectors have low radiation length
- "Cheap"
- Good spatial resolution + dE/dx
  - But rate limited by ion drift time
  - Reducing the cell size reduces that problem

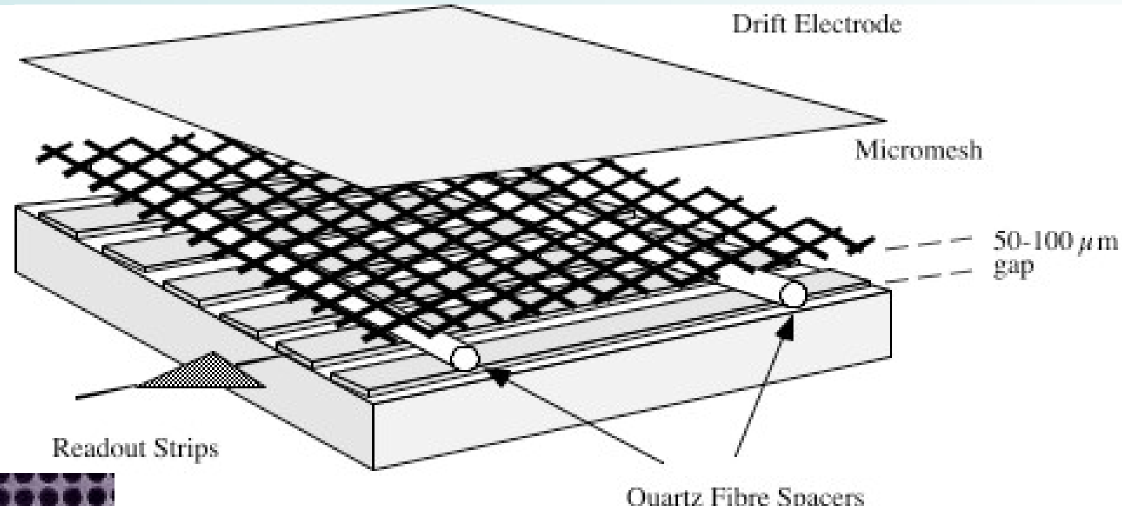




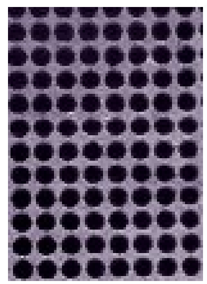
MicroMegas

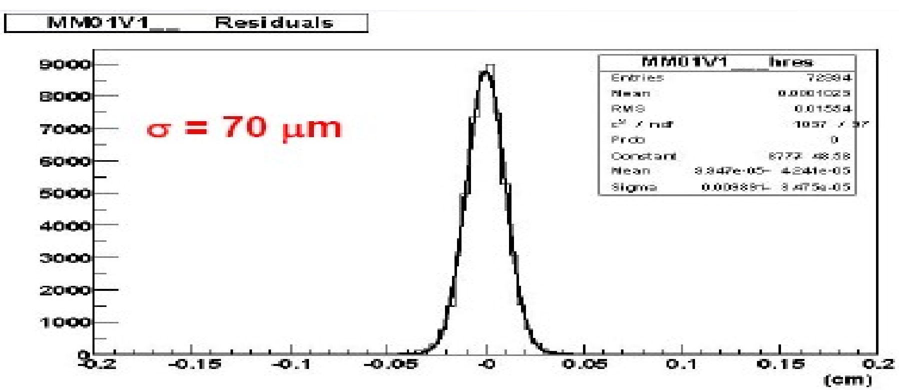


100 μm

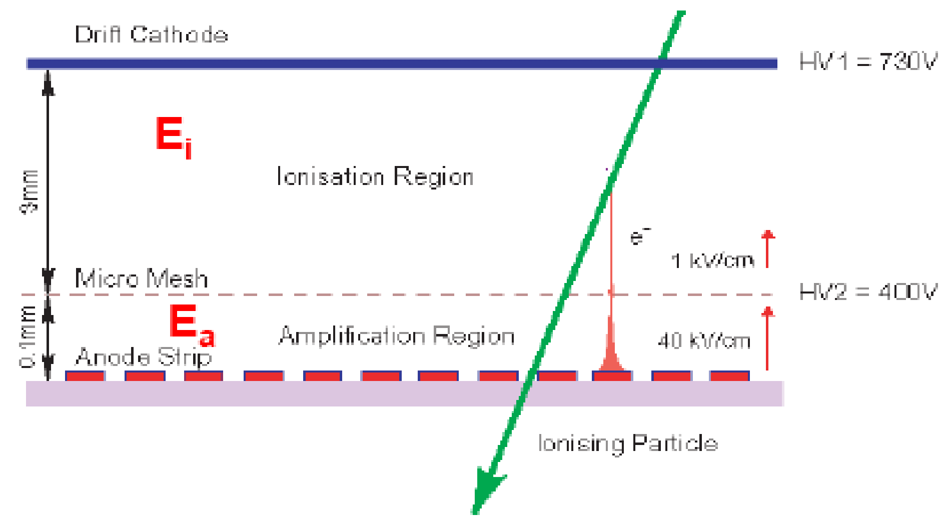


Drift Electrode
Micromesh
50-100 μm gap
Readout Strips
Quartz Fibre Spacers



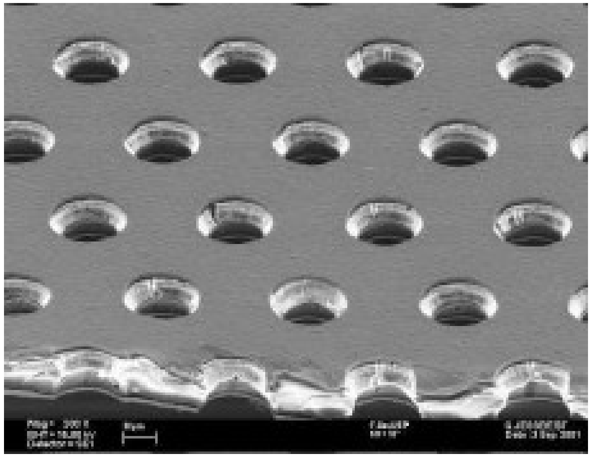


MM01V1__ Residuals
σ = 70 μm
MM01V1__ hres
Entries
Mean
RMS
Prob 0
Constant
Mean
Sigma
(cm)

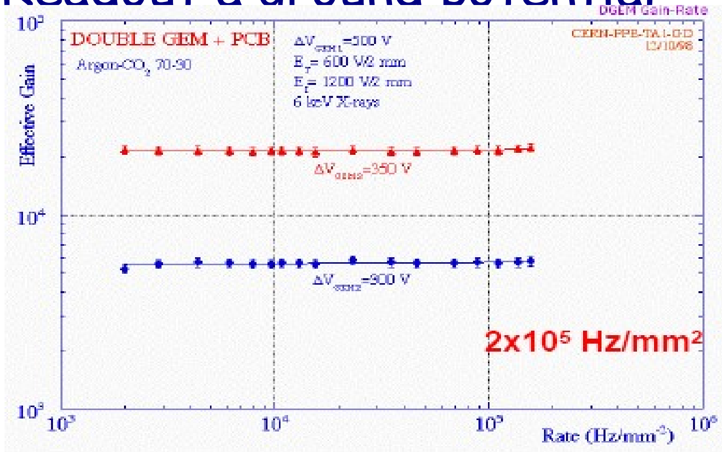


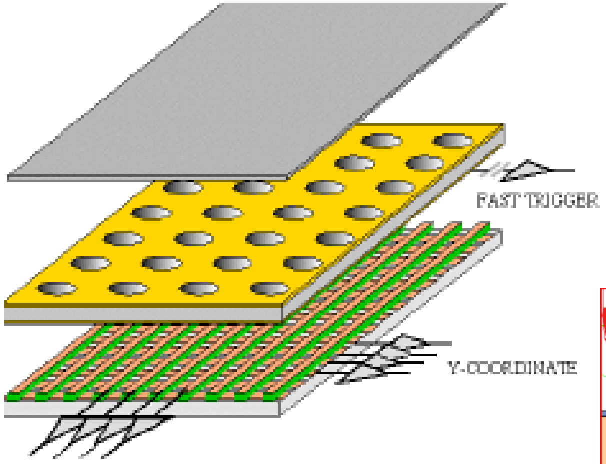
Drift Cathode
HV1 = 730V
E_i
Ionisation Region
3mm
e⁻
1 kV/cm
Micro Mesh
HV2 = 400V
E_a
Amplification Region
40 kV/cm
0.1mm
Anode Strip
Ionising Particle

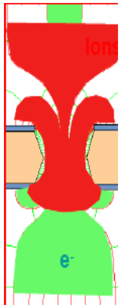
GEM

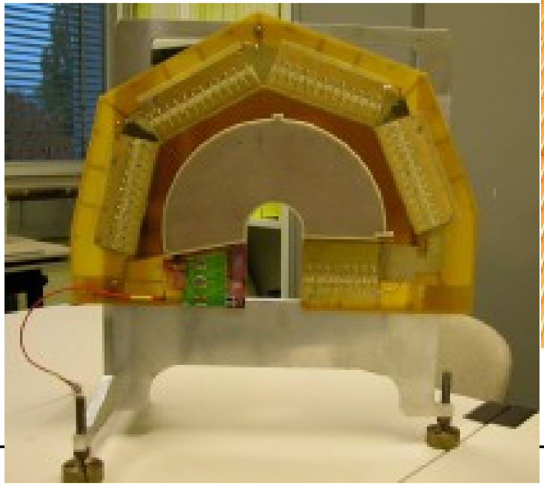


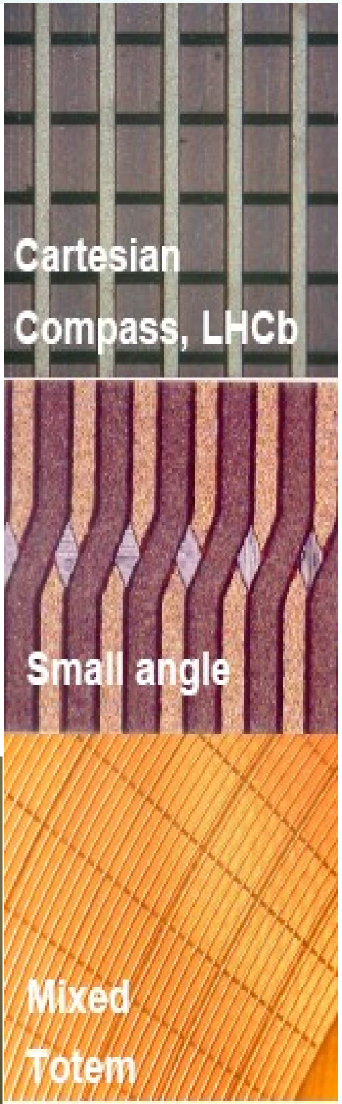
- Thin, metal coated polyimide foil perforated with high density holes.
- Readout a ground potential





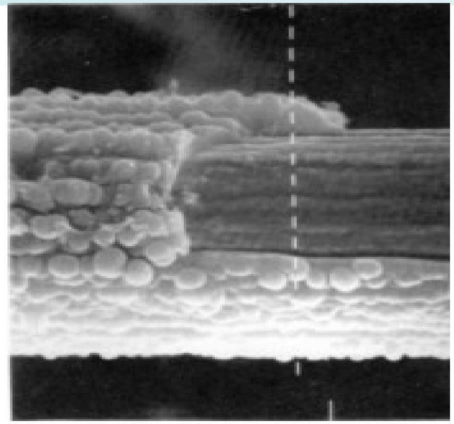


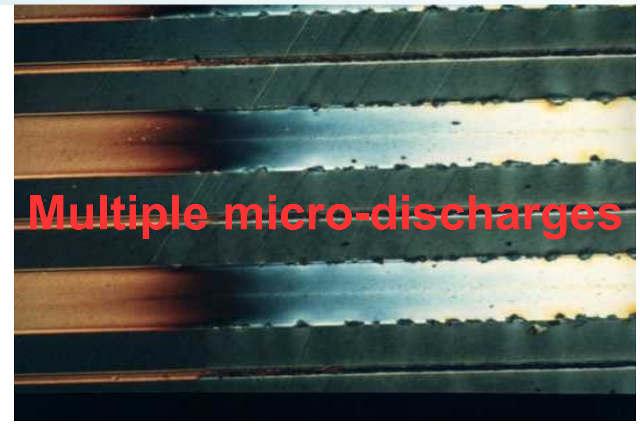




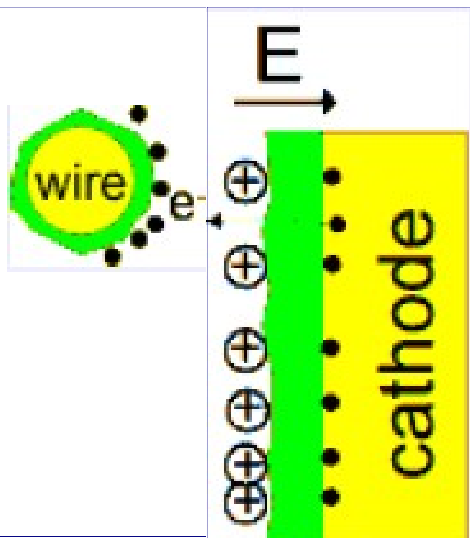
Limitation of gas detectors : Ageing

- Polymerisation of the organic gas
- Dissociation and creation of free radicals
- Insulating organic deposits on the electrodes





Anode: increase of wire ∅ variable E, gain

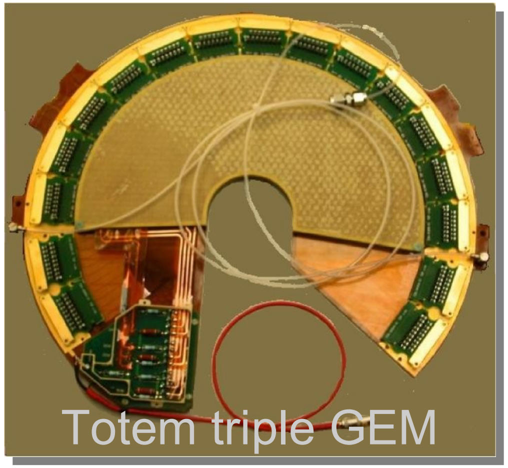


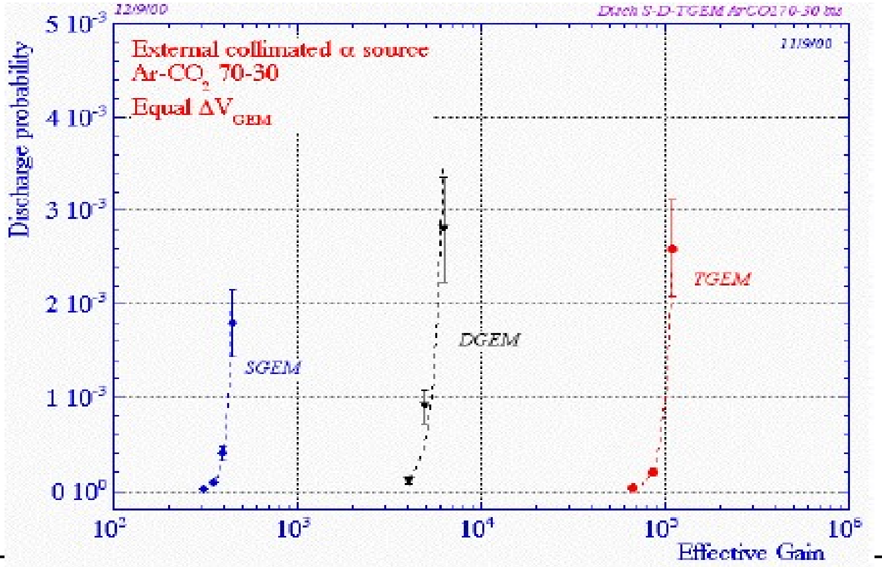
Cathode: strong dipole field creation, field emission

- careful material selection for the detector and gas system, detector type working point, non-polymerizing gases,
- anti-polymer-additives (alcohols, methylal),
- surface conductivity increasing additives (H_2O vapour),
- cleaning additives (CF4).

Limiting factors

- Discharges
  - Field and charge density dependent effect.
  - Solution: multistep amplification
- Rate limited by space charge
  - Solution: reduction of the length of the positive ion path
- Insulator charging up resulting in gain variable with time and rate
  - Solution: slightly conductive materials





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

Gas detectors used at LHC

- 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)

References

- O. Ullaland CERN Summer Student Lectures 2005
- L. Ropelewski CERN Summer Student lectures 2006
- W. Blum, L. Rolandi, "Particle detection with Drift Chambers"
- F. Sauli, IEEE Short Course on Radiation Detection and Measurement, Norfolk (Virginia) November 10-11, 2002
- Field simulation in detectors: P. Cwetanski , http://pcwetans.home.cern.ch/pcwetans/
- Gaseous detector group @ CERN : http://gdd.web.cern.ch/GDD/