(dis)cours / lectures on detectors for high energy physic, astro-particle physic and nuclear physic

Matthew Charles
LPNHE, IN2P3 and Paris Sorbonne university
matthew.charles@lpnhe.in2p3.fr

Thomas Patzak
APC, IN2P3 and Paris Cité university
patzak@apc.in2p3.fr

Philippe Schune
Irfu, CEA - Saclay and Paris-Saclay university
philippe.schune@cea.fr

Lectures and evaluation

Lecture #1 (Ph.S.) : **02/09 afternoon (Orsay campus : b.100-A)**
Working aspects of a complex detector

Lecture #2 (M.C.) : **05/09 morning (Jussieu campus)**
Interaction of particle with matter

Lecture #3 (M.C.) : **08/09 morning …**

Lecture #4 (M.C.) : **12/09 morning …**

→ Lecture #5 (Ph.S.) : **15/09 morning (Orsay campus : b.100-A)**
Gaseous detectors

Lecture #6 (Ph.S.) : **19/09 morning (Jussieu campus : tour 24-34, room 101)**
Gaseous detectors (con't), calorimeters, magnets, trigger

Lecture #7 (T.P.) : **04/10 …**

Lecture #8 (T.P.) : **11/10 …**

Lecture #9 (T.P.) : **18/10 …**

Remember to look at the place + room !
(also morning or afternoon)

After these lectures : writing test + oral exam (analysis of a detector paper)
Evaluation will be discussed/presented later in September.

Bibliography

Particle Data Group (tables, figures, etc.) accessible from: http://pdg.lbl.gov

- Claus Grupen, Particle Detectors (Cambridge University Press, 1996)
- Robert S. Gilmore, Single particle detection and measurement (Taylor & Francis, 1992)
- → Walter Blum and Luigi Rolandi, Particle detection with drift chambers (Springer-Verlag, 1994)
- Instrumentation in high energy physics (World Scientific, ed. F.Sauli, 1992)
- Experimental techniques in high-energy nuclear and particle physics (World Scientific, ed. Th.Ferbel, 1991)
- Konrad Kleinknecht, Detectors for particle radiation (Cambridge Univ. Press, 1986)
- W.R. Leo, Techniques for Nuclear and Particle Physics Experiments (Springer, 1994)
- Spark, streamer, proportional and drift chambers, Peter Rice-Evans (Richelieu Press, 1974)
- Review of Particle Physics (European Physical Journal, 2000)
- Revue Nuclear Instruments and Methods
- ATLAS TDR (from 1999 to 2003), ATLAS internal notes (http://www.cern.ch)
- → Resistive Gaseous Detectors, *Designs, Performance, and Perspectives,* 2018 (Wiley-VCH) Marcello Abbrescia, Vladimir Peskov, and Paulo Fonte

Lecture on Gaseous detectors

Lecture on Gaseous detectors

Outline: Reminder
Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Q*uencher* / gain variation
δ-ray

Our goal : understand how it works!!

Practical examples: applying our knowledge (finally!)
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

Conclusions

REMINDER

Summary on interactions

During first lectures, we have seen that:

What a particles detector should do:

Measure of: E, $p_{x,y,z}$ (i.e. angular measurement), x, y, z, dE/dx, id. (mass), charge, time,…

Which particle would we see in our detectors: e, μ, γ, π, K, proton, n, jets (at high energy), (ν), α (=He^{2+}), $\beta^{+/-}$ (=$e^{+/-}$)

Energy loss/interactions in matter:

for charged particles: ionisation, described by Bethe-Bloch formula (*): $10^{-1} \lesssim \beta\gamma \lesssim 10^4$

Remark : a *m.i.p.* particle looses ~2 MeV/(g/cm²)

radiation for $e^{+/-}$ above $E_c^e \sim 660$ MeV/(Z+1.2)

for $\mu^{+/-}$ $E_c^\mu \sim 7000$ GeV/$(Z+2.1)^{0.89}$

for γ : photoelectric effect: $E_\gamma \lesssim 1$ MeV

Compton diffusion: 10 keV $\lesssim E_\gamma \lesssim$ 10 MeV

pair creation: $2.m_e \lesssim E_\gamma$

for hadrons, there is also strong interaction: $\sigma_{inel} \approx \sigma_0 A^{0.7}, \quad \sigma_0 \approx 35\,mb$

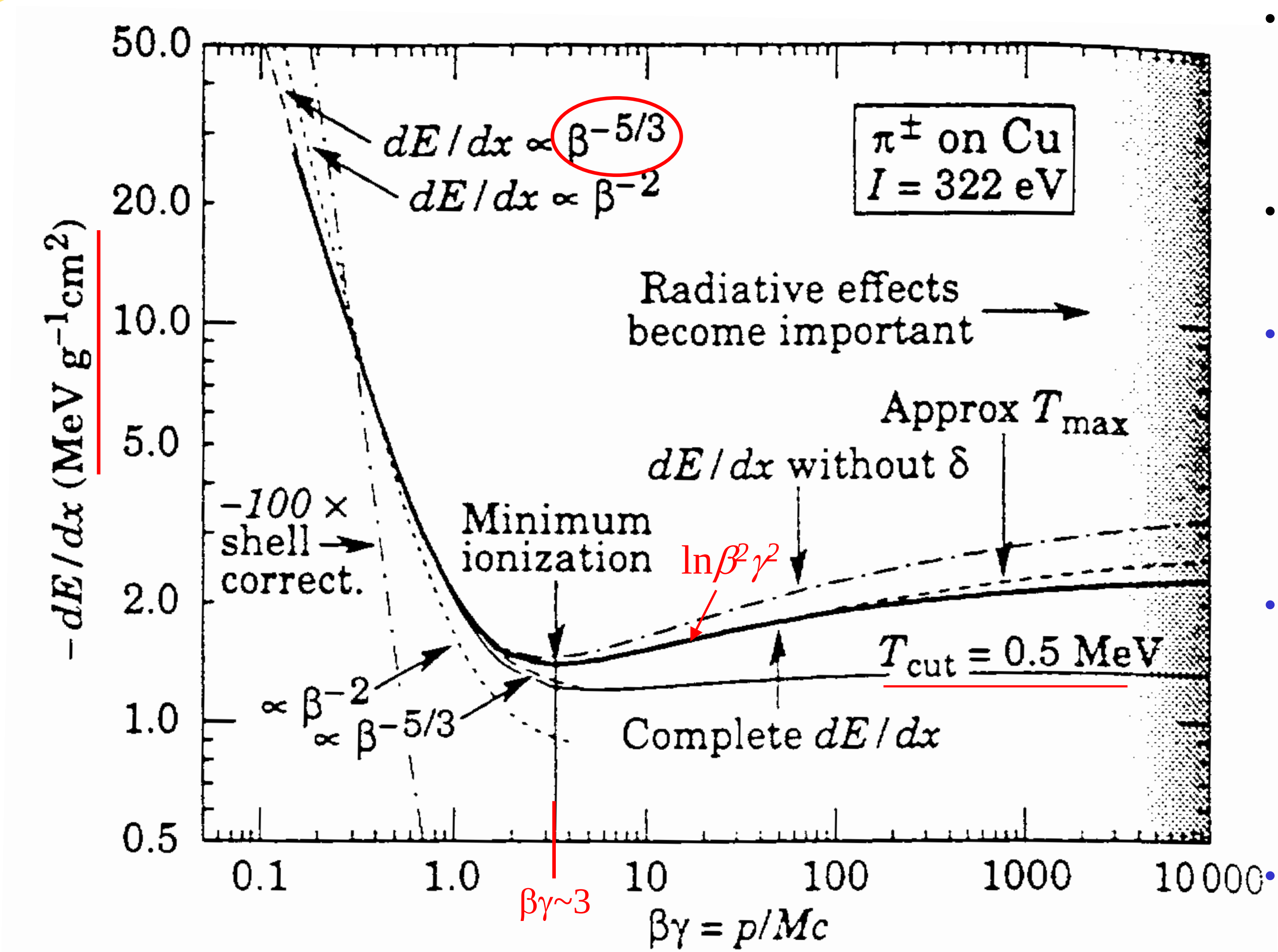
Radiation interactions and multiple scattering are characterized by: $X_0 = \frac{716.4\ g.cm^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$

strong interaction by: $\lambda_I \approx 35(\mathrm{g.cm^{-2}})A^{1/3}$

(*) with some correction for e^+/e^-

REMINDER

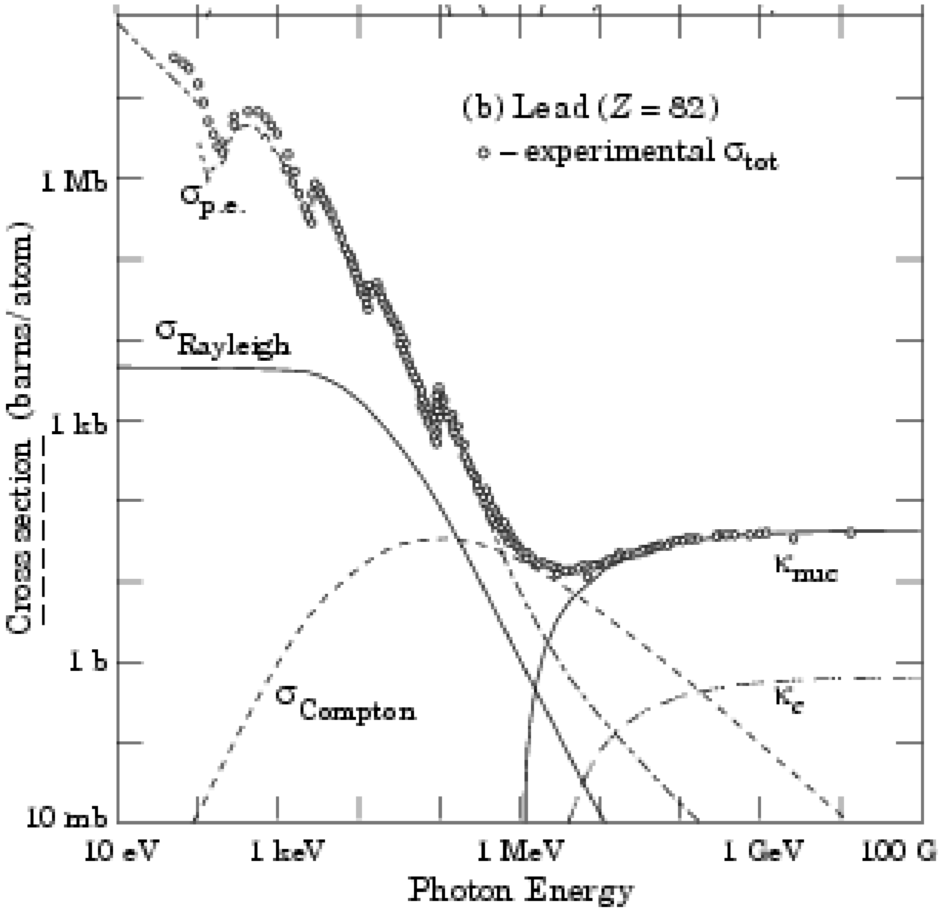
Mean energy loss in matter (heavy part.)

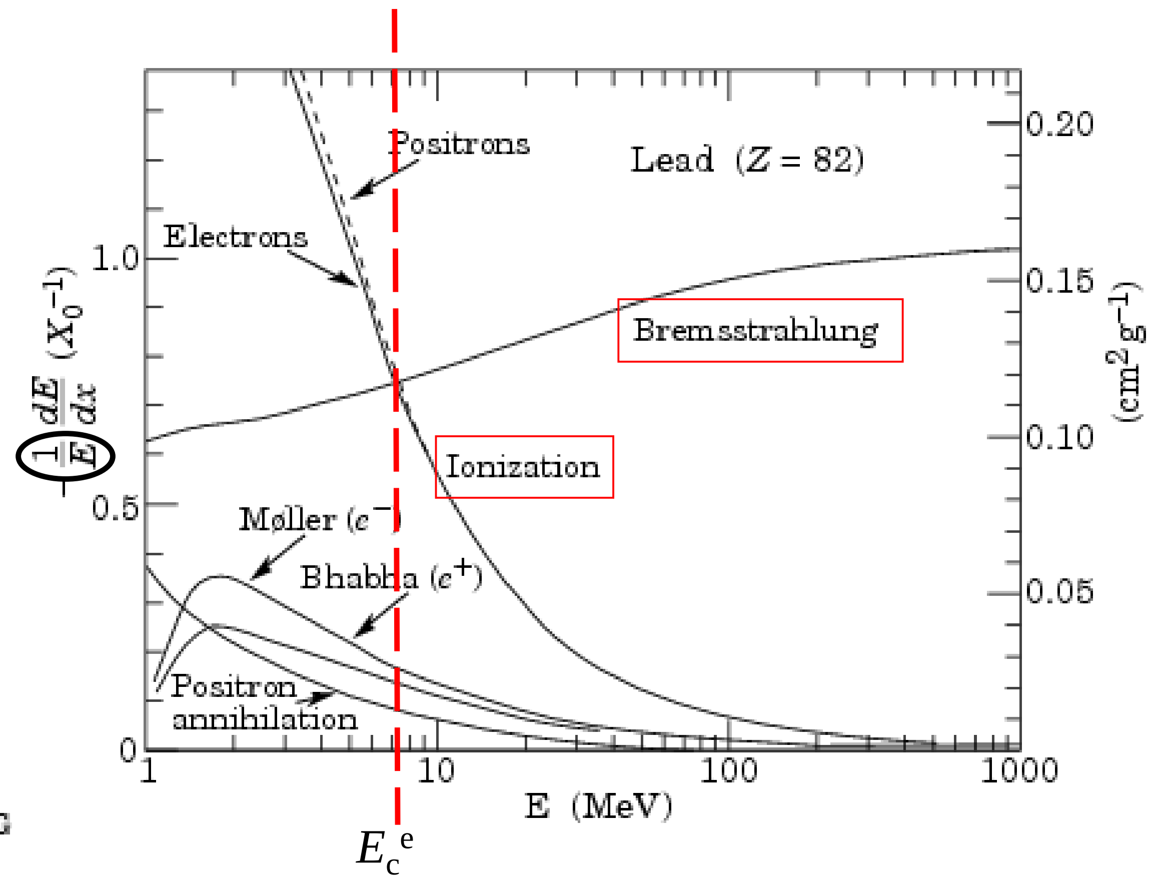


- "decrease", classical effect: as the particle speed decreases it has more time to ionise matter.
- Large minimum around βγ ~3
- Relativistic increase: transverse electric field is proportional to γ ; when energy increases, distant collisions are more probable.
- "Plateau" : when impact parameter is of the order of atomic distances polarisation effects (and thus correction) are getting more important.
- Large dE/dx (δ-ray): may be considered as new particle or simply dE/dx.

REMINDER

Interaction of γ and electrons in matter





Photoelectric effect

pair creation

Compton diffusion

$E_c^\mu \sim E_c^e .(m_\mu/m_e)^2 \gtrsim 100$ GeV

Dependence of "density factor" with pressure (for H_2)

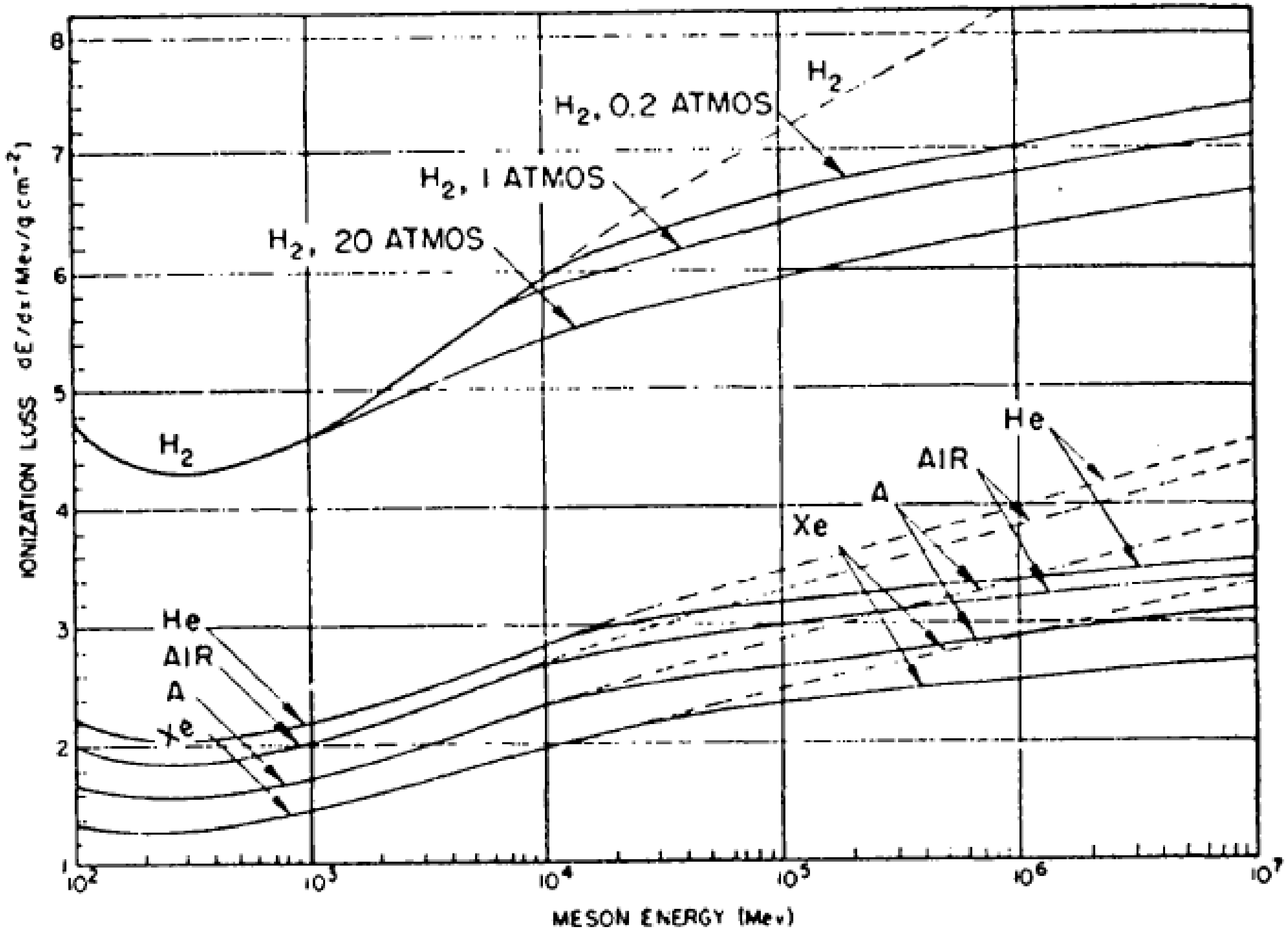


FIG. 4. Ionization loss of μ-mesons in various gases. The broken curves give the values of $(1/\rho)(dE/dx)$ which would be obtained without the density effect.

plasma freq. :

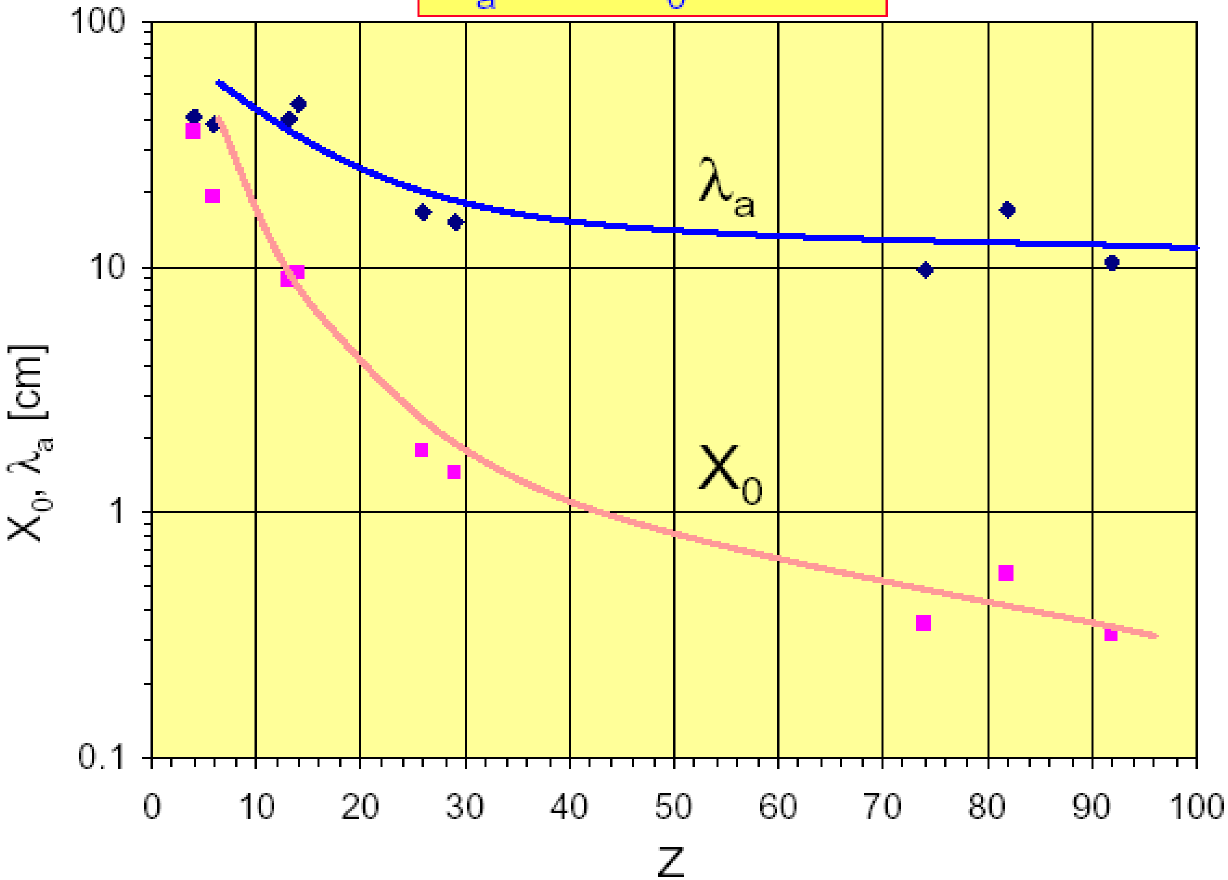
$$\omega^2 = ne^2/\varepsilon_0 m$$

(n = #el./cm^3)

Radiation length vs interaction length

At high energies ($E>E_c$) radiation phenomena's could be describe by a coefficient of absorption : after going through a certain amount of matter of thickness x, there is only $e^{-x/L}$ initial particules remaining. L is written X_0 EM process and λ_I for hadronic process. Unit is cm or g/cm^2.
<u>Remark :</u> $\lambda_I > X_0$ pour Z > 6.

λa and X0 in cm



<u>Unit :</u>

$$\lambda_I \approx 35(\mathrm{g.cm^{-2}})A^{1/3}$$

And N.A = ρ. N_a so λ_I/ρ in cm varies like $A^{-2/3}$

$$X_0 = \frac{716.4(\mathrm{g.cm^{-2}})A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

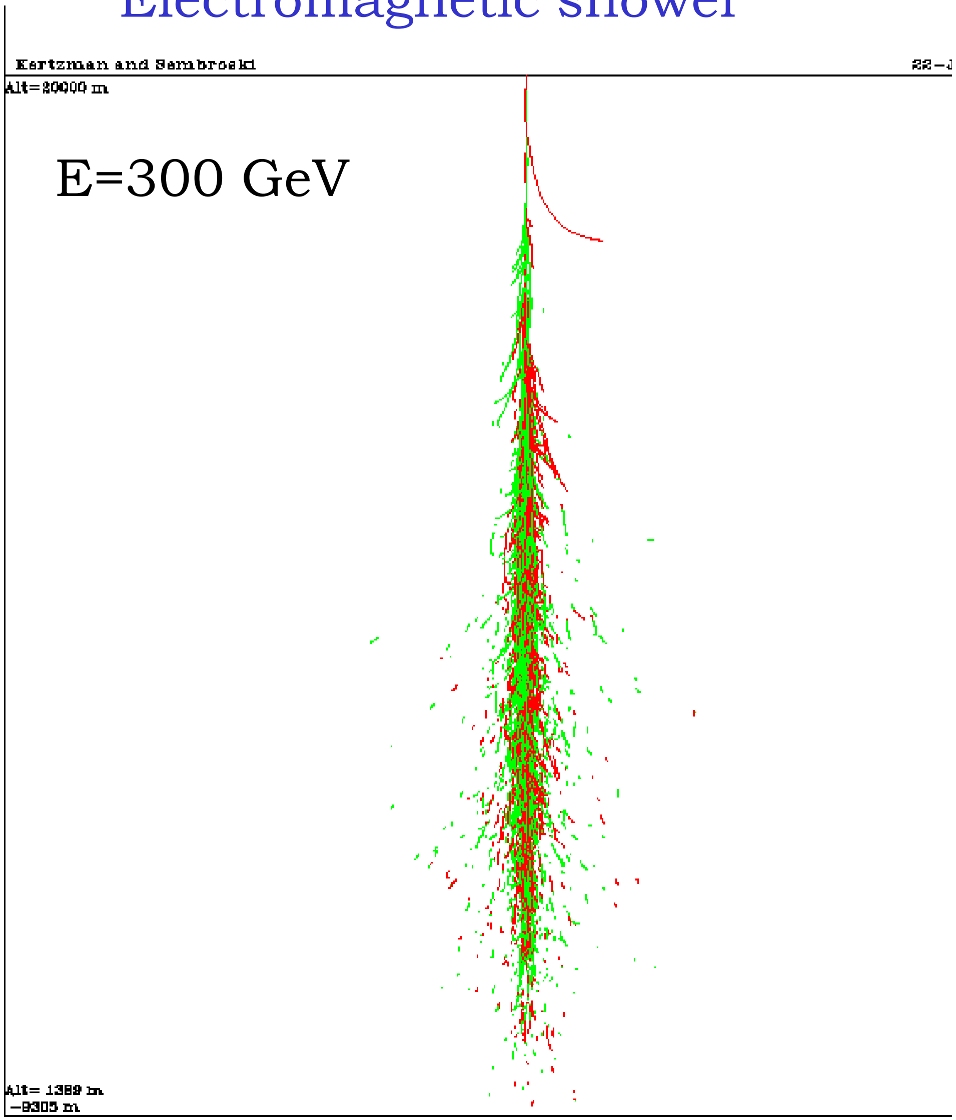
$\lambda_I > X_0$ for Z>6 thus for a given material, electrons and photons are more efficiently absorbed than hadrons.

<u>For material above Z=50 :</u>
$\lambda_I > 10 \times X_0$

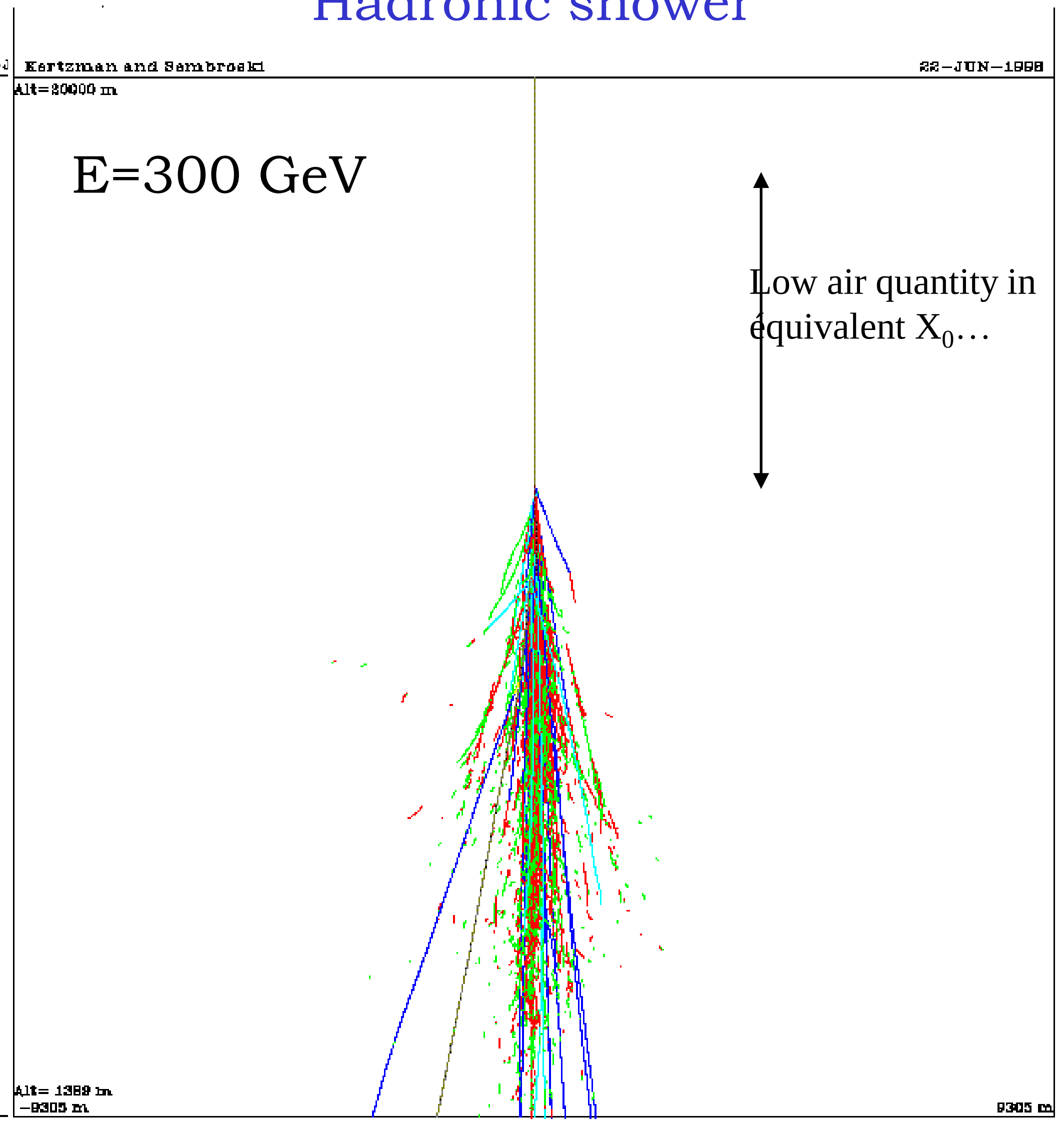
For lead : $\lambda_I / X_0 \sim 0{,}12.Z^{4/3} \sim 30$

EM shower versus Had. shower in air

Electromagnetic shower



Hadronic shower

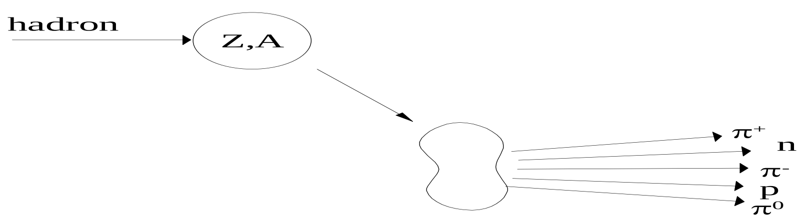


Total amount of air at sea level ~23.X_0

REMINDER

Implication : the hadronic showers

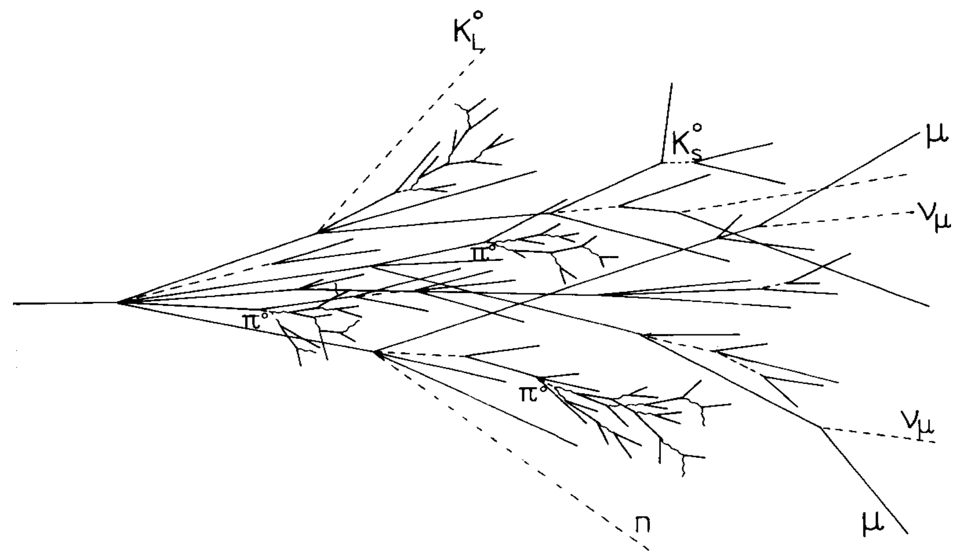
In an hadronic shower, there will be production of many π, K and neutrons. π^0 will give an EM component (from 15 to 20% of initial E), some of the π et K at low energies will give – by decay - μ, ν. Neutrons are difficult to detect (neutral, heavy part.) and will escape. This gives with neutrino the invisible energy of the shower.



Multiplicity varies with E ∝ ln*(E)*
=> Quick development of the shower

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\, mb$$

~ independant of the energie above 1GeV for p, π, K…



$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example 100 GeV: $n(\pi^0) \approx 18$

Remarq : energy profil deposition are different between EM and Had. showers : higher multiplicity for hadronic interaction at the begining of the shower development.

secondaries : $p_t \approx 0.35$ GeV/c

How the hadronic shower is produced ?

Secondary particules production in hadronic showers are coming from "spallation" :

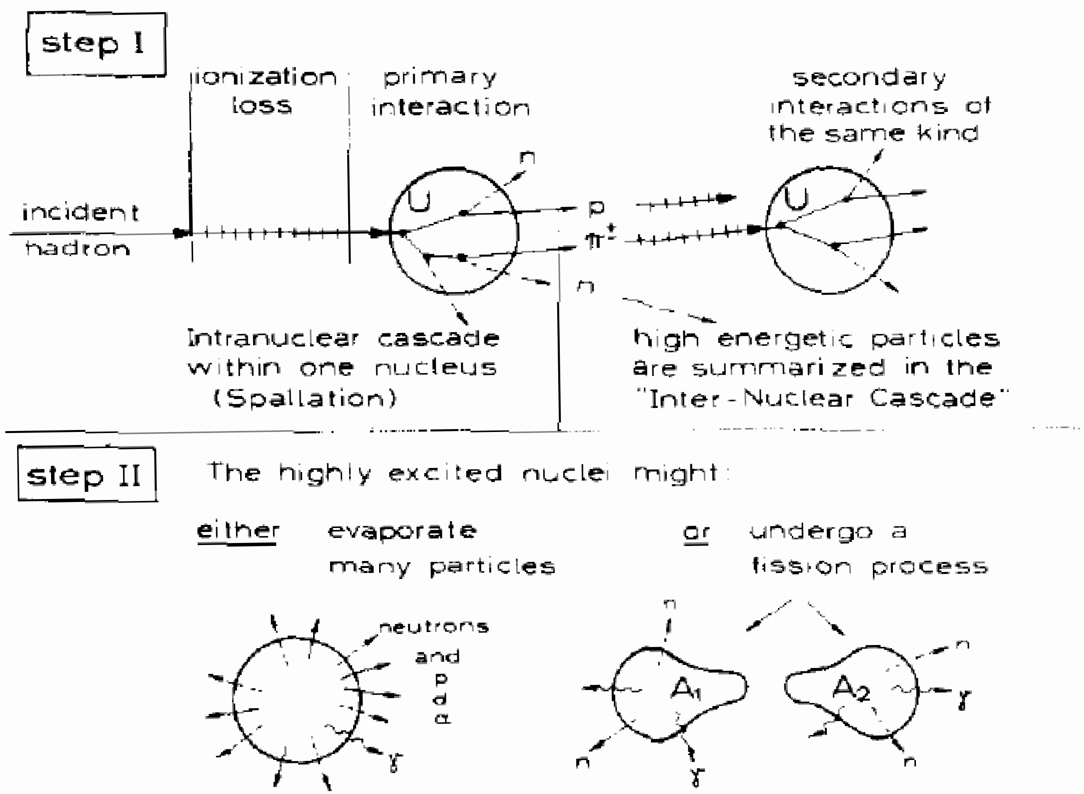
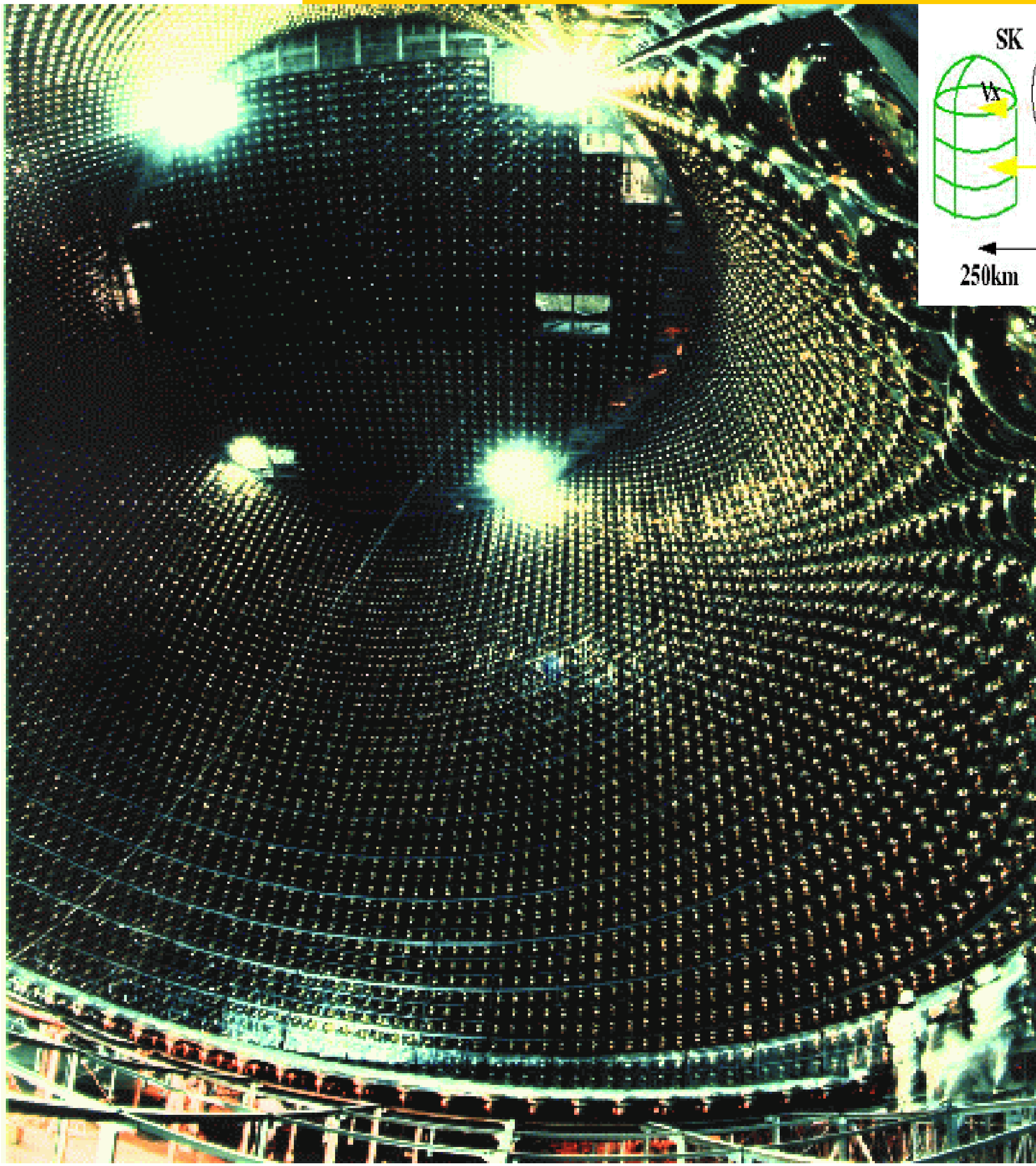


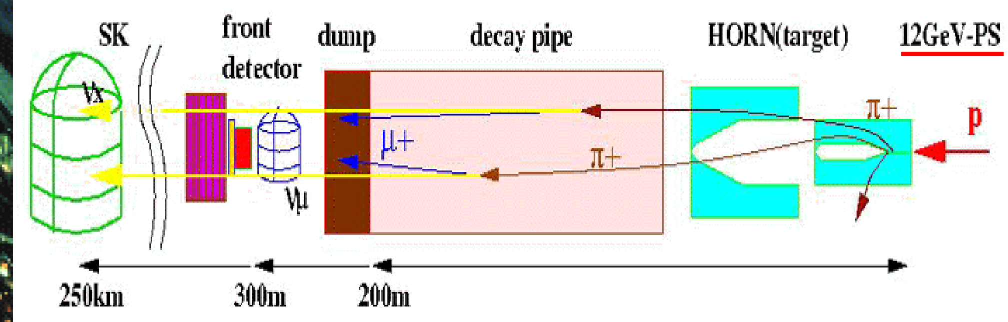
Fig. 6. Step I: Development of an "internuclear cascade". From one nucleus an intranuclear cascade releases a few high energetic spallation products, which are able to iniciate further intranuclear cascade processes. Step II: The highly excited nuclei remaining from each intranuclear cascade deexcite.

H.Bruckmann et al., NIM-A263(1988) 136

(parenthesis

Super-Kamiokande experiment (Japan)





~11 150 PM
~50 k-tonnes ultra pure water
H_2O : $1.X_0^{eau} = 36$ g/cm^2 (= 36 cm)
n=1.33 => $\theta_{Cerenkov} \sim 40^o$

Detection of *Cerenkov* rings
produced in water.

Neutrino energy ~1.5 GeV
=> energy of μ and e
in Super-K $\lesssim$ 1.5 GeV

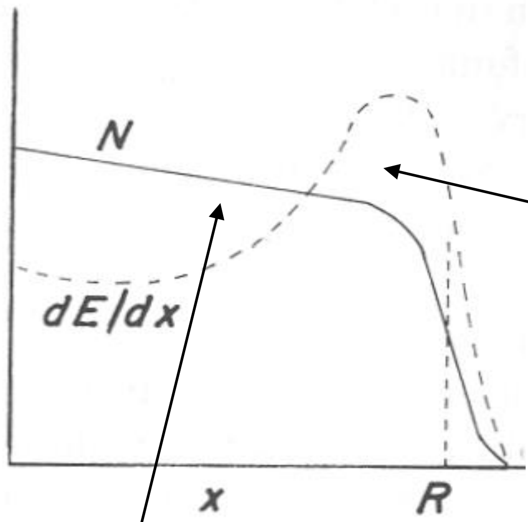
Reminder: $E_c^e \sim < 1.5$ GeV.

REMINDER

"*Range*" of particle in matter

$$\frac{dE}{dx} = \sum w_i \left.\frac{dE}{dx}\right|_i$$

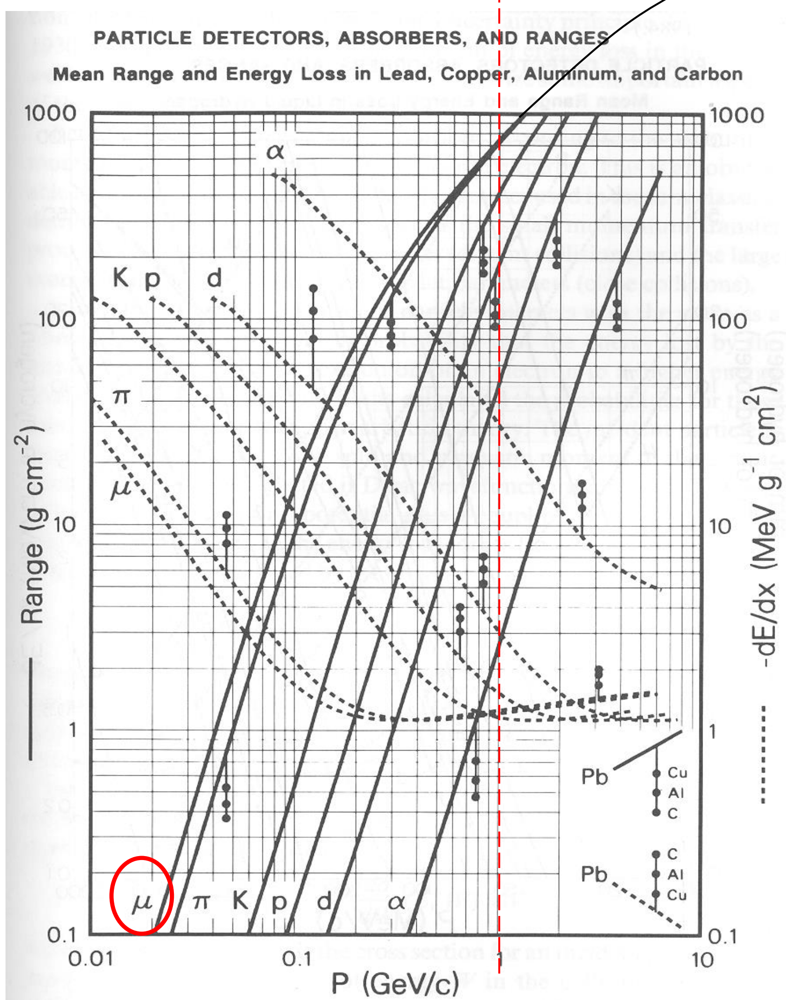
w_i = fractional mass of element #i



Fast brake due to dE/dx variation like $\beta^{-5/3}$. This is the Bragg peak

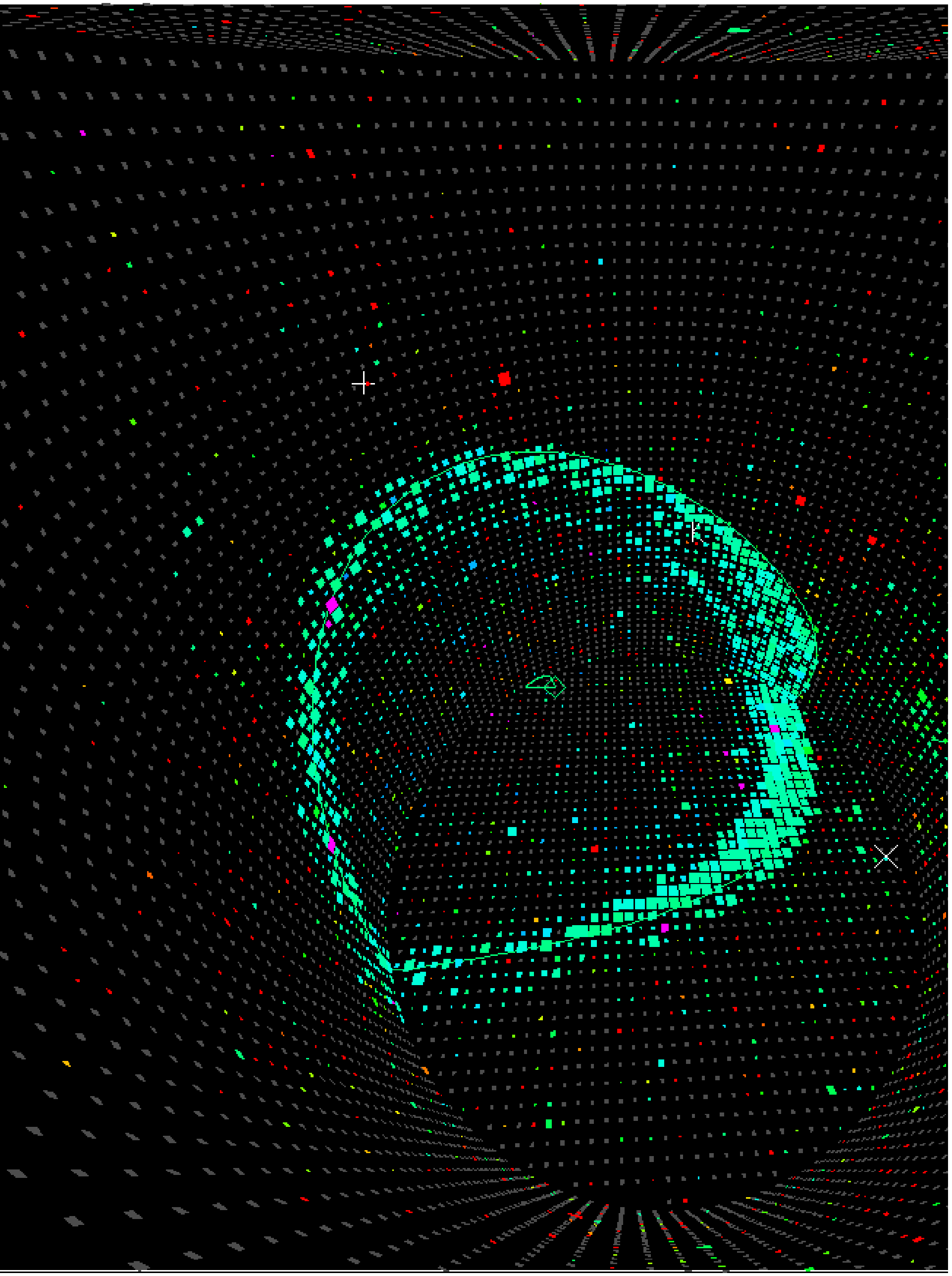
Slow decrease due to (rare) interaction with high momentum transfer.

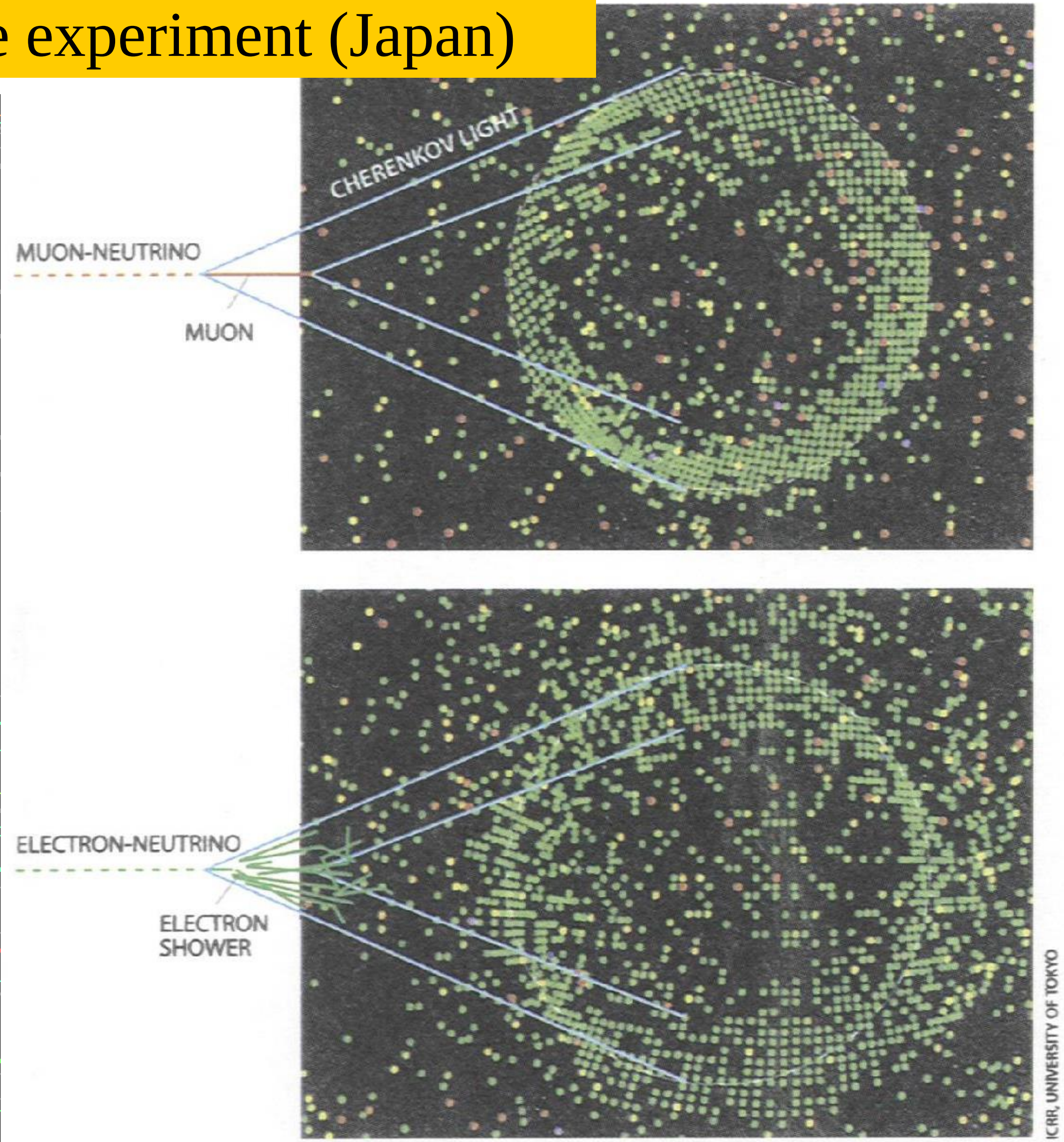
~ 400 g/cm^2 (≈ 4m in water)



E_μ~1 GeV

Super-Kamiokande experiment (Japan)

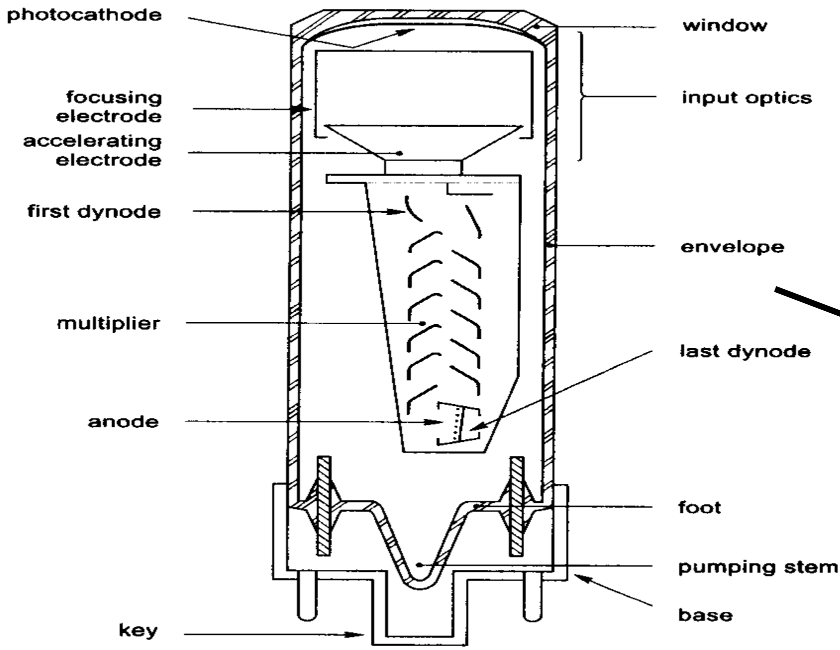




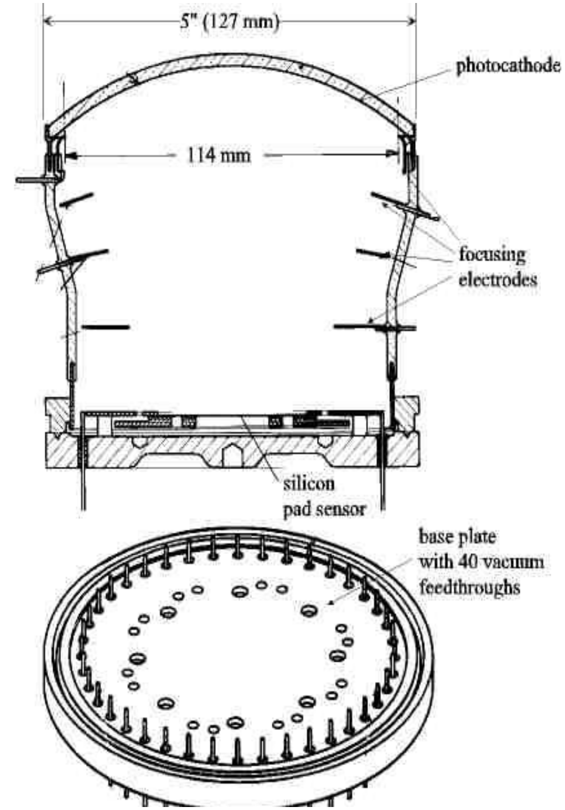
CONES OF CHERENKOV LIGHT are emitted when high-energy neutrinos hit a nucleus and produce a charged particle. A muon-neutrino (*top*) creates a muon, which travels perhaps one meter and projects a sharp ring of light onto the detectors. An electron, produced by an electron-neutrino (*bottom*), generates a small shower of electrons and positrons, each with its own Cherenkov cone, resulting in a fuzzy ring of light. Green dots indicate light detected in the same narrow time interval.

PM and HPD (Hybrid Photo Diodes)

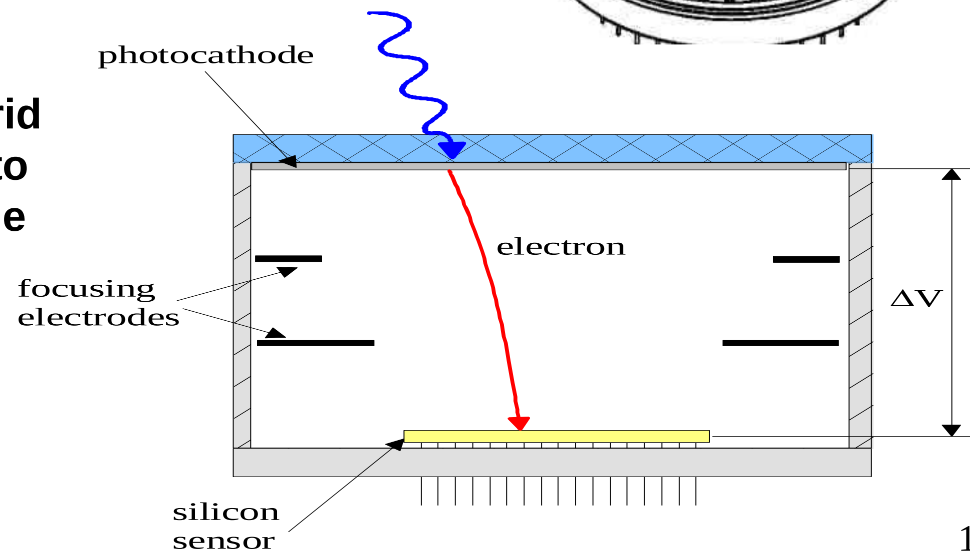
Photo Multiplier Tube



Remove dynodes and anode
add silicon sensor inside tube



Hybrid Photo Diode



~4000 to 5000 electrons-holes pairs → good energy resolution parenthesis)

Lecture #4
Gaseous detectors

Outline:

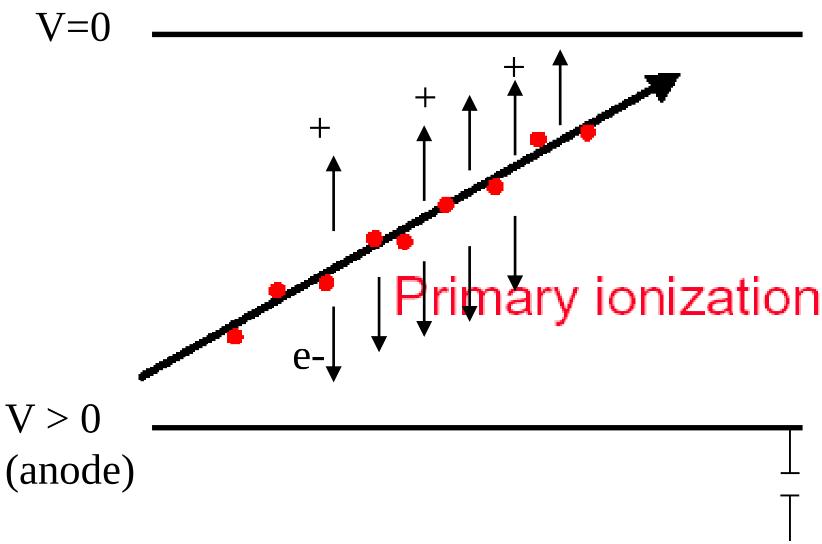
→ Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
δ-ray

Our goal : understand how it works!!

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

Conclusions

Electrons and ions drift in gas



Gas density ρ, of the order of 0.001
So dE/dx ~ 0,001×1×2 ~ 2 keV
More precise calculation gives 4 keV in Ar.

First case:
A *m.i.p* particle. in 1 cm of gas (Ar) will create ~30 e^-/ions pairs.

Question: What is the mean energy required to create an e-/ion pair?
(see PDG *Booklet*)

In general, primary electrons have enough energy to locally ionise the gas:
In total, $n_T \approx 3\times$ to $5\times$ $n_{primaire}$

If we collect all these charges, we measure:
V = ne/C   (← Q = C.V)

Assuming:
C = 10pF, n = 30 => V~ μ–volt (to small)

PDG *booklet* page on material properties

Page 317 of 2004 edition

Material	Z	A	$\langle Z/A\rangle$	Nuclear[a] collision length λ_T {g/cm^2}	Nuclear[a] interaction length λ_I {g/cm^2}	$dE/dx\|_{min}$[b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length[c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28[d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28[d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265[e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33

Mean energy for e-/ion pair production

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

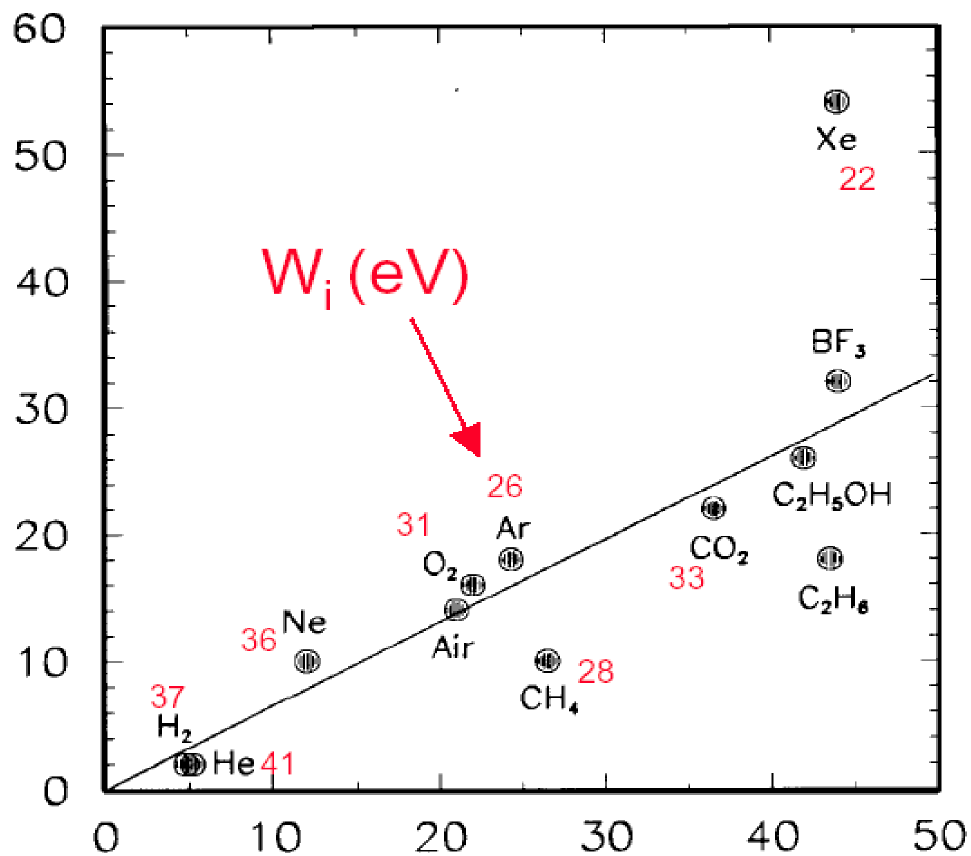
$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

Total number of electron/ion pairs

W_i = energy needed for one pair

# of primary pairs in some common gas (and W_i)

$\overline{Z}$ (mean Z)



n_{prim} (# pairs / cm / atm)

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

Remark on e-/ion pair production and on energy resolution

Different ways to produce pairs (p= incident particle):

Excitation: $X+p \rightarrow X^*+p$ then $X^* \rightarrow X^++e-$

Ionisation: $X+p \rightarrow X^++p+e-$

Penning effect: $Ne^*+Ar \rightarrow Ne+Ar^++e-$
direct desexcitation is "very low" and happen through collision with Ar.

Resolution on energy will be (mean value):

$$R = 2.35\sqrt{\frac{F.w_i}{\Delta E}}$$

with:

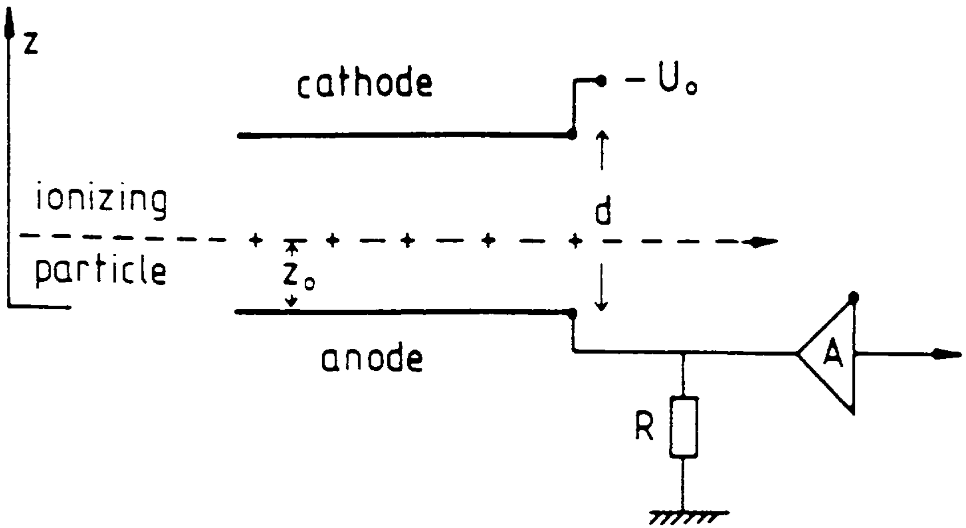
- F = *Fano* factor ; F<1 due to non independent ionisations
- ΔE = energy deposited
- $2.35 \approx 2\sqrt{2}\sqrt{\ln 2}$ (FWHM coef.)

Increase the resolution!

Depending of the gas, we measure F from 0.15 to 0.4 (constant changing with material): Ar (0.2) ; Ar+5%Xe (0.14); Ar+5%Kr (0.37), etc.

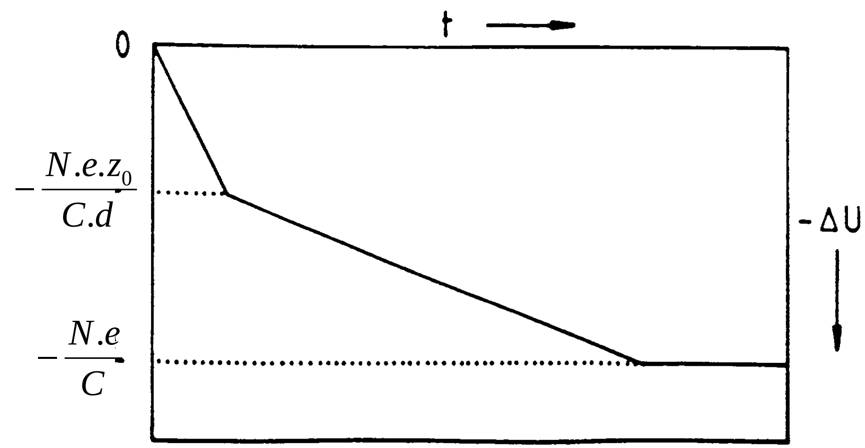
Development of signal in a **ionisation chamber**

Fig. 2.1. Parallel-plate ionization chamber (schematic).



V = ne/C (← Q = C.V)

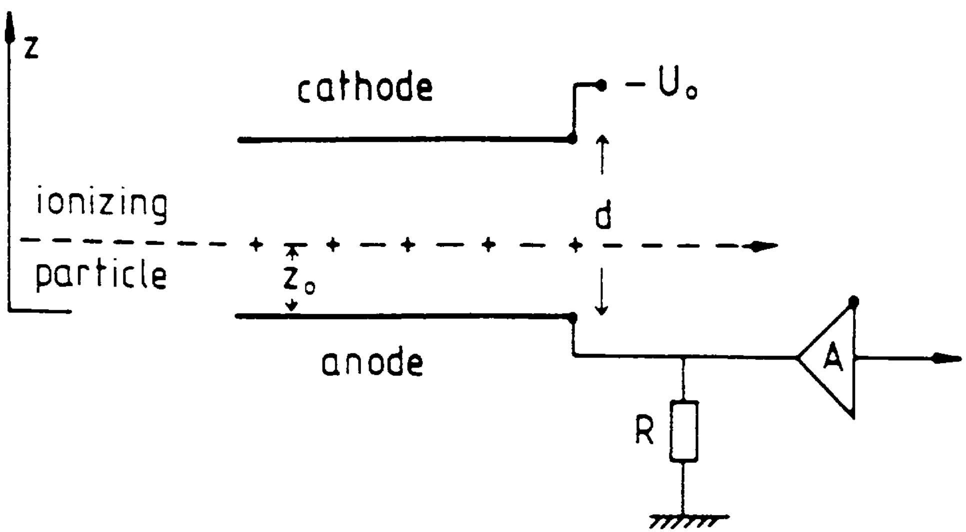
Fig. 2.2. Time development of a voltage pulse $\Delta U(t)$ from
ionization chamber for resistance $R = \infty$.



N=number of charges created
C=capacity (hyp. R=∞)

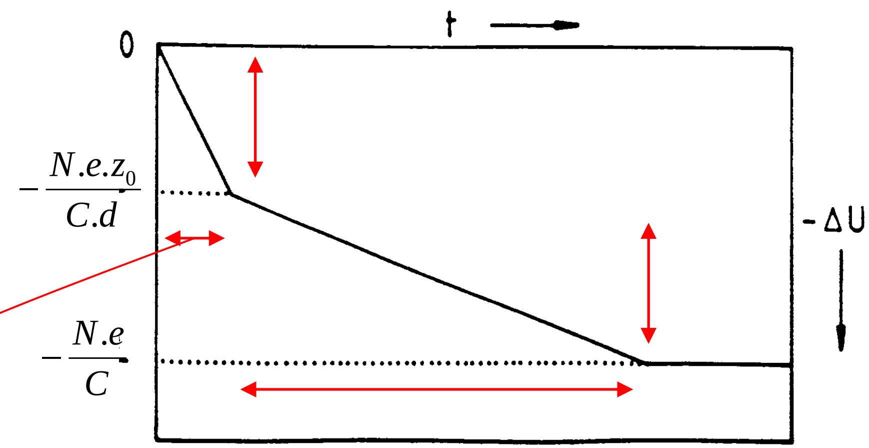
Development of signal in a **ionisation chamber**

Fig. 2.1. Parallel-plate ionization chamber (schematic).



V = ne/C (← Q = C.V)

Fig. 2.2. Time development of a voltage pulse $\Delta U(t)$ from
ionization chamber for resistance $R = \infty$.



In practice <u>all</u> these quantities will <u>fluctuate</u> and will depend on e-/ions <u>drift velocity</u>; so will depend on <u>gas properties</u>, <u>conditions</u> (E, pressure, etc.), B, etc.

N=number of charges created
C=capacity (hyp. R=∞)

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas

→ Electrons and ions mobility in gas

Pure gas and gas mixture properties

Dependences of signal on geometry and applied voltage

Proportional, *streamer* and *Geiger-Muller* modes

Quencher / gain variation

δ-ray

Practical examples: applying our knowledge!

Few examples of gaseous detectors (including some information on diffusion in gas):

MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

Electrons and ions mobility in gas

When created, electrons and ions will drift in the gas.
Drift velocity is very different for electrons w.r.t. ions since their masses are very different. We define: $v_{drift\ +/-} = \mu^{+/-}.E$

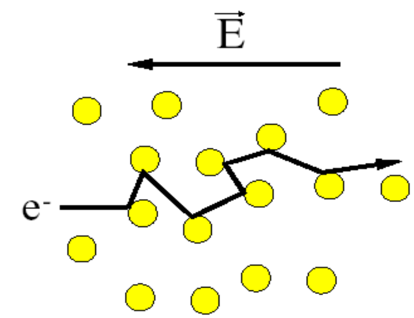
For ions:
Mean velocity is $v^+ \propto E/P$
with: E = electric field and P = gas pressure.

For ions, mobility is μ^+ ($=v^+/E$, by definition) and is ~ constant since ions do not increase their energy between two collisions.

For electrons:

$$v^- = (e/2m).E.\tau \qquad \text{(Townsend)}$$

with: τ = mean time between two collisions
v^- goes up to few 10^6 cm/s



But σ, so τ, varies rapidly with E for electrons
(in particular when $\lambda_e \sim \lambda_{e\text{-atomique}}$, Ramsauer effect)
(Often) drift velocity of e- increases rapidly for low field, and then saturate. This is interesting for application in drift chambers.

Mobility of **ions** in some gas mixture

Gas	Ion	Mobility μ^+ ($cm^2/V\ s$)
He	He^+	10.2
Ar	Ar^+	1.7
H_2O	H_2O^+	0.7
Ar	$(OCH_3)_2CH_2^+$	1.51
Iso-C_4H_{10}	$(OCH_3)_2CH_2^+$	0.55
$(OCH_3)_2CH_2$	$(OCH_3)_2CH_2^+$	0.26
Ar	Iso$C_4H_{10}^+$	1.56
Iso-C_4H_{10}	Iso$C_4H_{10}^+$	0.61
Ar	CH_4^+	1.87
CH_4	CH_4^+	2.26
Ar	CO_2^+	1.72
CO_2	CO_2^+	1.09

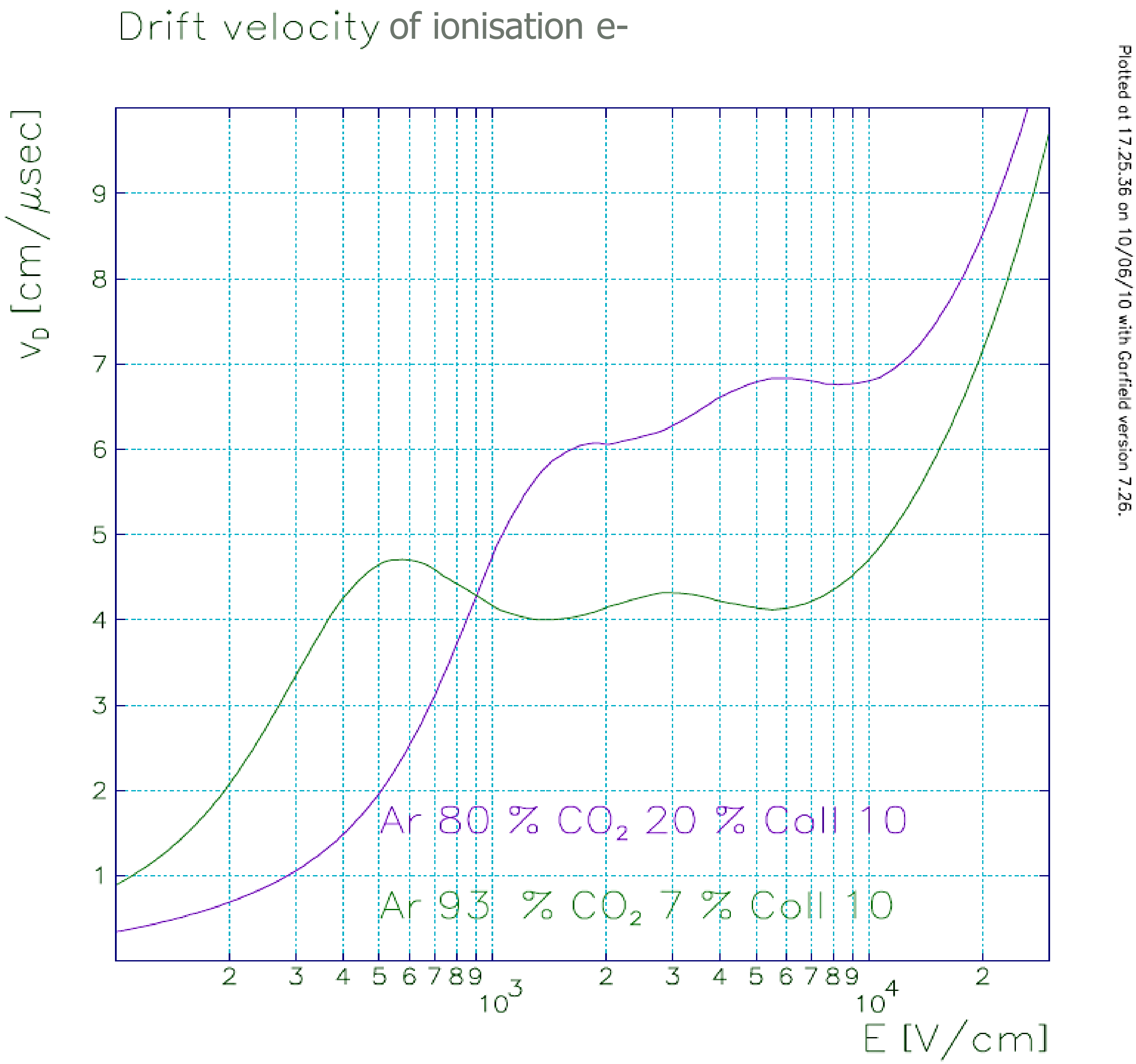
$\mu^+ = v^+/E$ (by definition)

Unit:
v^+/E (cm/s)/(V/cm)

If E=1000 V/cm so
μ^+=1,72 cm^2/V.s
i.e. **1,72 cm/ms**
ions

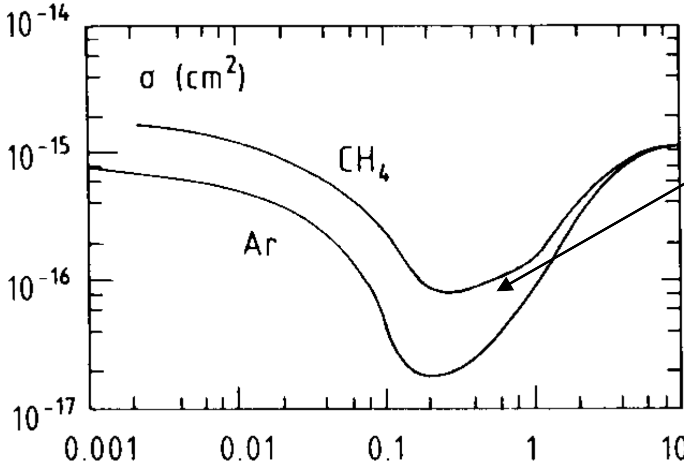
Mobility of **electrons** in some gas mixture : Garfield simulation

About ~1000 times speed of ions



Mobility of electrons in gas

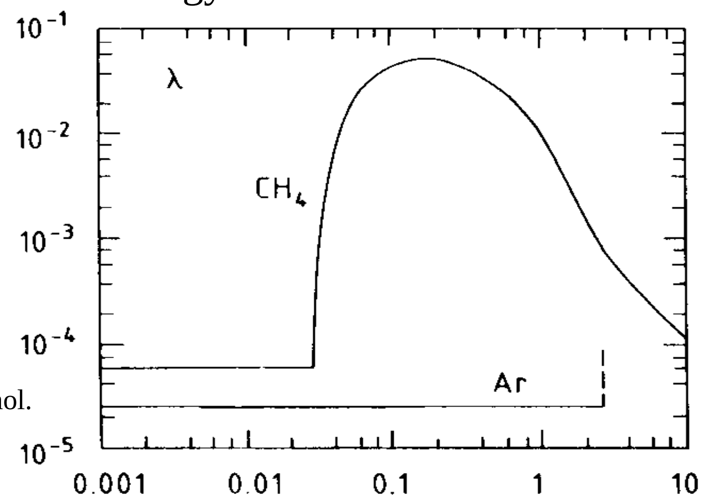
σ = cross section



ε_{e-} [eV]

Rapid variation of σ= Ramsauer effect

λ = fraction of energy loss / collision

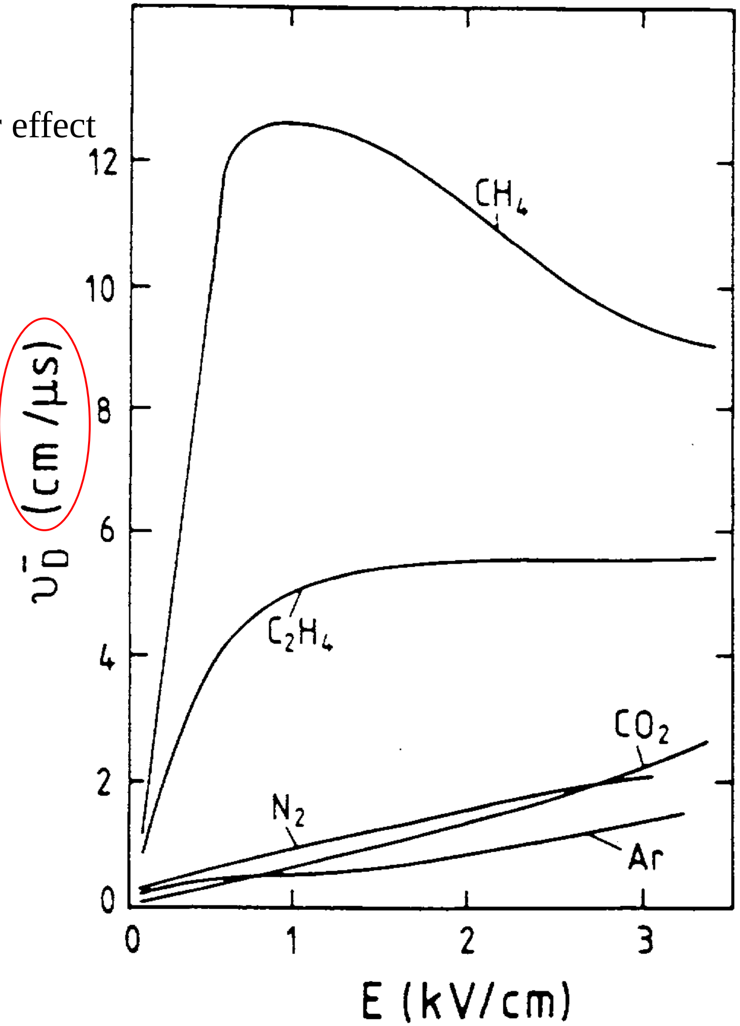


$\sim 2m_e/m_{mol.}$

ε_{e-} [eV]

(CH_4 polyatomique gas)

Normal condition of T and P



One can show that <u>drift velocity:</u>

$$v_D^2 = \frac{eE}{mN\sigma}\sqrt{\frac{\lambda}{2}}$$

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas
Electrons and ions mobility in gas
→ Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

"Attachment time" of electrons in gas

Or how long can an electron be free in gas…

Coefficient, number of collisions, and average time for electron attachment in several gases under normal conditions[12,18,21]

Gas	h	N (sec^{-1})	t (sec)
CO_2	6.2×10^{-9}	2.2×10^{11}	0.71×10^{-3}
O_2	2.5×10^{-5}	2.1×10^{11}	1.9×10^{-7}
H_2O	2.5×10^{-5}	2.8×10^{11}	1.4×10^{-7}
Cℓ	4.8×10^{-4}	4.5×10^{11}	4.7×10^{-9}

"Attachment time" t is: $t = (hN)^{-1}$

avec : h = attachment probability (~0 for noble gas and for hydrogen)

N = # of collision per unit of time

Num. application: in oxygen and resp. in water, mean "attachment time" is only of the order of 190 ns and resp. 140 ns! In CO_2 it is of the order of milli-sec.

Other gas: 1% of air in Argon will remove 1/3 of electrons per cm of drift (at E=500 V/cm).
(remember ~1cm per µs)

Some gas properties

Table 4. *Properties of gases at normal conditions: density ρ, minimal energy for excitation E_{ex}, minimal energy for ionization E_i, mean effective ionization potential per atomic electron $I_0 = I/Z$, energy loss W_i per ion pair produced, minimal energy loss $(dE/dx)_0$, total number of ion pairs n_T and number of primary ions n_p per centimetre of path for minimum ionizing particles* [SA 77]

Gas	Z	A	ρ (g/cm³)	E_{ex} (eV)	E_i (eV)	I_0 (eV)	W_i (eV)	$(dE/dx)_0$ (MeV/g cm⁻²)	$(dE/dx)_0$ (keV/cm)	n_p (cm)⁻¹	n_T (cm)⁻¹
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	10	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	22	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	21.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	34	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	46	195

ρ(gaz) ~ ρ(solid/liquid)/1000

n_p is used for efficiency calculation ×2 à ×5

n_T is used for signal calculation

Energy needed for creating and electron-ion pair

Table 1.3. Energy W spent, on the average, for the creation of one ionization electron in various gases and gas mixtures [CHR 71]; W_α and W_β are from measurements using α or β sources, respectively. The lowest ionization potential is also indicated

Gas	W_α (eV)	W_β (eV)	I (eV)	Gas mixture[a]	W_α (eV)
H_2	36.4	36.3	15.43	Ar (96.5%) + C_2H_6 (3.5%)	24.4
He	46.0	42.3	24.58	Ar (99.6%) + C_2H_2 (0.4%)	20.4
Ne	36.6	36.4	21.56	Ar (97%) + CH_4 (3%)	26.0
Ar	26.4	26.3	15.76	Ar (98%) + C_3H_8 (2%)	23.5
Kr	24.0	24.05	14.00	Ar (99.9%) + C_6H_6 (0.1%)	22.4
Xe	21.7	21.9	12.13	Ar (98.8%) + C_3H_6 (1.2%)	23.8
CO_2	34.3	32.8	13.81	Kr (99.5%) + C_4H_8-2 (0.5%)	22.5
CH_4	29.1	27.1	12.99	Kr (93.2%) + C_2H_2 (6.8%)	23.2
C_2H_6	26.6	24.4	11.65	Kr (99%) + C_3H_6 (1%)	22.8
C_2H_2	27.5	25.8	11.40		
Air	35.0	33.8	12.15		
H_2O	30.5	29.9	12.60		

[a] The quoted concentration is the one that gave the smallest W.

Application

How many primary and secondary pairs will be created for a *m.i.p.* particle in a mixture of Ar:Butane = 70:30 at normal condition (NTP) ?

Gas	Z	A	ρ (g/cm^3)	E_{ex} (eV)	E_i (eV)	I_0 (eV)	W_i (eV)	$(dE/dx)_0$ (MeV/g cm^{-2})	$(dE/dx)_0$ (keV/cm)	n_p (cm)$^{-1}$	n_T (cm)$^{-1}$
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	10	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	22	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	21.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	34	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	46	195

Application

How many primary and secondary pairs will be created for a *m.i.p.* particle in a Ar:Butane mixture 70:30, at normal condition (NTP) ?

Gas	Z	A	ρ (g/cm^3)	E_{ex} (eV)	E_i (eV)	I_0 (eV)	W_i (eV)	$(dE/dx)_0$ (MeV/g cm^{-2})	$(dE/dx)_0$ (keV/cm)	n_p (cm)$^{-1}$	n_T (cm)$^{-1}$
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	10	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	22	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	21.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	34	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	46	195

W_i (Ar)= 26 eV
W_i (C_4H_{10})= 23 eV

dE/dx (Ar)= 2.44 keV/cm
dE/dx (C_4H_{10})= 4.50 keV/cm

n_p(Ar)=29.4 /cm
n_p(C_4H_{10})= 46 /cm

So for this mixture, we have:

$$n_T = (2440/26)\times 0.7 + (4500/23)\times 0.3 = 124 \text{ pairs/cm}$$
$$n_p = 29.4\times 0.7 + 46\times 0.3 = 34 \text{ pairs/cm}$$

i.e. a distance ~300µm between each <u>primary</u> pair (and a factor ~3,5 from n_T to n_p)

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
→ Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
δ-ray

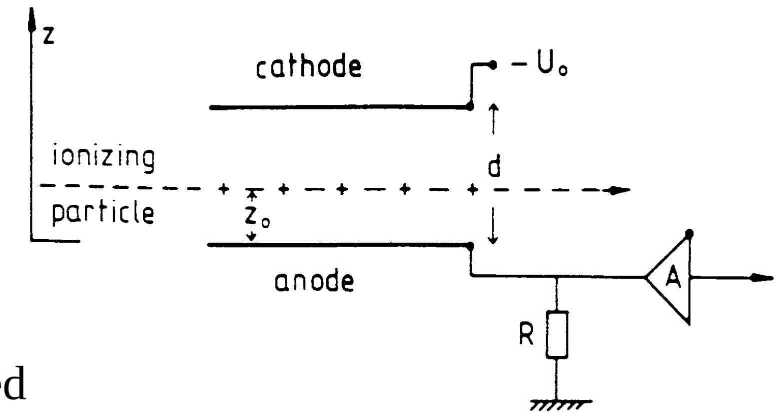
Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

Signal for different practical configurations

Different cases should be considered in order to understand where the signal comes from. It will depend on:

chamber geometry
electric field intensity
(front-end electronic)



1rst case: chamber with // plates

Signal comes from variation of electrostatic energy stored in the capacitor:

$$\Delta\left(\tfrac{1}{2}CU^2\right)+\int_{Z_{\min}}^{Z_{\max}} NqE.dz=0 \Rightarrow CU_0\Delta U=-NqE.\Delta z$$

Thus for electrons : $\Delta U^- = -Nez_0/Cd$ and for ions : $\Delta U^+ = -Ne(d-z_0)/Cd$

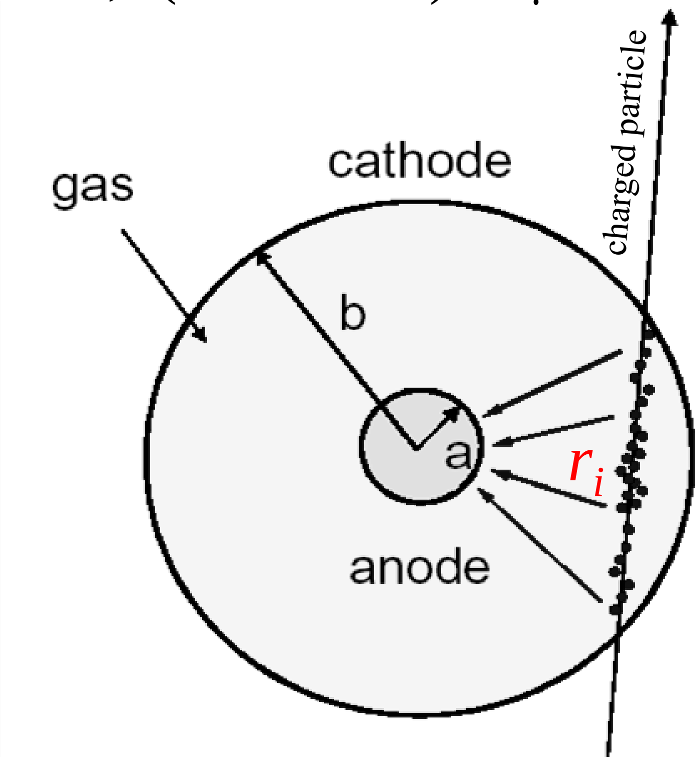
Drift time is: $\Delta t^{+/-}=\int \frac{dz}{v_D^{+/-}} \Rightarrow \Delta t^- = \frac{z_0}{v_D^-}$

It is ~10µs for electrons and ~6ms for ions in 5cm of Argon, E=500 V/cm

(E=U/d)

2nd case: Case of a cylinder geometry **without amplification** (low E field) : **ionisation chamber**

Typical example
b=10 mm, a(anode=wire)=10µm



As before (for electrons):

$$\Delta\left(\tfrac{1}{2}CU^2\right)+\int_{r_a}^{r_i} NqE.dr = 0$$

with: $E(r) = \dfrac{U_0}{r\ln(r_b/r_a)}$

Then we have: $\Delta U^- = -\dfrac{N.e}{C}\dfrac{\ln(r_i/r_a)}{\ln(r_b/r_a)}$

and: $\Delta U^+ = -\dfrac{N.e}{C}\dfrac{\ln(r_b/r_i)}{\ln(r_b/r_a)}$

Thus: $\dfrac{\Delta U^+}{\Delta U^-} = \dfrac{\ln(r_b/r_i)}{\ln(r_i/r_a)}$ always <1

typically ~ 0.1
⇒ **signal comes from electrons!!**

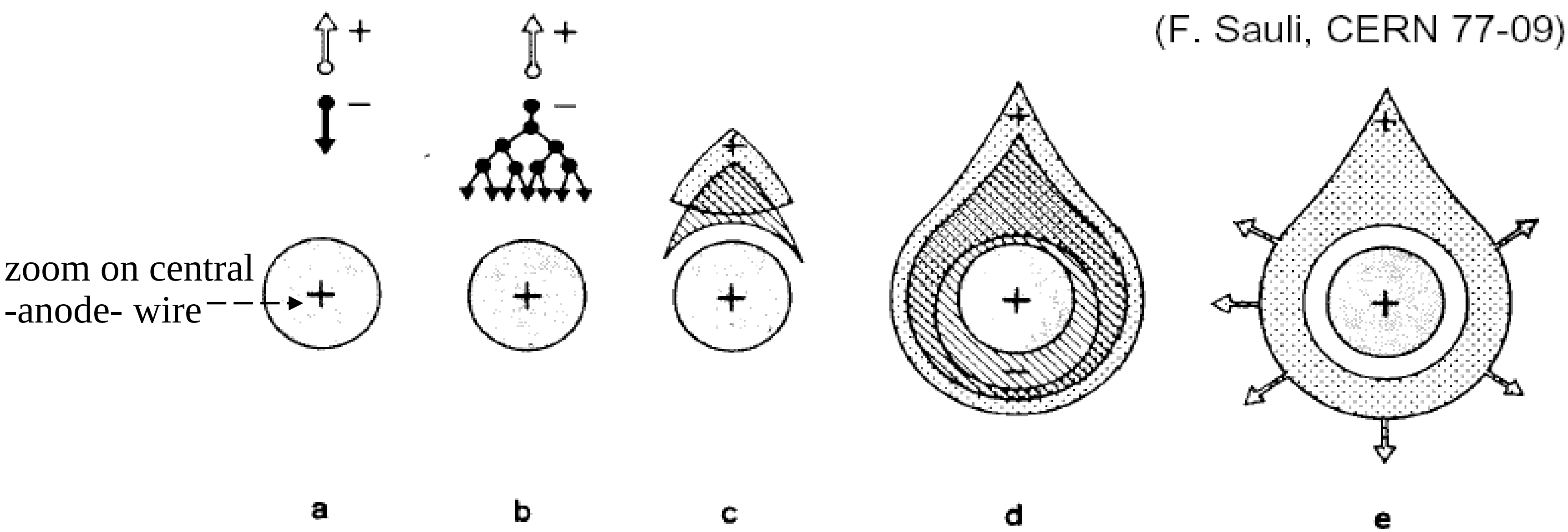
≠ from previous case

3rd case: High *E* field: avalanche on -anode- wire

- It is almost mandatory to “multiply” electrons obtained from first ionisation (from ~10 to ~100)
- These electrons will drift to wire thanks to electric field
- Close to central wire (~few times wire radius) they “fill” an important acceleration,

  The electrons energy increases ⇒ ionisation by collision amplifying the phenomena

  (timescale of the amplification: few ns)

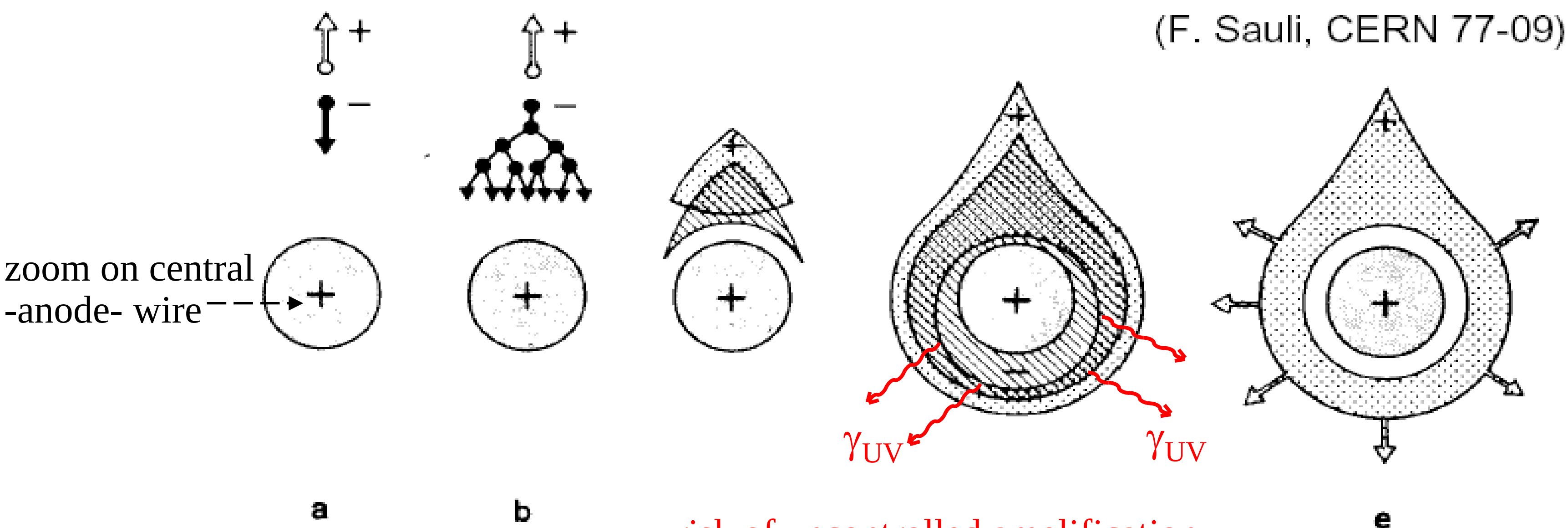


≠ from previous case

3rd case: High *E* field: avalanche on -anode- wire

- It is almost mandatory to "multiply" electrons obtained from first ionisation (from ~10 to ~100)
- These electrons will drift to wire thanks to electric field
- Close to central wire (~few times wire radius) they "fill" an important acceleration,

  The electrons energy increases ⇒ ionisation by collision amplifying the phenomena
  (timescale of the amplification: few ns)



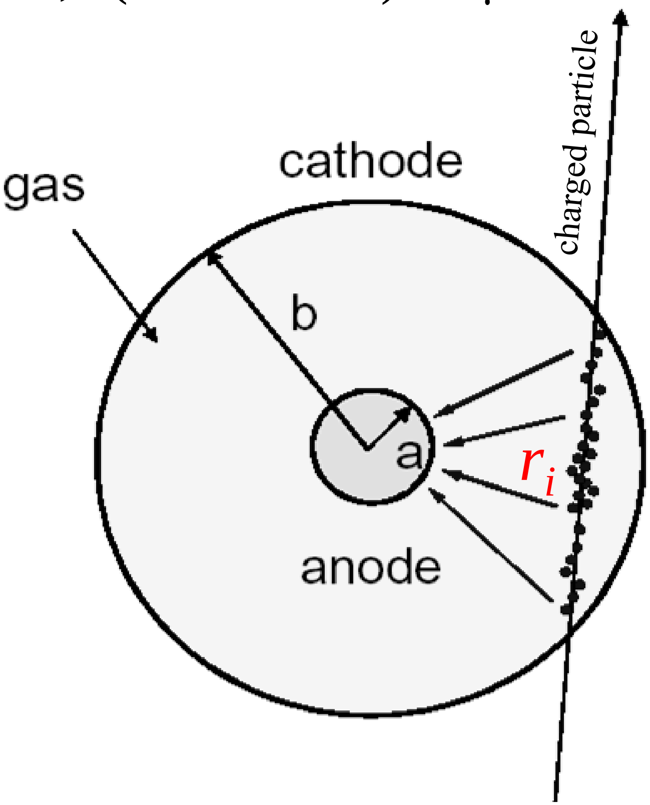
risk of uncontrolled amplification…

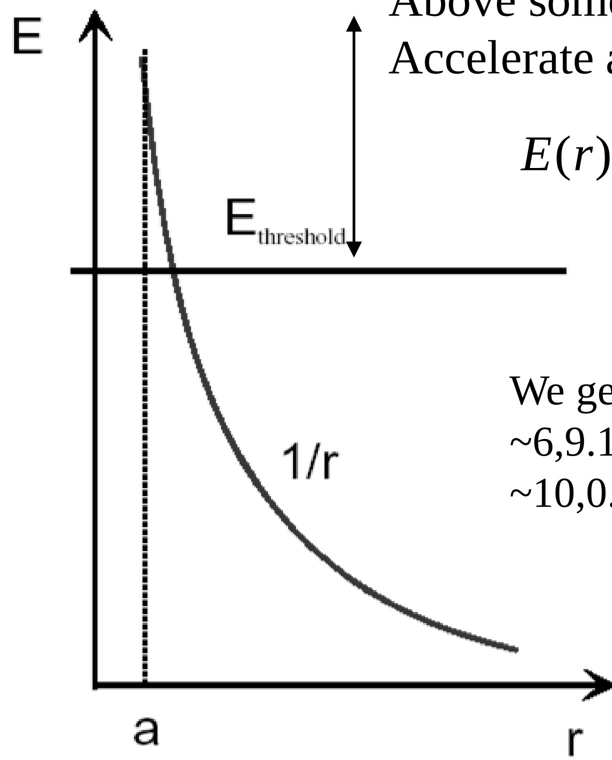
≠ from previous case

3rd case: Case of a cylinder geometry **with amplification** (high E field) : **proportional chamber**

r	E
10 mm	5000 V/m
1 mm	50000 V/m
10 µm	5 MV/m
Bizarre…	

Typical example
b=10 mm, a(anode=wire)=10µm





Above some threshold *E*, each e- Accelerate and will also ionise the gas.

$$E(r) = \frac{U_0}{r \ln(r_b/r_a)}$$

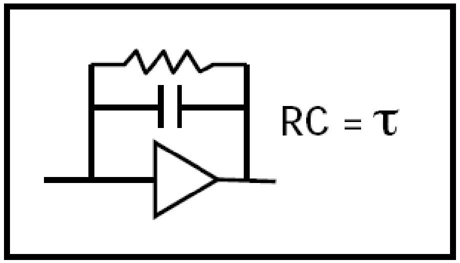
We get (H. Fischer, 1975) :
~6,9.10^4V/cm.atm, methane (CH_4)
~10,0.10^4V/cm.atm, propane (C_3H_8)

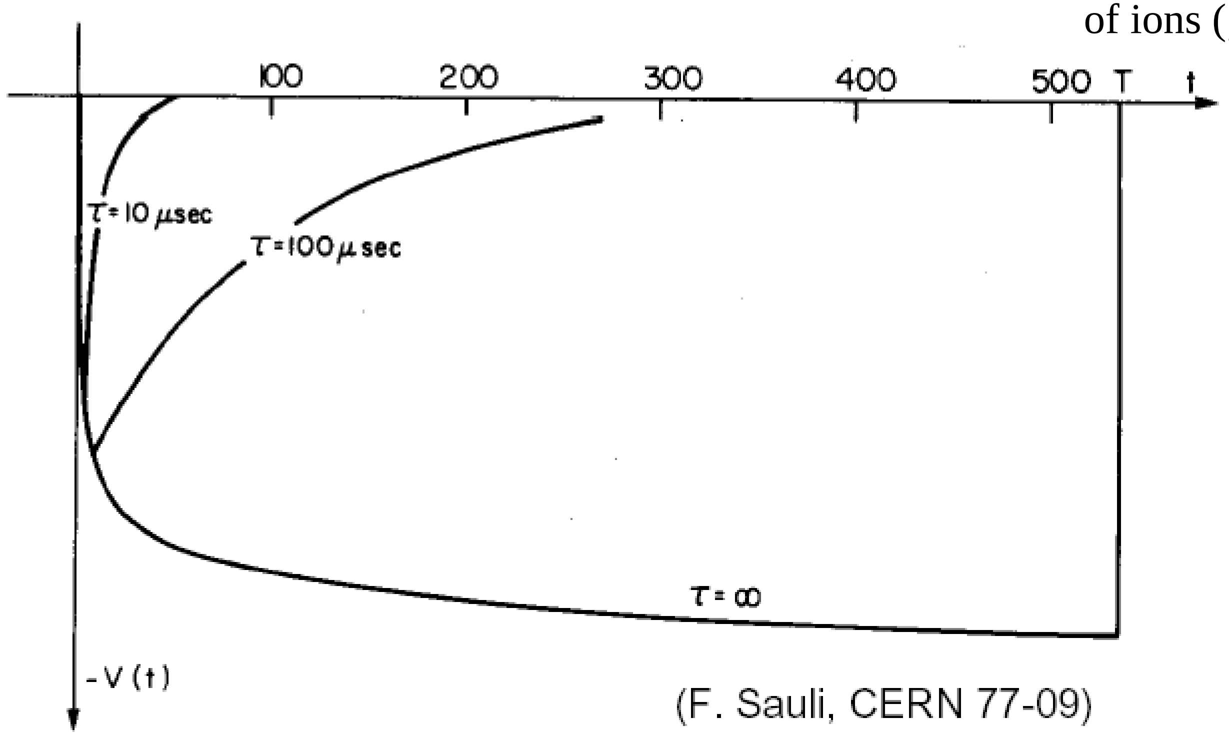
$$\frac{\Delta U^+}{\Delta U^-} = \frac{\ln(r_b/r_i)}{\ln(r_i/r_a)} \approx \frac{\ln(r_b/(r_a+n\lambda))}{\ln((r_a+n\lambda)/r_a)} \sim \frac{\ln(r_b/r_a)}{n\lambda/r_a}$$

Avalanche appears in last tenth of microns (=$n\lambda \sim r_a$), when the ratio is ~7 => **signal comes from ions** !! Still: t_{ions} ~ ms et t_{e-}~ns.

Signal in a proportional counter

T = max. drift time of ions (μs)



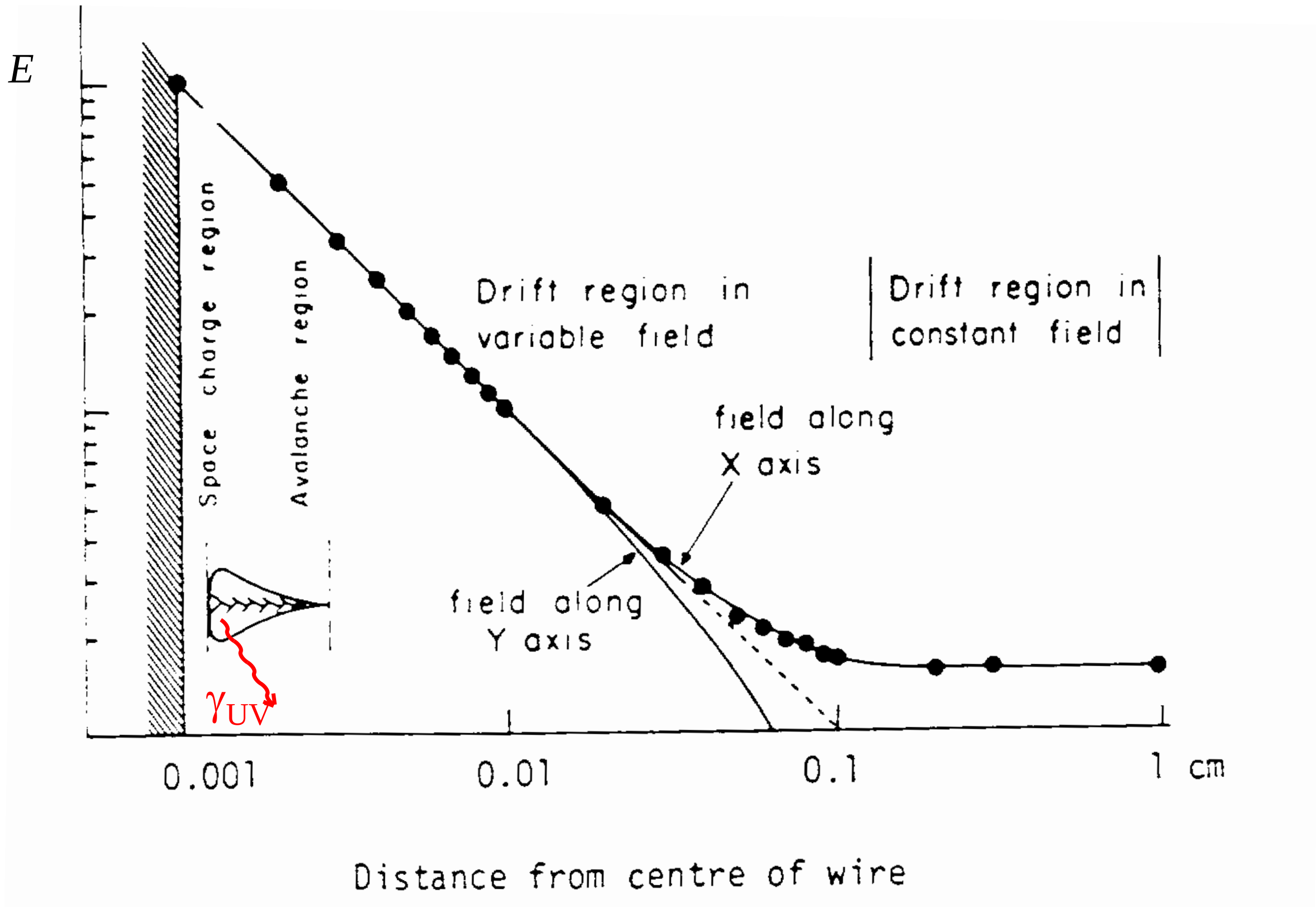


(F. Sauli, CERN 77-09)

Charge preamplifier:
Signals varies with preamplifier

Output pulse duration varies with the (integration) time constant of the front-end electronic

Working condition of a wire chamber



Variation of the electric field along the axis perpendicular to the wire plane and centred on one wire in a multiwire proportional chamber (x), and along the direction parallel to the wire plane (y) [38]

Charge multiplication: *Townsend* coefficients

When increasing E, an electron will create αn "new" electrons:

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

α= first *Townsend* coefficient (varies with E, i.e. with r)

$$\alpha = \frac{1}{\lambda}$$

with λ=mean free path of electrons

since α≠cte ⇒ $$A = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)dr\right]$$ Gain

$$A \approx k e^{CV_0}$$

Valid when the applied voltage is "above" the proportional zone: A varies like exp.(V_{anode}).

- α should be measured for all gas (modelling by Rose and Korff).

Above a gain of the order of ~10^8, there is a spark (**this is the *Raether* limit**).

- Voltage where the avalanche starts depend on gas (mixture) and is of the order of ~10^4 V/cm.atm ($\propto$ E/p -pressure p-)

- There is a **2nd *Townsend* coefficient γ**, describing the influence of created photons during the avalanche, on the amplification.

Thus: $A \rightarrow A_\gamma = A/(1-A\gamma)$. When $\gamma < 1/A$ we are in the limited proportional region. Above there is spark region (Geiger-Muller).

Lecture #4
Gaseous detectors

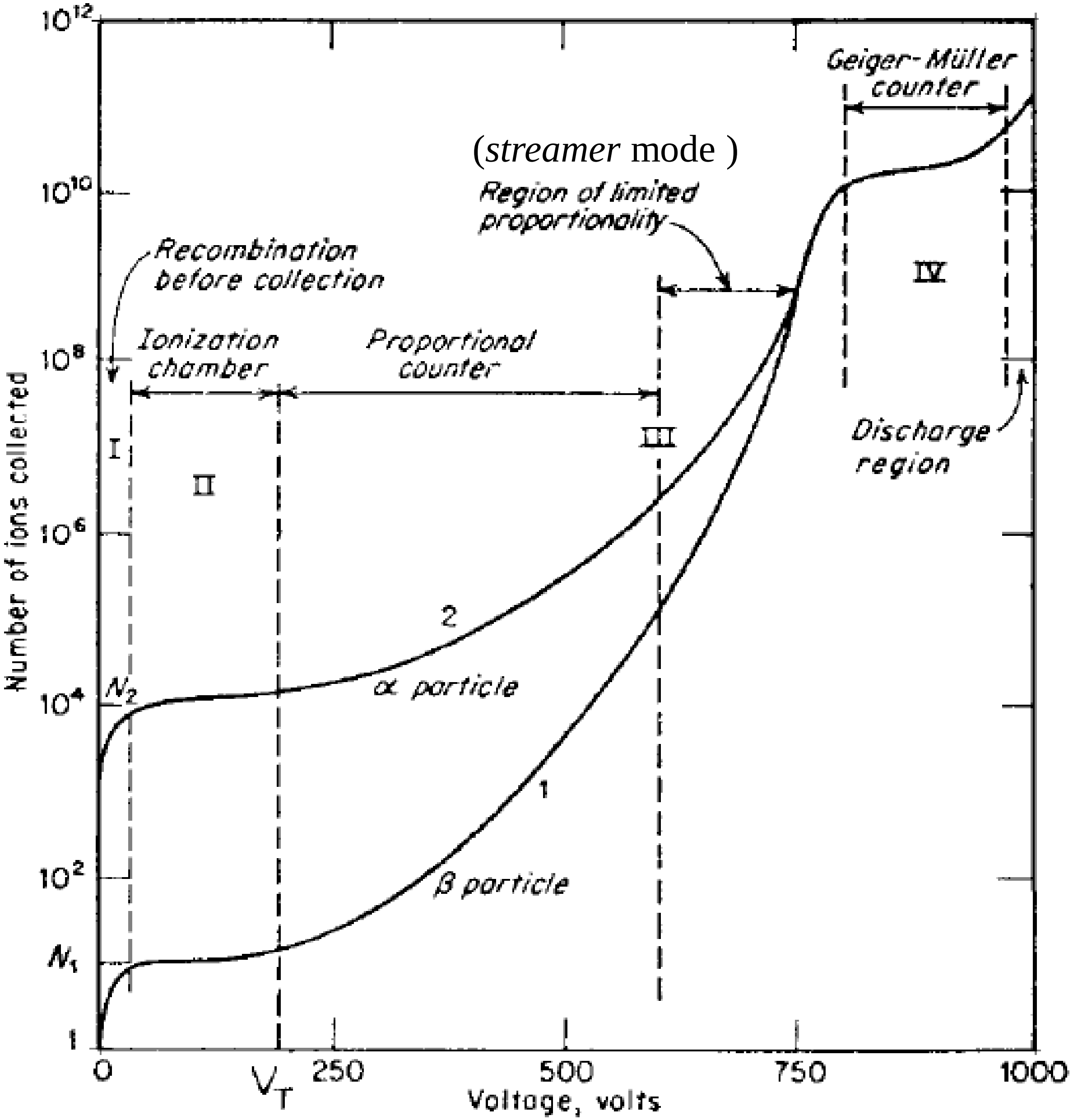
Outline:

Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
→ Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

Working condition of a proportional counter



I: too small voltage: recombination of pairs.

II: ionisation chamber. Charge collection without amplification.

IIIa: proportional mode. Signal is amplified and proportional to deposit ionisation. Gain goes from 10^4 to 10^5. Gain ↗ expon. with anode voltage.

IIIb: *streamer* mode. Secondary avalanches induced by first -principal- avalanche. Large *quenching* needed or pulsed HV. Gain of the order of ~10^{10}.

IV: *Geiger-Müller* mode. Avalanche in the whole detector.

Geiger-Müller principle

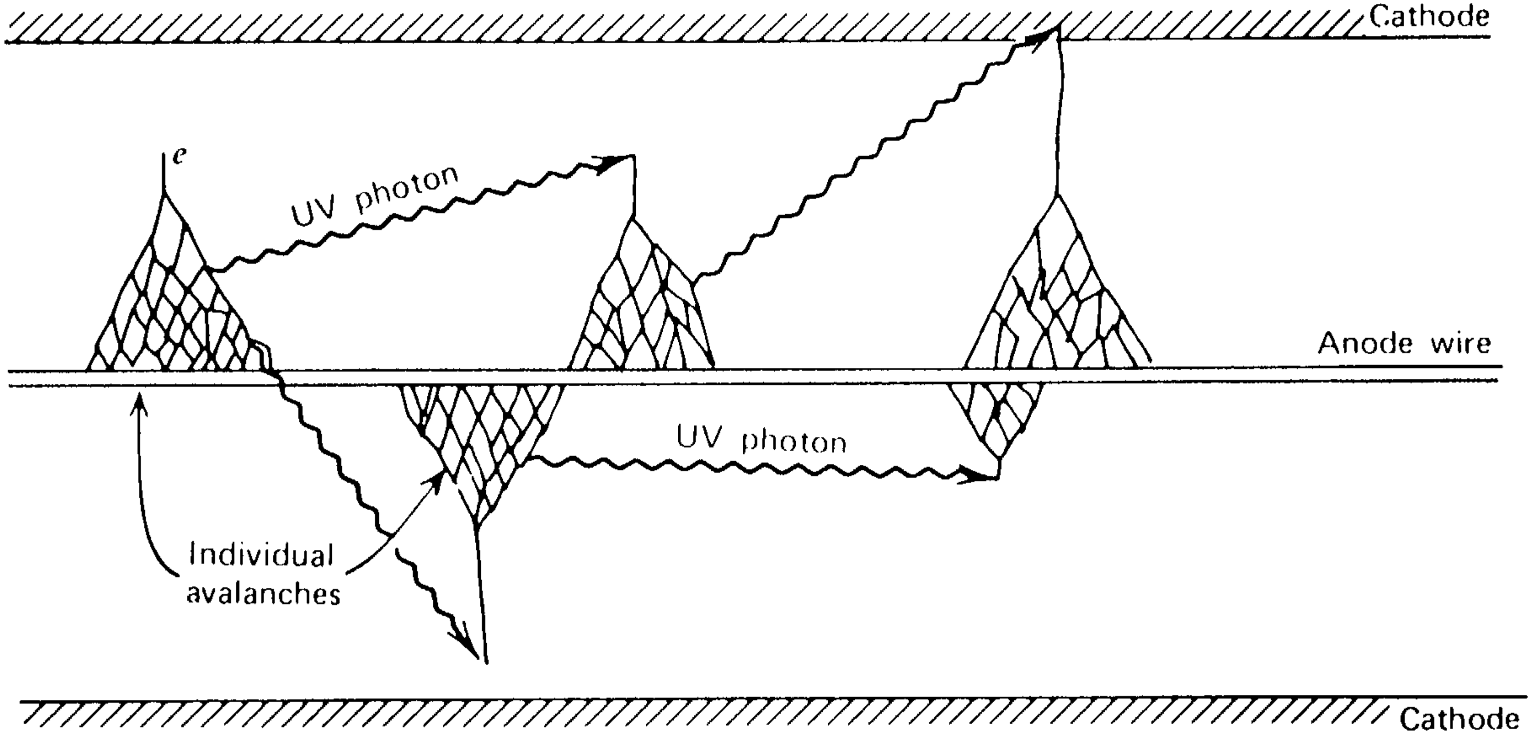
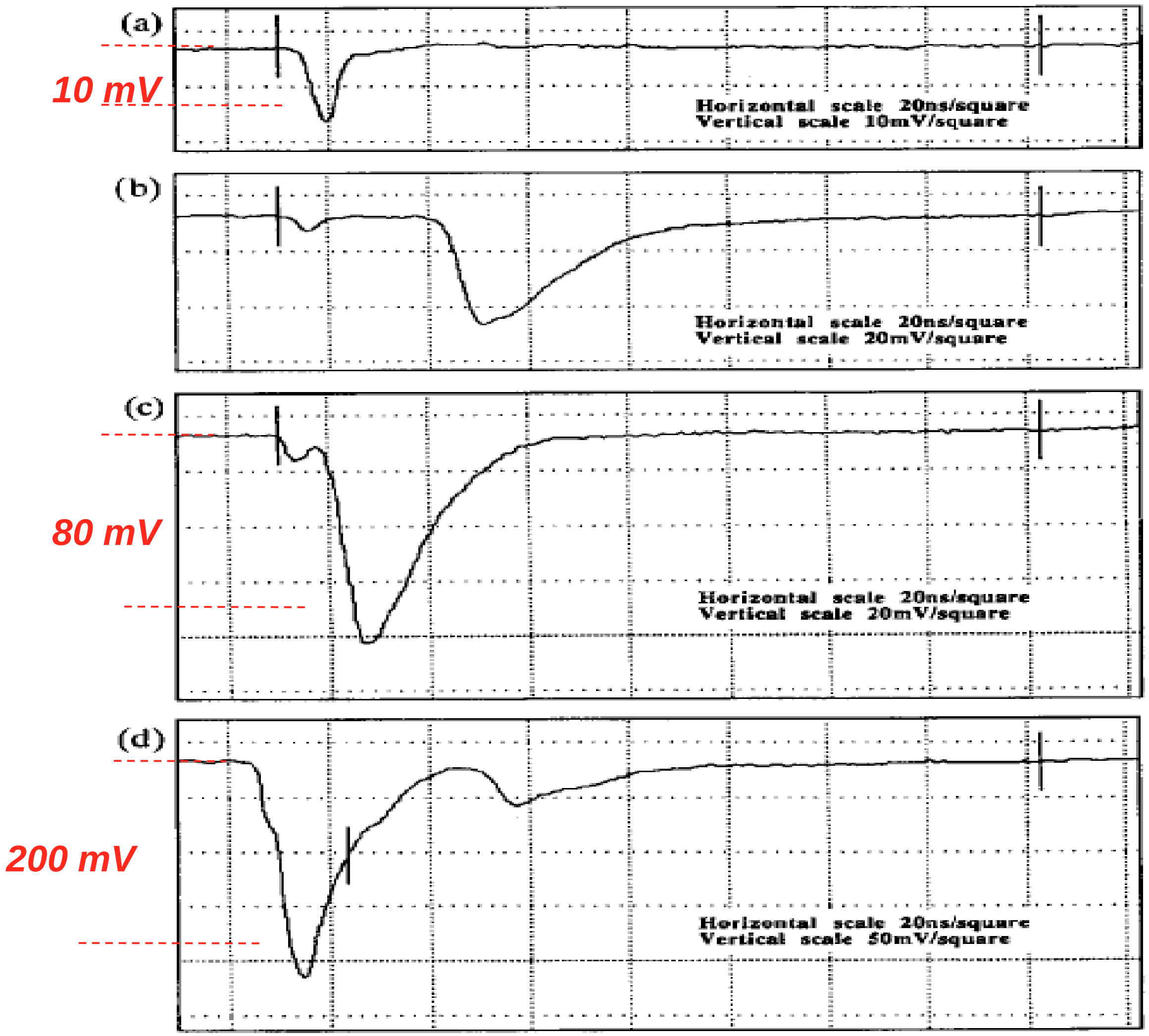
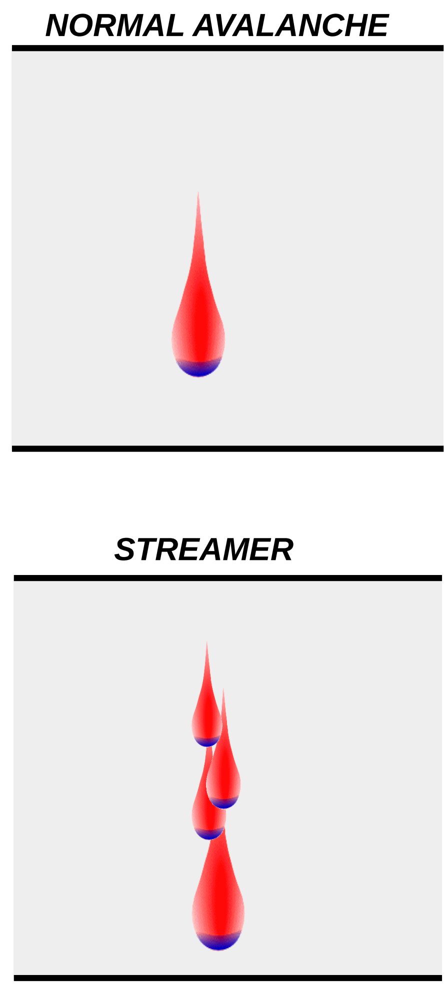


Figure 7-1 The mechanism by which additional avalanches are triggered in a Geiger discharge.

UV photons coming from first avalanche could also eject electrons (photo-electric effect) which will also induce a new avalanche.

Avalanche in *streamer* mode





R. Cardarelli, V. Makeev, R. Santonico, Nucl. Instr. and Meth. A382(1996)470

Avalanche simulation

Fig. 5 Two dimensional display of a simulated drift process of one electron from starting point to anode wire surface.

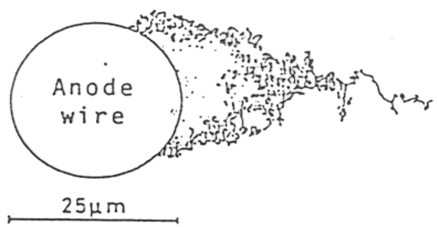


Fig. 6 Two dimensional display of a simulated electron avalanche.

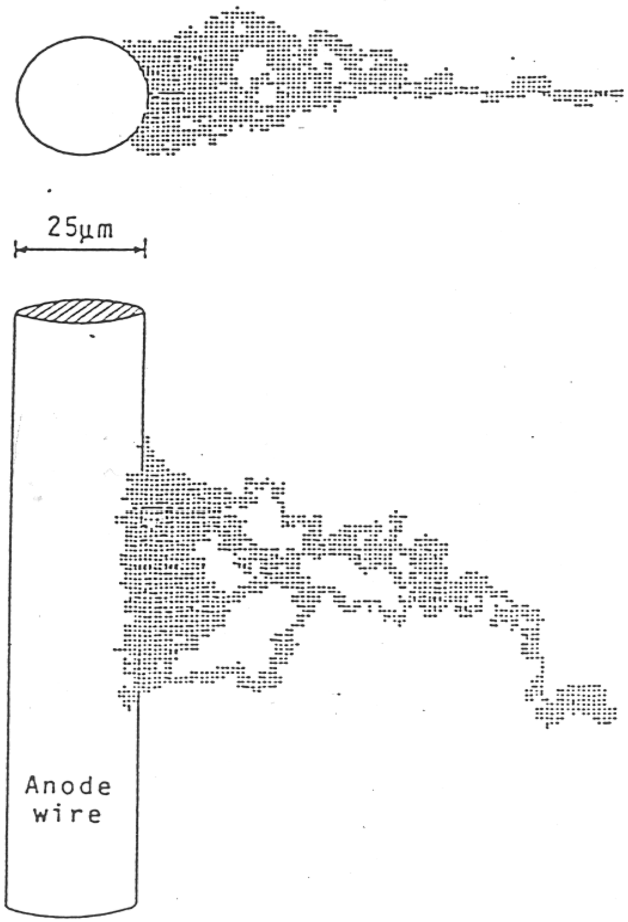


Fig. 7 Two dimensional displays of a simulated electron avalanche. Shading shows the density of electrons in the avalanche.

(Townsend avalanche)

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
→ *Quencher* / gain variation
δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

Quencher gas

- Polyatomic gas (with some vibration et rotation modes) where the energy coming from UV photons could be absorbed by collision or dissociation.

- Some quencher gas often used: methane CH_4, isobutane C_4H_{10}, ethanol, CO_2 (sometimes water…)

- Many mixtures tested…

- (some) “Magic gas” : 70% Ar, isobutane 29.6%, Freon 0.4% .
  High gains possible.

Problems induced by quencher gas

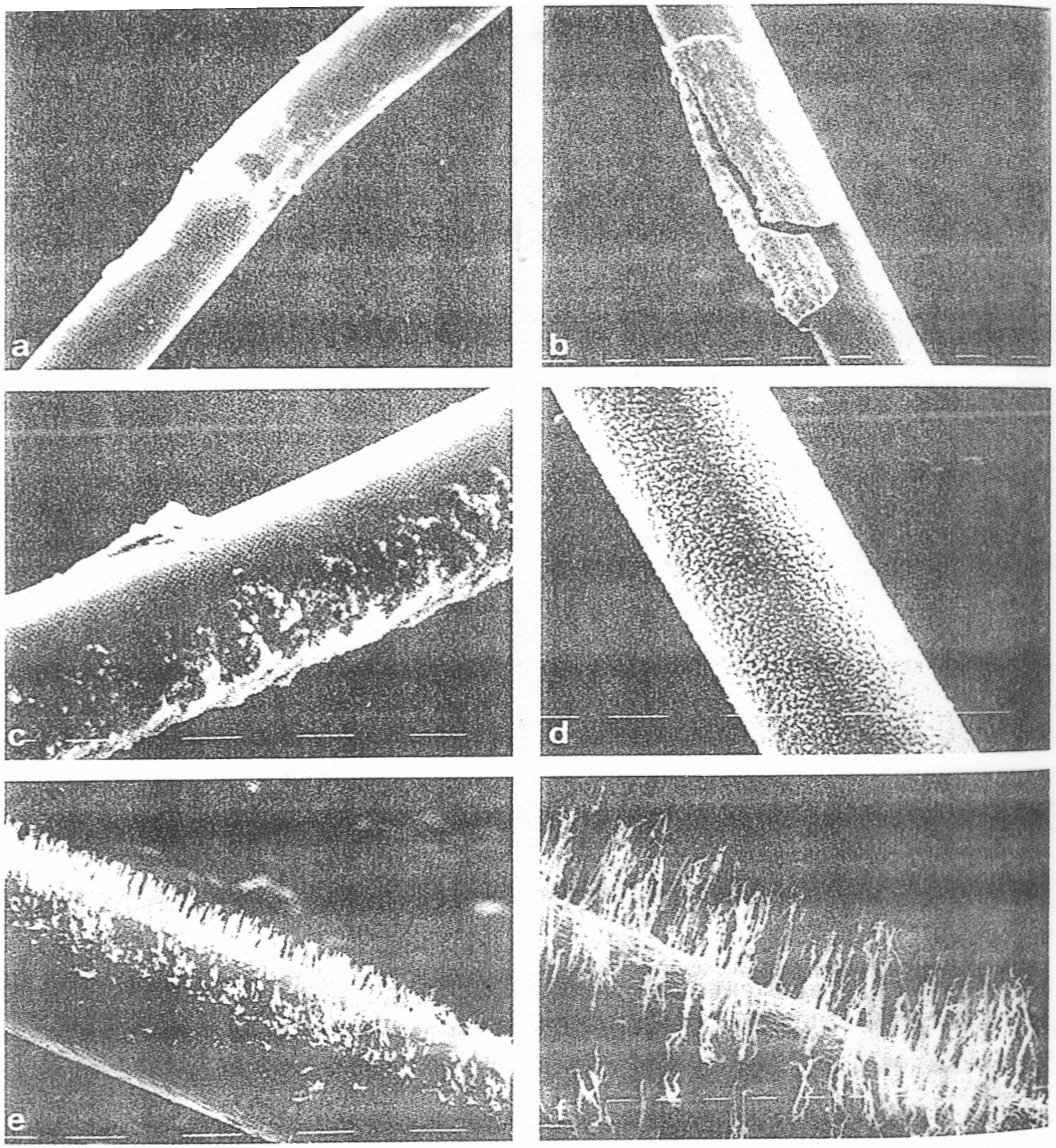


Fig. 4.31. Deposits on anode wires: (a) – $Ar+C_2H_6$; (b) – $Ar+C_2H_6$ + methylal; (c) – $Ar+CO_2$; (d) – perspex chamber; (e, f) – chambers with G10 fiber-glass and a cold trap (Adam 1983)

Quencher debris (polyatomic gas) could deposit and polymerise on the wire.

In general debris isolate. At the end, they could modify the functioning of the detector (modify working conditions, or sparks and large charge deposit).

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
→ δ-ray

Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):
MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

Range of electrons (δ-ray) in gas

1 mm → for 10keV δ-ray

100 μm →

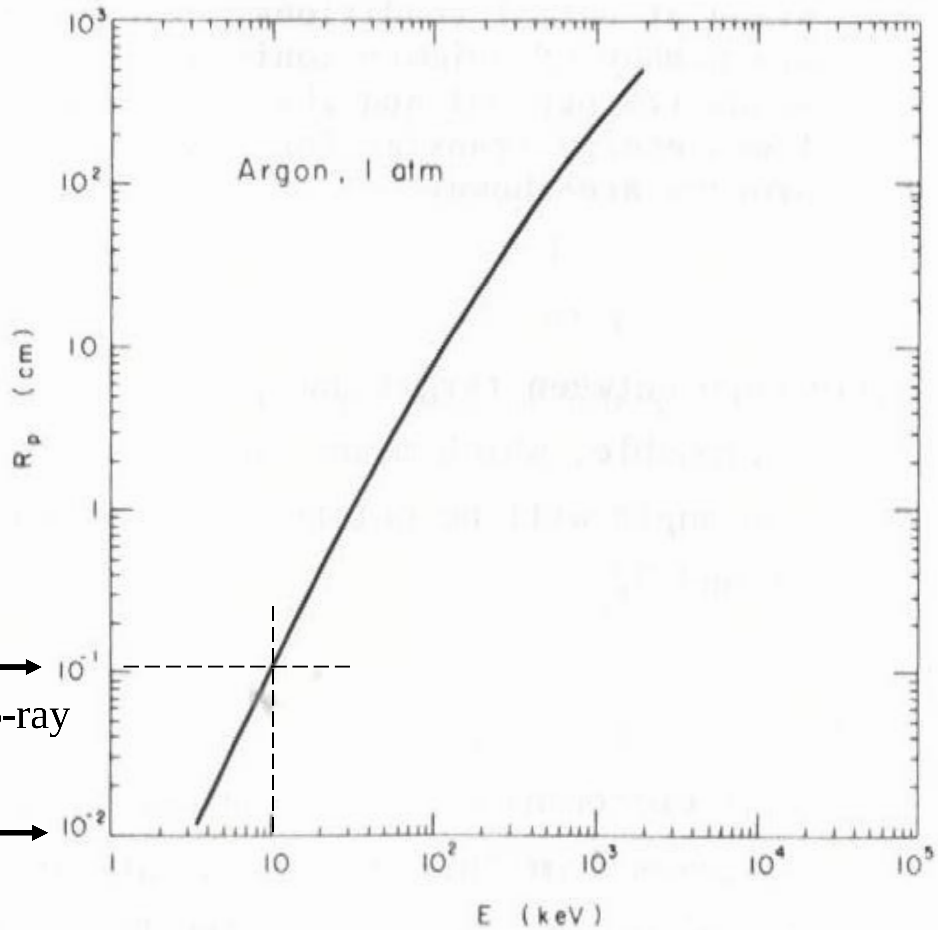


Fig. 5 Range of electrons in argon, at normal conditions as a function of energy, deduced from measurement in light materials[8]

For E ≲ few 100 keV, range R_p of ejected electrons could be parameterised by:

$R_p \sim 0.71\, E^{1.72}$ (E in MeV)

and $R_p \sim R_{Bethe\text{-}Bloch} / (2 \text{ to } 3)$ because of fluctuation…

The angular emission of δ-ray of energy E is:

$$\cos^2(\theta) = E/E_M \ll 1$$

valid since $N(E \geq E_0) \sim cte/E_0$

Up to now, what do we learned?

Electrons drift ~100 to ~1000 faster than ions. Drift time of electrons is ~5 cm/μs

Noble gas do not "attach" e- but to a certain extend, O_2 and H_2O could be considered as unwanted component

At high *E* field, electrons induce an avalanche when E field is high enough. Signal may come from e- or ions depending of the geometry and the field.

An ionisation chamber goes through a *proportional* mode, a *streamer* mode then a *Geiger-Muller* mode (when increasing high voltage).

Quencher gas is used to avoid avalanche to become sparks (like in *G-M* mode).
There exist also other "tricks" (see application).

We will also see that transverse diffusion of electrons is about ~1cm/m (a magnetic field B // E decrease the transverse diffusion)

etc, etc…

<u>We still have to see practical applications to this "theory"!!</u>

Gain variation with some parameters

Gain (amplification) of the gaseous detector will depend on:

• Component stability (in %), applied voltage, temperature

• Anode wire centering -positioning- in the detector (cylinder, w.r.t. to other wires), wire diameter variations, pitch variations (if several wires like for *MWPC*)

• Drift of (slow) ions which may induce a space charge effect. Also if large amplification, we may have a large space charge effect (from electron)

• anode and cathode surface deterioration (deposit of debris, sparks…): "aging"

• fluctuations of initial charge creation

etc.

Remark: gain will drop close to the end-plug (where the wire is attached: crimped, glued…)

All this can be parameterised and measured

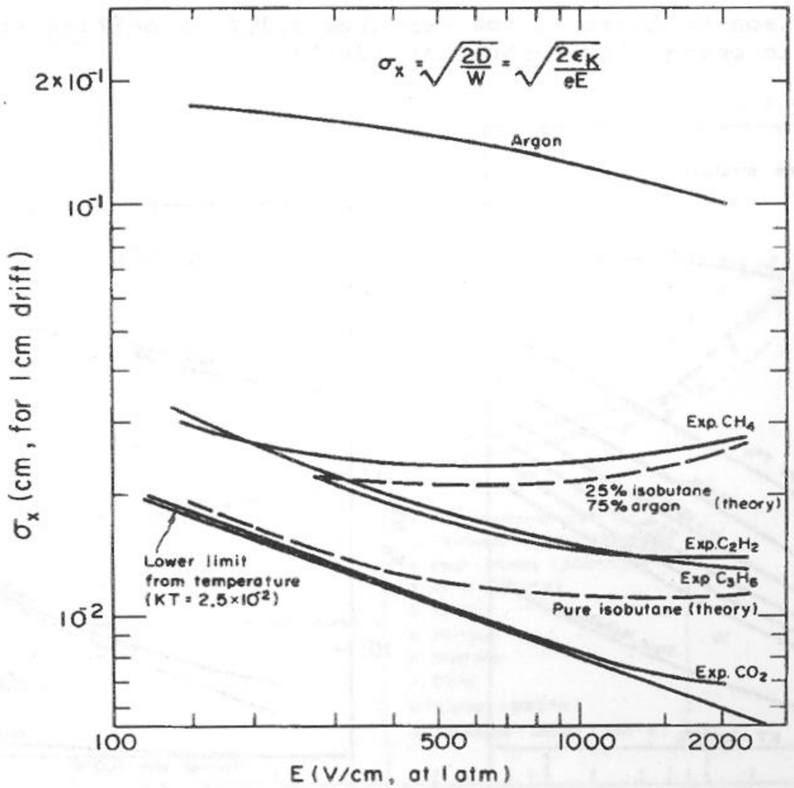


Fig. 35 Computed and experimental dependence of the standard deviation of electron diffusion from the electric field for 1 cm drift, in several gases at normal conditions[25]

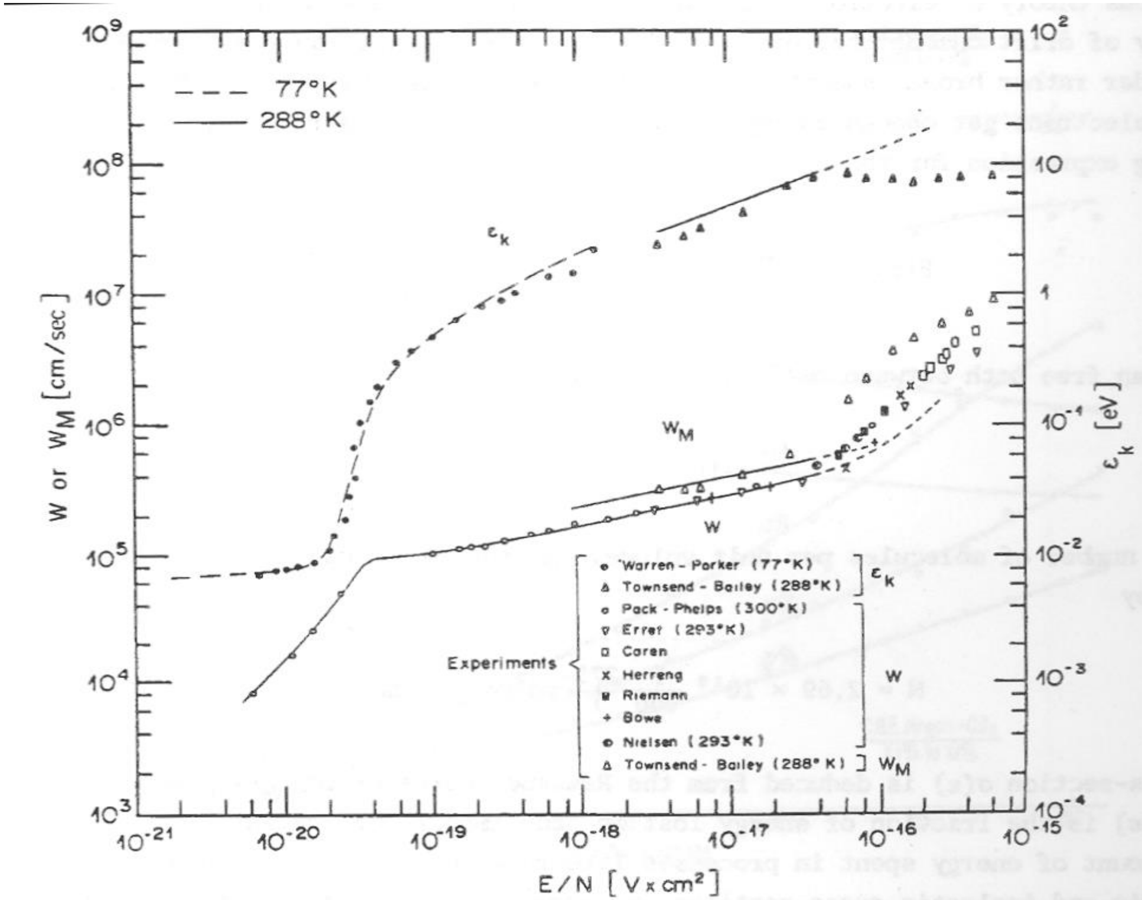
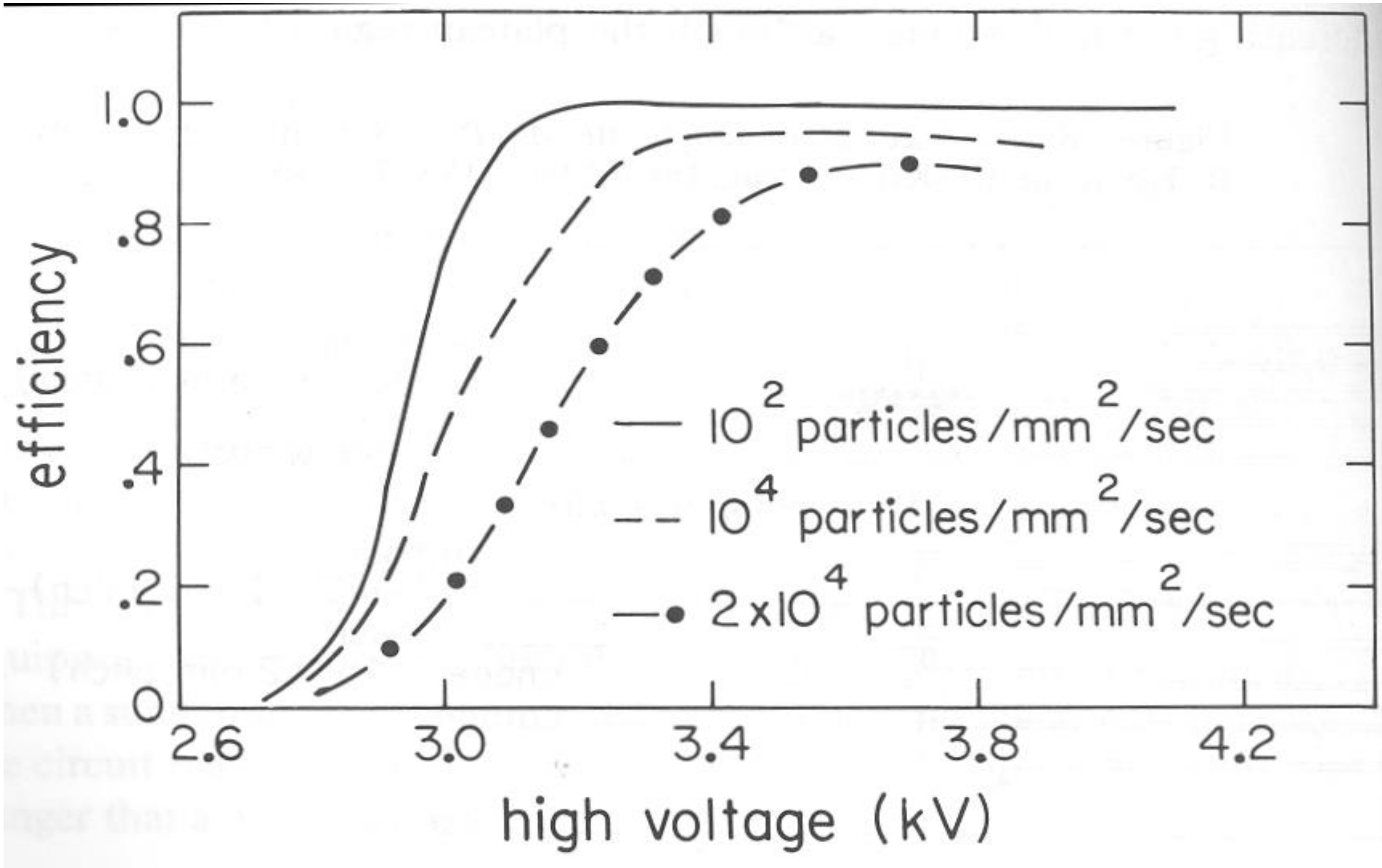


Fig. 31 Comparison of measured and computed drift velocities and characteristic energy for argon[26]

Order of magnitude: drift over 1m ⇒ σ ≈1 cm

Drift velocity: few cm/μs

Detection (in)efficiency: importance of ions space charge



One could have a ~100% efficiency.

But at high flux, ions could not escape between collisions (on an accelerator).

Lecture #4
Gaseous detectors

Outline:

Ionisation in gas
Electrons and ions mobility in gas
Pure gas and gas mixture properties
Dependences of signal on geometry and applied voltage
Proportional, *streamer* and *Geiger-Muller* modes
Quencher / gain variation
δ-ray

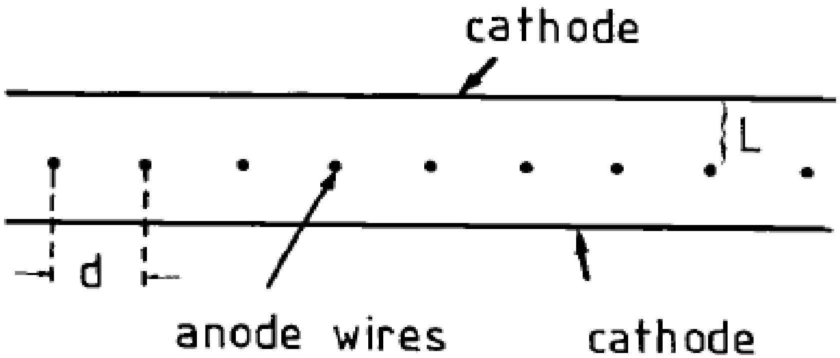
Practical examples: applying our knowledge!
Few examples of gaseous detectors (including some information on diffusion in gas):

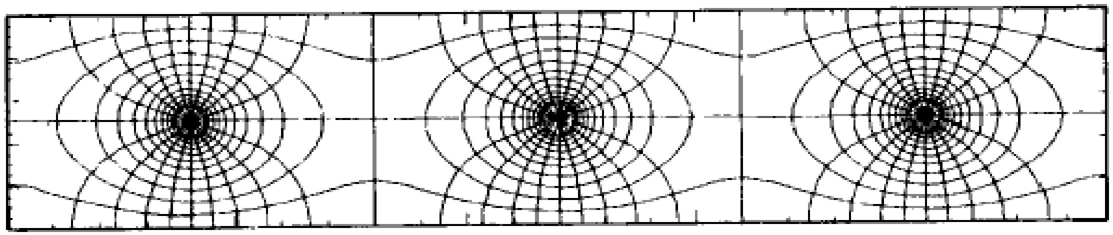
→ MWPC, RPC, MSGC, GEM, Micromegas,
drift chambers, TPC, *straw* (pailles)

conclusion

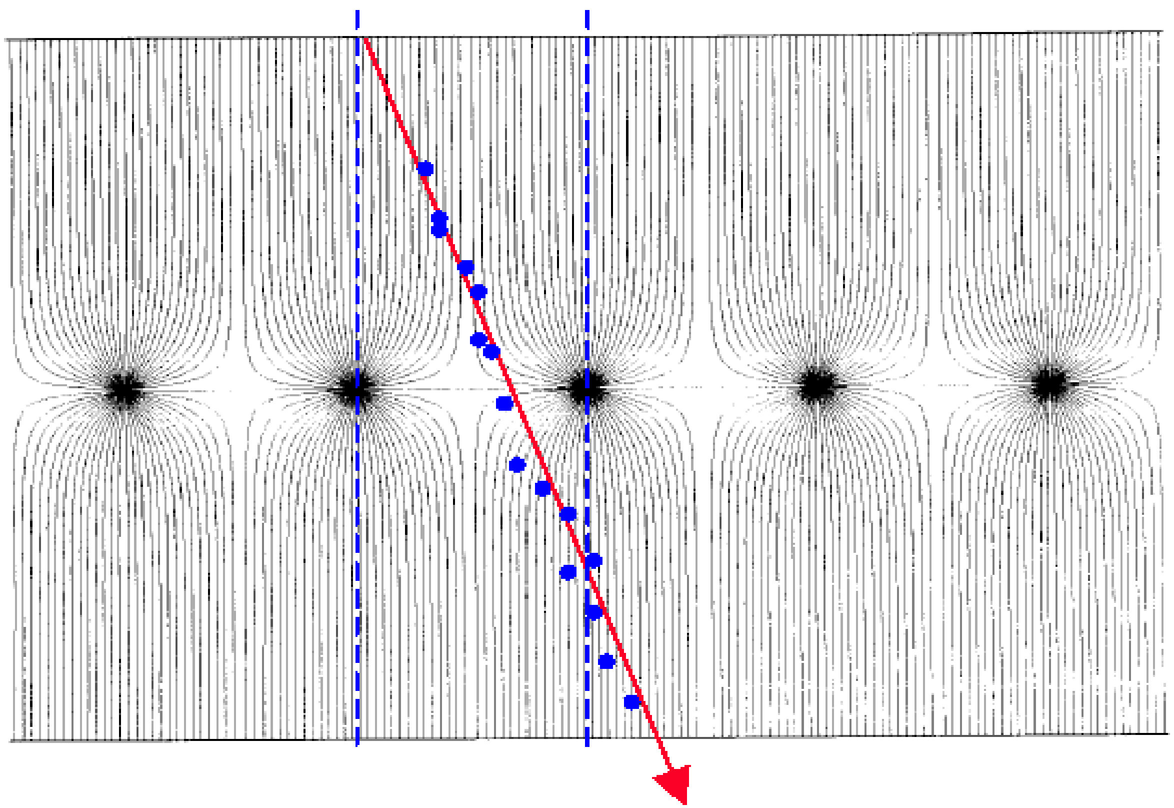
Multi-Wire Proportional Chamber (*MWPC*)

G.Charpak
F.Sauli





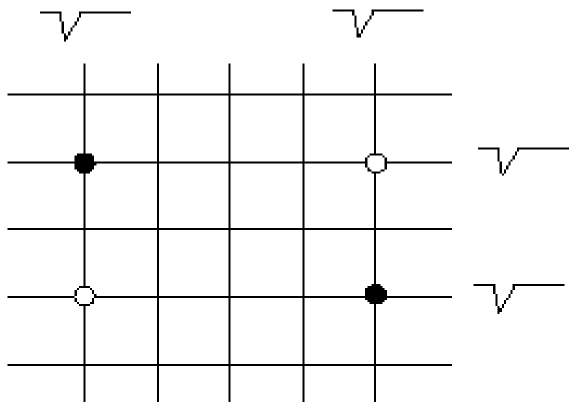
field lines and equipotentials around anode wires



Typical values:
L=8 mm, d=2 mm,
Wire diameters: 20-30 μm
in general, L/d ≈ 3-4

Spatial resolution :
$\sigma = d/\sqrt{12} \approx 600\mu m$

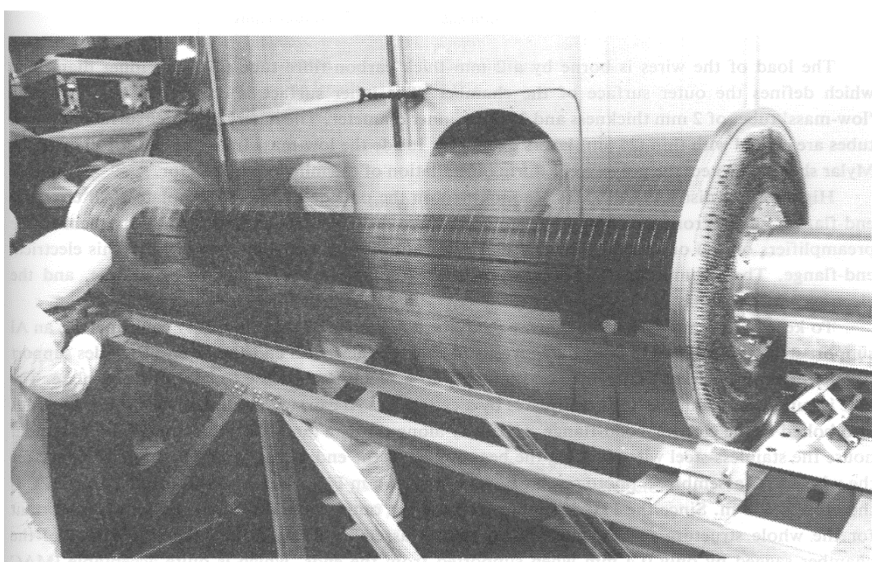
Several measurements with one detector



Simple solution:
two planes of crossing wires (90°). Because of ambiguities only possible if the multiplicity is not to high (otherwise combinatory problems)

Also: wires with small stereo angles (or U, V, Z planes, etc.)

One may also use the time resolution.
e.g.: ITC of ALEPH, resolution ≈3 cm (100 ps)



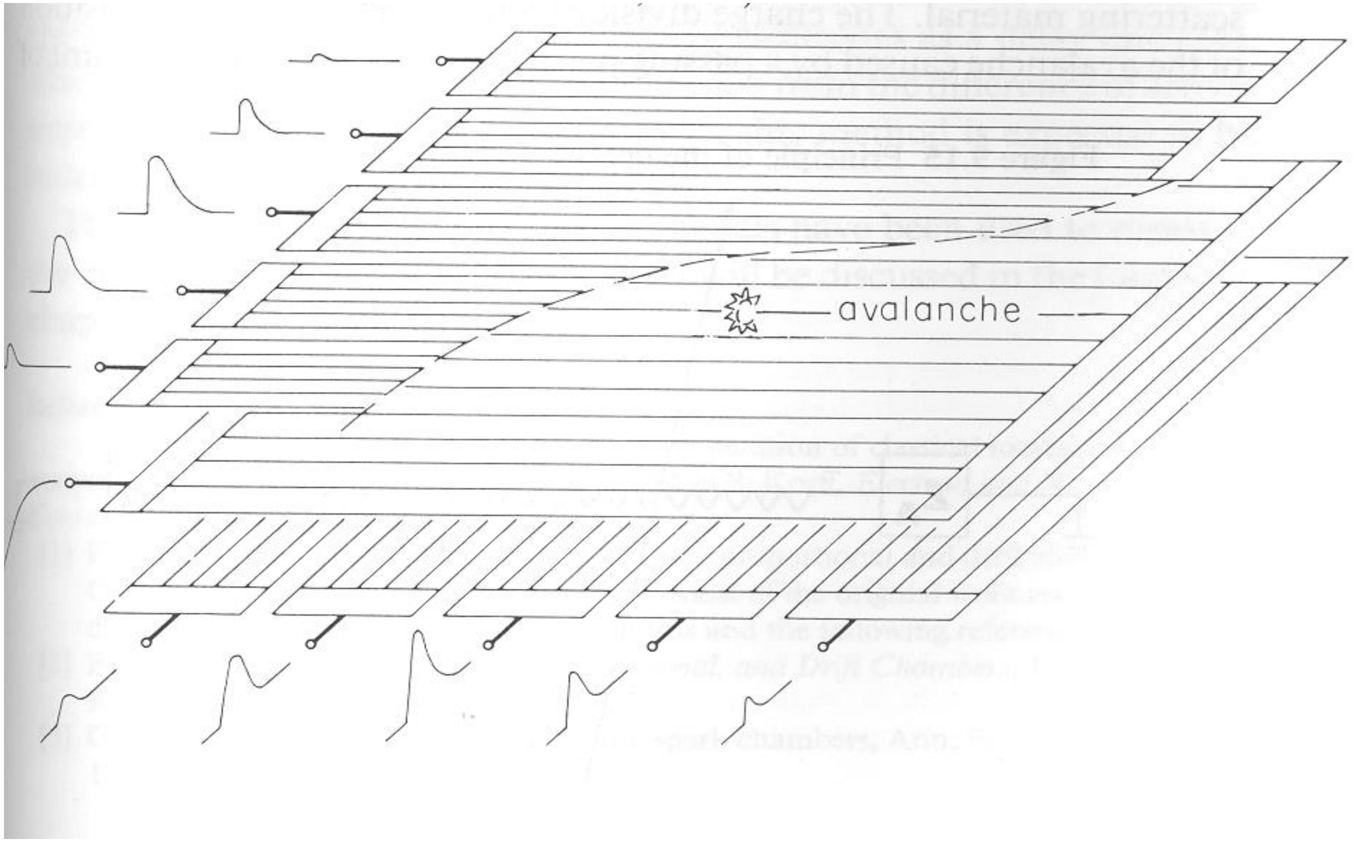
Remark about wire sag:

$$x(L/2) = s_g = \frac{L^2.g.\rho.\sigma}{8T}$$

with σ=wire section (mm^2), T=stretching (kg)
Tungsten: s_g~300µm
for L=5m and Ø=100µm, T=350g

Deformation (!) if: T_c/σ > 200 to 400 kg/mm^2 for W

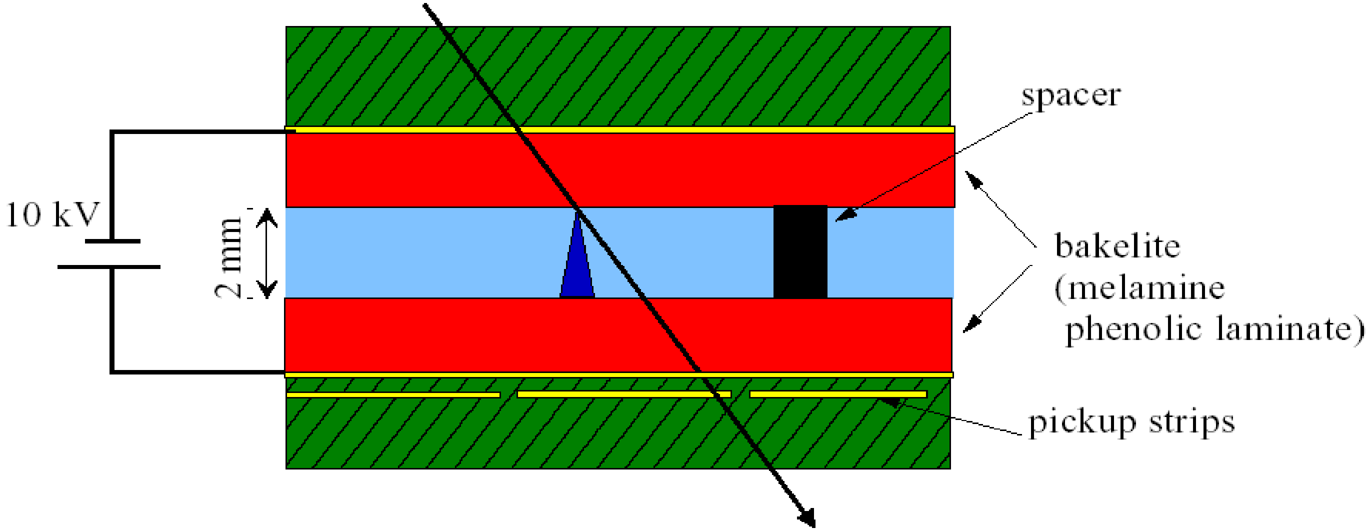
Other possible solution



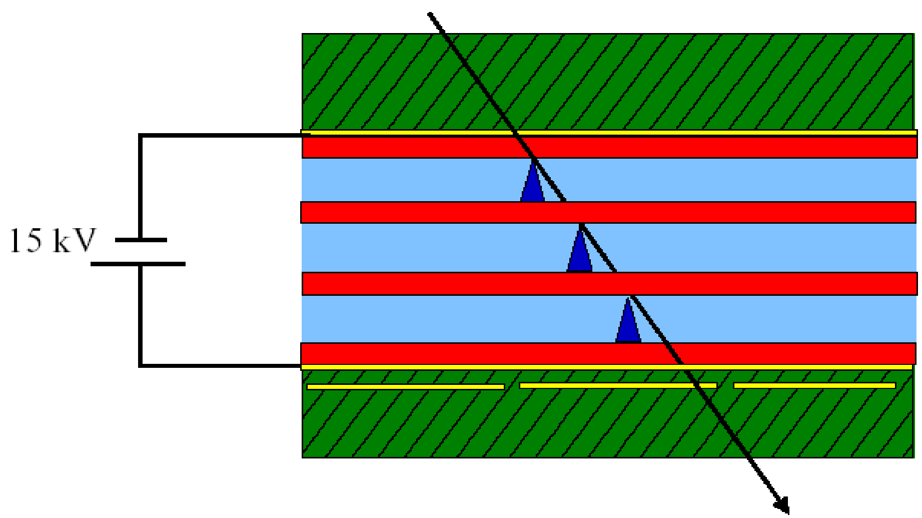
One divide cathode planes in strips, each, readout individually

No wires !!

Resistive Plate Chamber (RPC)



Gas: $C_2F_4H_2$, (C_2F_5H) + few % isobutane



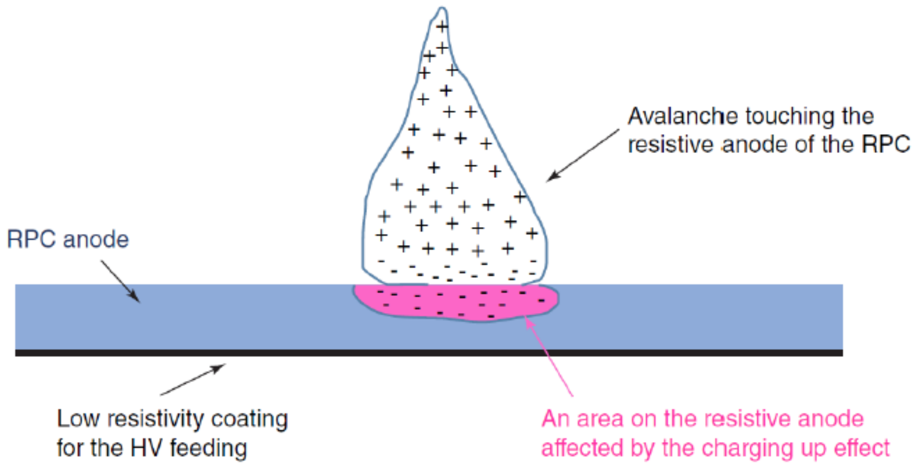
No more wires (pillars to maintain space)

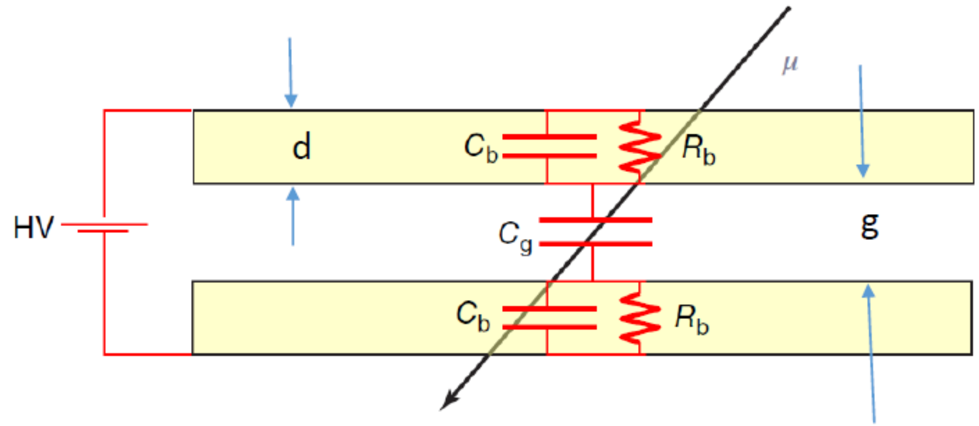
Timing resolution varies from 1 to 2 ns. Why?

Could be improved by inserting several slices.

Careful running conditions since it is close to streamer mode.

Physics behind their operation





$$\tau = 2R_b\left(\frac{C_b}{2} + C_g\right) = 2\rho_b\frac{d}{S}\left(\frac{1}{2}\varepsilon_0\varepsilon_r\frac{S}{d} + \varepsilon_0\frac{S}{g}\right) = \rho_b\varepsilon_0\left(\varepsilon_r + 2\frac{d}{g}\right)$$

Could be useful for RD51 community

V.Peskov *et al*., Resistive gaseous detector (ed. Wiley-VCH)

Micro-Strip Gaz Chamber (MSGC)

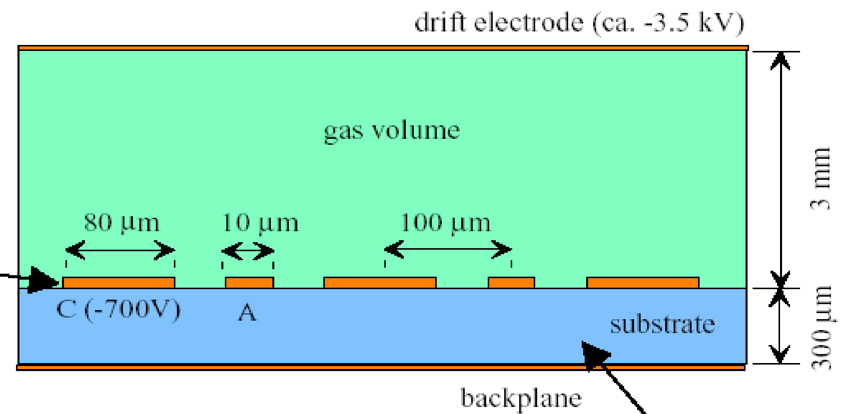
Considered by CMS experiment,
but aging problems…(replace by Si)

Ar:DME 50:50

Resolution ~30 to 40μm

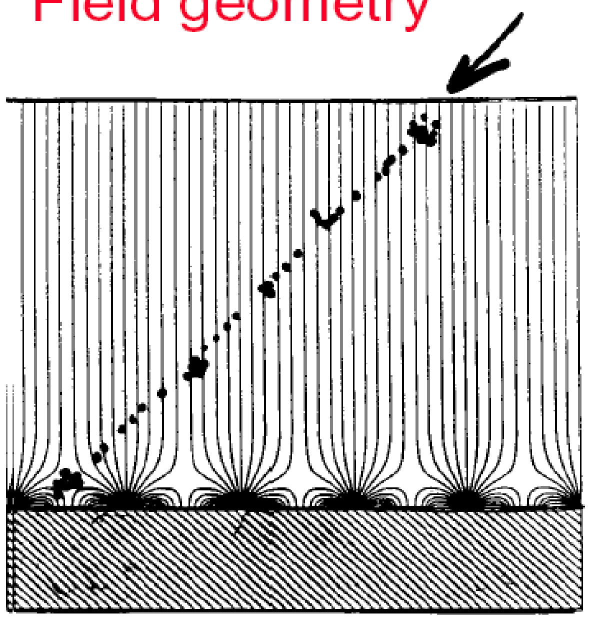
Gain <10000

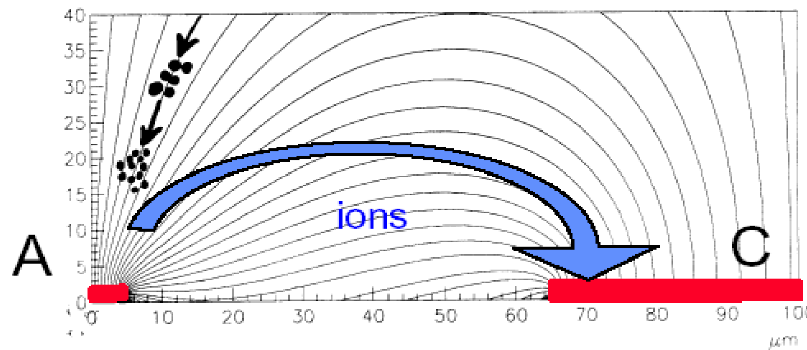
Gold strips
+ Cr underlayer



Glass DESAG AF45 + S8900
semiconducting glass coating,
$\rho = 10^{16}\ \Omega/\square$

Field geometry

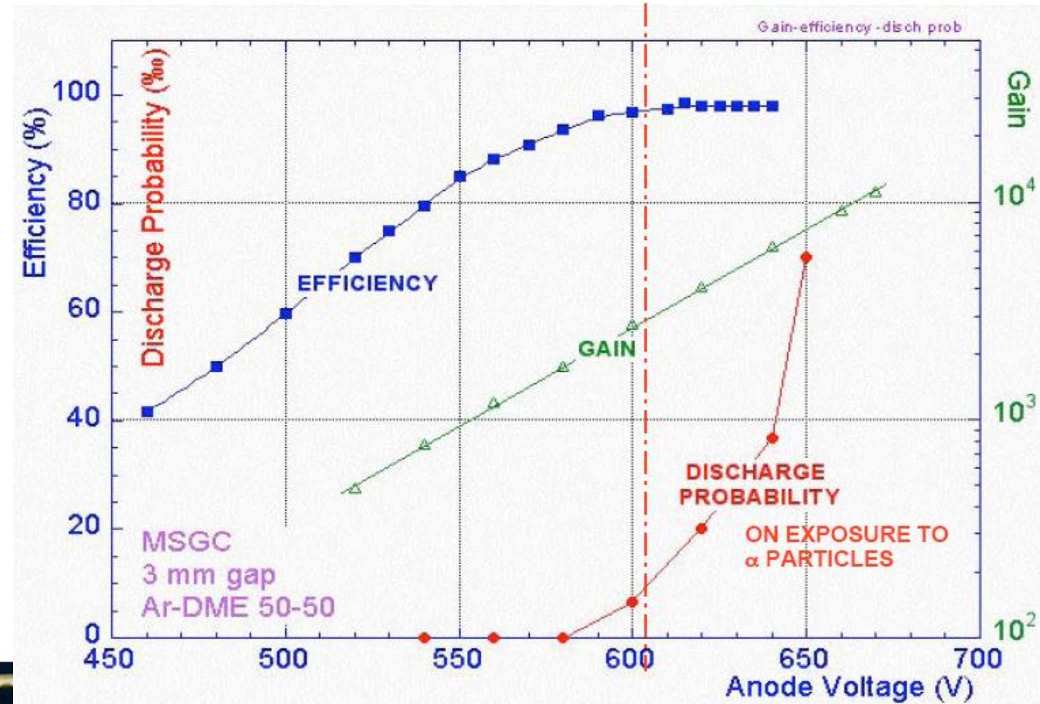




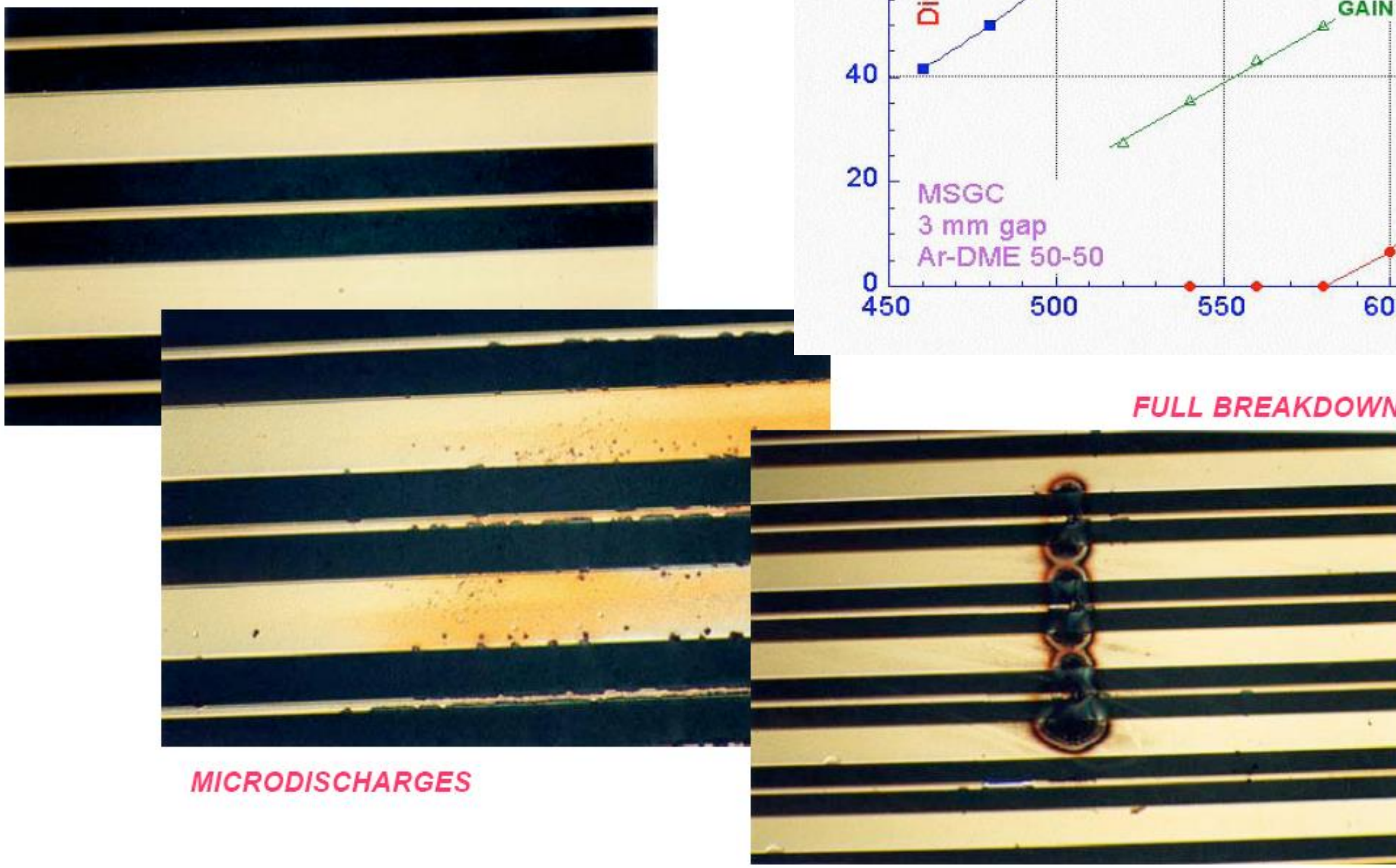
Fast ion evacuation → high rate capability
$\approx 10^6$ /(mm$^2\cdot$s)

Micro-Strip Gaz Chamber (MSGC)

Considered by CMS experiment,
but aging problems…(replace by Si)



MSGC DISCHARGE PROBLEMS:



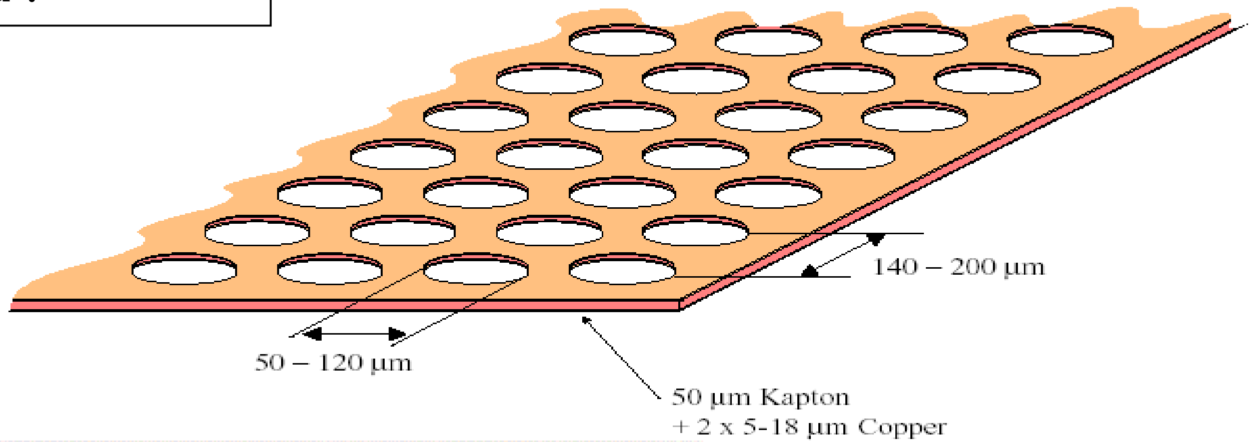
MICRODISCHARGES

FULL BREAKDOWN

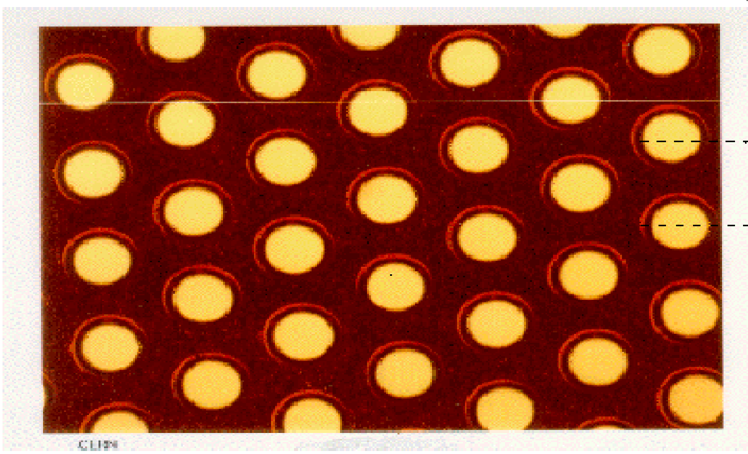
Gaz Electron Multiplier (GEM)

Signal zone (drift zone) and amplification zone are separated !

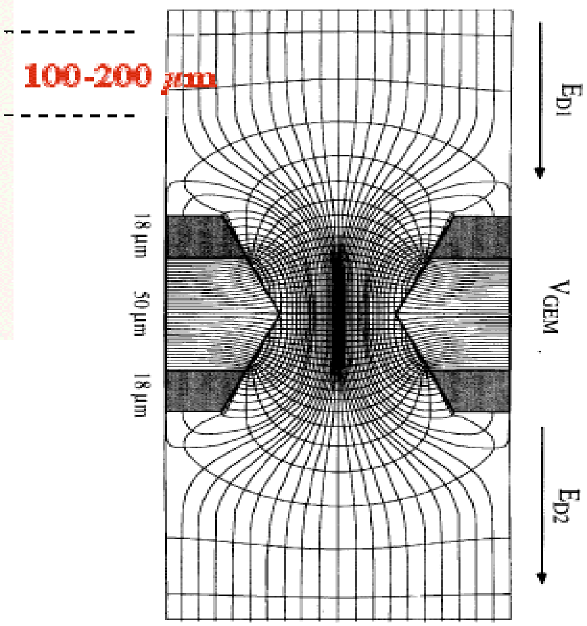
(R. Bouclier et al., NIM A 396 (1997) 50)



Kapton = isolant



Micro photo of a GEM foil



<u>Limitations:</u>
shorts in one “hole”
=> short on the full area

Gain limitation?

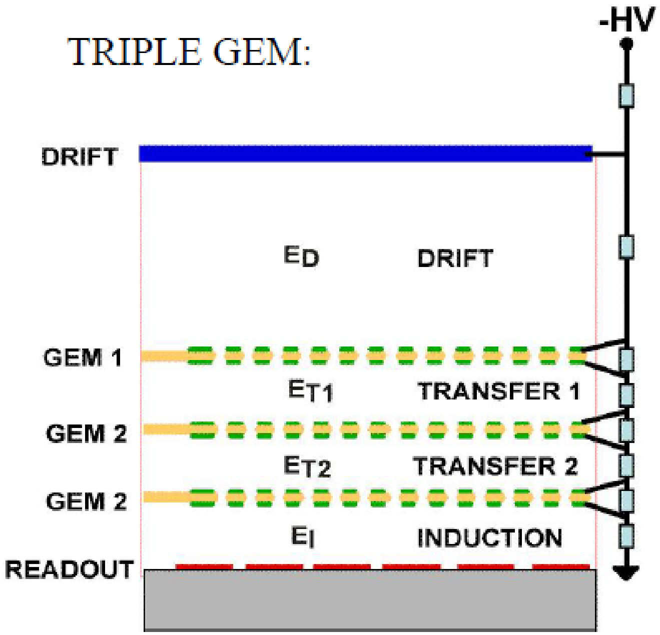
amplification gap of ~ 2mm => signal width ~20ns

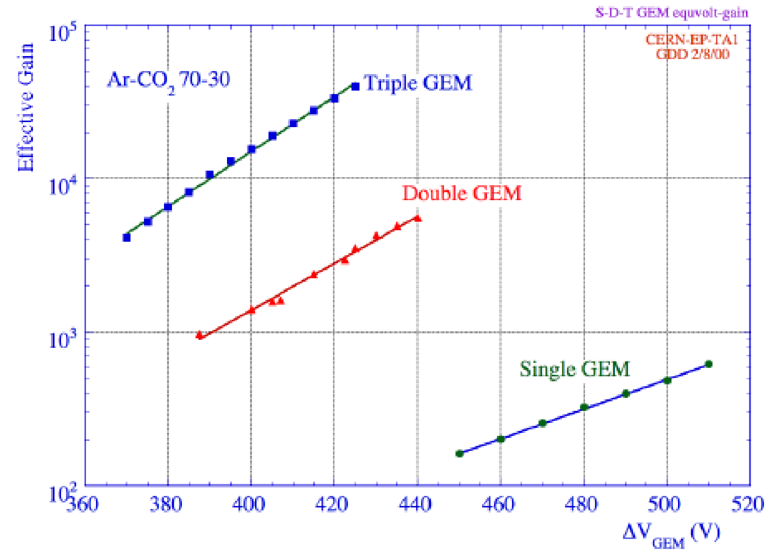
Gaz Electron Multiplier (GEM) (multi-stage)

Construction complexity?

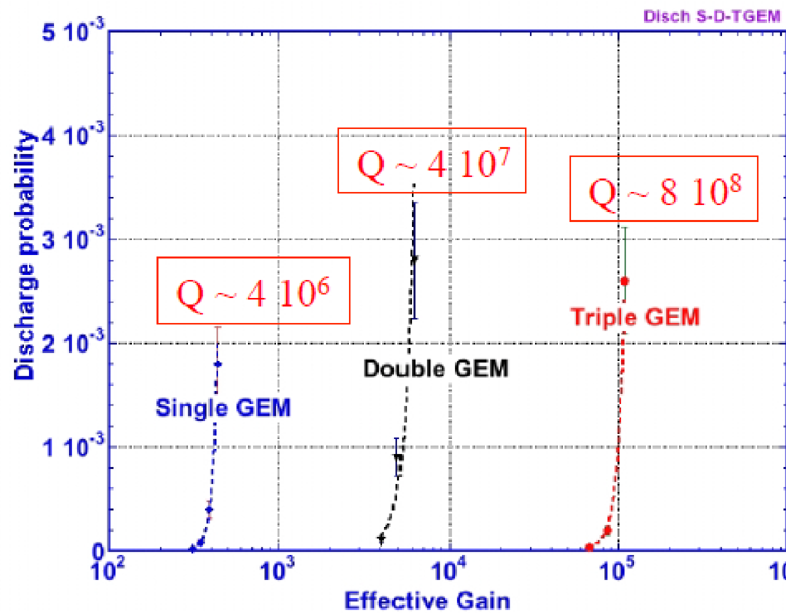
THE DISCHARGE VOLTAGE (MAXIMUM GAIN) INCREASES IN CASCADED MULTI-MPGD

TRIPLE GEM:





DISCHARGE PROBABILITY VS GAIN:



S. Bachmann et al, NIMA479(2002)294

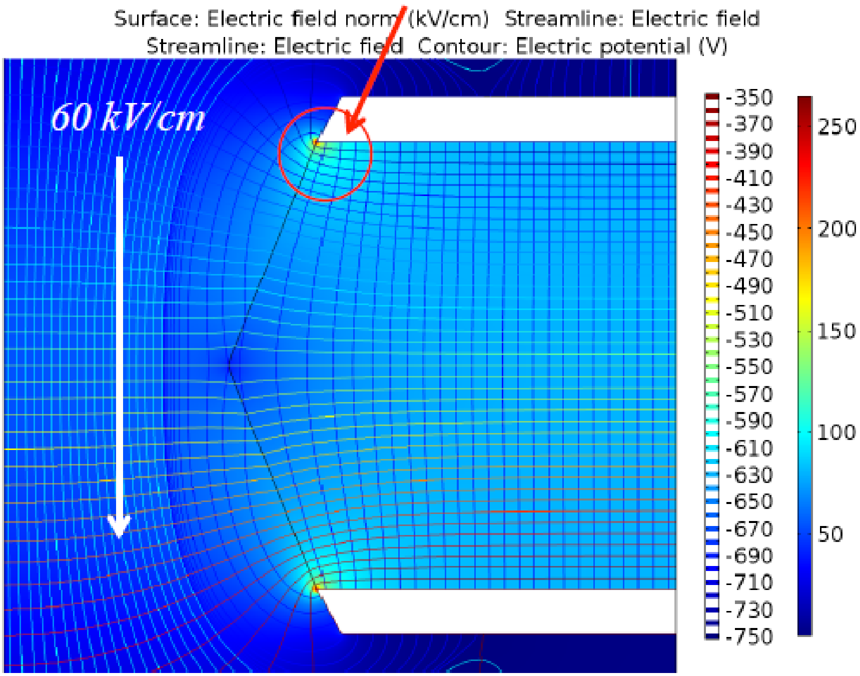
COMPUTED FIELD NEAR THE CATHODE RIMS IN GEM

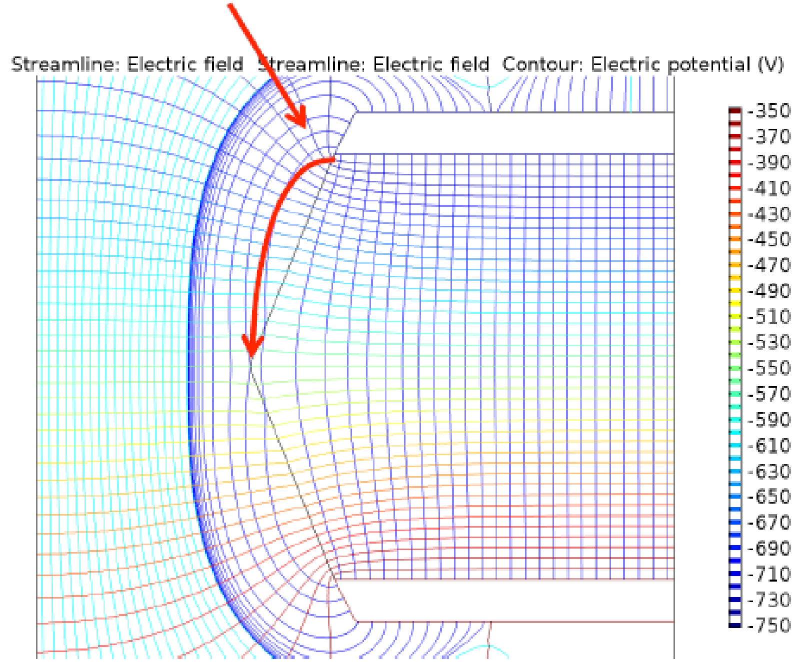
V_{GEM}= 375 V V_T=V_I=3.5 kV/cm

Filippo Resnati, Personal communication today

160 kV/cm

FIELD EMISSION
AND/OR
IONIZATION

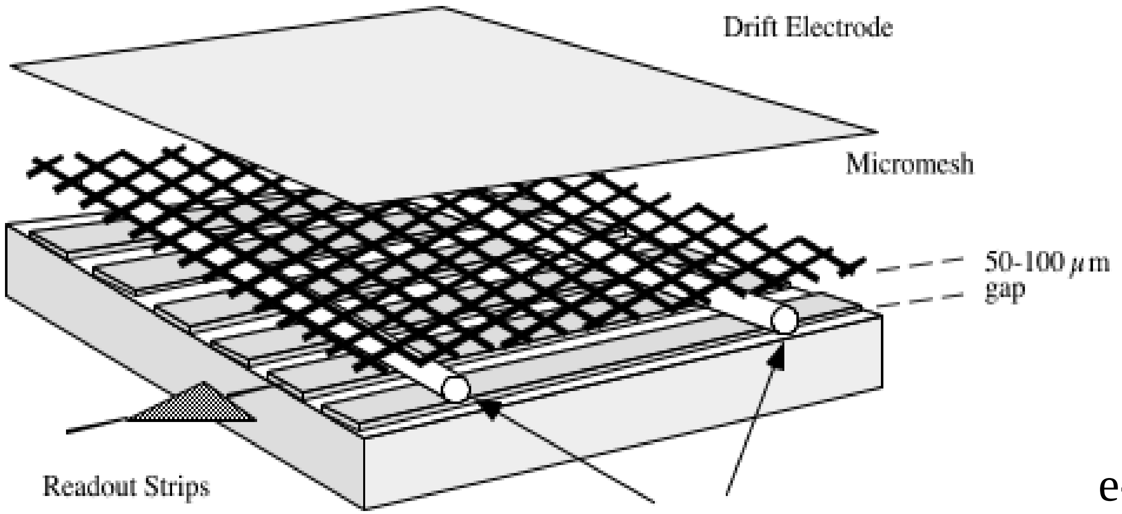




WAITING FOR A DEDICATED FULL GAIN CALCULATION “A LA MSGC”

MicroMegas

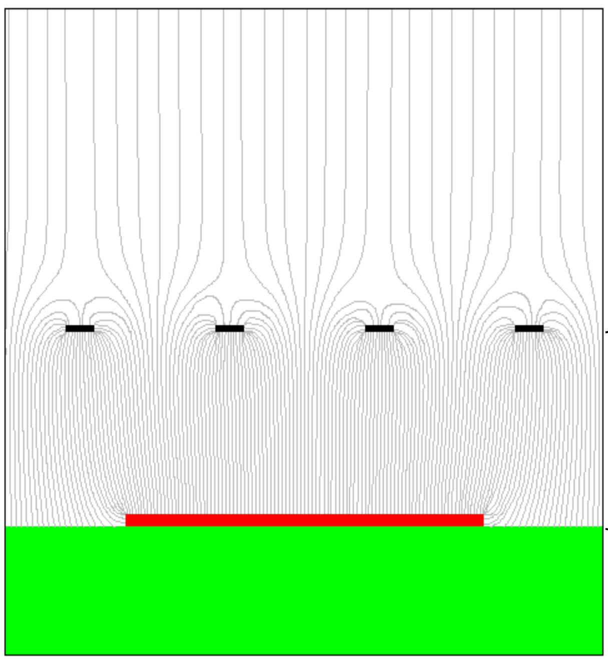
I.Giomataris, G.Charpak, Ph.Rebourgeard et al.



In few years, many improvements in these detectors construction: mainly using industrial lithography process.

e- trajectory in the amplification zone.

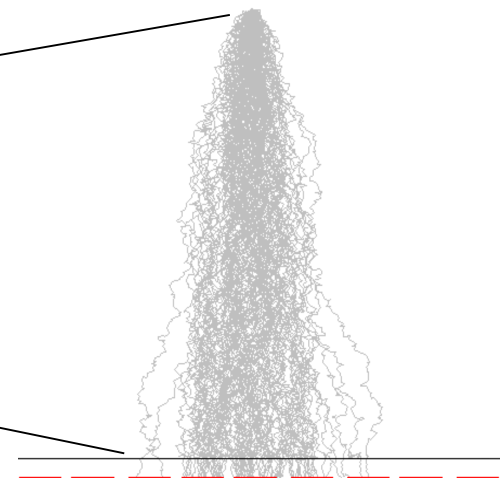
e- are scattered, so ions will be catch by the grid -micromesh- (they go back). Ions disappeared in about ~100ns



Field line

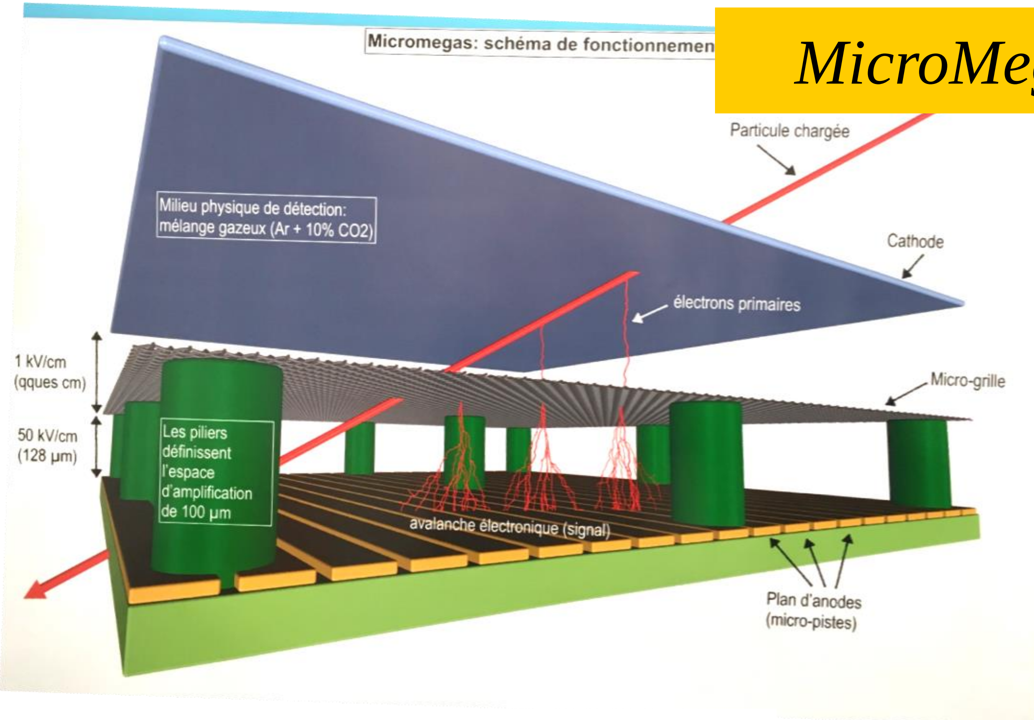
~1kV/cm

~few 10kV/cm

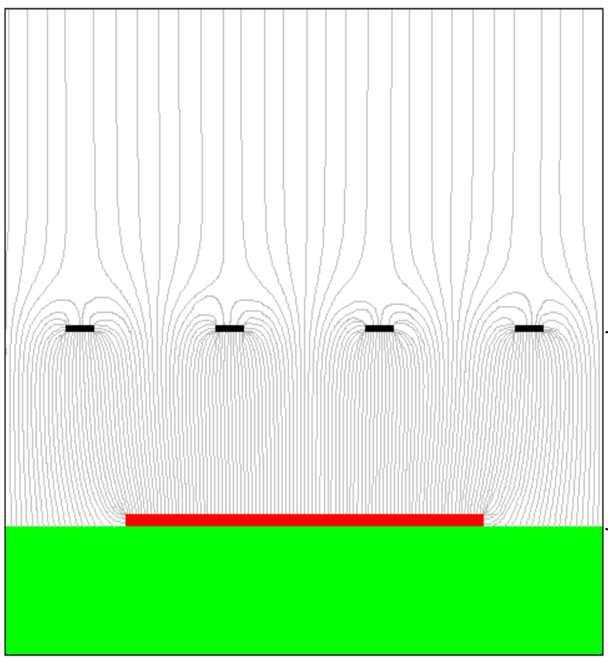


MicroMegas

I.Giomataris, G.Charpak, Ph.Rebourgeard et al.



<u>In few years, many improvements in these detectors construction:</u> mainly using industrial lithography process.



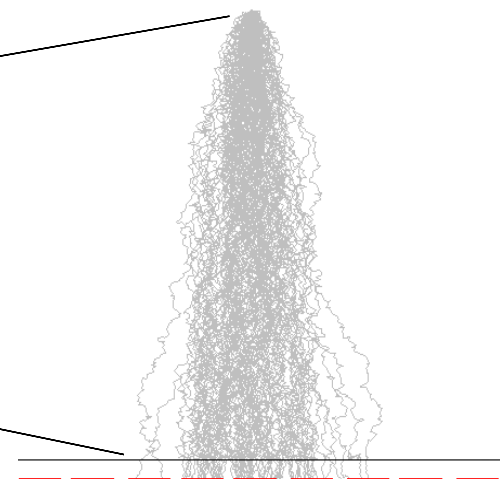
Field line

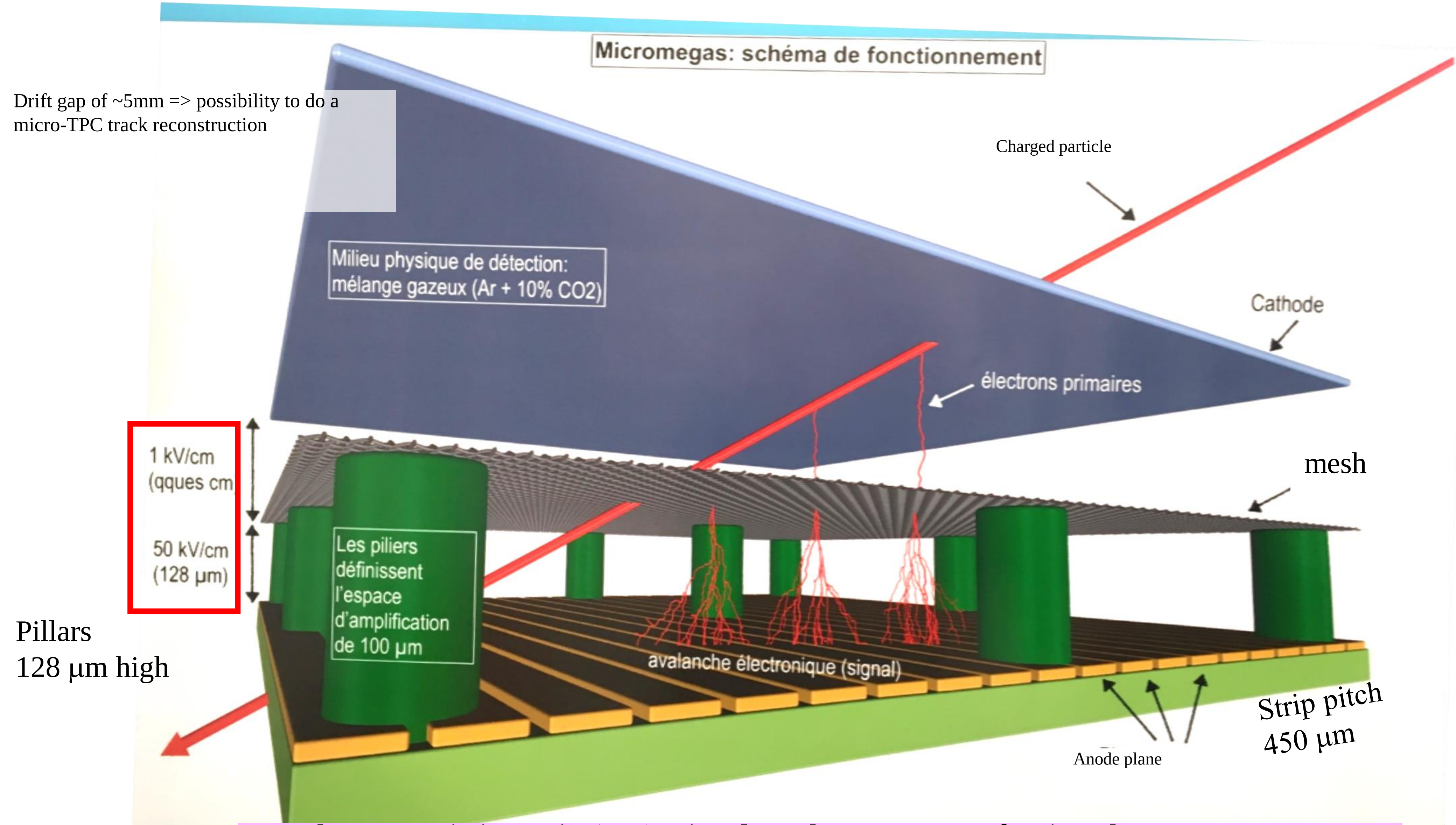
~1kV/cm

~few 10kV/cm

e- trajectory in the amplification zone.

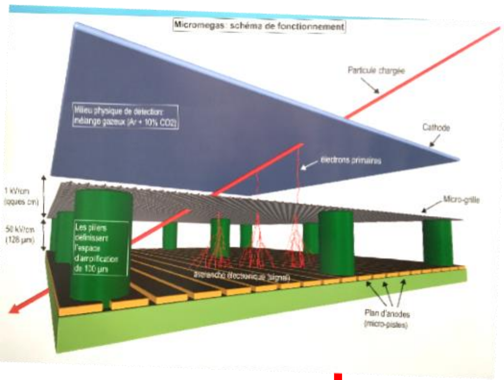
e- are scattered, so ions will be catch by the grid -micromesh- (they go back). Ions disappeared in about ~100ns

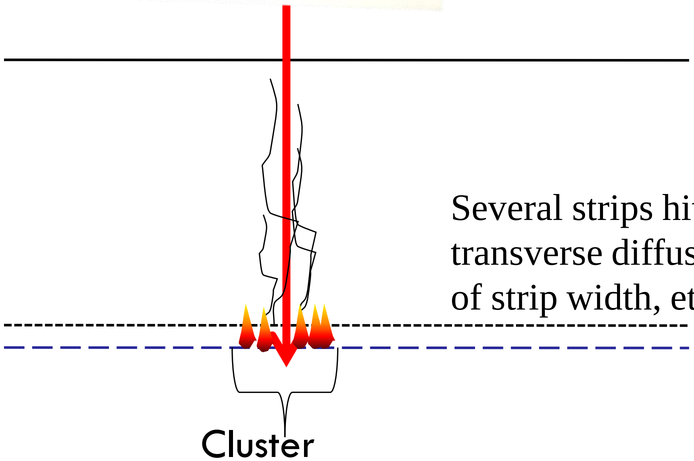




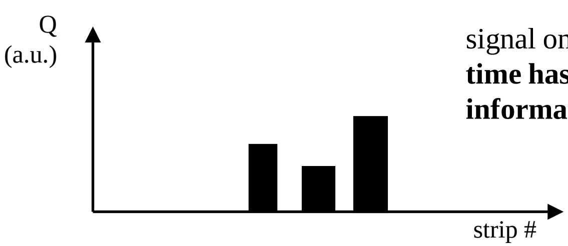
Not shown : resistive strip (HV) + insulator layers on top of strips plane

Micromegas (micro-) TPC mode





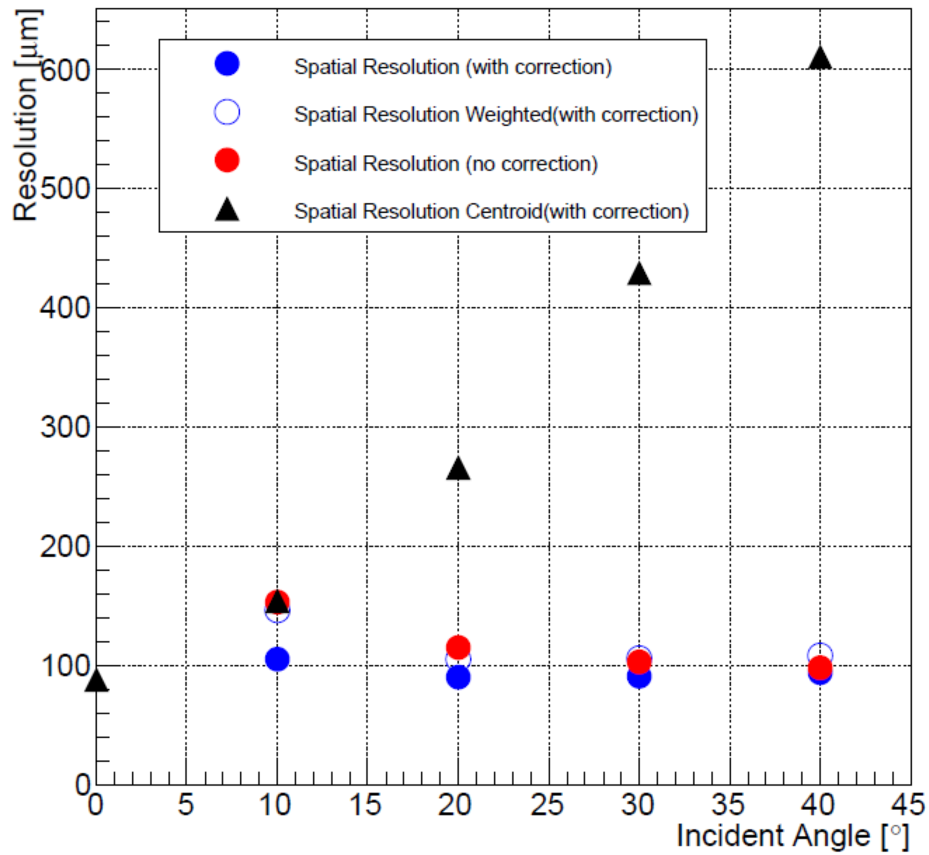
Several strips hitted due to transverse diffusion (depends of strip width, etc.)



signal on strip **with time has almost no information**

In MM gaz, ~1 ionization cluster each ~200 microns of track.

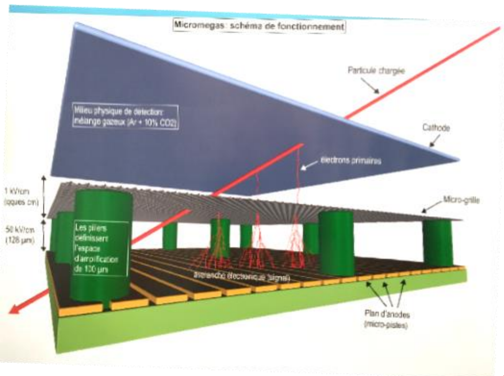
microns

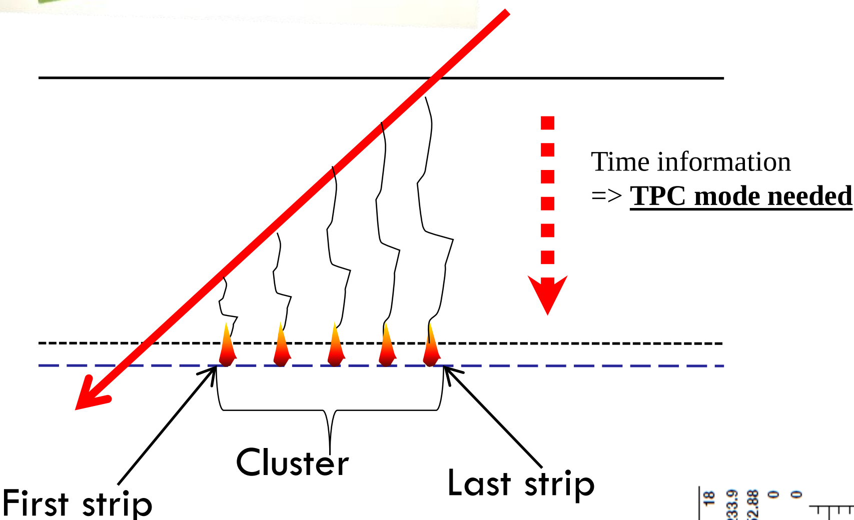


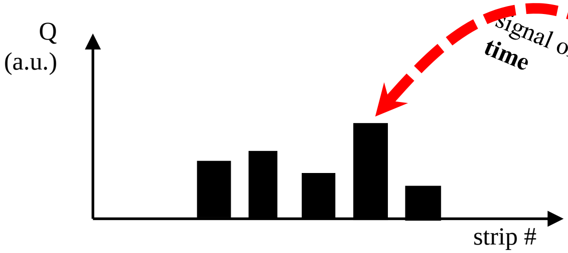
Track angle (deg.)

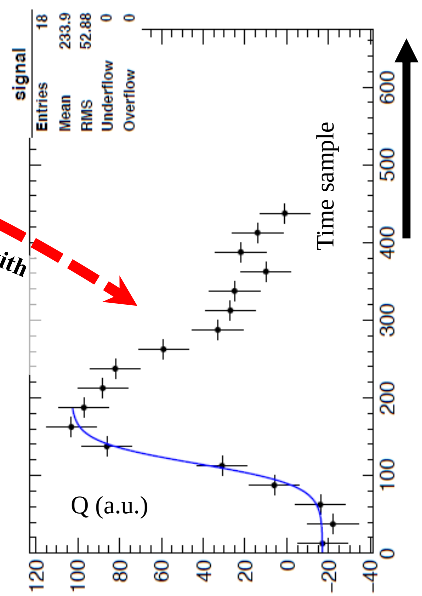
angular range of the NSW

Micromegas (micro-) TPC mode



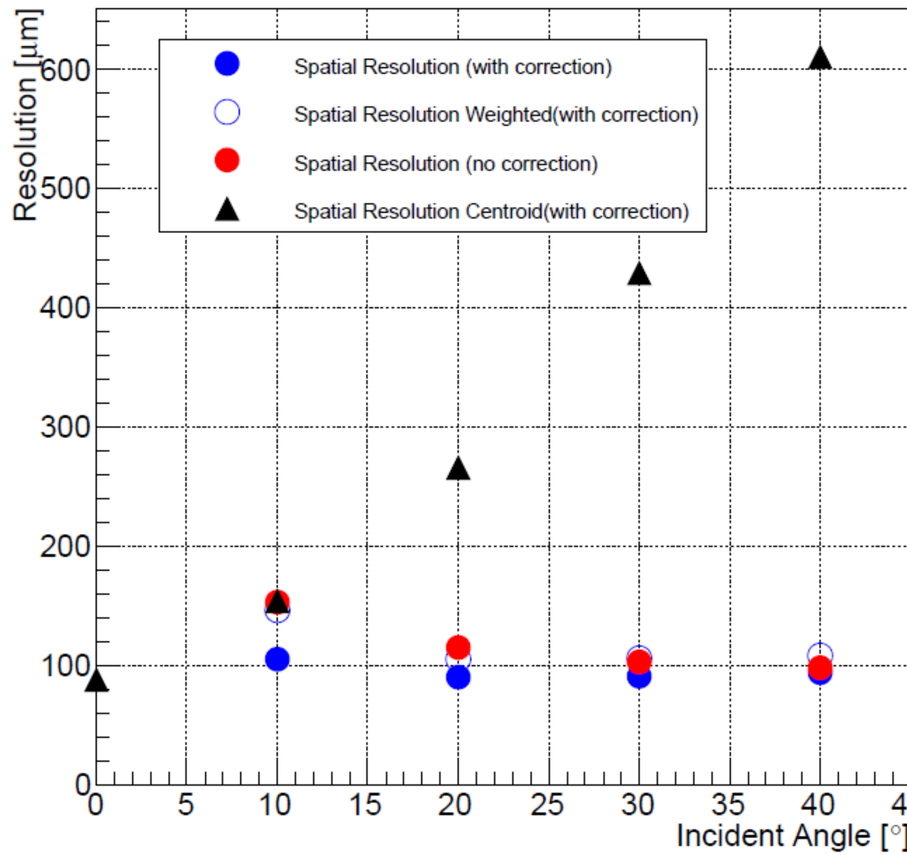






In MM gaz, ~1 ionization cluster each ~200 microns of track.

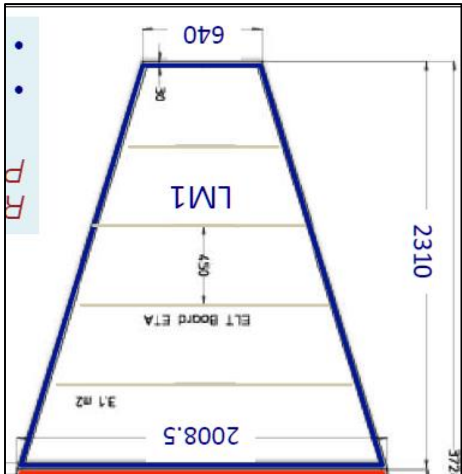
microns



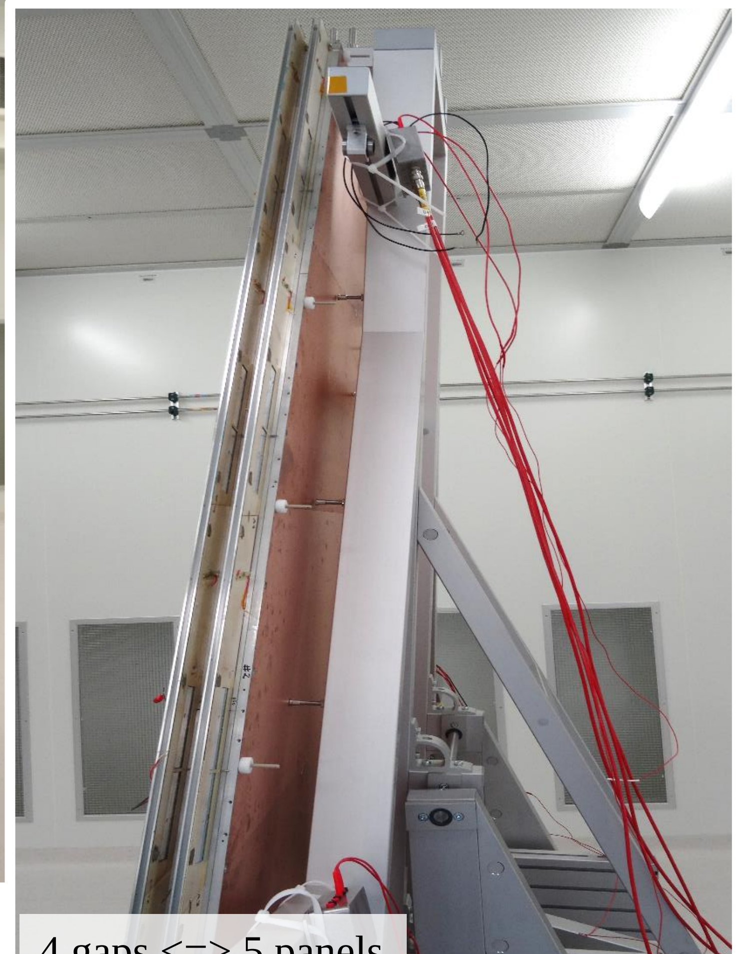
Track angle (deg.)

angular range of the NSW

Micromegas 4 gaps chamber/module when finished

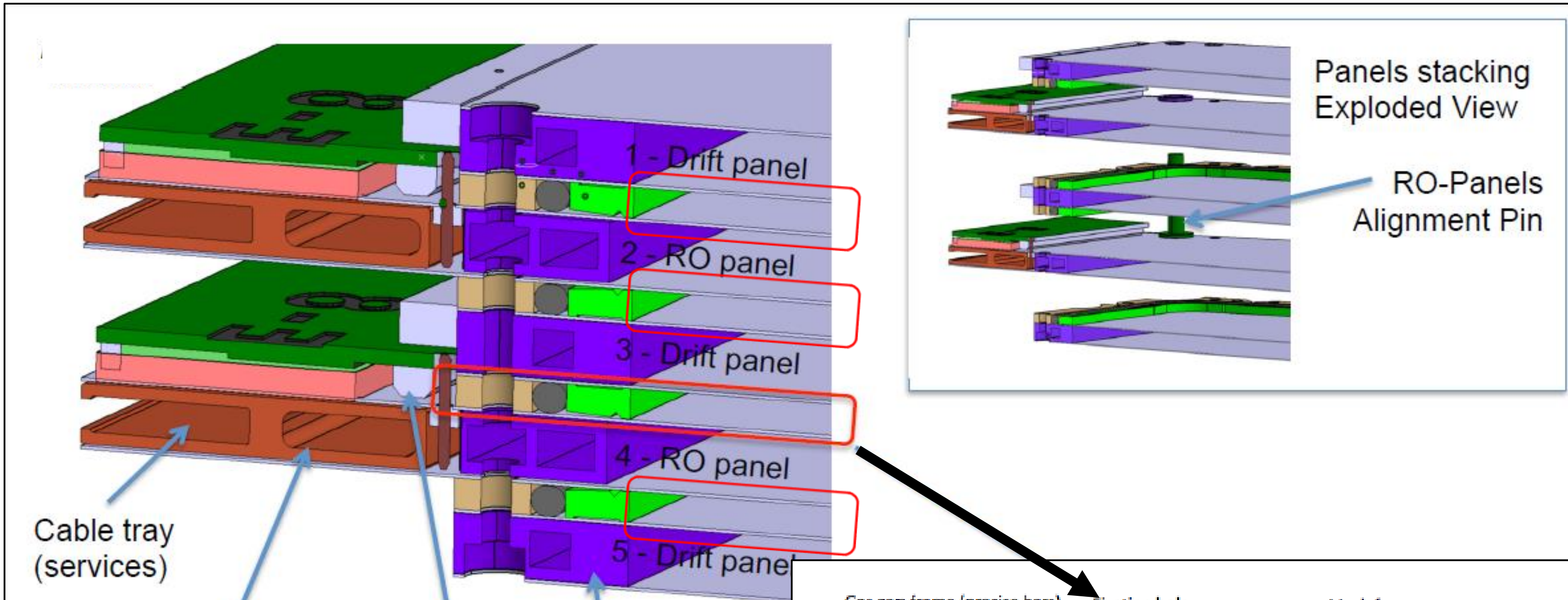


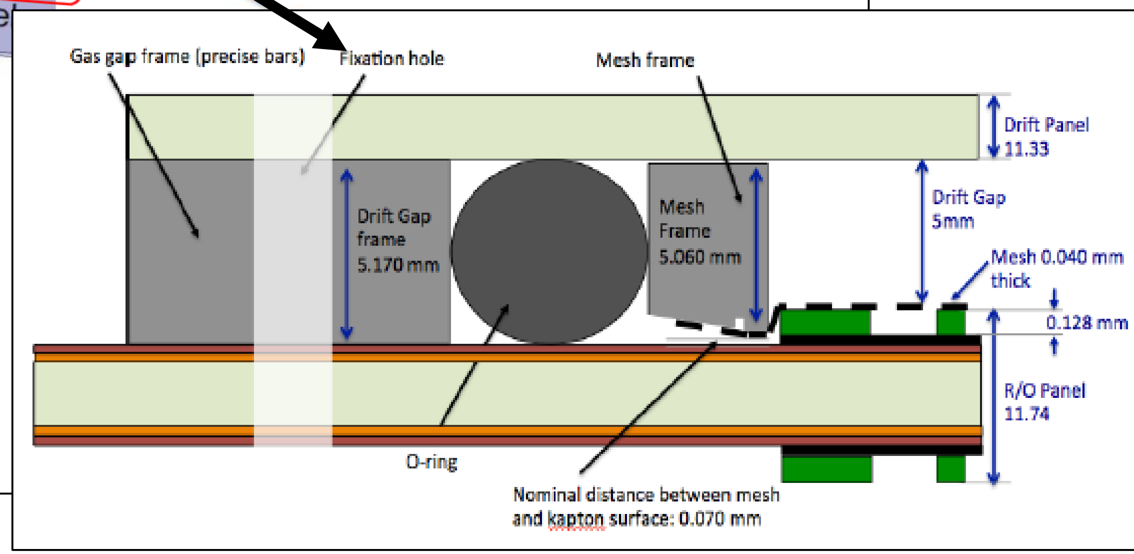
2.3 x 2.0 ~3 m^2
(h x L)

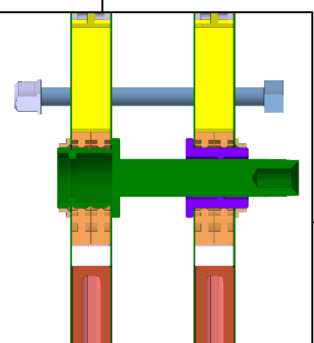


4 gaps <=> 5 panels

Micromegas detector design (physicist and engineer work)

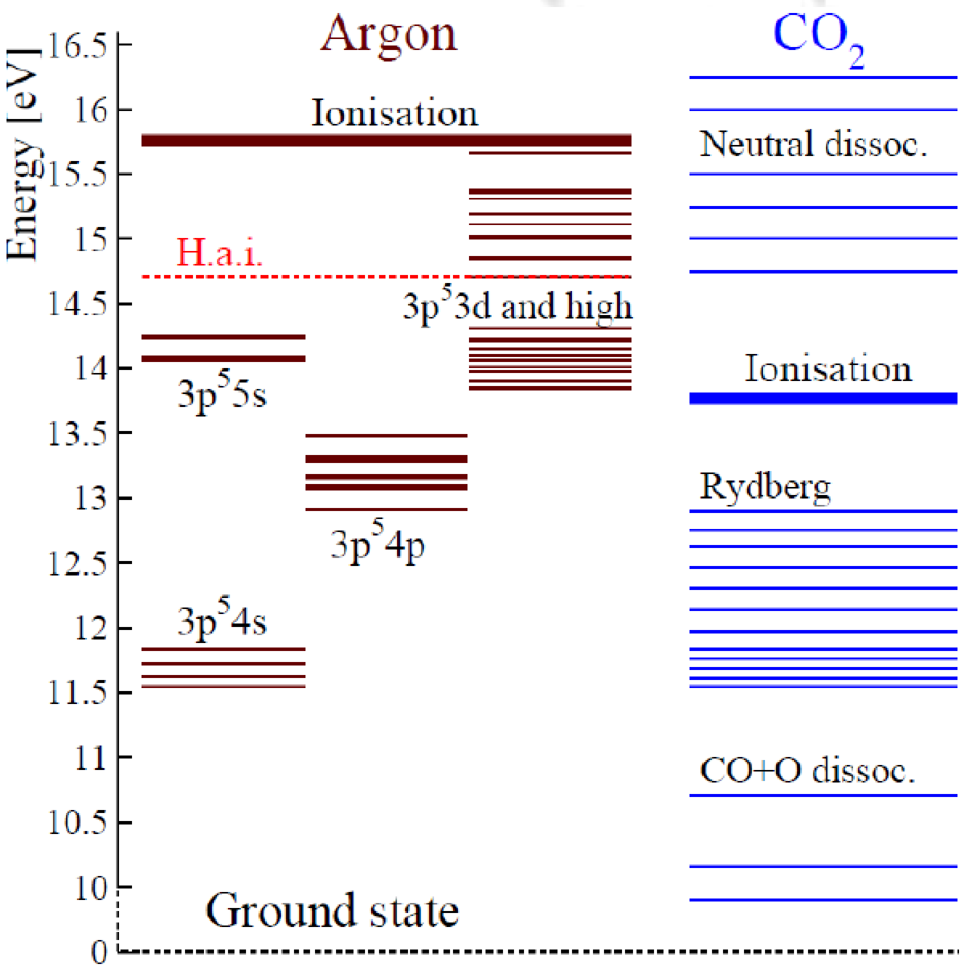





Locking pins

Micromegas detectors could be opened for repairing them. ***Mesh attached to the drift panel***…

Gain calculation (correction parameters)



$$G = e^{\int \alpha_{Pen}(E(r))\, dr}$$

- $Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$
- Ar^* $3p^5 3d$ (13.8 eV) and higher level excitations can ionise CO_2 (13.77 eV)

$$\alpha_{Pen} = \alpha \left(1 + r_{Pen} \frac{f_{Ar}^{exc}}{f_{mix}^{ion}} \right)$$

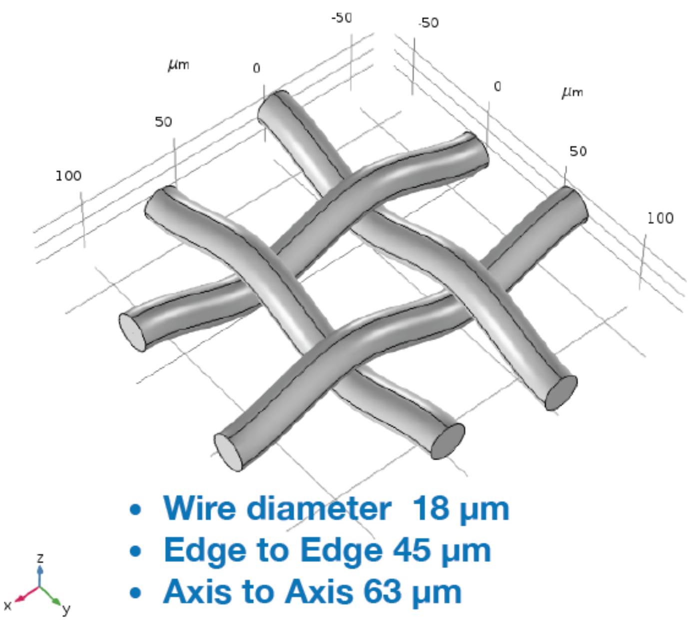
- Townsend coefficients (α), production frequencies of the ionisations and excitations calculated with **Magboltz**
- $\mathbf{r_{Pen}}$: Penning transfer rate

O.Sahin

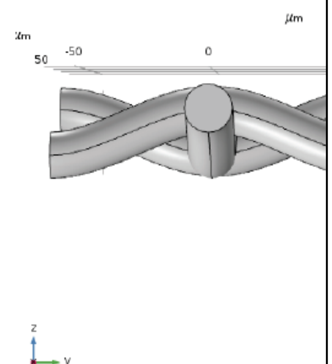
- **Feedback correction** for the over-exponential increases in gas gain

$$G_{total} = G/(1 - \beta G)$$

18/45 Standard Woven :

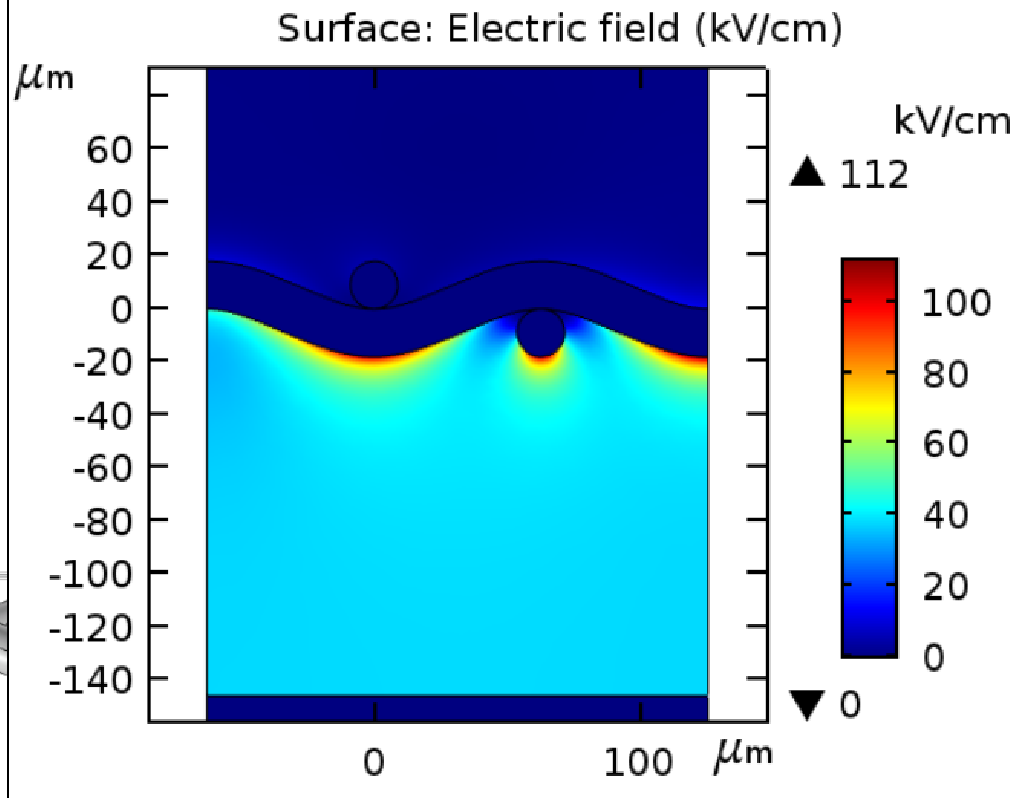


- Wire diameter 18 µm
- Edge to Edge 45 µm
- Axis to Axis 63 µm



The wires hav

on the YZ plane, through a wire



the maximum field is 112 kV/cm

the drift gap, amplification gap are the same

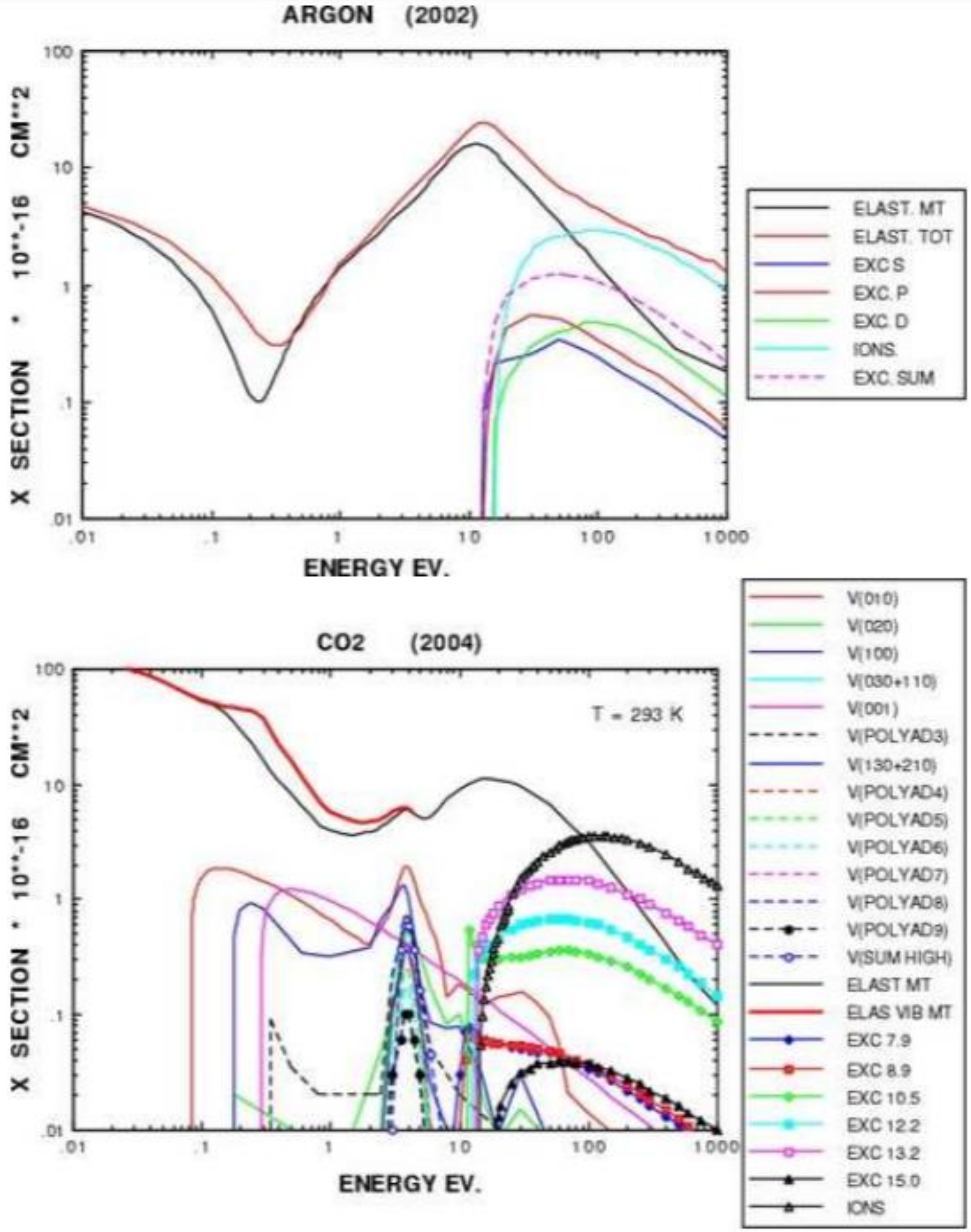
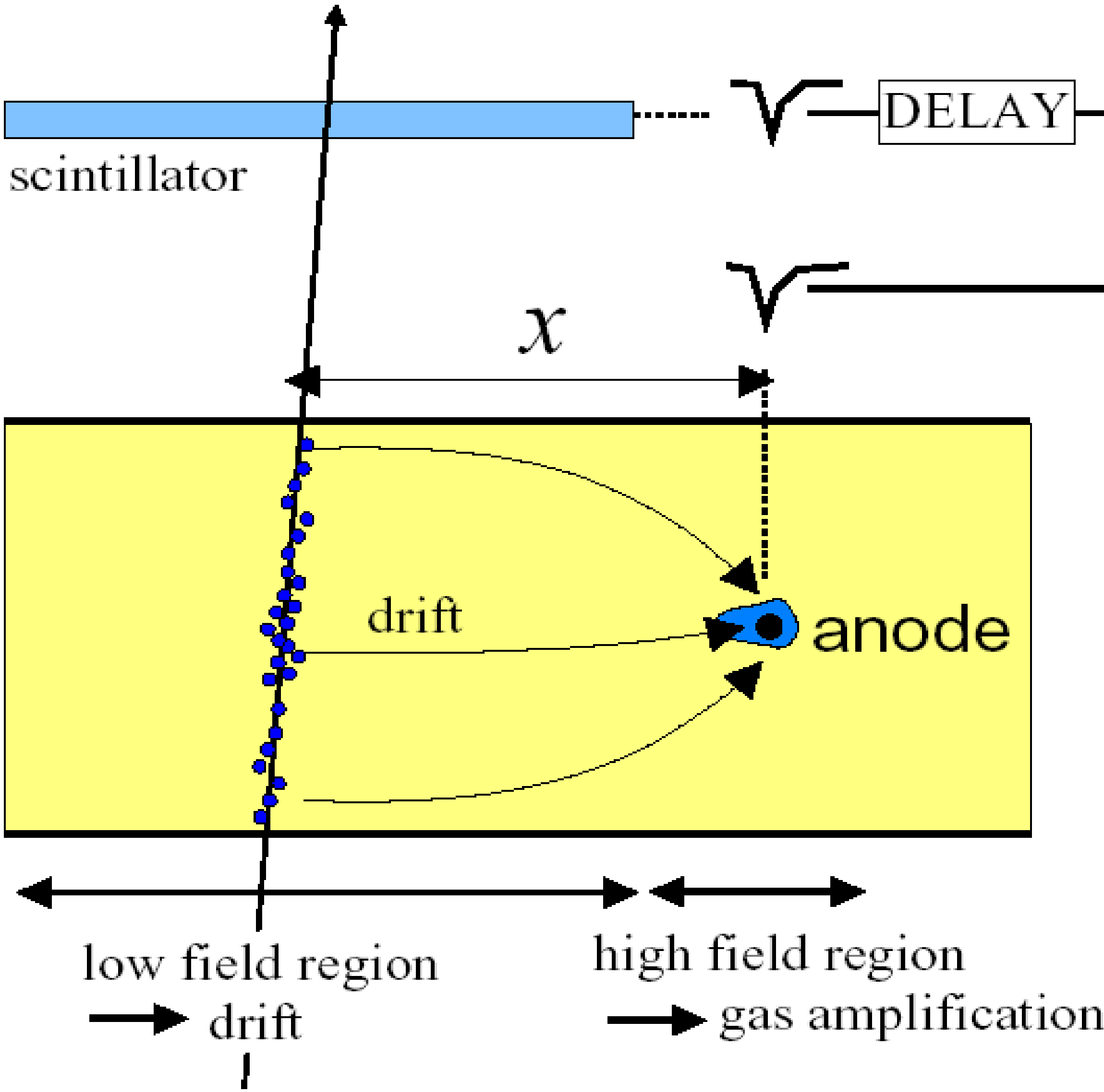


Figure 7: Cross Section of argon and carbon dioxide as a function of energy. These graphs are taken from the Magboltz 7.1 database for gas properties.

Drift chambers



One need an external time stamp (trigger) taken as a reference for the time measurement provided by the drift chamber.

<u>Resolution:</u>
from few tenth of μm, knowing gas properties: r-t relation

(non linear effect like Ramsauer effect, electronics, diffusion -trajectory fluctuations-, *Lorentz* angle…)

Useful parameters of drift chambers

- One need fewer wires:
  - Cost
  - Mechanical structure less constrained w.r.t. M.W.P.C.
  - Good transverse resolution thanks to a good r-t relationship knowledge

- Large possible volumes

- But:
  - They need an external trigger
  - Electronic may be more complex than MWPC (which signal are we looking at?)
  - Slow detectors (drift time up to few 100ns, even ~1μs)

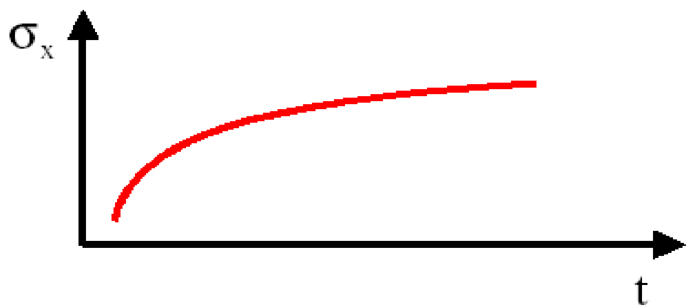
Diffusion and drift

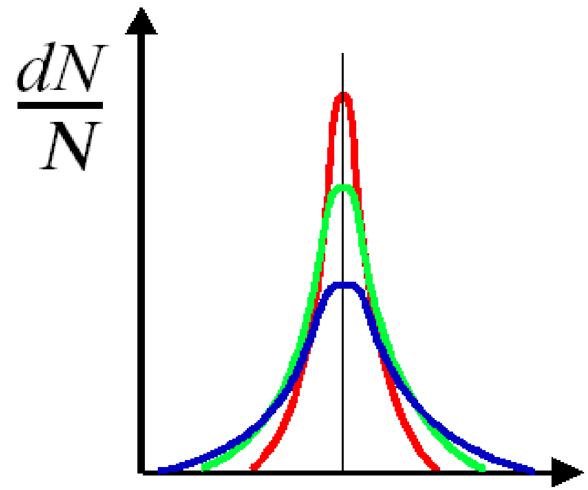
- En l'absence de champ externe (E ou B), les électrons diffusent sous l'effet des collisions avec les atomes :

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi D t}} e^{-(x^2/4Dt)}\, dx$$

D: diffusion coefficient en cm^2/sec

le σ équivalent = $\sigma_x(t) = \sqrt{2Dt}$ or $D = \frac{\sigma_x^2(t)}{2t}$





Ordre de grandeur : dérive de 1m ⇒ σ ≈1 cm

Il y a aussi une dérive longitudinal, i.e. un étalement en temps

Diffusion and drift

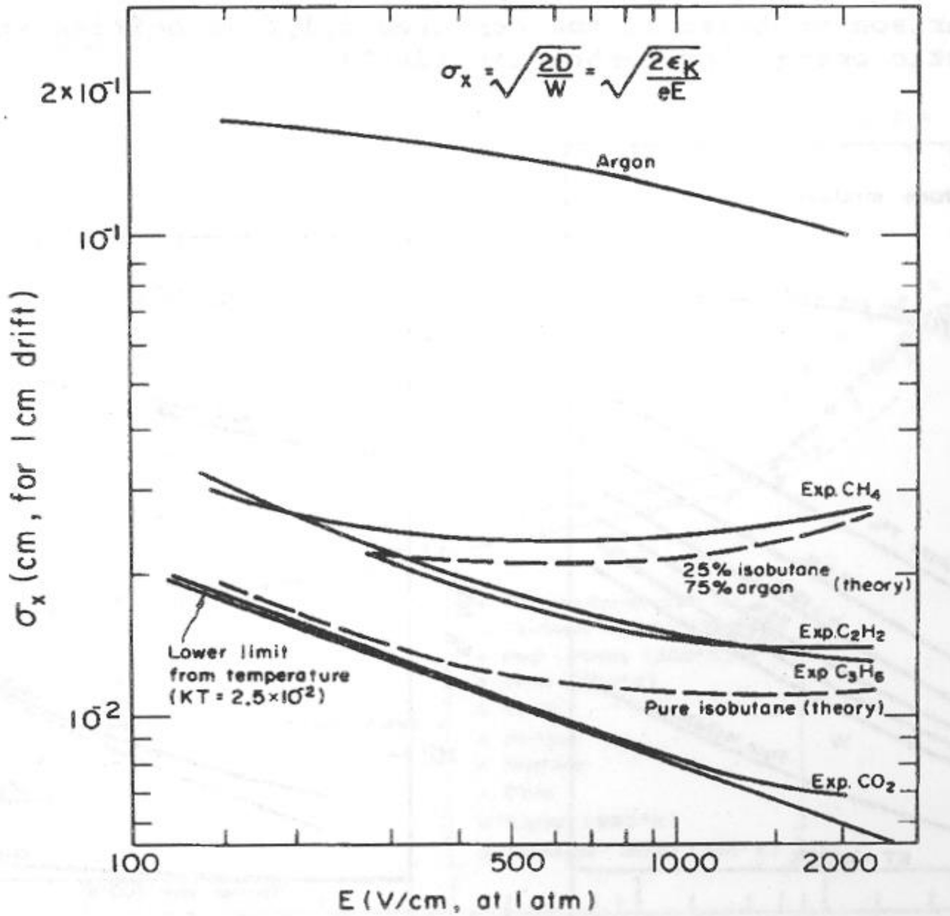
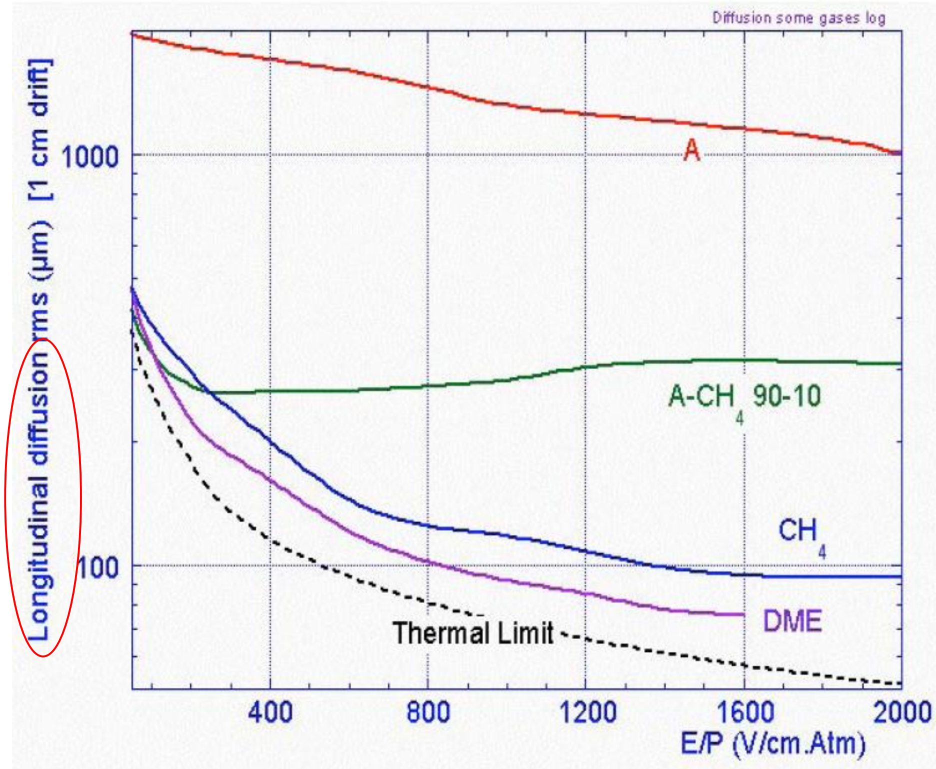


Fig. 35 Computed and experimental dependence of the standard deviation of electron diffusion from the electric field for 1 cm drift, in several gases at normal conditions[25]



<u>Order of magnitude of *transverse* diffusion:</u>

drift over 1cm $\Rightarrow \sigma \approx$ 0.1 to 0.01 cm

so:

drift over de 1m $\Rightarrow \sigma \approx$ 1 to 10 cm

Mean position value stays identical but signal is smeared.

Diffusion and drift

when we have together a E and B fields

Longitudinal diffusion (in B field direction) doesn't change

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

<u>But</u> in transverse plane, electrons are spinning -following- "around" B field line

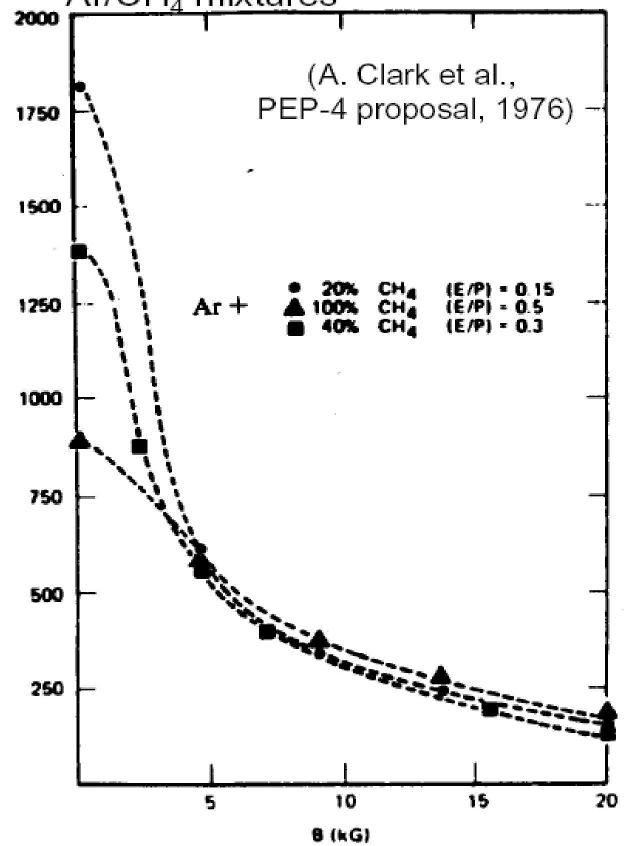
=> diffusion coefficient is:

$$D_T(B) = \frac{D_0}{1+\omega^2\tau^2}$$

$$\sigma \propto \sqrt{D}$$

with $\omega = eB/m$ cyclotron frequency

Transverse diffusion σ (μm) for a drift of 15 cm in different Ar/CH_4 mixtures



(this phenomena is used in **TPC** -Time Projection Chamber-)

Diffusion and drift

Lorentz angle effect may be different depending of the geometry of the detector: field, anode wire, e- arrival direction…

when we have (a *E* and) *B* fields

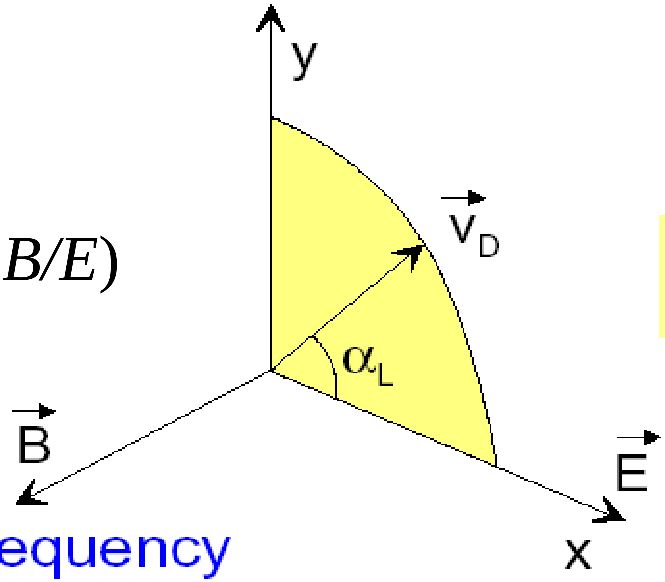
=> *Lorentz* angle between *E* and drift velocity of e-

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

$$\tan \alpha_L = \omega\tau = v_{drift\text{-}e\text{-}} \cdot (B/E)$$

α_L: Lorentz angle

$$\omega = \frac{e\vec{B}}{m}$$ cyclotron frequency



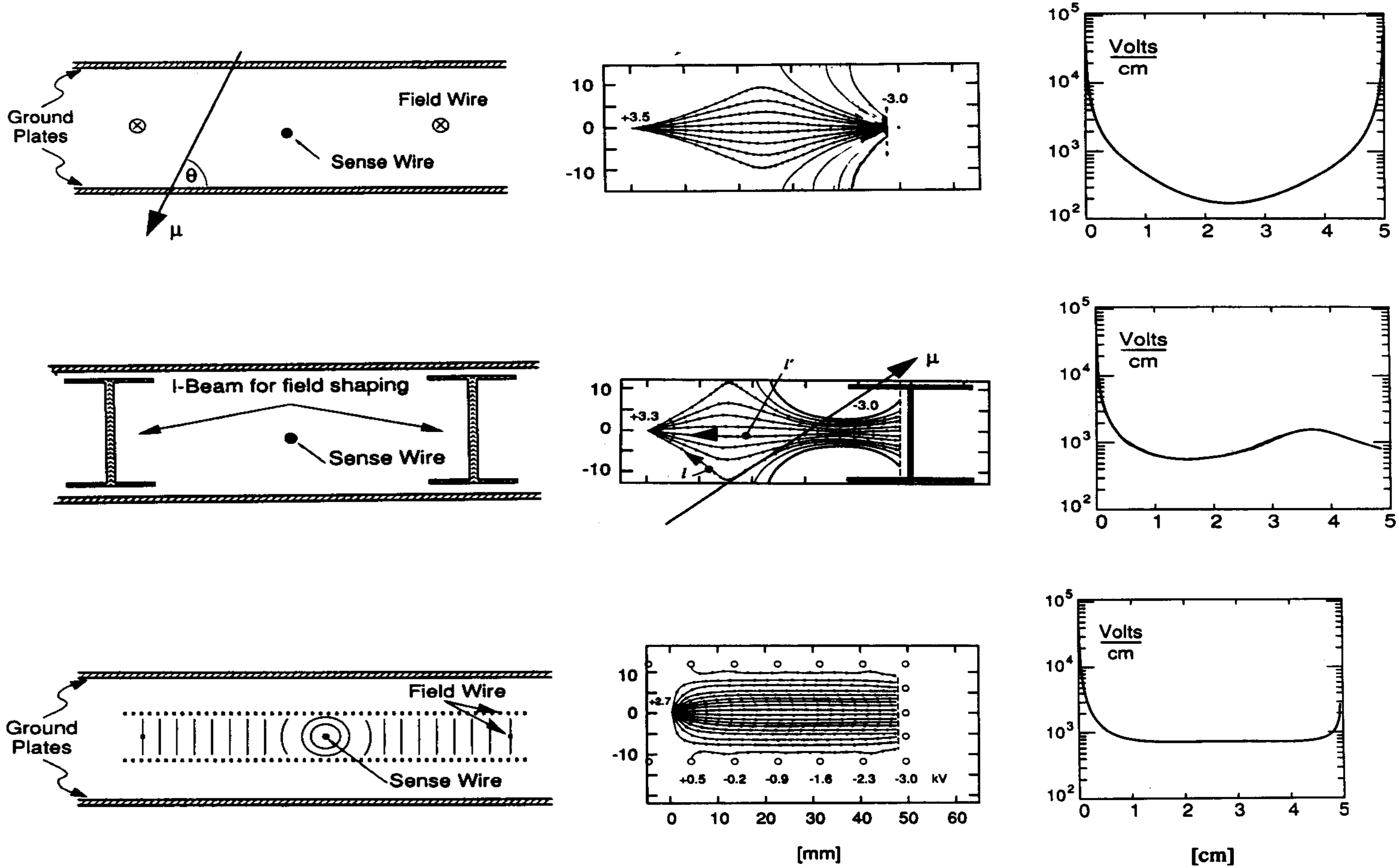
$$\vec{v}_D \not\parallel \vec{E}$$

Typical angle ~30 degrees for *B*=1Tesla and *E*=0.5kV/cm in Ar:C_4H_{10}:methylal (67:30:3)
Increase each electron trajectory length => Δt to be measure

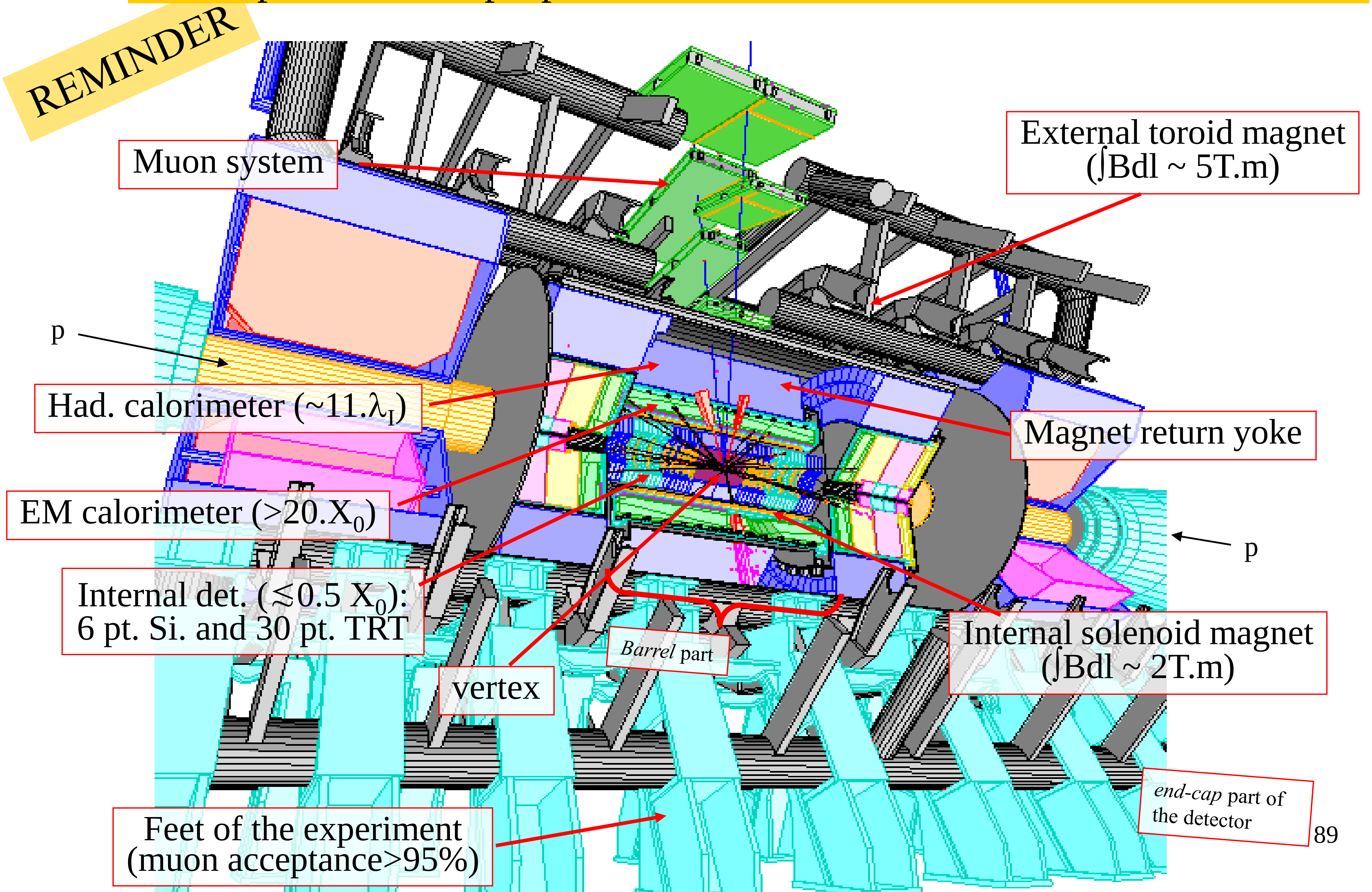
Example for Atlas drift chambers: up to 20ns over ~700ns in total (Ar:CO_2 : 93:7, 3 bars)

As the gas is "faster" α_L increases (collisions -diffusion- are limiting this effect)

Drift chambers: different geometries

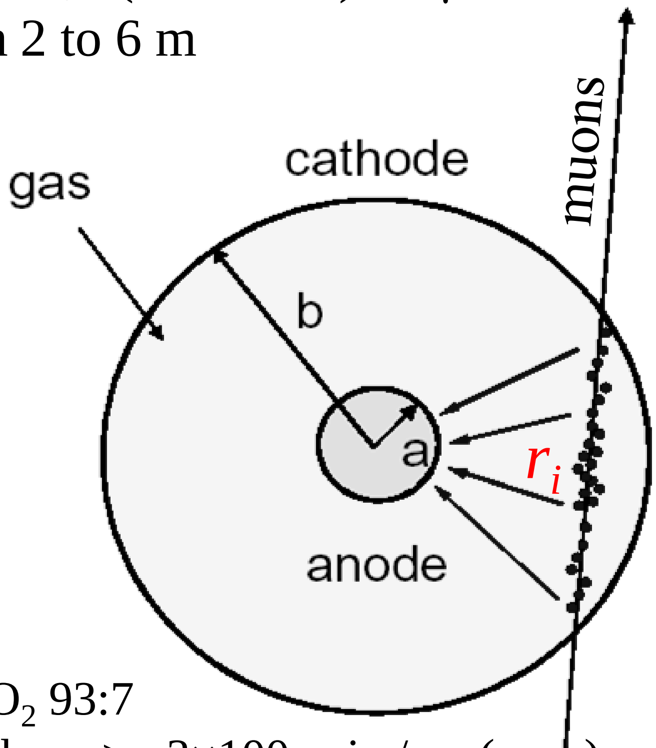


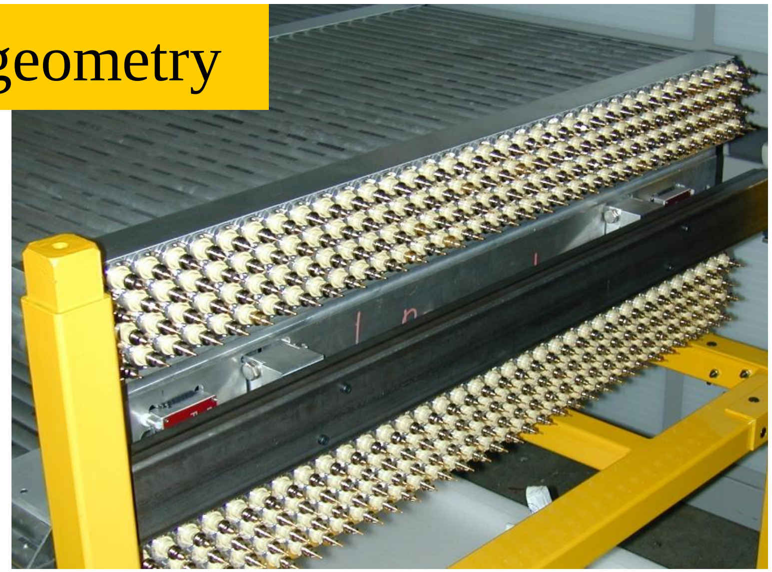
Example of a multipurpose detector on a collider: ATLAS at the LHC

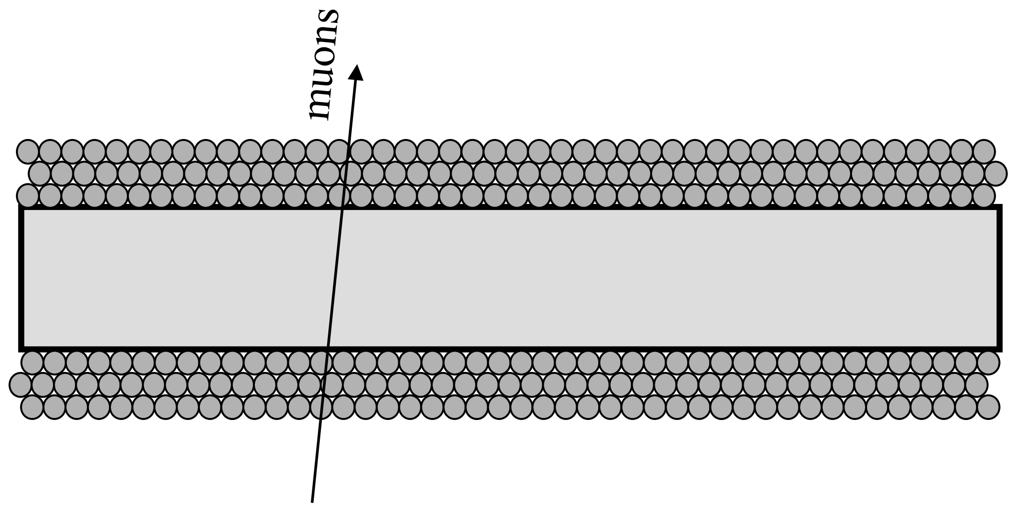


Drift chambers : ATLAS geometry

b=15 mm, a(anode=fil)=50μm
L from 2 to 6 m



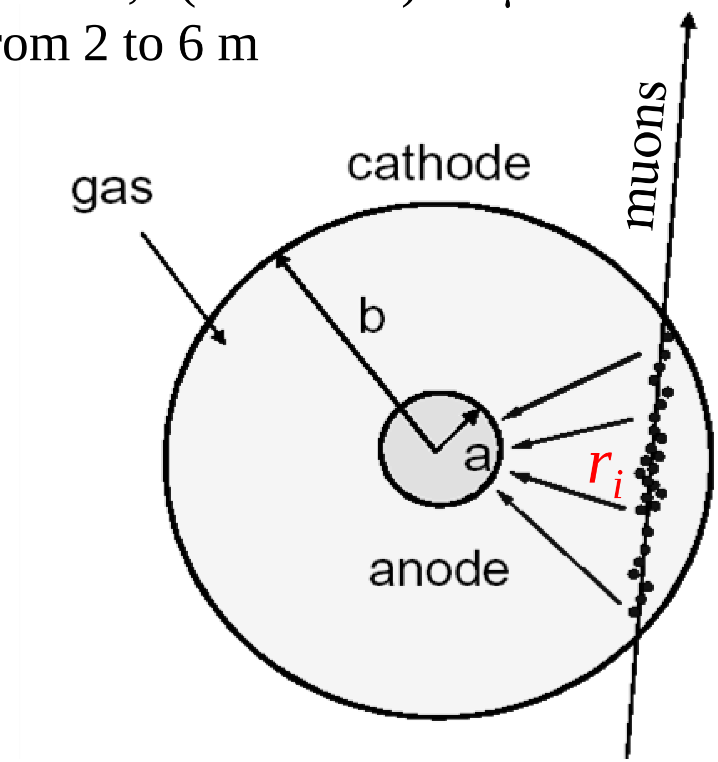




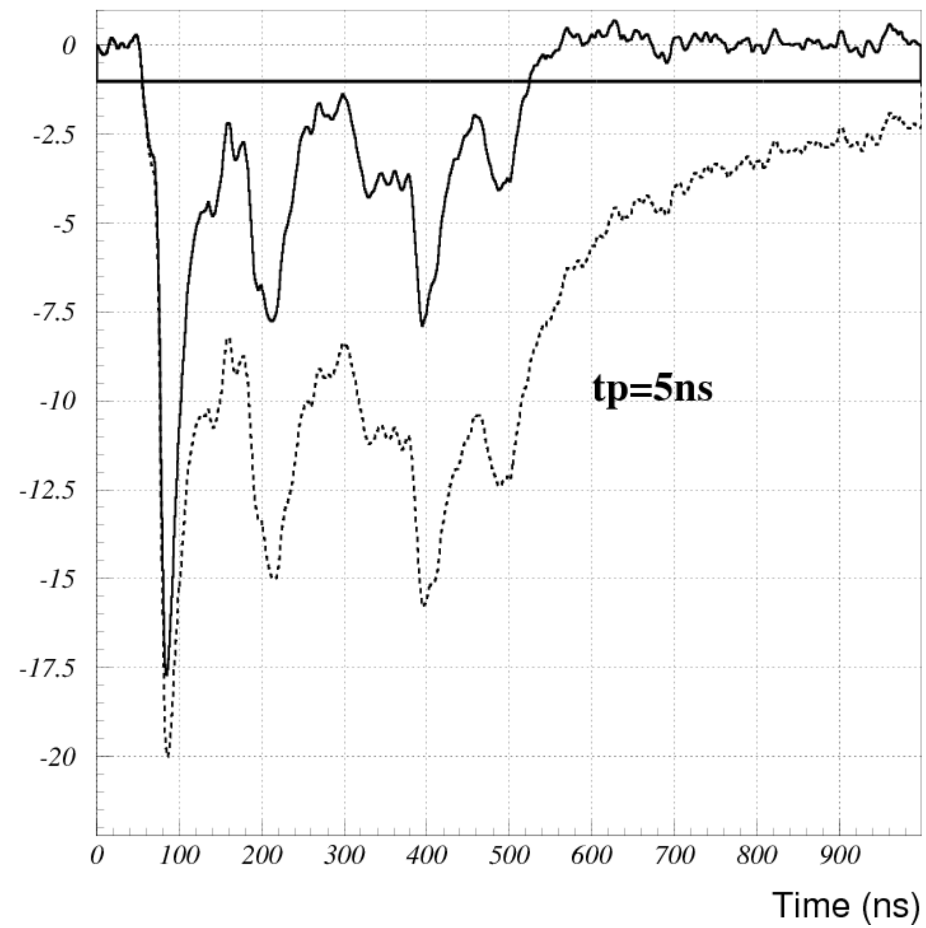
Ar:CO_2 93:7
p = 3 bar => ~3×100 pairs/cm (n_{Total})
V ~ 3000V (2.10^5 V/cm)
Gain: 2.10^4
Max drift time of e- : 700ns, i.e. “slow” good for *Lorentz* angle limitation
v~3cm/μs (=30μm/ns)
Centring of wire < 100μm all along the tube (20μm at the end-plug)
Threshold at the ~25th e-
σ ~ 80 μm / tube => combining tubes of one chamber gives ~50μm locally

Drift chambers : ATLAS geometry

b=15 mm, a(anode=fil)=50µm
L from 2 to 6 m

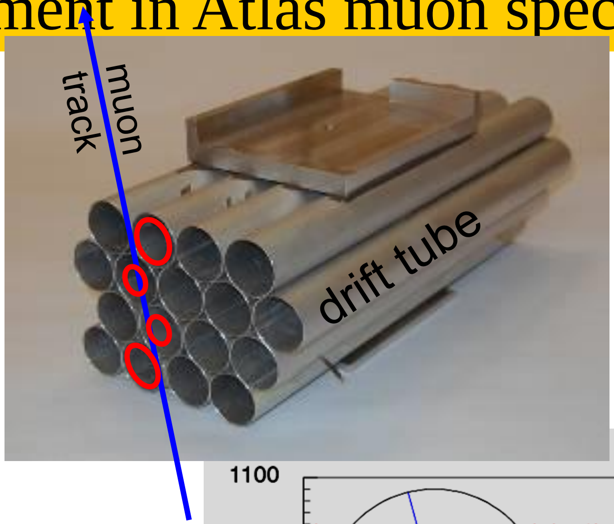


dE/dx(µ) = 14 keV
i.e. several e- clusters

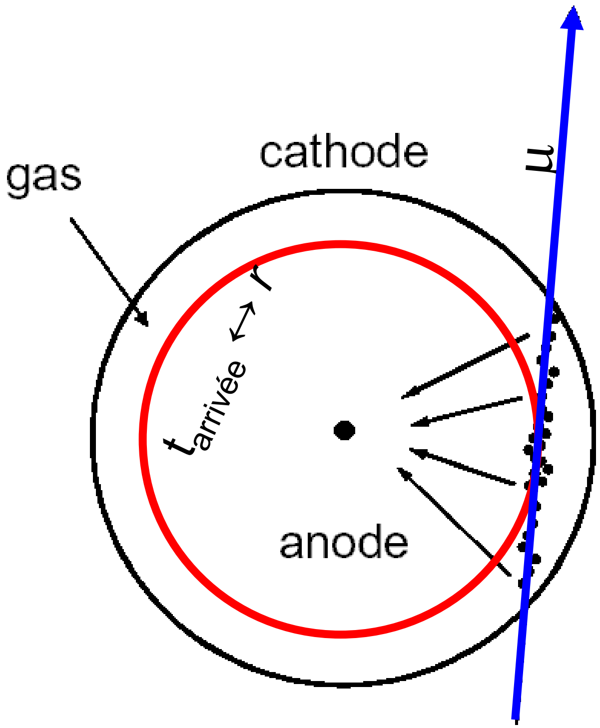


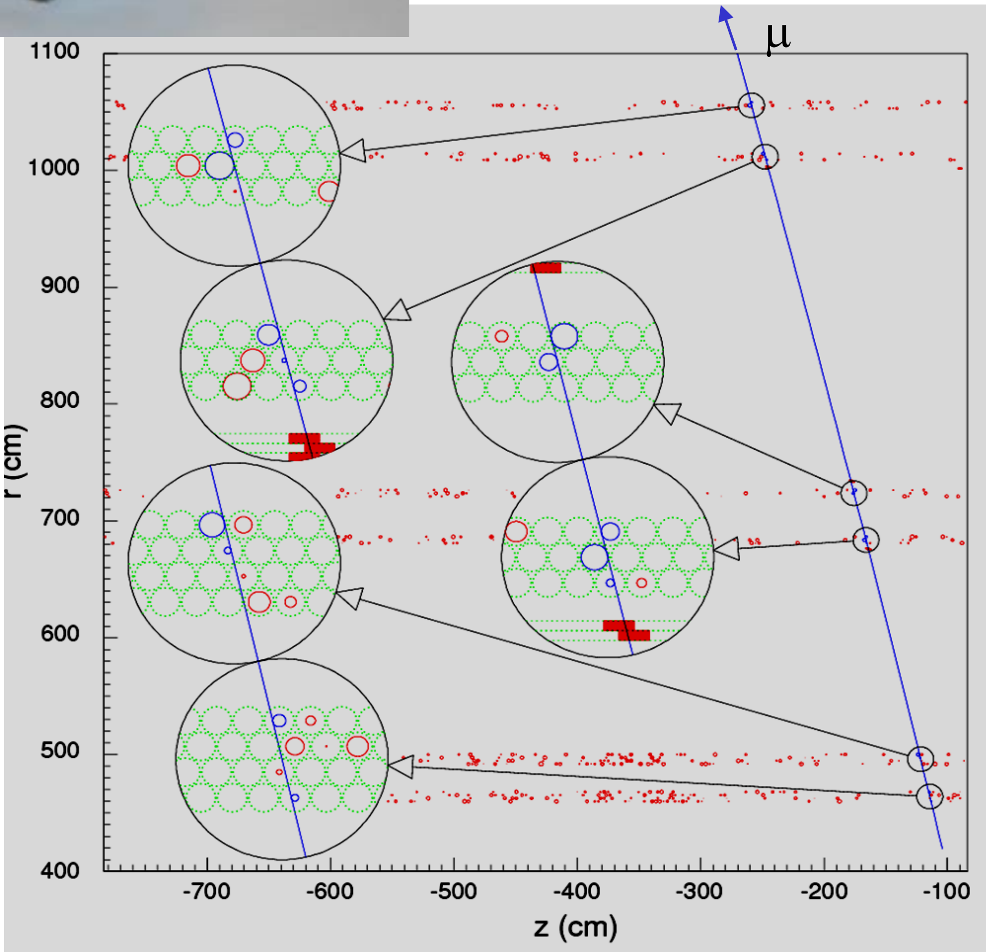
Arrival time fluctuation of each e- cluster on the anode wire

Sag measurement in Atlas muon spectrometer



MDT are sensitive to Lorentz angle (in *B field)*, up to 20ns delay over 680ns (not for CSC chambers).

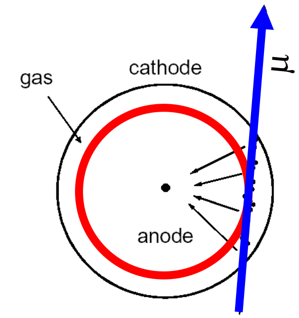


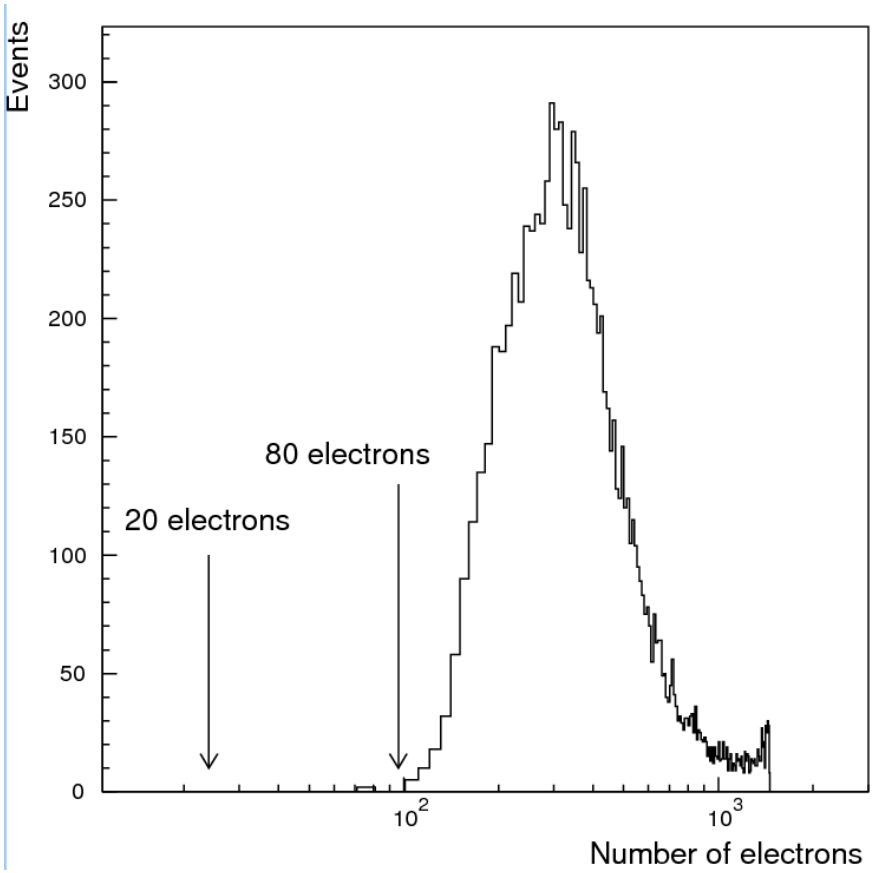


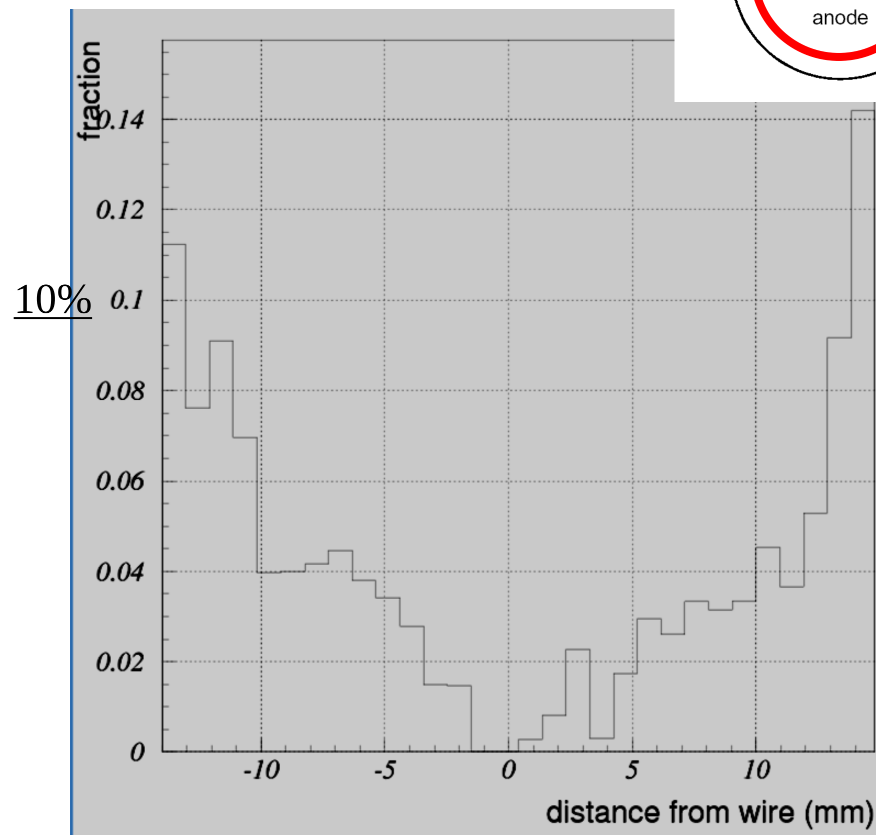
σ~ 80 μm/tube, and combining them by 2×3 or 2×4 tubes within a chamber: **<u>σ ~ 60 μm locally</u>**

Also an <u>angular measurement</u> (vector) ~200 μrad.
ε(tube)~95% (half from tube wall, half track centred w.r.t. wire)

Drift chambers : ATLAS geometry







Mean # of e- from ionisation (<> ~ 400)

Inefficiency = f(radius)

close to tube walls, because of δ-ray!

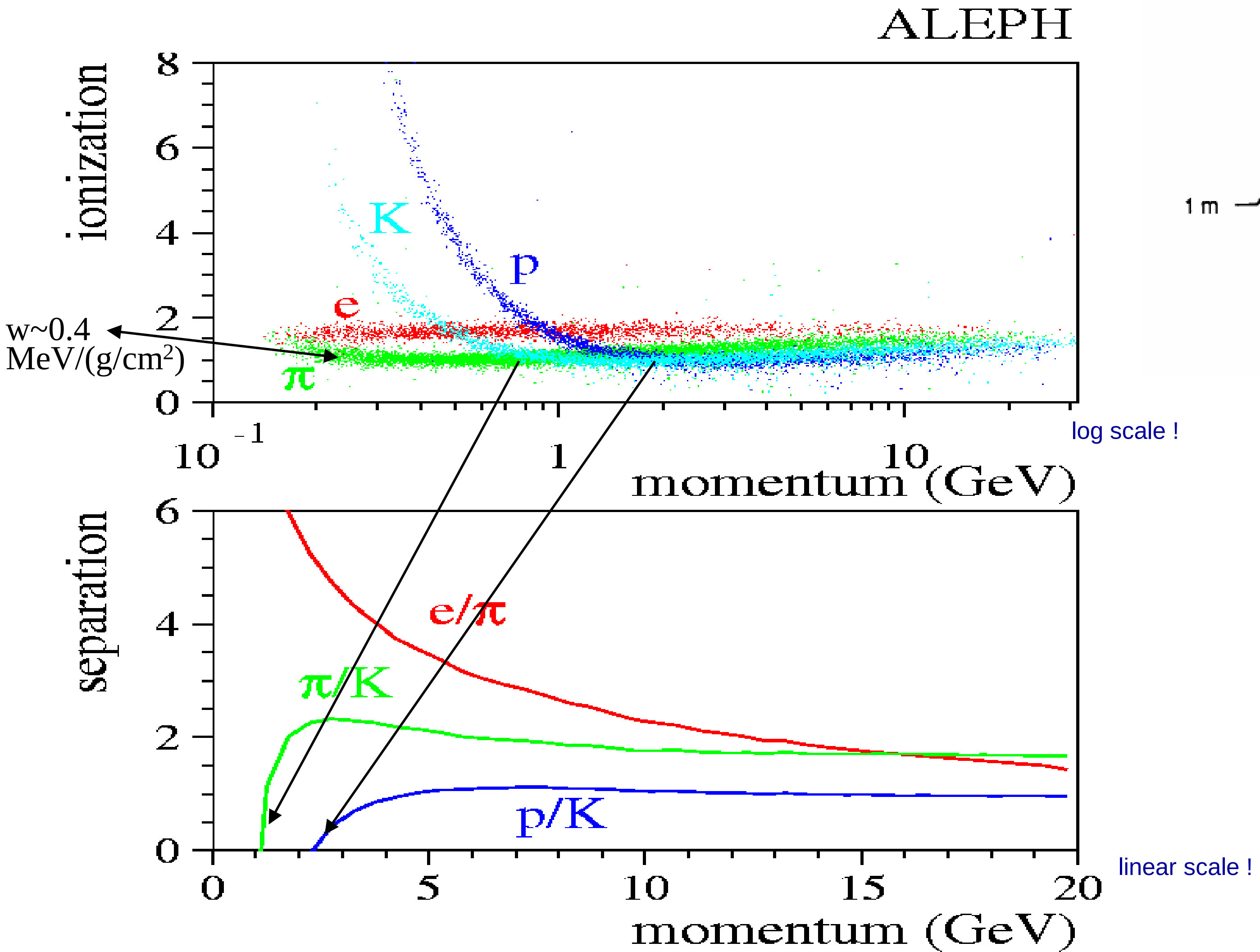
Remark: bad resolution for tracks centred on the wire

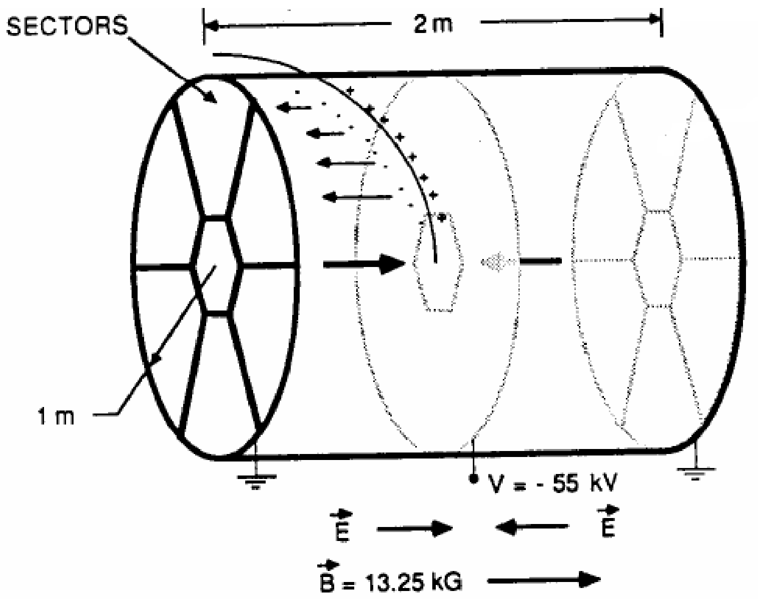
TPC: example of dE/dx measurement

Example: **Aleph TPC (gas: Ar/CH_4 90/10)**

$N_{samples}$: 338, wire spacing 4 mm

dE/dx resolution: 5% for m.i.p.





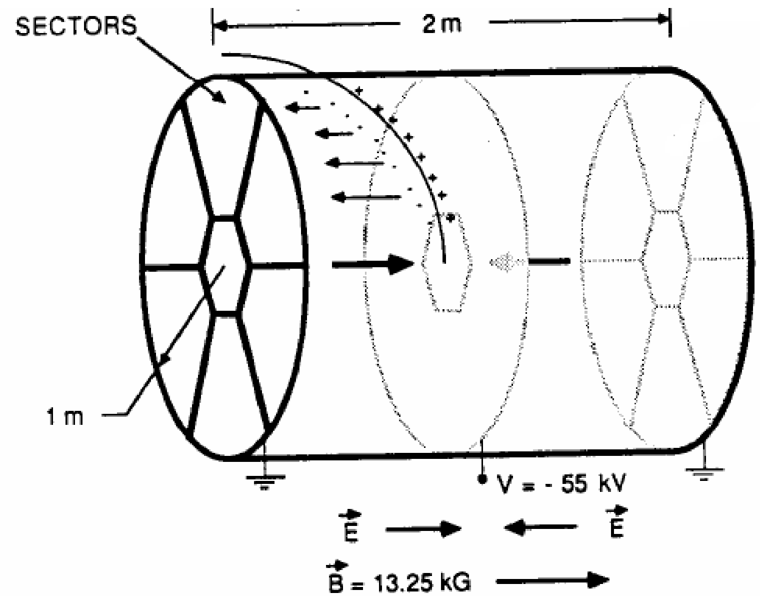
Each track gives ~338 measurements for a given particle seen in the detector (Time Projection Chamber –TPC–).

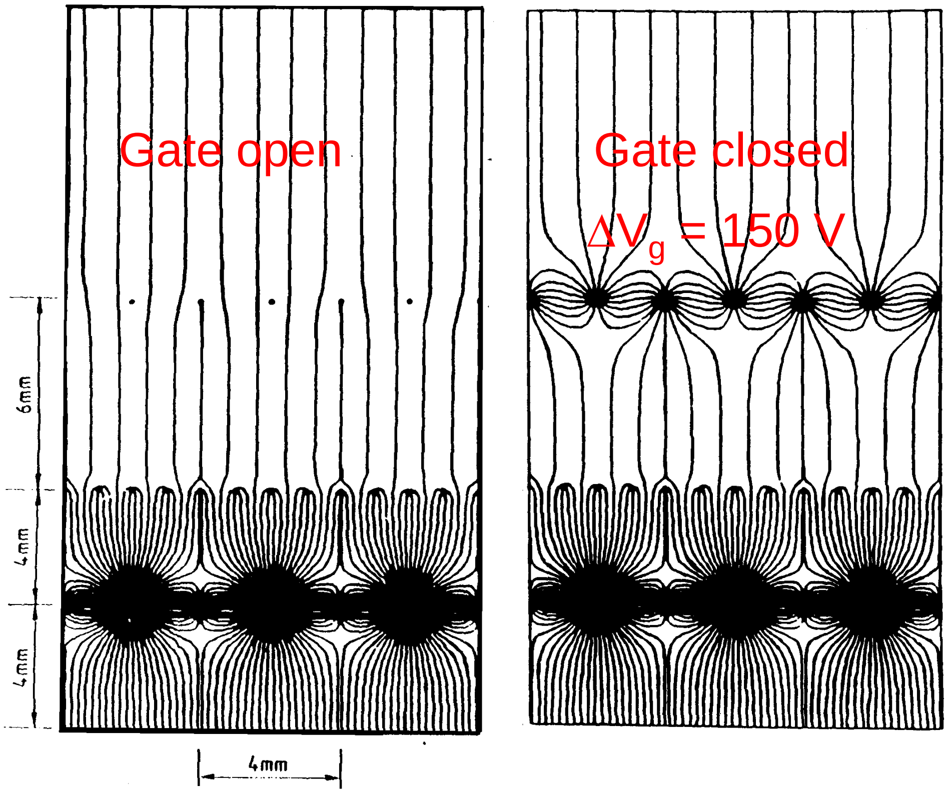
Limiting factor comes from fluctuation "*Landau* tails".

TPC: example of dE/dx measurement

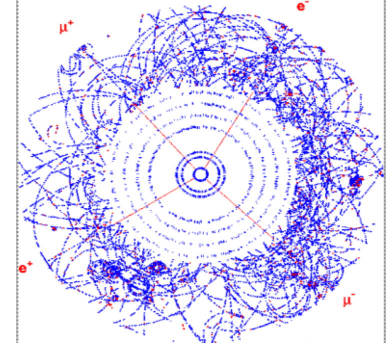
Slow detector: ~100μs

<u>Space charge problem:</u> between two "collisions" (bunch) one activates an intermediate grid (at a given potential) in order to avoid ions to drift back to the drift space.





How does *straw* tubes work?



Example an LHC experiment:

>350 000 straws of Ø=4mm, L_{max}=150cm

Particle flux: 200 kHz/cm => occupancy ~ 25%

Gas with 3 components: 70%Xe+20%CF_4+10%CO_2 (±2%)

Xe for a good X-ray absorption ($\propto Z^{\sim 3}$; Z=54)

CF_4 fast gas (+ plastic foils for trans. radiation)

CO_2 as a *quencher* (auto-limited *streamer* mode, i.e. close to)

End 2003: new gas! Aging problem of connexions… 70%Xe+27%CO_2+3%O_2

$dE/dx_{m.i.p.}$ ~ 2 keV

Lorentz angle ~ 30° ($B_{solenoide}$=2T)

Wire diameter 30µm (gain limitation to 4.10^4)

streamer fraction ~ 7 ‰ (if 5% more of Xe => *streamer* event fraction ~ 2%)

Temperature variation < 10 deg. ($\Delta g/g$<2%)

Wire centring ≲ 200µm

Anode HV: 1570 ± 30 V (if higher *streamer* ↗)

Maximum collection time ~40ns

Threshold for drift time measurement at 200 eV (i.e. 8000 e-) : σ~150µm ↔ 8ns

Threshold of soft X-ray detection: 6.5 keV.

For ε_e=90% we get 8% of π => rejection > 10

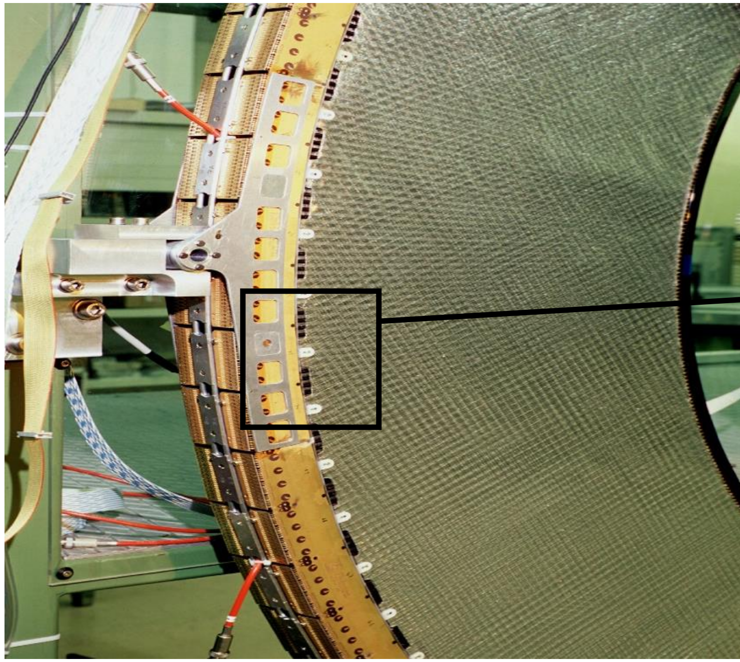
etc, etc…

Heat produced ~400W. Cooling using CO_2. Temp. <50° on electronics

REMINDER

Transition Radiation Detector

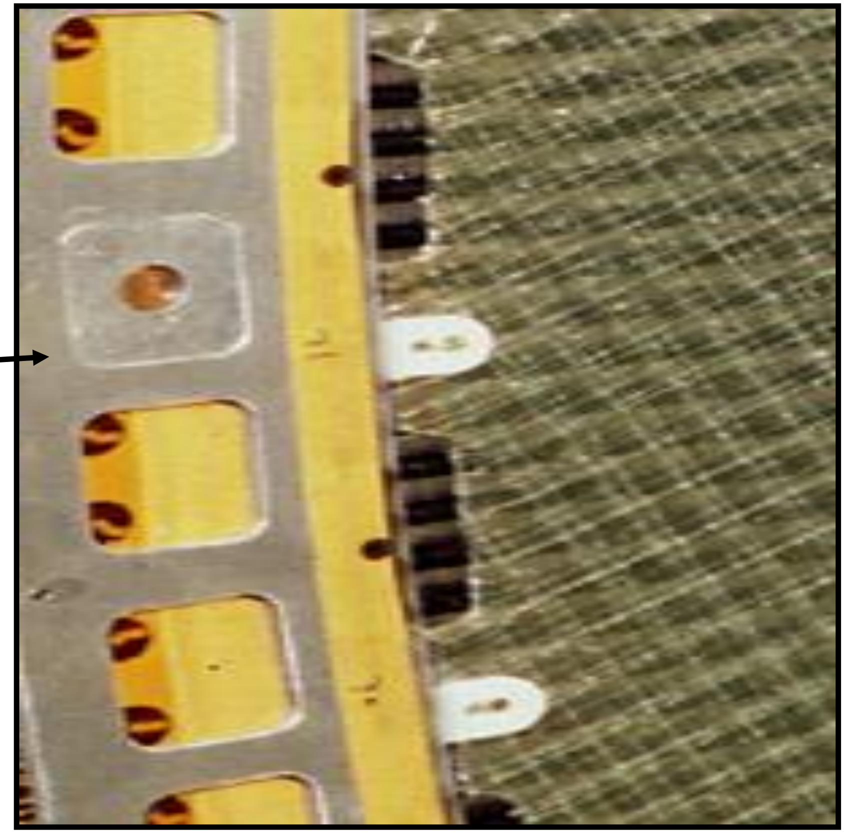
<u>Discriminating e/π</u>



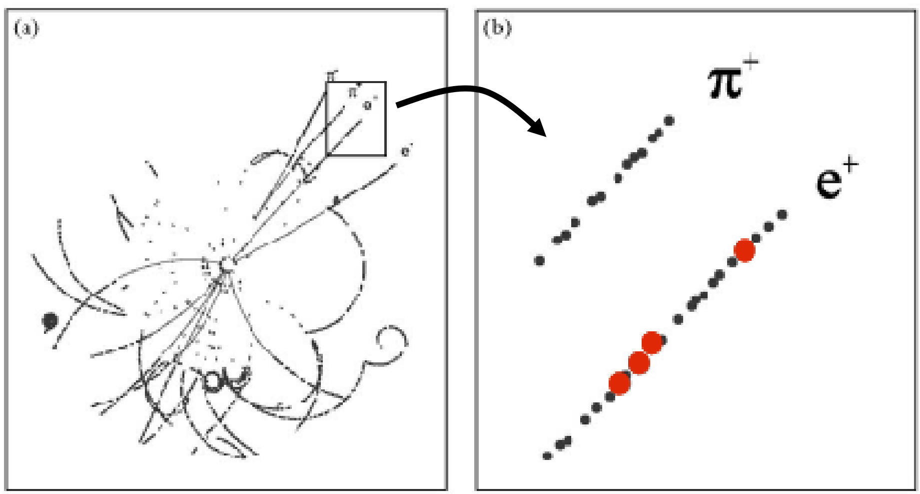
$\theta \sim 1/\gamma$ so ~ μ-radian for e of about 10 GeV.

Also $N\gamma \sim 0,5\%\ Z^2$ For each "radiator".

Soft X-ray emission associated of few keV.

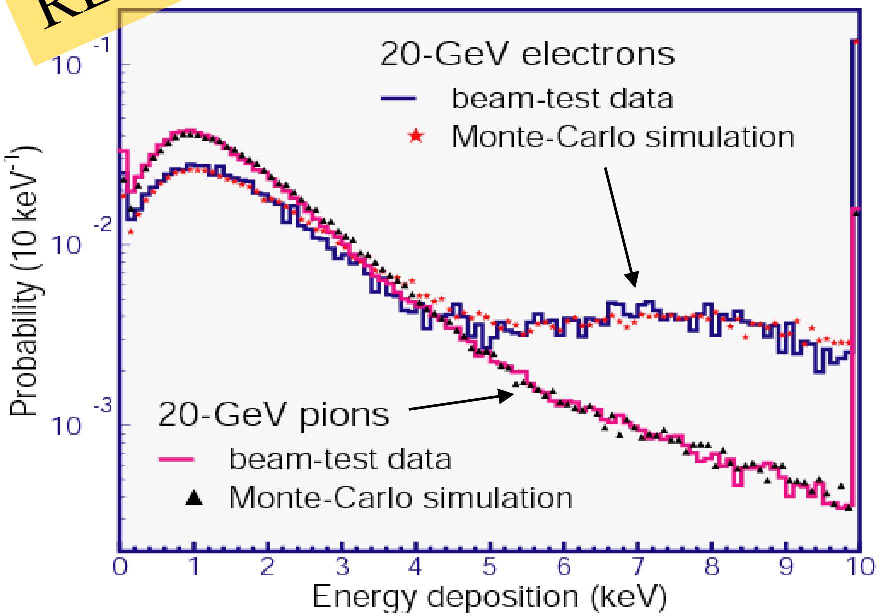


Assembly of plastic foils (reinforced) and *straws* of 5mm diameter

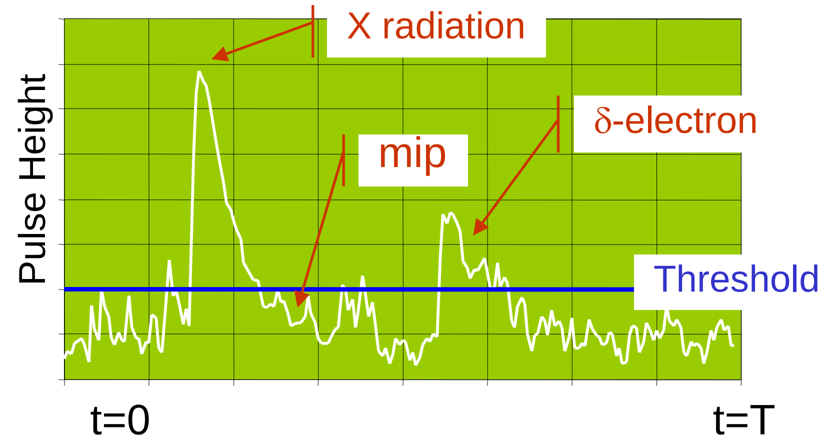


REMINDER

Discriminating π / e thanks to Transition Radiation

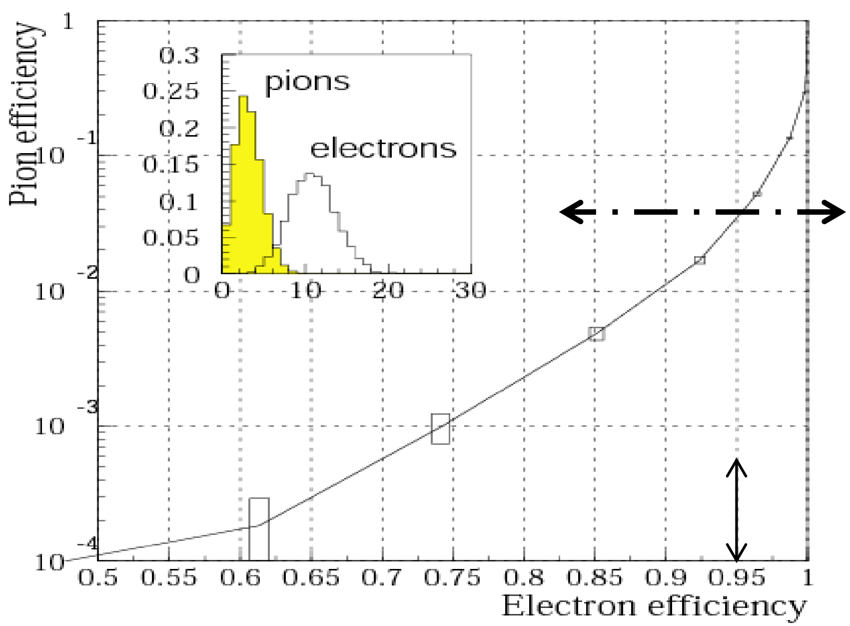


Without plastic foils energy loss is almost the same for π or electrons.



X-ray absorbed in ~1mm (if Argon gas)

M.L. Cerry et al.
Phys. Rev. 10(1974)3594



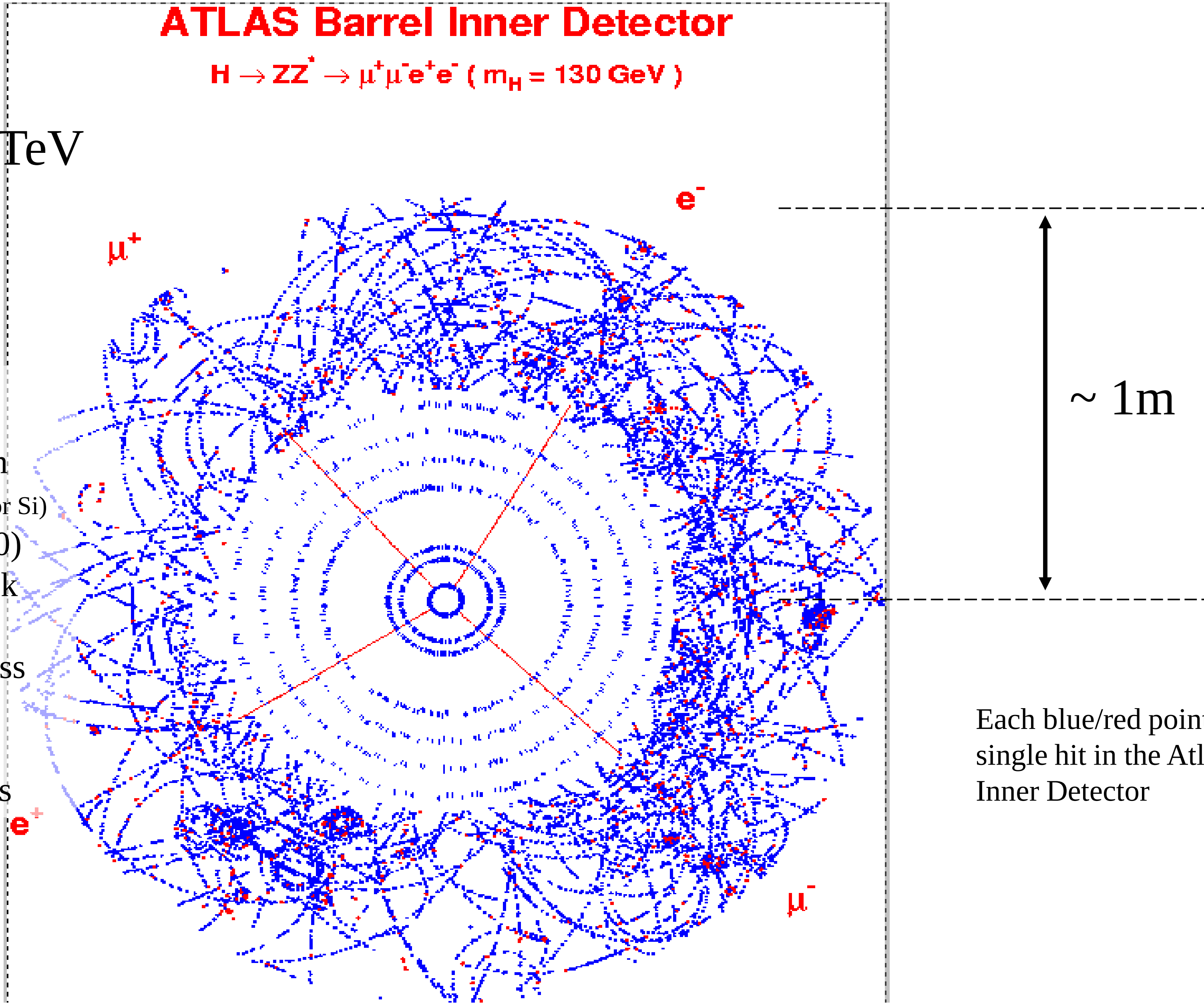
ATL-CONF-2003-012

Asking to keep 95% of e- (the wanted signal) we get ~4% de π in the final sample.

REMINDER

Simulation of $H^0 \rightarrow Z Z^* \rightarrow e^+ e^- \mu^+ \mu^-$ in ATLAS

$E_{\text{Center of mass}}$=14 TeV



We observe that:

- lot of track (~2000), high occupancy (for straw but not for Si)
- curved tracks (B field ≠ 0)
- e+/-, μ+/- ~ straight track
- lot of hit on first 3 inner layers and then less and less
- lot of aligned hit at large radius
- red hits (?) at large radius

Each blue/red point is a single hit in the Atlas Inner Detector

Conclusions

We have seen:

• Signal formation and detection (including fluctuations)

• Velocity(electrons) ~100 to ~1000× velocity(ions). Drift time of electrons is ~5 cm/μs

• Working condition of a ionisation chamber goes from *proportionnel* mode, then *streamer* mode, then *Geiger-Muller* mode (when increasing HV)

• *quencher* gas is used to avoid sparks (risk of deterioration for some detectors)

•…/… other effects …/…

• We (you!) have understood how work the following gaseous detector:

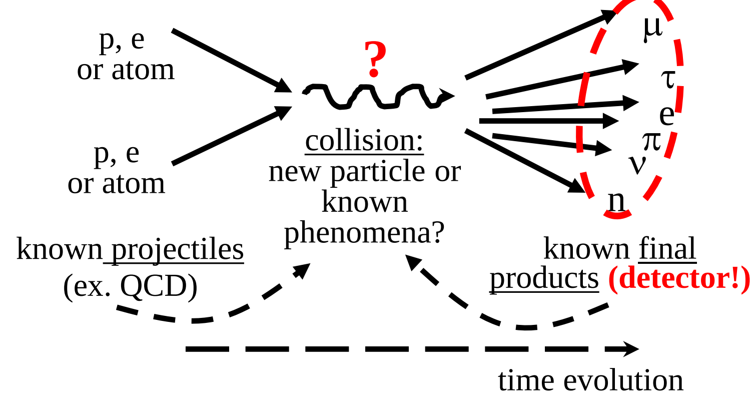
MWPC, drift chambers, RPC, MicroMegas (i.e. new detectors MPGD), …

• We are able to understand (!!!) :

TPC (e.g. DELPHI/ALEPH),
central tracker (e.g. ATLAS/CMS or others!)
muon system

etc, etc…

Lecture #4



Moral #1:

Discuss with specialists (physicists **and** engineers **and** technicians) in order to understand a detector, and **before** starting a new one!!

Moral #2:

An experiment could be built only with an **experienced team** (with know-how). Otherwise one may "re-invent the wheel"…

Moral #3:

There is no unique universal detector (unfortunately).
One need to **test** the detector (also simulate it) **in real conditions** in order to understand/optimize the working conditions (prototype).

etc…

REMIND

Signal collection: typical characteristics for different detectors

Table 28.1: Typical spatial and temporal resolutions of common detectors. Revised September 2003 by R. Kadel (LBNL).

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	< 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim$ 10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	[h]	[h]
Silicon pixel	2 μm[i]	[h]	[h]

[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give ±150 μm parallel to anode wire.
[d] wirespacing/$\sqrt{12}$.
[e] For two chambers.
[f] n = index of refraction.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$ 25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [9]. (Time resolution of $\leq$ 25 ns is planned for the ATLAS SCT.)
[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

From PDG.

Remark: Time collection of signal is related to drift time of charged carriers (deposit energy is almost instantaneous: ps in liquid/ solid, ns in gas).

Choice of electronics also determine total collection time of signal.

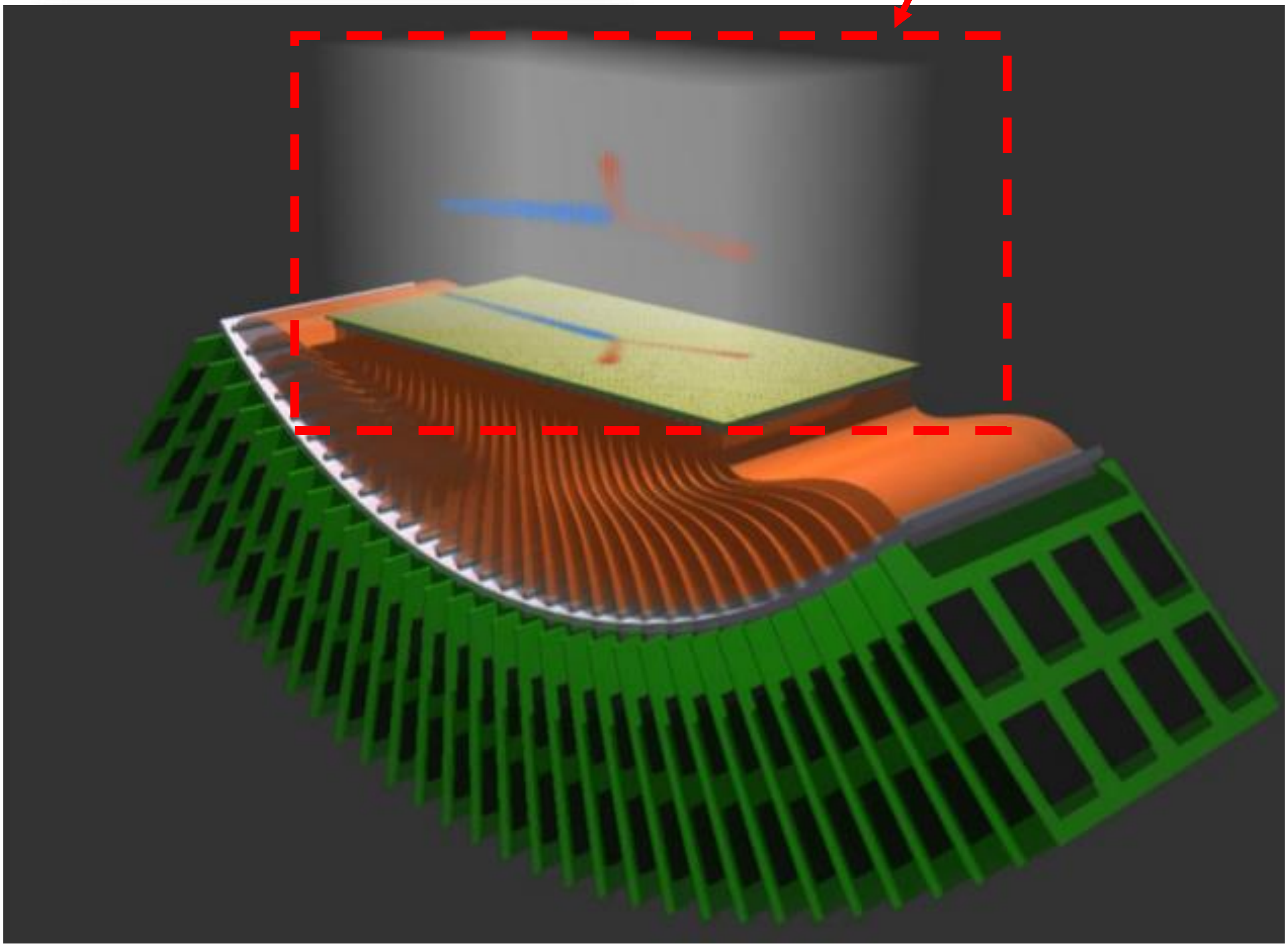
Veresatile detection volume.
Choice of gas depend of nuclear
that you want to detect.

ACTAR TPC

a versatile instrument for nuclear physics

J. Giovinazzo - CENBG
and the ACTAR TPC collaboration

- **what is ACTAR TPC**
- **General design**
- **Characterization**
- **Status**



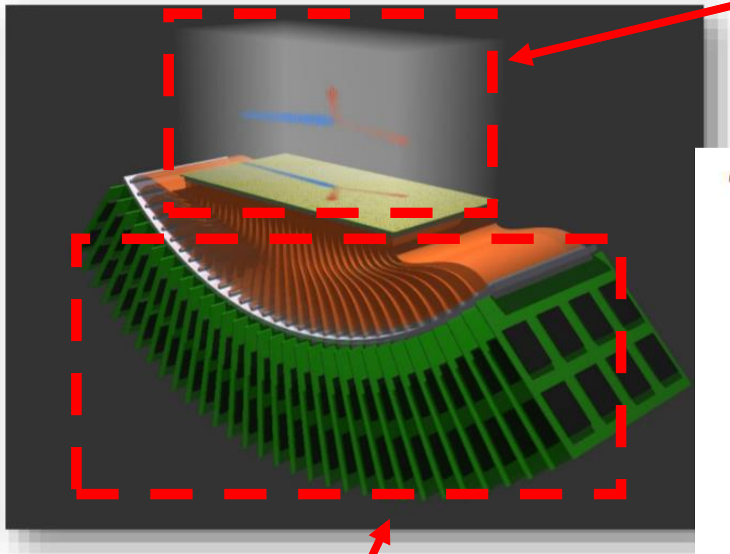
ACTAR TPC

a versatile instrument for nuclear physics

J. Giovinazzo - CENBG
and the ACTAR TPC collaboration

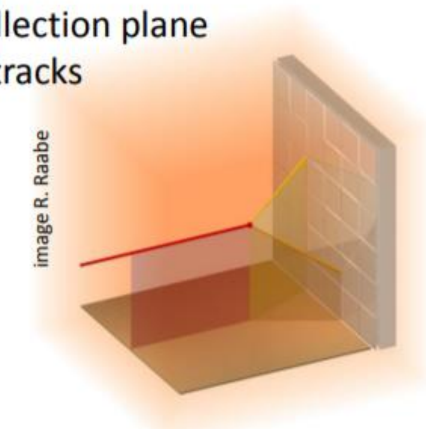
Veresatile detection volume.
Choice of gas depend of nuclear
that you want to detect.

- ▷ **what is ACTAR TPC**
- ▷ **General design**
- ▷ **Characterization**
- ▷ **Status**



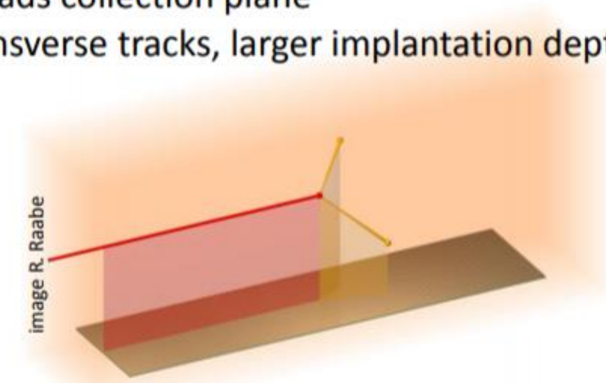
"reaction" chamber

128x128 pads collection plane
large transverse tracks



"decay" chamber

256x64 pads collection plane
short transverse tracks, larger implantation depth

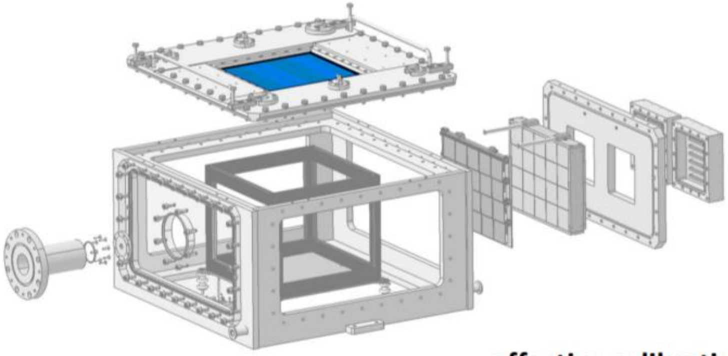


Elongated gas detection volum with 2 readout area (read from below)

TPC mode (i.e. elx with timing information)

ACTAR TPC design: amplification

detector scan with collimated X-ray source (^{55}Fe)

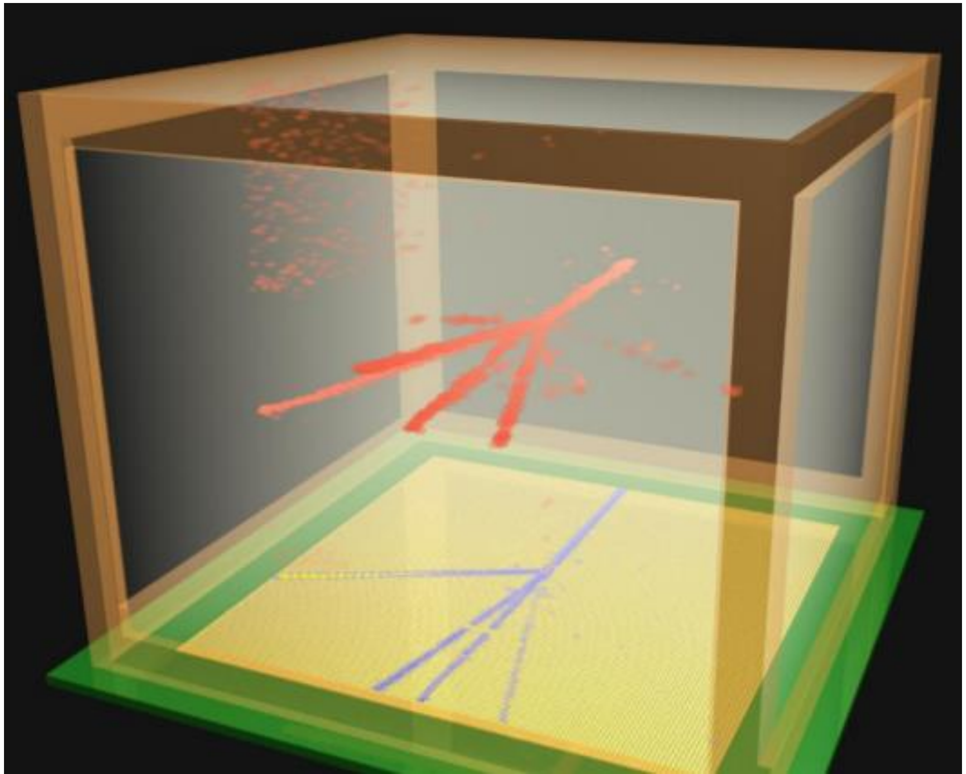


effective calibration

- scan
- electronics chains gain matching

effective calibration

- scan
- electronics chains gain matching



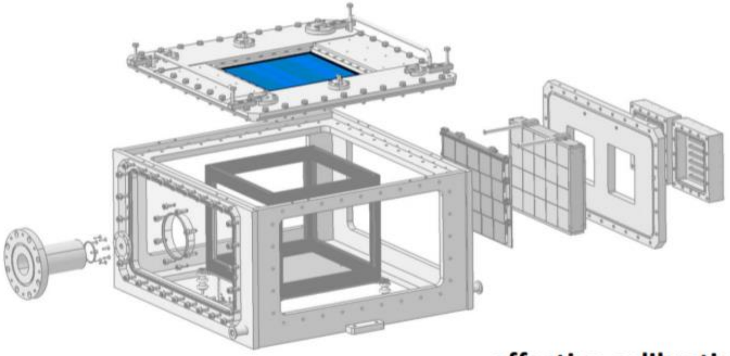
Detector caracterization :
i.e. which gain (relatively or better absolutely)

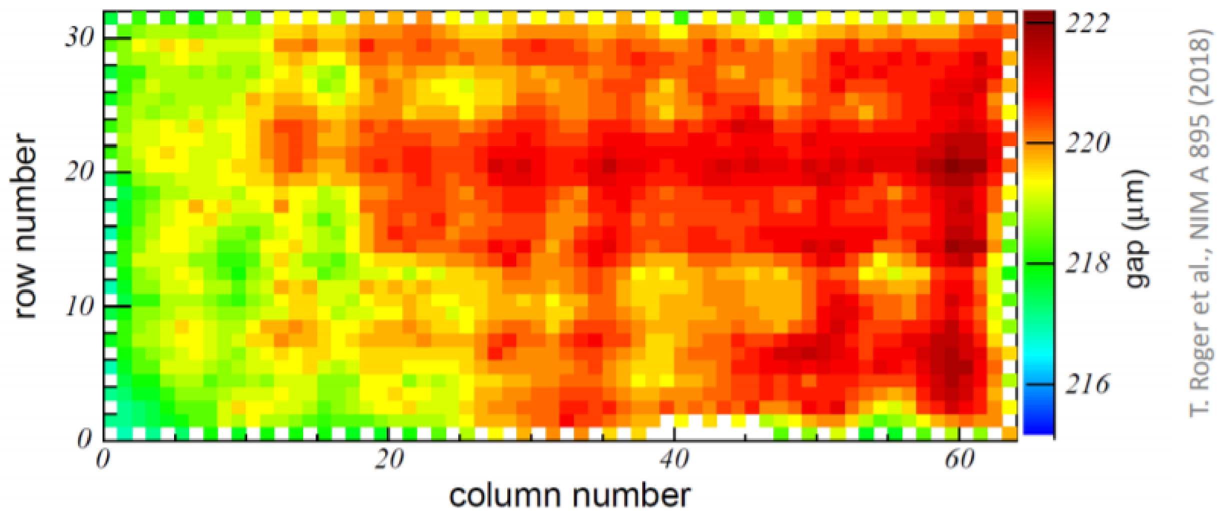
How to do that ?

ACTAR TPC design: amplification

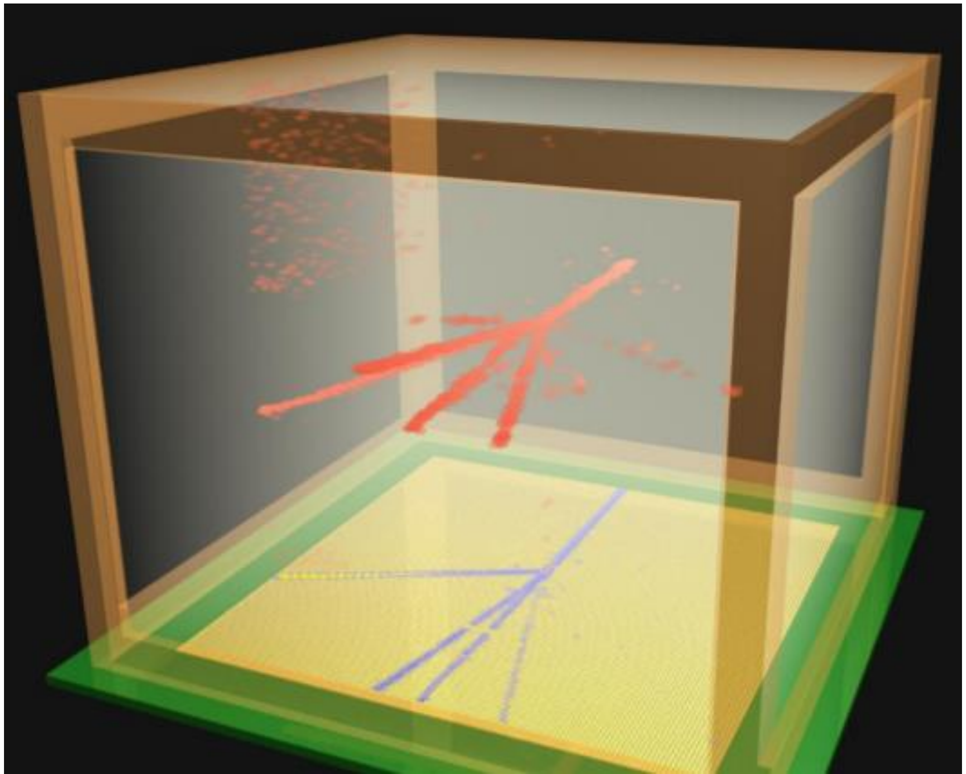
GANIL scanning tabl

detector scan with collimated X-ray source (^{55}Fe)





effective calibration
- **scan**
- **electronics chains matching**



Detector caracterization :
i.e. which gain (relatively or better absolutely)

How to do that ?