

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

Julien Bolmont
LPNHE, IN2P3 and Sorbonne University
bolmont@lpnhe.in2p3.fr

Alessandra Tonazzo
APC, IN2P3 and Paris Sciences Lettre University (PSL)
tonazzo@in2p3.fr

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

Lectures and evaluation

- Lecture #1 (Ph.S.) : **Thursday 03/09 afternoon**
Working aspects of a complex detector
- Lecture #2 (J.B.) : **Tuesday 08/09 afternoon**
Interaction of particle with matter (part #1)
- Lecture #3 (J.B.) : **Tuesday 15/09 afternoon**
Scintillateurs, PM and applications in astro gamma (1)
- Lecture #4 (J.B.) : **Tuesday 22/09 afternoon**
Scintillateurs, PM and applications in astro gamma (2)
- Lecture #5 (Ph.S.) : **Tuesday 29/09 afternoon**
Gaseous detectors
- Lecture #6 (Ph.S.) : **Tuesday 06/10 afternoon**
Gaseous detectors (con't), calorimeters, magnets, trigger
- Lecture #7 (A.T.) : **Tuesday 13/10 afternoon**
Si/Ge, Cerenkov detectors, HPD, RICH, neutrinos detectors, DUNE, LAr, Bolometres
- Lecture #8 (A.T.) : **Tuesday 20/10 afternoon**
Si/Ge, Cerenkov detectors, HPD, RICH, neutrinos detectors, DUNE, LAr, Bolomètres
- Lecture #9 (A.T.) : **Tuesday 10/11 afternoon**
Si/Ge, Cerenkov detectors, HPD, RICH, neutrinos detectors, DUNE, LAr, Bolomètres

Remember to look at the place + room !

After these lectures : writing test + oral exam.
Evaluation will be discussed/presented later in September.

Bibliography

→ Particle Data Group (tables, figures, etc...)
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 et 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). In particular, part from F.Sauli & G.Charpak.
- Konrad Kleinknecht, Detectors for particle radiation (Cambridge Univ. Press, 1986)
- • W.R. Leo, Techniques for Nuclear and Particle Physics Experiments (Springer, 1994)
- Peter Rice-Evans, Spark, streamer, proportional and drift chambers (Richelieu Press, 1974)
- Review of Particle Physics (European Physical Journal, 2000)
- • Periodic publication of Nuclear Instruments and Methods
- ATLAS TDR(1999 to 2003), ATLAS internal notes (<http://www.cern.ch>)
- Lectures from: J.Chauveau, M.-H.Schune et A.Stocchi, Ph.Schwemling, Th.Patzak,
- • Ch.Joram, O.Ullaland... **and many discussion with colleagues!!**
- • Bruno Rossi, High energy particles (Prentice-Hall, 1952)

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

Quencher / 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

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), **$(\nu), \alpha$** ($=He^{2+}$), **$\beta^{+/-}$** ($=e^{+/-}$)

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 loses $\sim 2 \text{ MeV}/(\text{g}/\text{cm}^2)$

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

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

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

Compton diffusion: $10 \text{ keV} \lesssim E_\gamma \lesssim 10 \text{ MeV}$

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

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

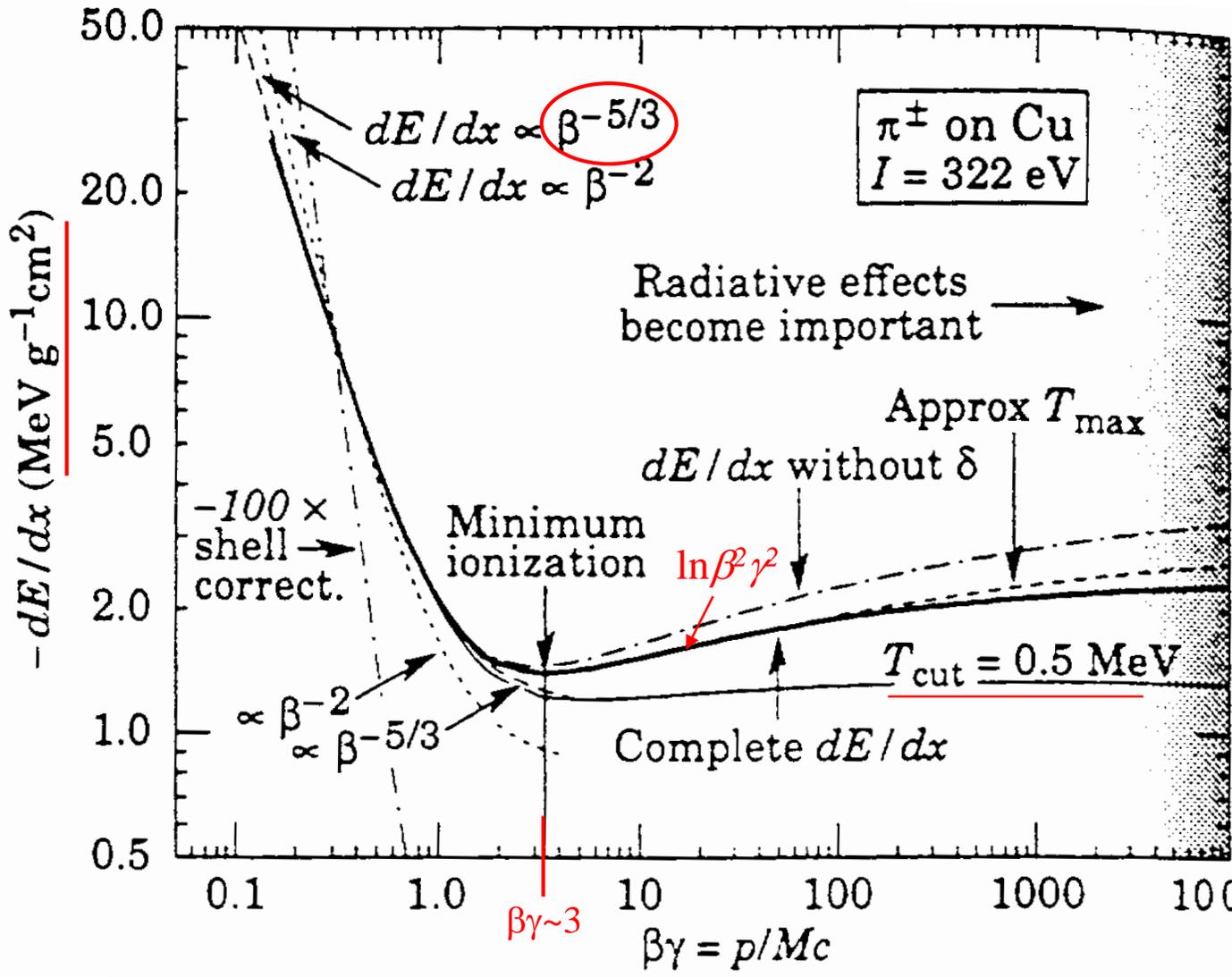
Radiation interactions and multiple scattering are characterized by: $X_0 = \frac{716.4 \text{ g.cm}^{-2} A}{Z(Z+1) \ln(287/\sqrt{Z})}$

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

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

REMINDER

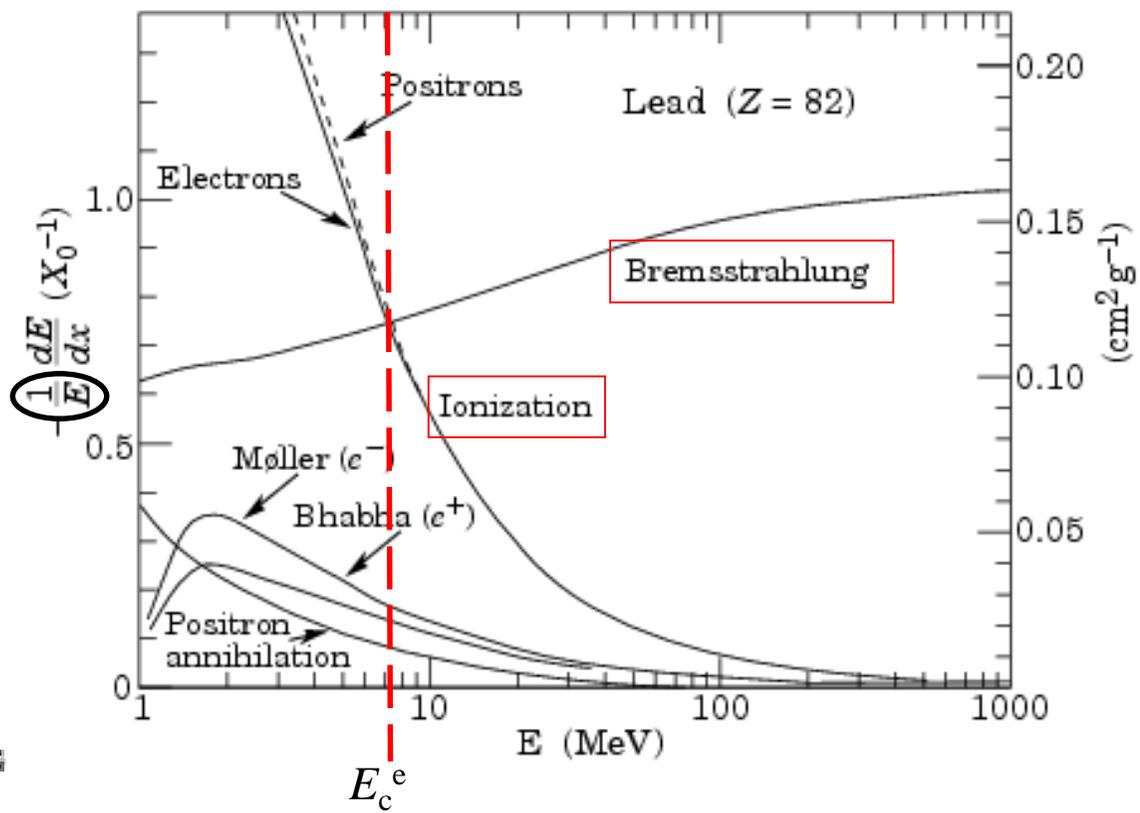
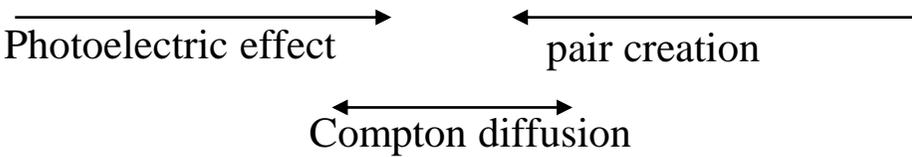
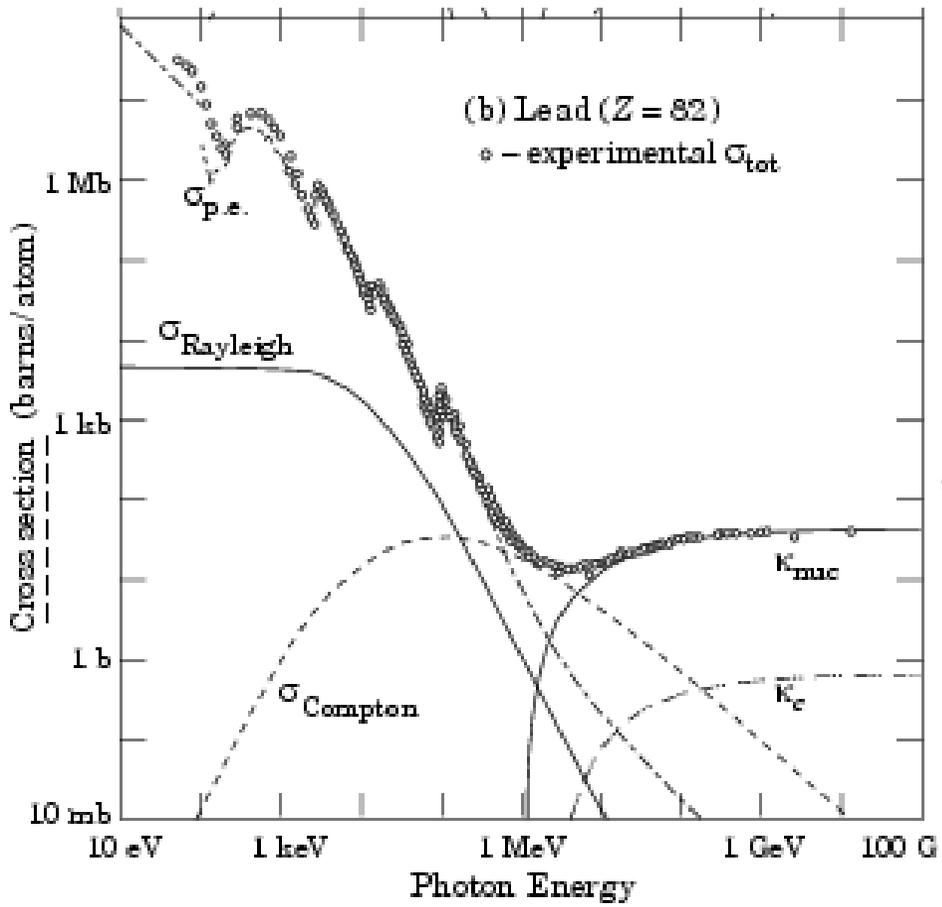
Mean energy loss in matter (heavy part.)



- “decrease”, classical effect: as the particle speed decreases it has more time to ionise matter.
- Large minimum around $\beta\gamma \sim 3$
- 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 .

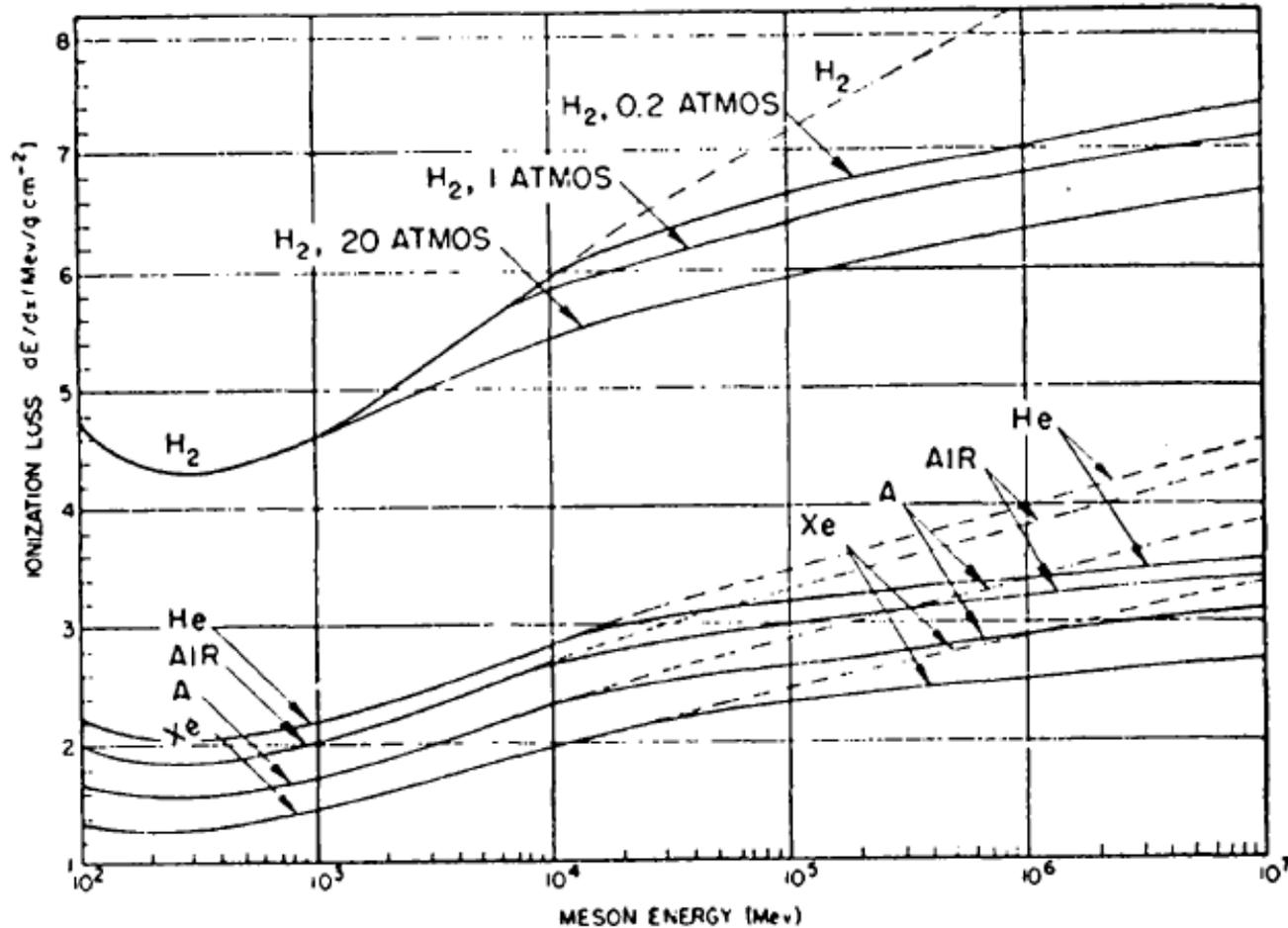
REMINDER

Interaction of γ and electrons in matter



$$E_c^\mu \sim E_c^e \cdot (m_\mu/m_e)^2 \gtrsim 100 \text{ GeV}$$

Dependence of “density factor” with pressure (for H₂)



plasma freq. :

$$\omega^2 = ne^2/\epsilon_0 m$$

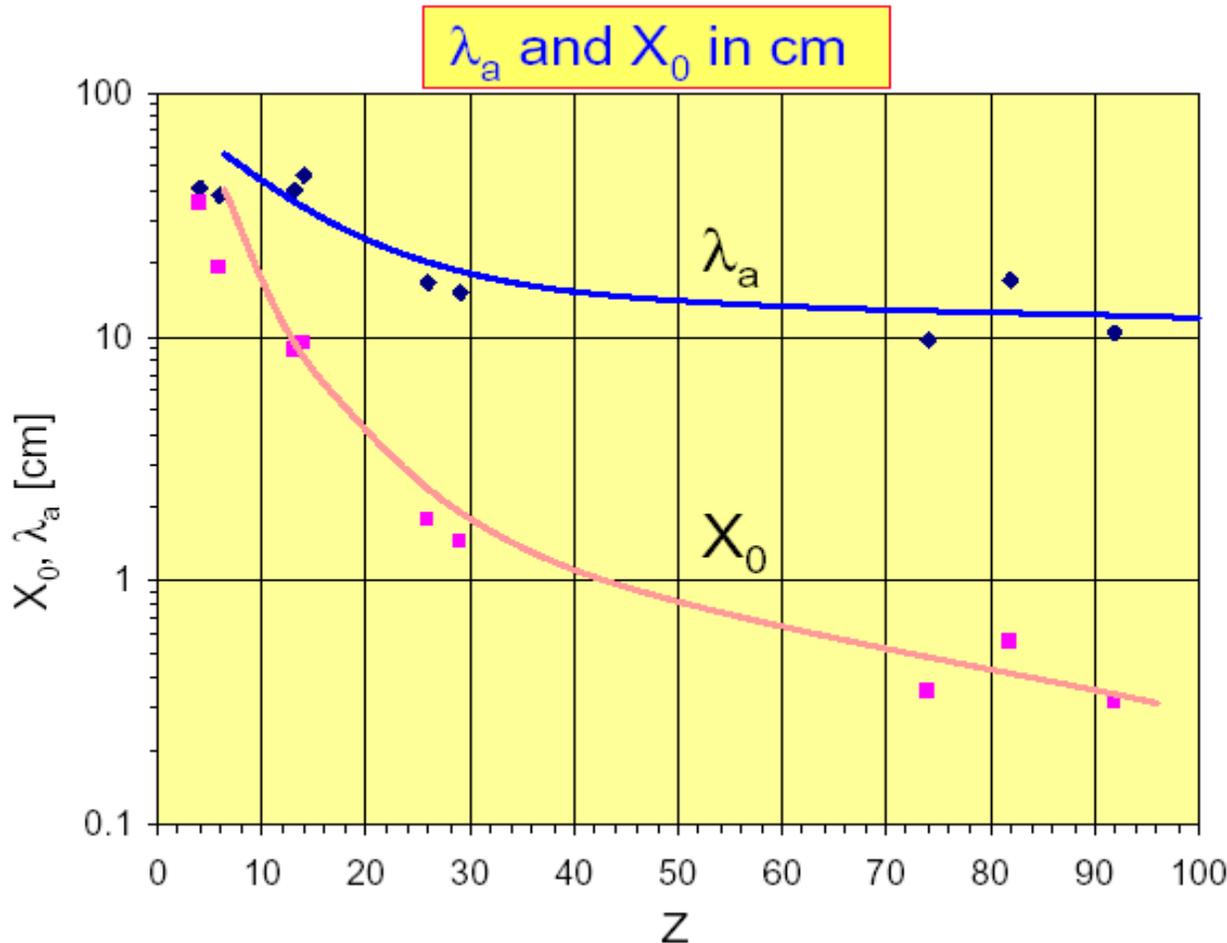
(n = #el./cm³)

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.

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 .

Remark : $\lambda_I > X_0$ pour $Z > 6$.



Unit :

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

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

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

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

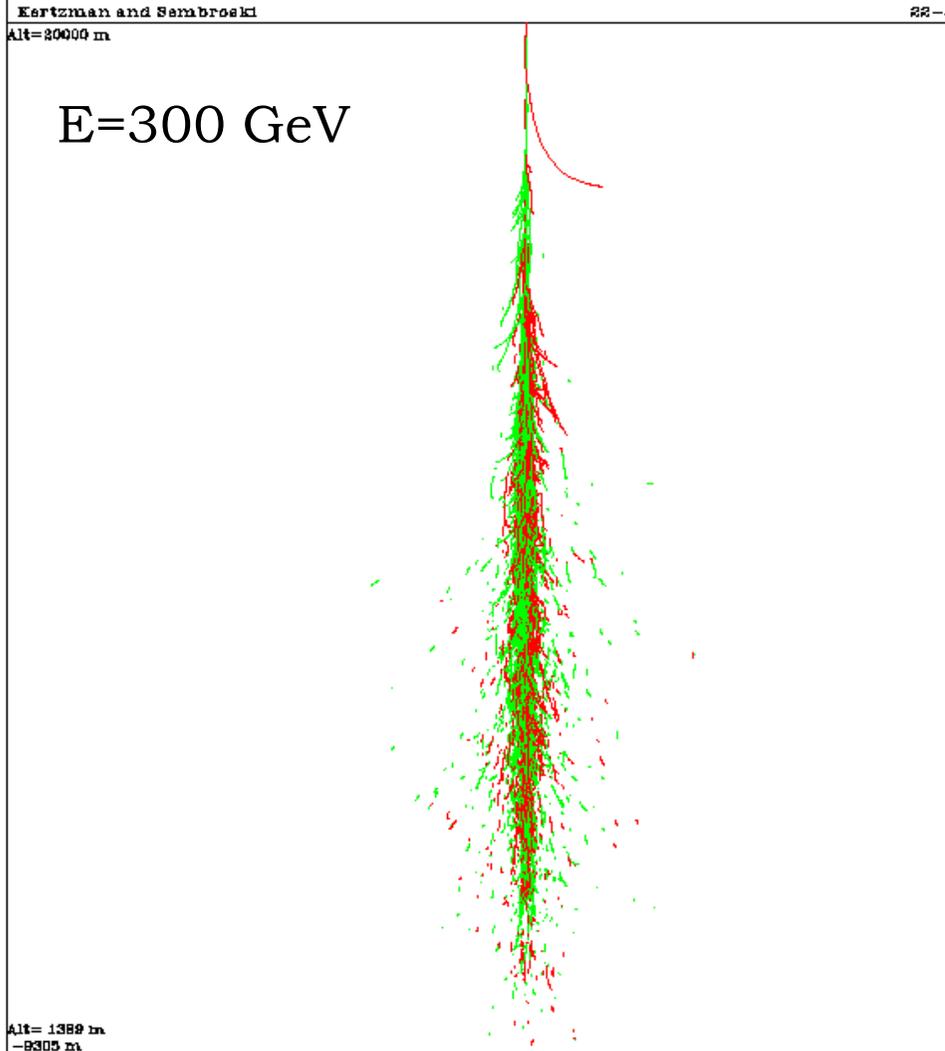
For material above $Z=50$:

$$\lambda_I > 10 \times X_0$$

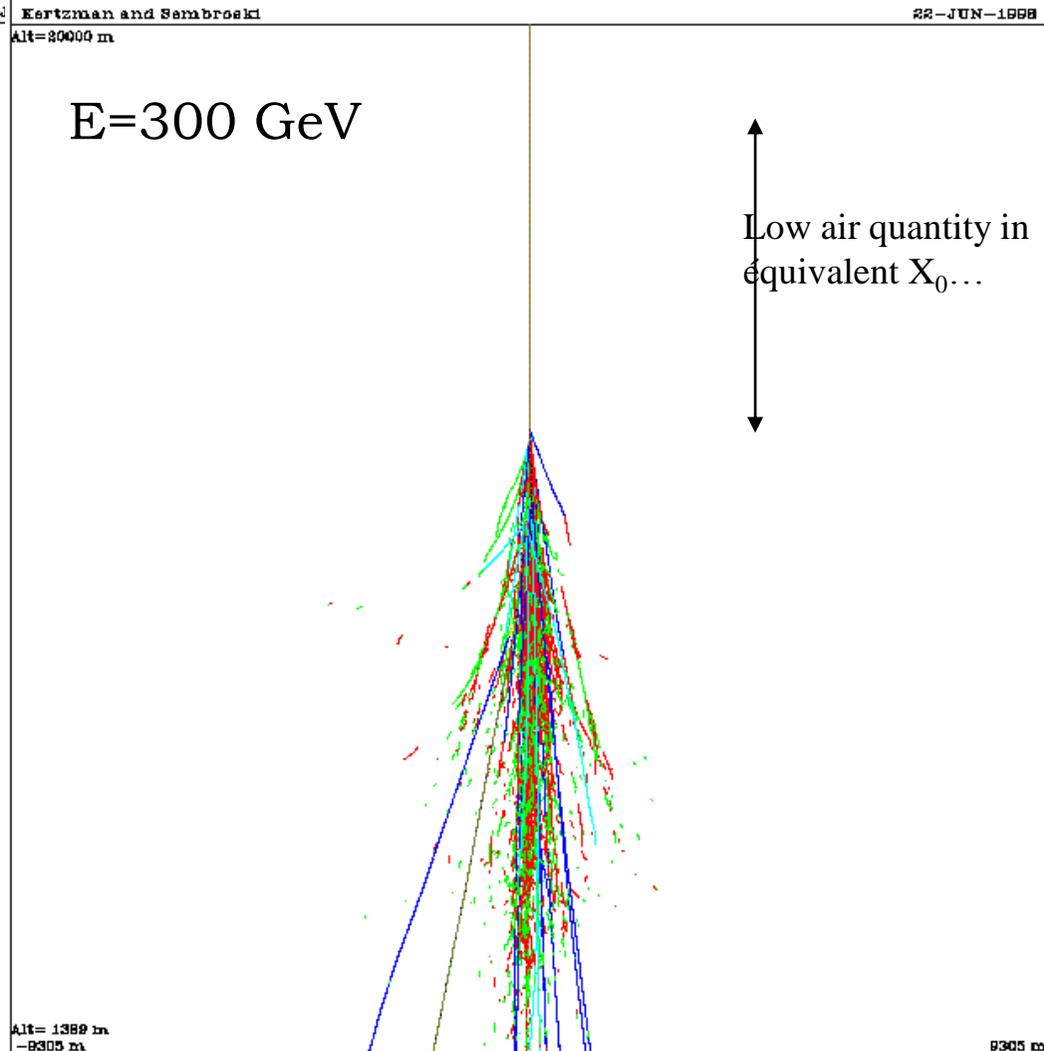
For lead : $\lambda_I / X_0 \sim 0,12.Z^{4/3} \sim 30$

EM shower versus Had. shower in air

Electromagnetic shower



Hadronic shower

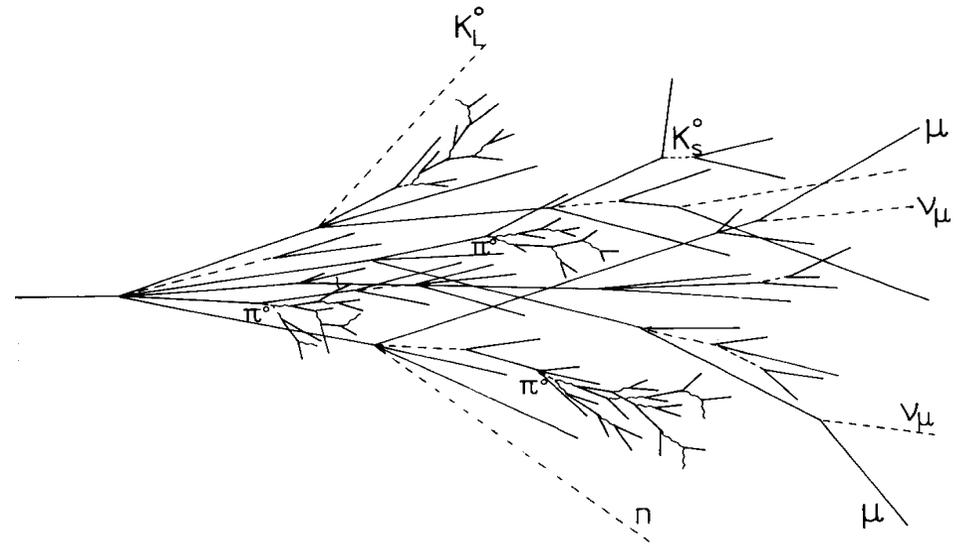
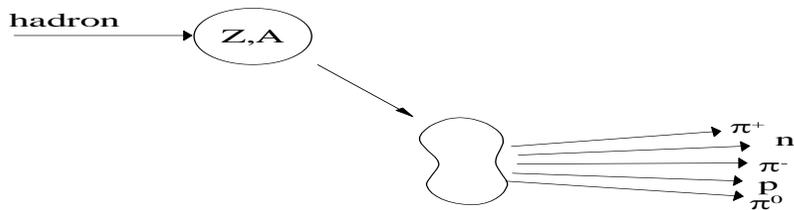


Total amount of air at sea level $\sim 23.X_0$

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 $E \propto \ln(E)$
 \Rightarrow Quick development of the shower

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \quad \sigma_0 \approx 35 \text{ mb}$$

\sim independant of the energie above 1GeV
 for p, π , K...

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

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 : $p_t \approx 0.35 \text{ GeV}/c$

How the hadronic shower is produced ?

Secondary particles production in hadronic showers are coming from “spallation” :

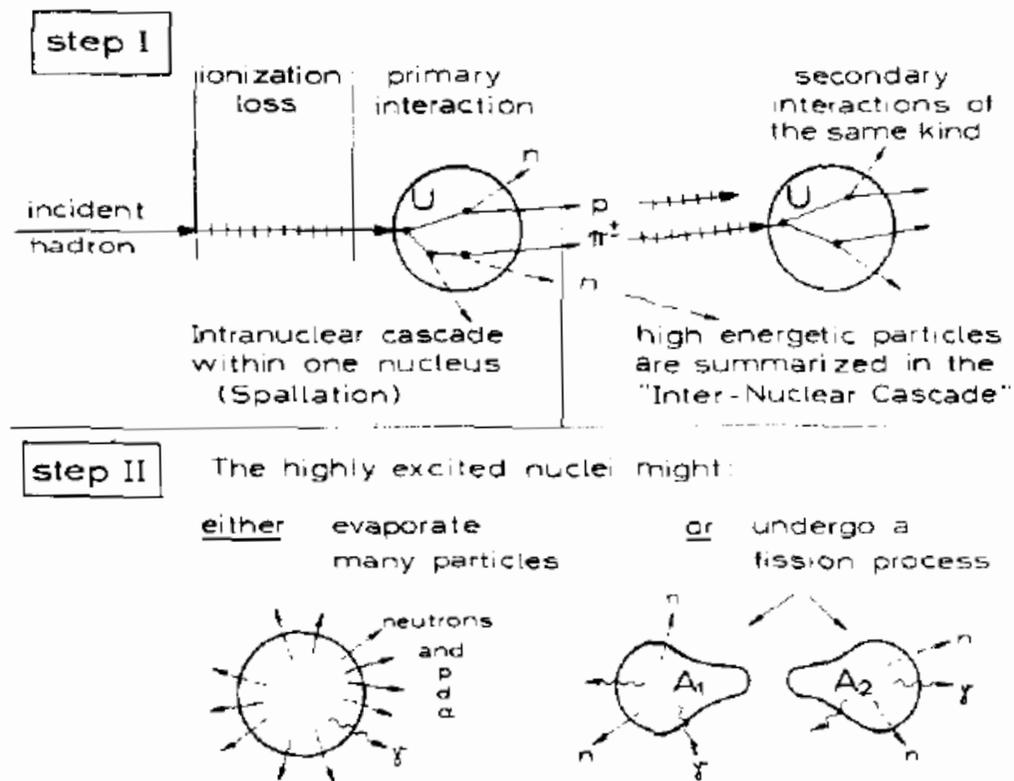
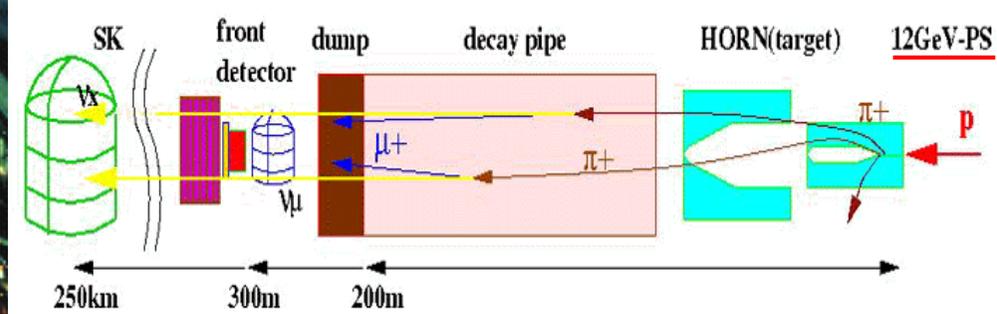
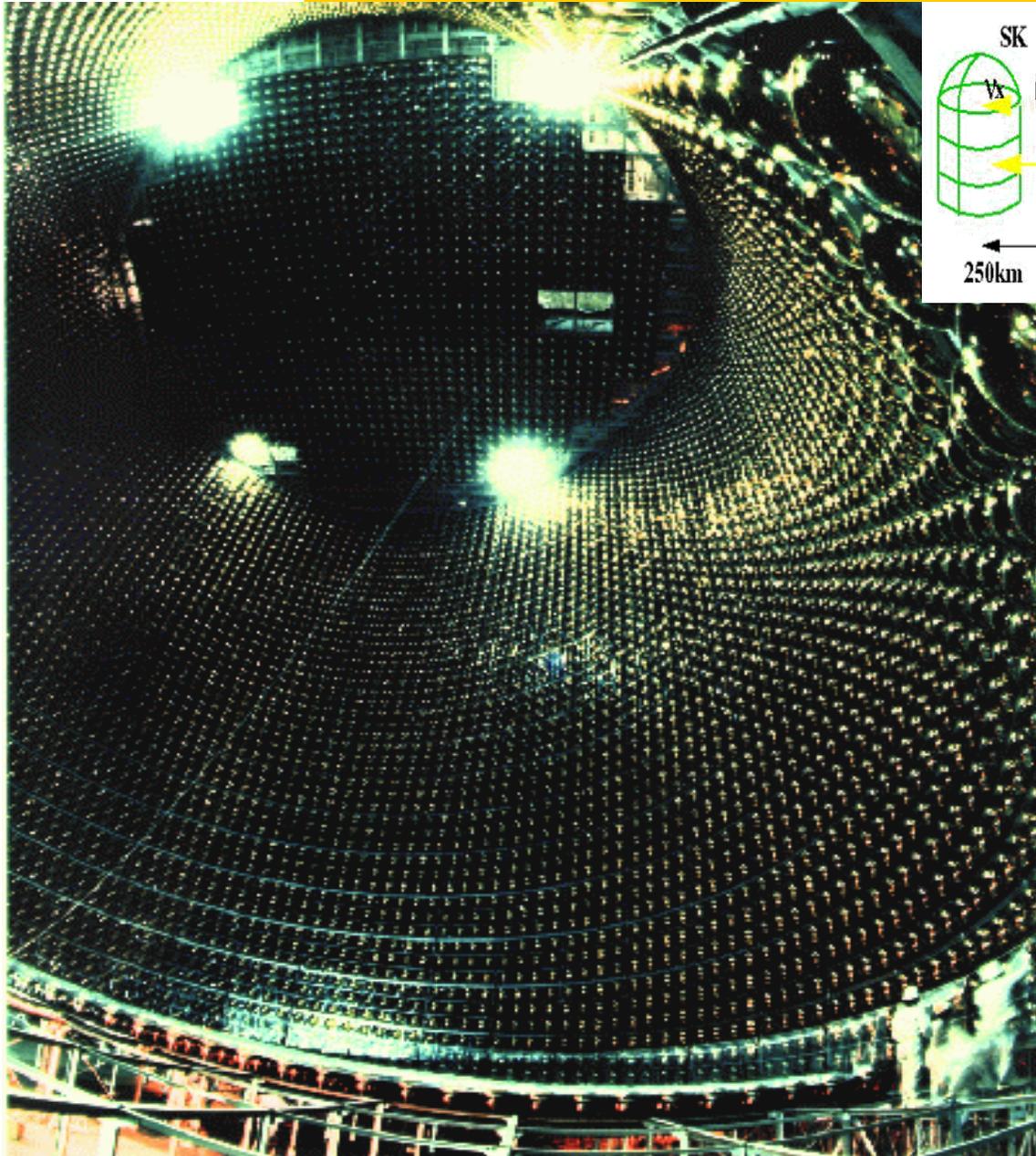


Fig. 6. Step I: Development of an “internuclear cascade”. From one nucleus an intranuclear cascade releases a few high energetic spallation products, which are able to initiate further intranuclear cascade processes. Step II: The highly excited nuclei remaining from each intranuclear cascade deexcite.

(parenthesis

Super-Kamiokande experiment (Japan)



~11 150 PM

~50 k-tonnes ultra pure water

$\text{H}_2\text{O} : 1.X_0^{\text{eau}} = 36 \text{ g/cm}^2 (= 36 \text{ cm})$

$n=1.33 \Rightarrow \theta_{\text{Cerenkov}} \sim 40^\circ$

Detection of *Cerenkov* rings
produced in water.

Neutrino energy ~1.5 GeV

\Rightarrow energy of μ and e

in Super-K $\lesssim 1.5 \text{ GeV}$

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

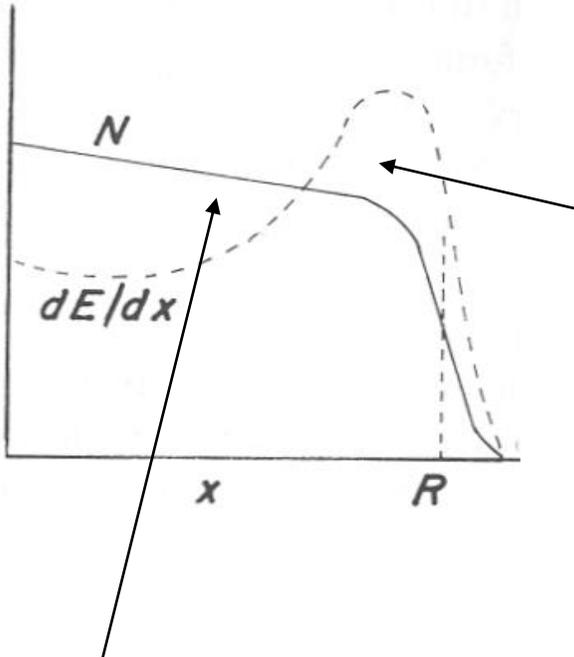
REMINDER

“Range” of particle in matter

$$\frac{dE}{dx} = \sum w_i \frac{dE}{dx} \Big|_i$$

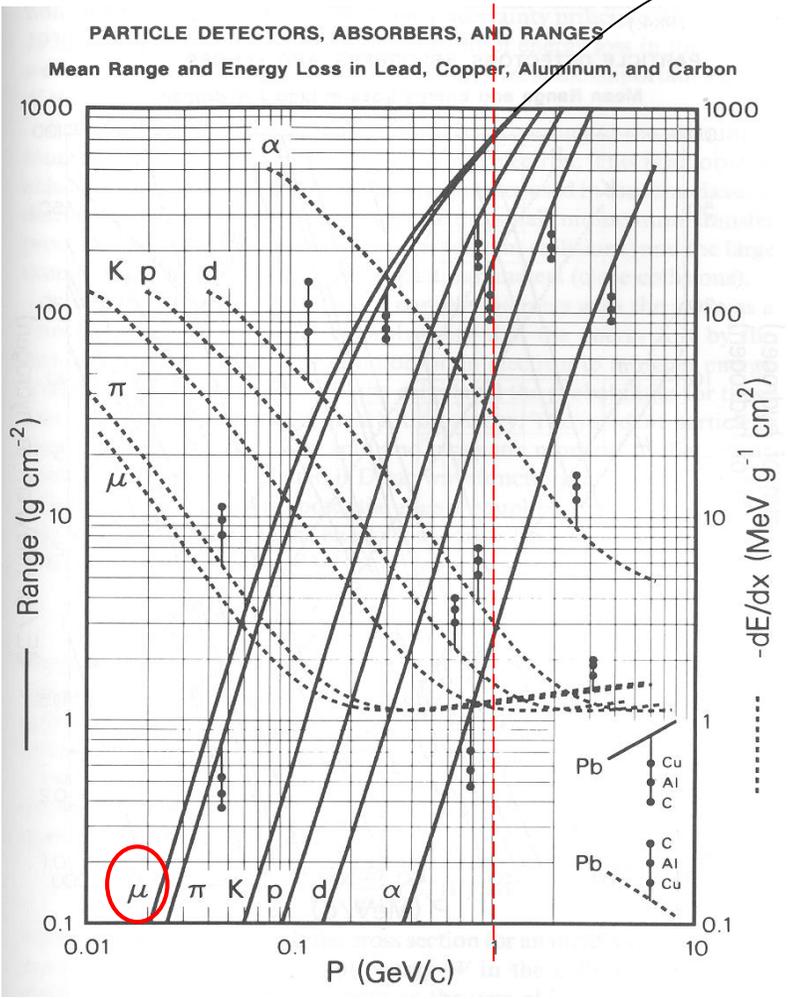
$w_i =$ fractional mass of element # i

$\sim 400 \text{ g/cm}^2 (\approx 4\text{m in water})$



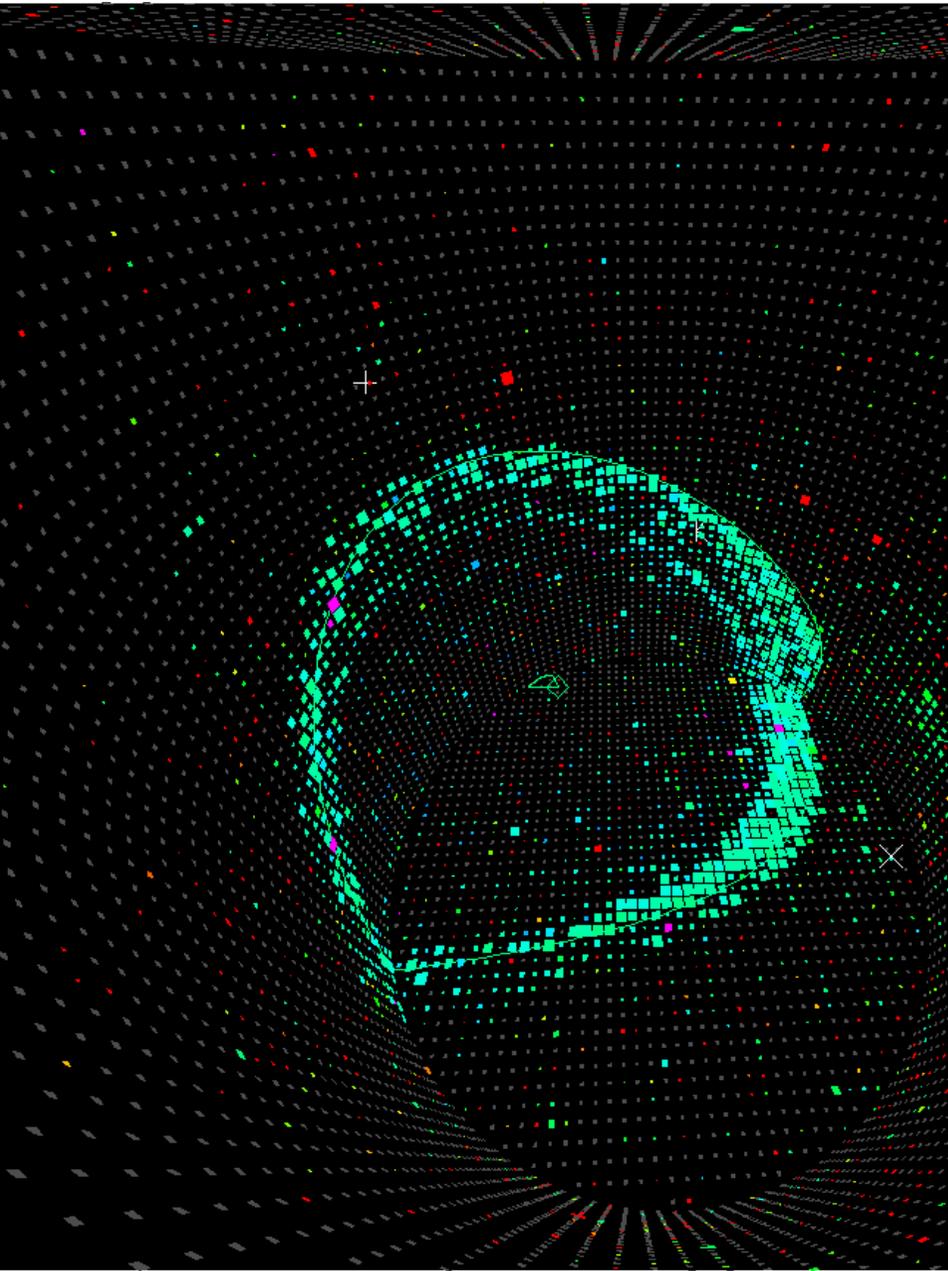
Fast brake due to dE/dx variation like $\beta^{-5/3}$.
This is the Bragg peak

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



$E_\mu \sim 1 \text{ GeV}$

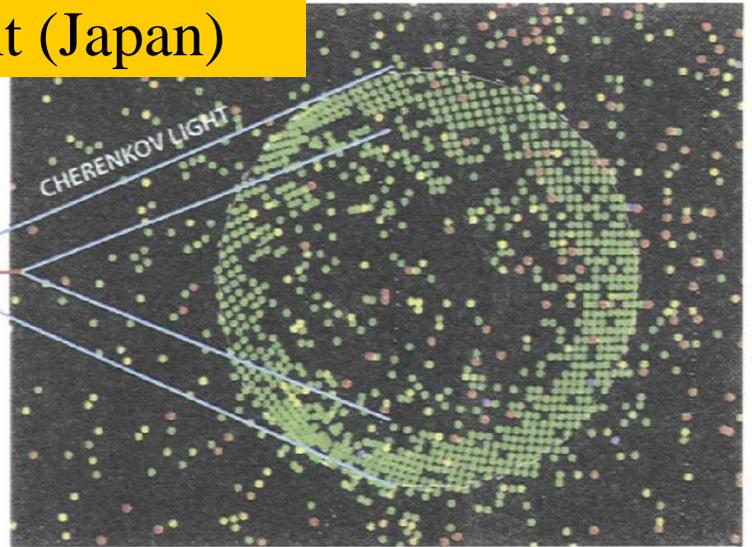
Super-Kamiokande experiment (Japan)



MUON-NEUTRINO

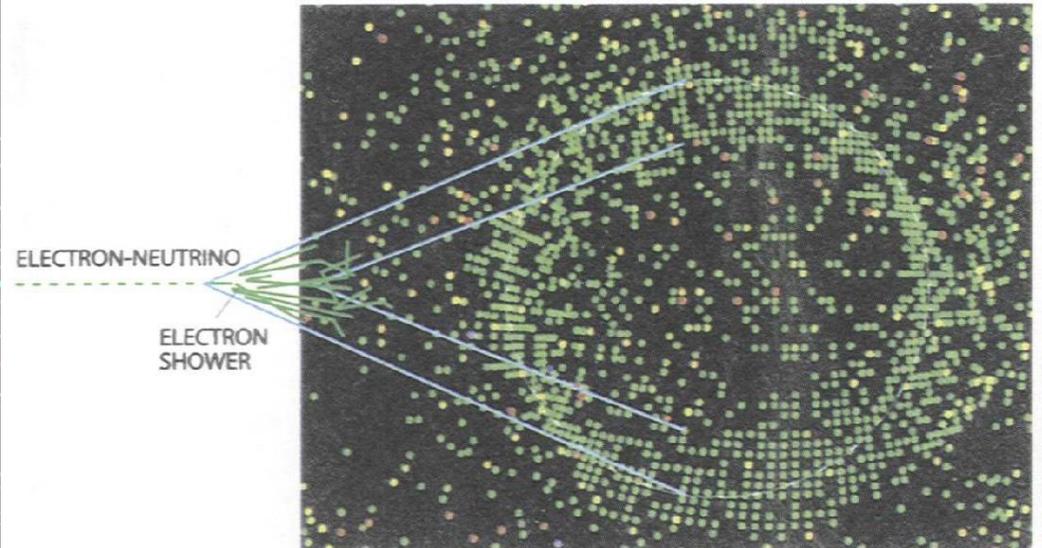
MUON

CHERENKOV LIGHT



ELECTRON-NEUTRINO

ELECTRON SHOWER

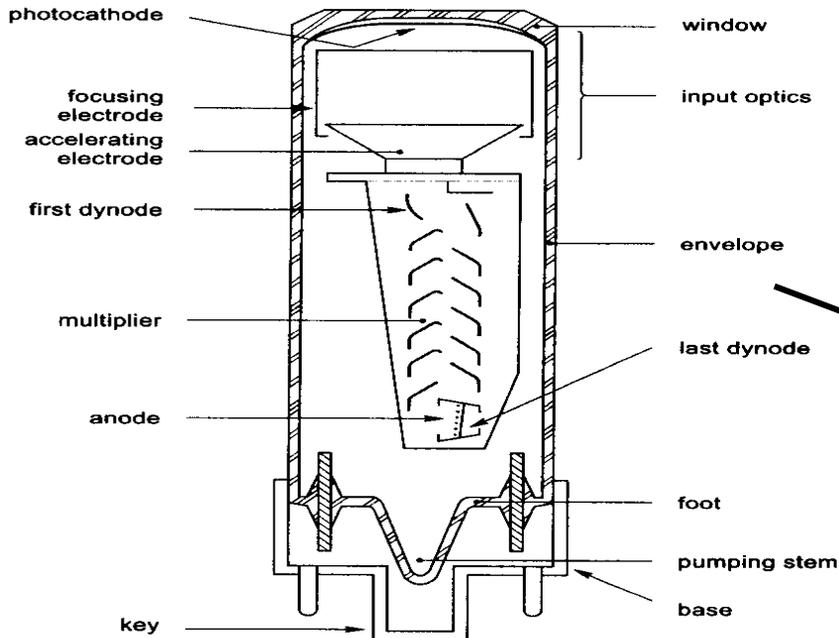


ICRR, UNIVERSITY OF TOKYO

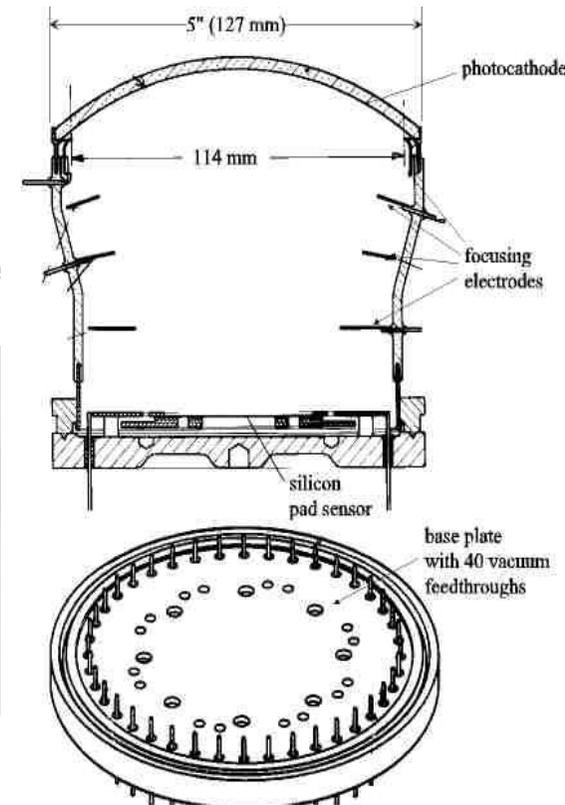
CONES OF CHERENKOV LIGHT are emitted when high-energy neutrinos hit a nucleus and produce a charged particle. A muon-neutrino (*top*) creates a muon, which travels perhaps one meter and projects a sharp ring of light onto the detectors. An electron, produced by an electron-neutrino (*bottom*), generates 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)

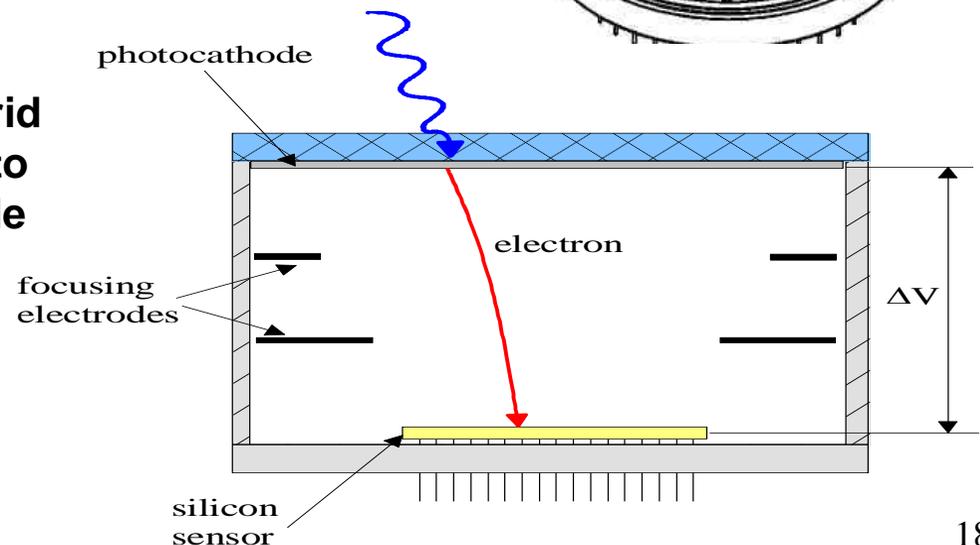
Photo Multiplier Tube



Remove dynodes and anode
add silicon sensor inside tube



Hybrid Photo Diode



~4000 to 5000 electrons-holes pairs \rightarrow 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!

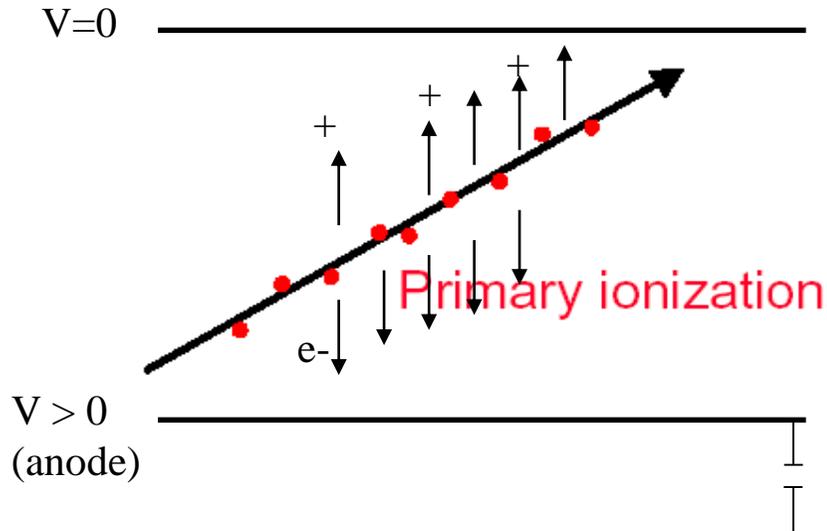
Few examples of gaseous detectors (including some information on diffusion in gas):

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 $dE/dx \sim 0,001 \times 1 \times 2 \sim 2 \text{ keV}$
 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 $5 \times n_{\text{primaire}}$

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

Assuming:

$C = 10\text{pF}$, $n = 30 \Rightarrow V \sim \mu\text{-volt}$ (to small)

Material	Z	A	(Z/A)	Nuclear α collision length λ_T {g/cm ² }	Nuclear α interaction length λ_I {g/cm ² }	$dE/dx _{\min}^b$ { $\frac{\text{MeV}}{\text{g/cm}^2}$ }	Radiation length X_0^c {g/cm ² } {cm}		Density {g/cm ³ } {g/l} for gas	Liquid boiling point at 1 atm(K)	Refractive index n (($n - 1$) $\times 10^6$) 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	[704]
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 ₂ O			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

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

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

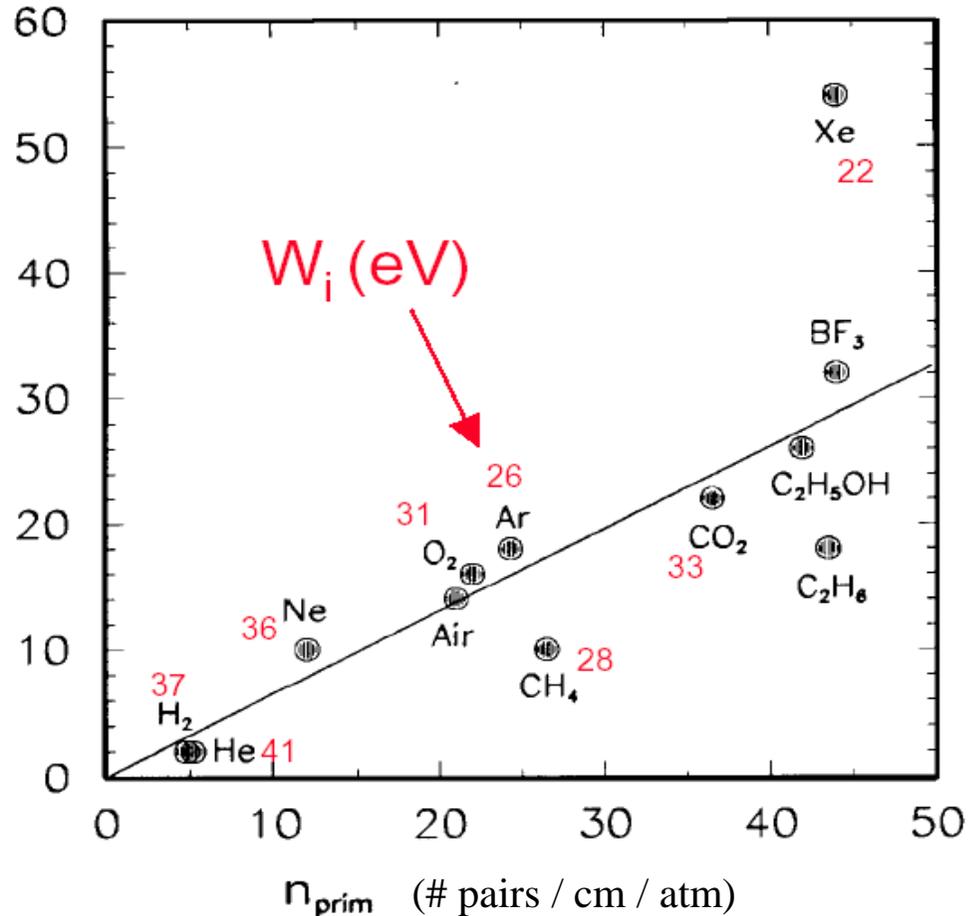
Total number of electron/ion pairs

W_i = energy needed for one pair

of primary pairs in
some common gas
(and W_i)

\bar{Z}
(mean Z)

(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):

with:

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

F = *Fano* factor ; $F < 1$ due to non independent ionisations

ΔE = energy deposited

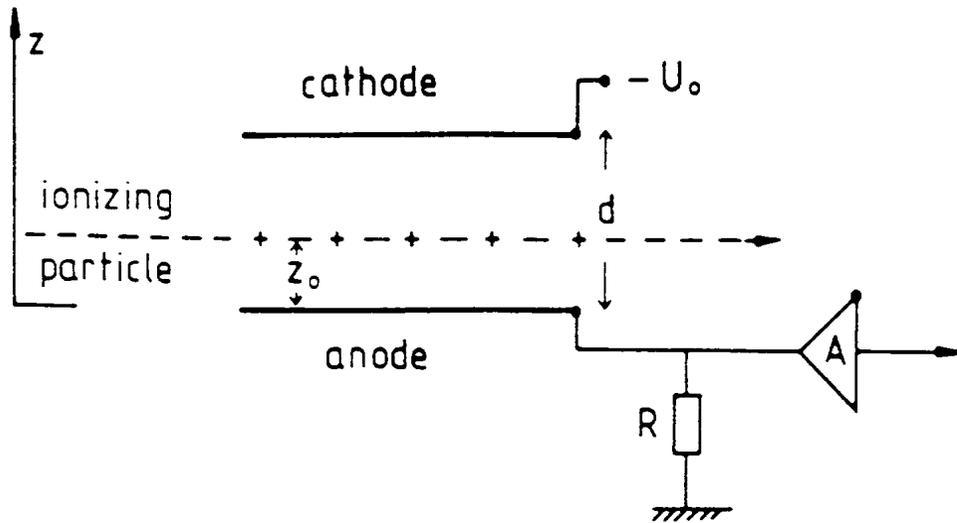
$2.35 \approx 2\sqrt{2}\sqrt{\ln 2}$ (FWHM coef.)

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.

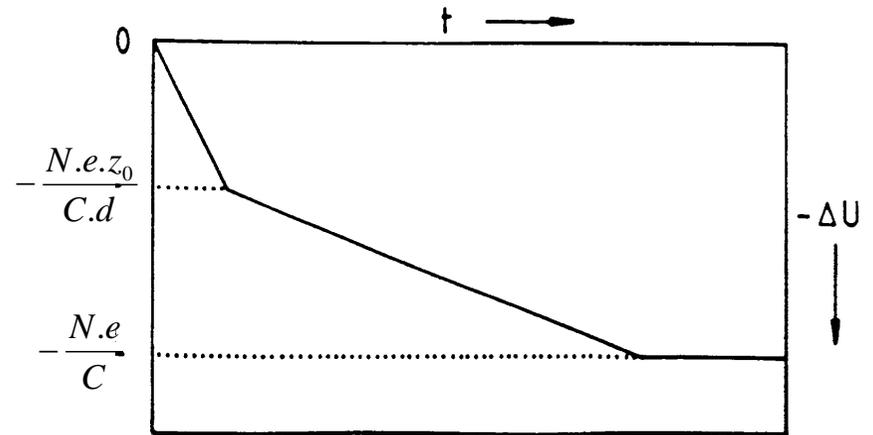
Development of signal in a ionisation chamber

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



$$V = ne/C \quad (\leftarrow Q = C.V)$$

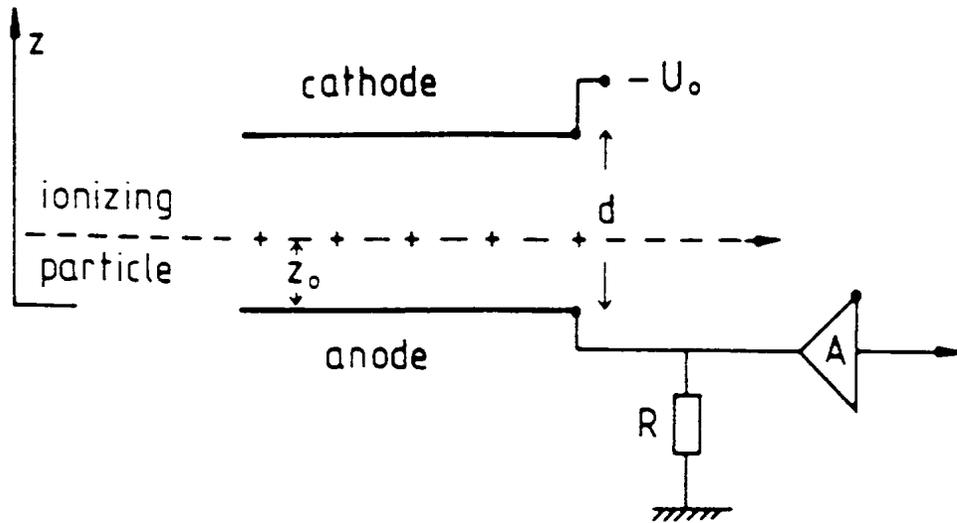
Fig. 2.2. Time development of a voltage pulse $\Delta U(t)$ from an ionization chamber for resistance $R = \infty$.



N =number of charges created
 C =capacity (hyp. $R=\infty$)

Development of signal in a ionisation chamber

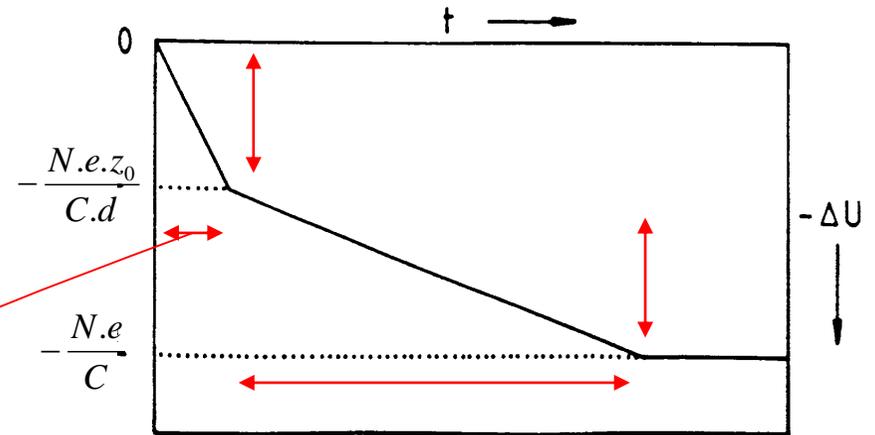
Fig. 2.1. Parallel-plate ionization chamber (schematic).



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

$$V = ne/C \quad (\leftarrow Q = C.V)$$

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N =number of charges created
 C =capacity (hyp. $R=\infty$)

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Gaseous detectors

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Ionisation in gas

→ Electrons and ions mobility in gas

Pure gas and gas mixture properties

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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: $v_{\text{drift } +/-} = \mu^{+/-} \cdot E$

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 \sim constant since ions do not increase their energy between two collisions.

For electrons:

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

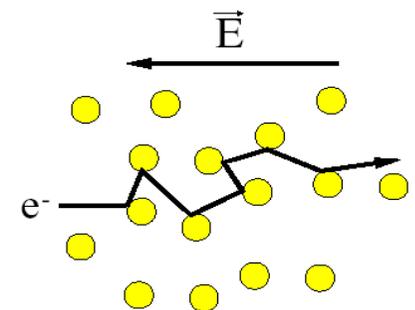
with: τ = mean time between two collisions

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 ₂ O	H ₂ O ⁺	0.7
Ar	(OCH ₃) ₂ CH ₂ ⁺	1.51
Iso-C ₄ H ₁₀	(OCH ₃) ₂ CH ₂ ⁺	0.55
(OCH ₃) ₂ CH ₂	(OCH ₃) ₂ CH ₂ ⁺	0.26
Ar	IsoC ₄ H ₁₀ ⁺	1.56
Iso-C ₄ H ₁₀	IsoC ₄ H 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

$$\mu^+ = v^+/E \quad (\text{by definition})$$

Unit:

$$v^+/E \text{ (cm/s)/(V/cm)}$$

If E=1000 V/cm so

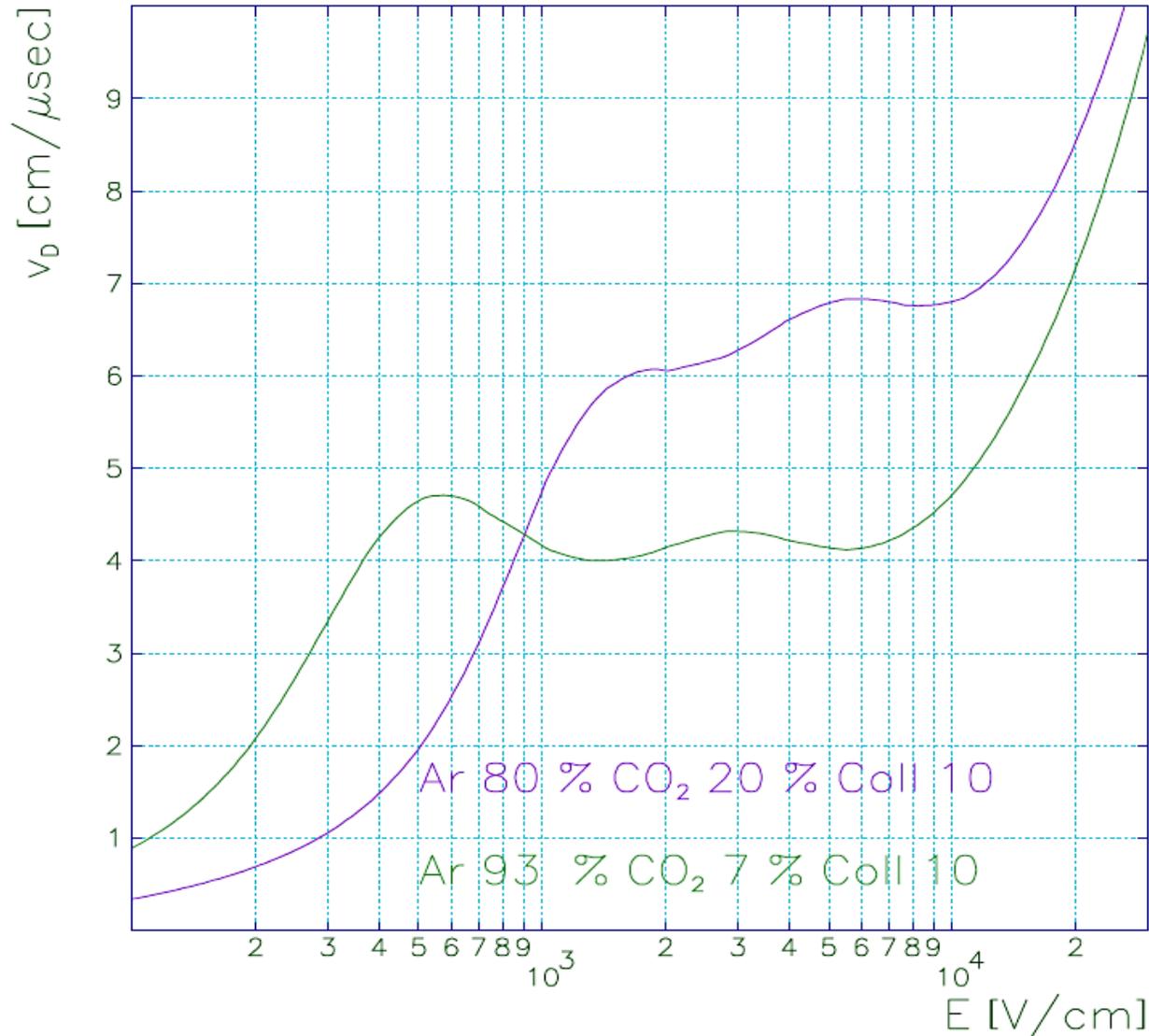
$$\mu^+=1,72 \text{ cm}^2/\text{V.s}$$

i.e. **1,72 cm/ms**

ions

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

Drift velocity of ionisation e-

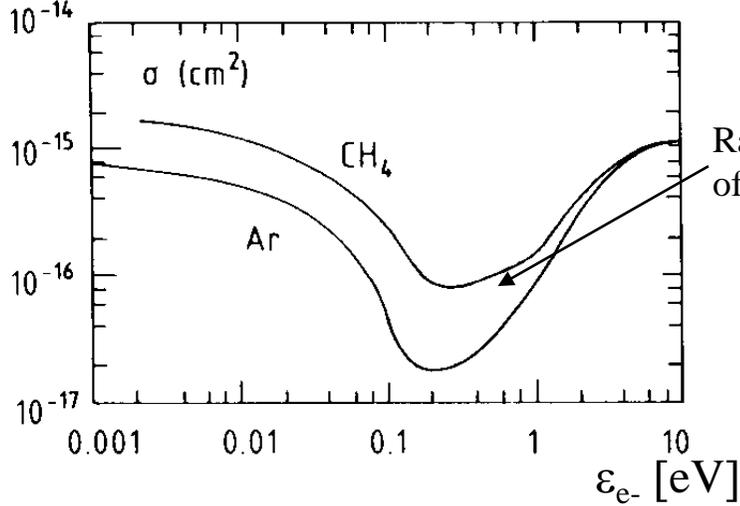


Plotted at 17.25.36 on 10/06/10 with Garfield version 7.26.

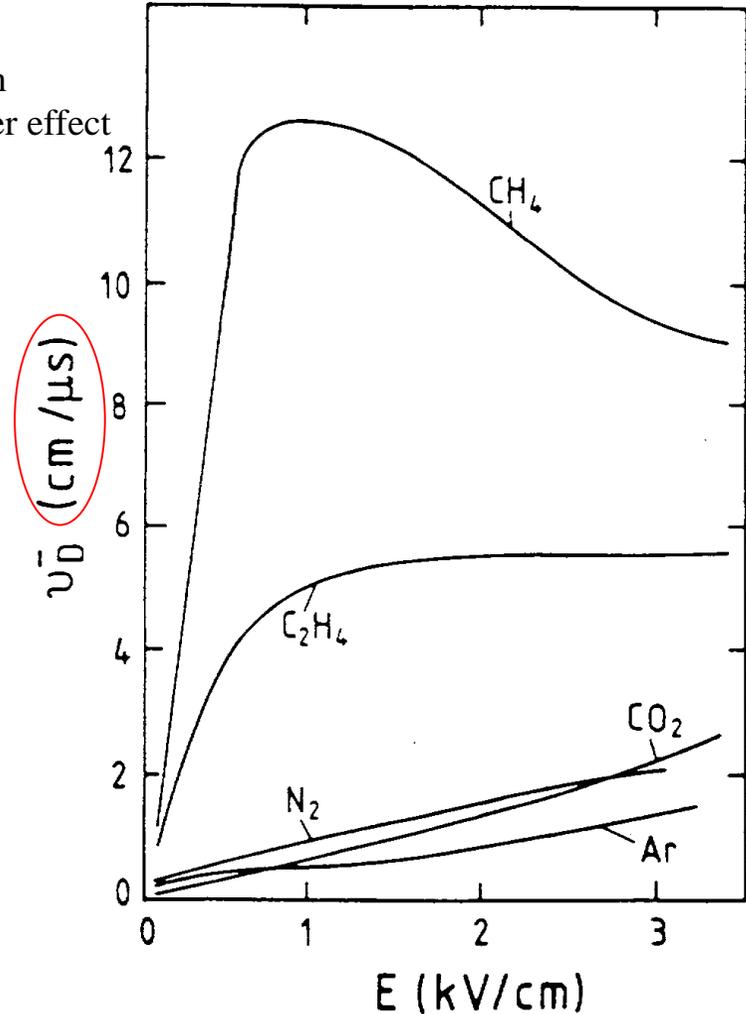
About ~1000 times
speed of ions

Mobility of electrons in gas

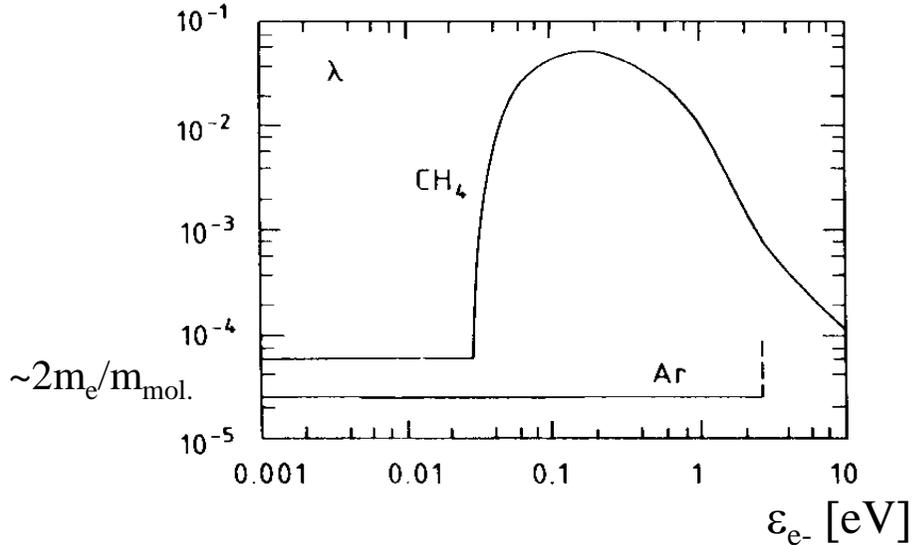
$\sigma =$ cross section



Normal condition of T and P



$\lambda =$ fraction of energy loss / collision



(CH₄ polyatomique gas)

One can show that
drift velocity: $v_D^2 = \frac{eE}{mN\sigma} \sqrt{\frac{\lambda}{2}}$

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

Coefficient, number of collisions,
and average time for electron attachment
in several gases under normal conditions^{12,18,21)}

Or how long can an
electron be free in gas...

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 ₂ O	2.5×10^{-5}	2.8×10^{11}	1.4×10^{-7}
Cl ₂	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 CO₂ 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/cm ³)	E_{ex} (eV)	E_i (eV)	I_0 (eV)	W_i (eV)	$(dE/dx)_0$		n_p (cm) ⁻¹	n_T (cm) ⁻¹
								(MeV/ g cm ⁻²)	(keV/cm)		
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 ₄ H ₁₀	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	46	195

$\rho(\text{gaz}) \sim \rho(\text{solid/liquid})/1000$

n_p is used for efficiency calculation

n_T is used for signal calculation

$\times 2 \text{ à } \times 5$

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 ₂ H ₆ (3.5%)	24.4
He	46.0	42.3	24.58	Ar (99.6%) + C ₂ H 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 ₃ H ₈ (2%)	23.5
Kr	24.0	24.05	14.00	Ar (99.9%) + C ₆ H ₆ (0.1%)	22.4
Xe	21.7	21.9	12.13	Ar (98.8%) + C ₃ H ₆ (1.2%)	23.8
CO ₂	34.3	32.8	13.81	Kr (99.5%) + C ₄ H ₈₋₂ (0.5%)	22.5
CH ₄	29.1	27.1	12.99	Kr (93.2%) + C ₂ H ₂ (6.8%)	23.2
C ₂ H ₆	26.6	24.4	11.65	Kr (99%) + C ₃ H ₆ (1%)	22.8
C ₂ H ₂	27.5	25.8	11.40		
Air	35.0	33.8	12.15		
H ₂ O	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)	$(dE/dx)_0$		n_p (cm) ⁻¹	n_T (cm) ⁻¹
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C ₄ H ₁₀	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	46	195

$$W_i(\text{Ar}) = 26 \text{ eV}$$

$$dE/dx(\text{Ar}) = 2.44 \text{ keV/cm}$$

$$n_p(\text{Ar}) = 29.4 / \text{cm}$$

$$W_i(\text{C}_4\text{H}_{10}) = 23 \text{ eV}$$

$$dE/dx(\text{C}_4\text{H}_{10}) = 4.50 \text{ keV/cm}$$

$$n_p(\text{C}_4\text{H}_{10}) = 46 / \text{cm}$$

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 $\sim 300 \mu\text{m}$ between each primary pair (and a factor $\sim 3,5$ 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!

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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)

1st case: chamber with // plates

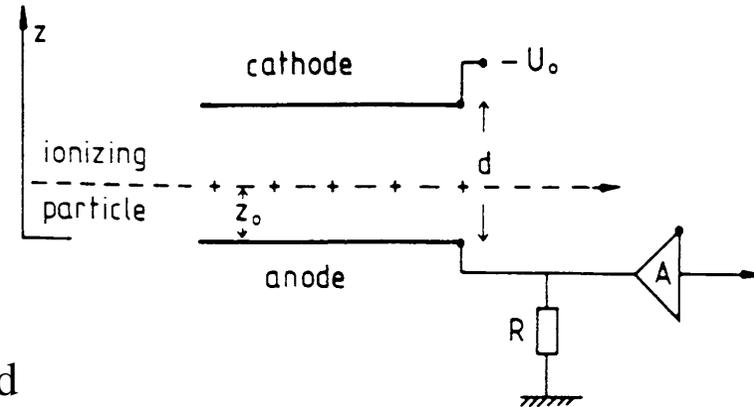
Signal comes from variation of electrostatic energy stored in the capacitor:

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

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

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

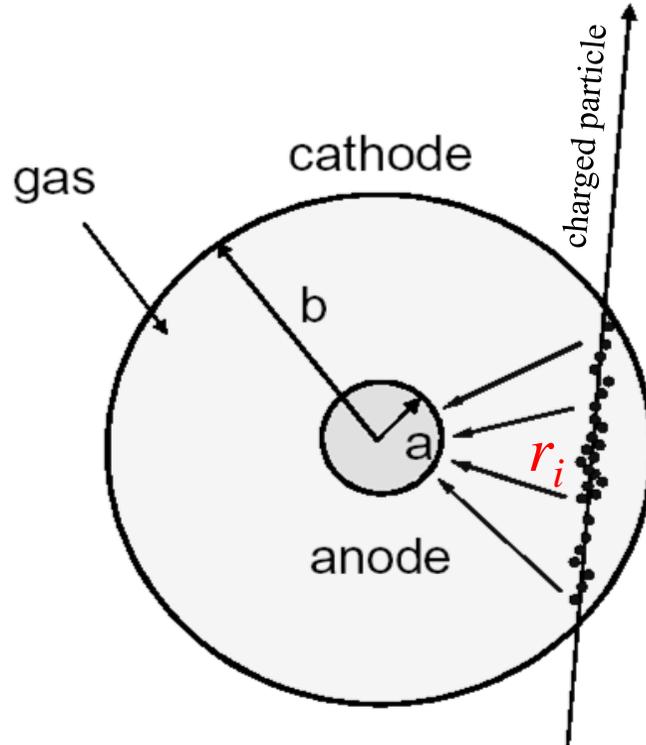
It is $\sim 10\mu\text{s}$ for electrons and $\sim 6\text{ms}$ for ions in 5cm of Argon, $E=500\text{ V/cm}$



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

Typical example

b=10 mm, a(anode=wire)=10 μ m



As before (for electrons):

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

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

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

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

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

typically ~ 0.1

\Rightarrow **signal comes from electrons!!**

≠ from previous case

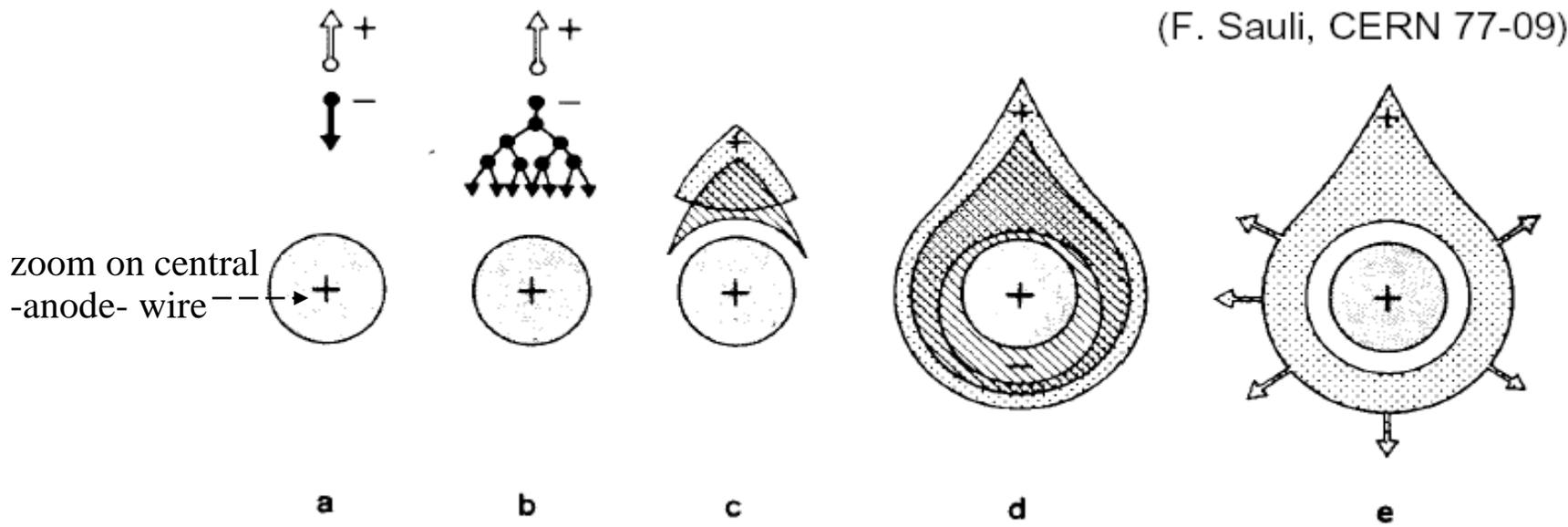
3rd case:

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 (\sim few times wire radius) they “fill” an important acceleration,

The electrons energy increases \Rightarrow ionisation by collision amplifying the phenomena

(timescale of the amplification: few ns)



≠ from previous case

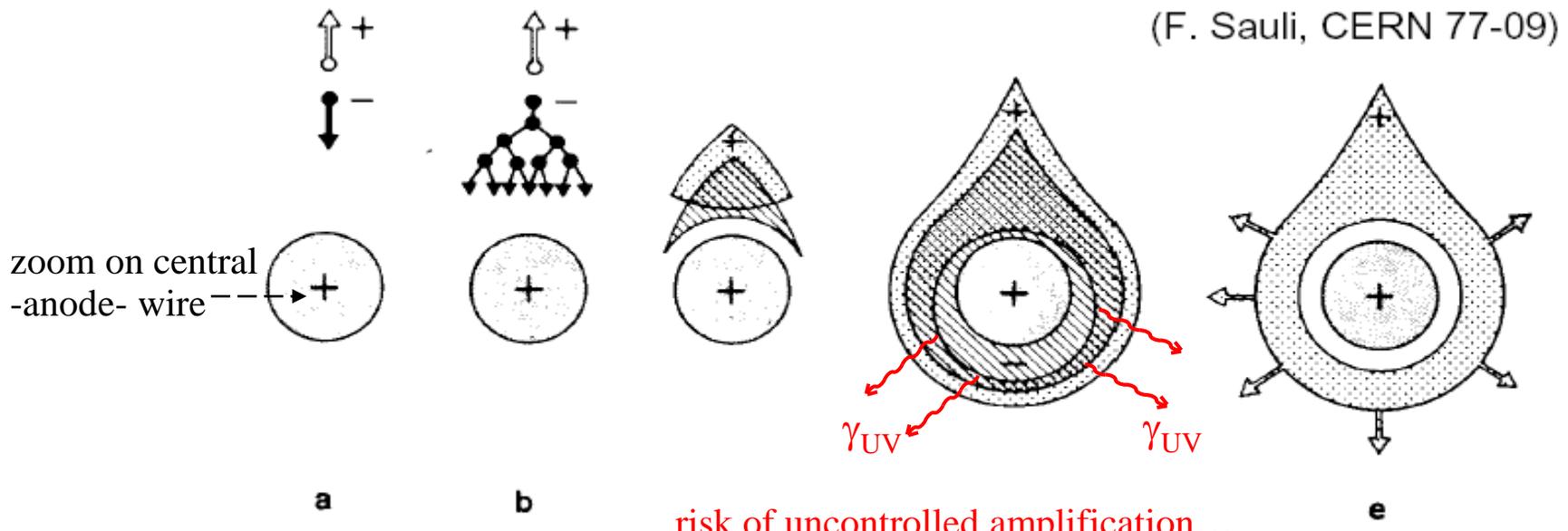
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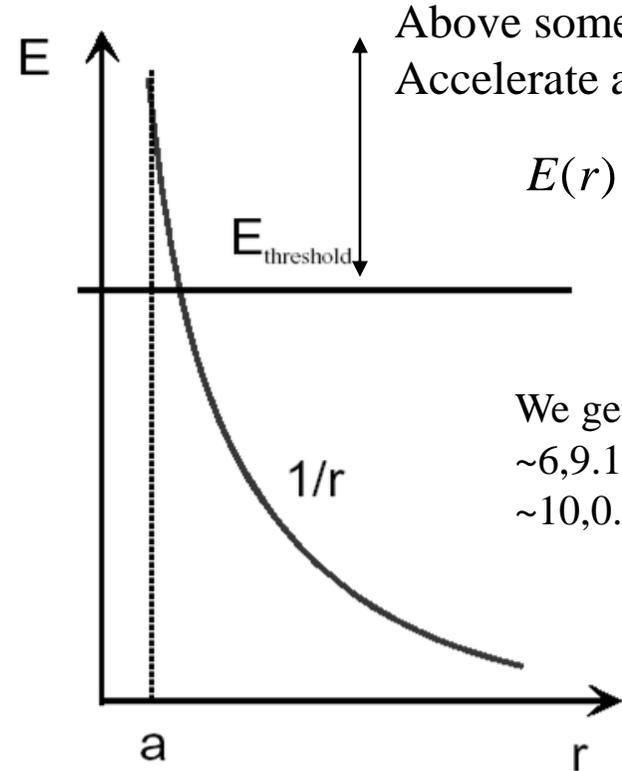
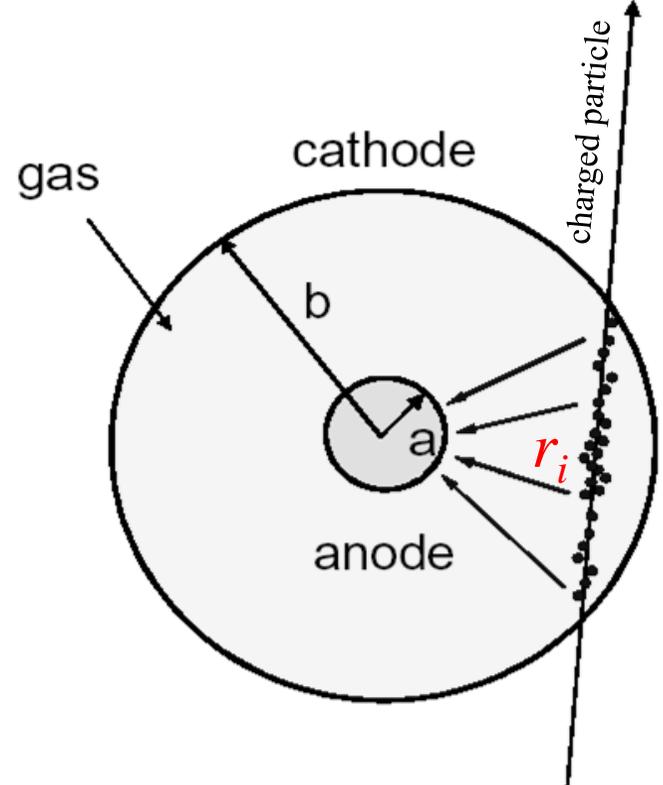
3rd case:

Case of a cylinder geometry with amplification
(high E field) : proportional chamber

Typical example

b=10 mm, a(anode=wire)=10μm

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



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

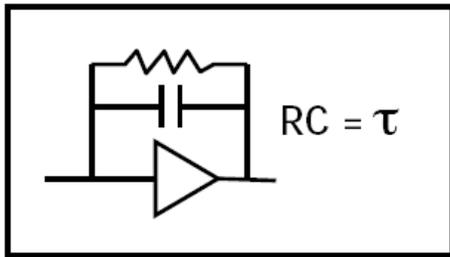
$$E(r) = \frac{U_0}{r \ln(r_b/r_a)}$$

We get (H. Fischer, 1975) :
 ~6,9.10⁴V/cm.atm, methane (CH₄)
 ~10,0.10⁴V/cm.atm, propane (C₃H₈)

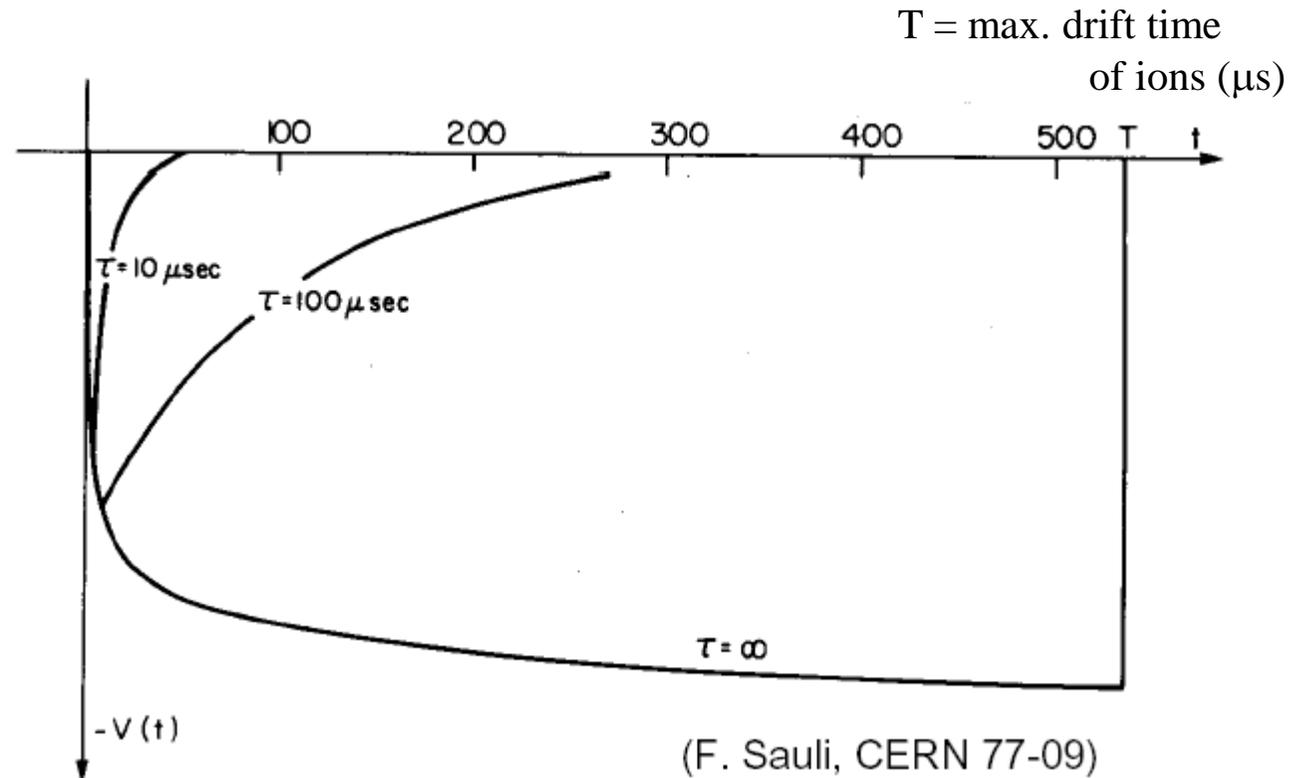
$$\frac{\Delta U^+}{\Delta U^-} = \frac{\ln(r_b/r_i)}{\ln(r_i/r_a)} \approx \frac{\ln(r_b/(r_a + n\lambda))}{\ln((r_a + n\lambda)/r_a)} \sim \frac{\ln(r_b/r_a)}{n\lambda/r_a}$$

Avalanche appears in last tenth of microns (=nλ ~ r_a), when the ratio is ~7 => **signal comes from ions** !! Still: t_{ions} ~ ms et t_e ~ ns.

Signal in a proportional counter

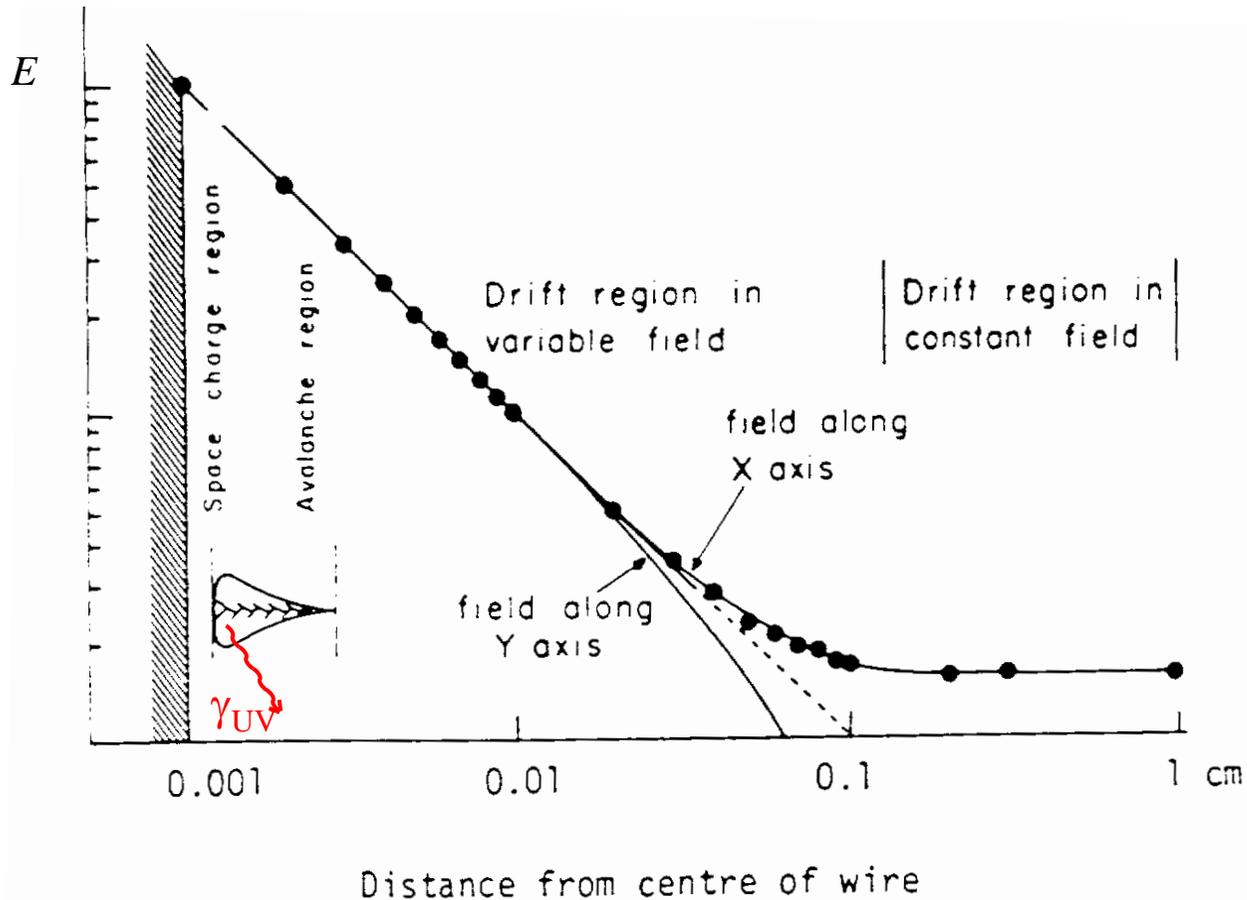


Charge preamplifier:
Signals varies with preamplifier



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:

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

(varies with E , i.e. with r)

$$\alpha = \frac{1}{\lambda} \quad \text{with } \lambda = \text{mean free path of electrons}$$

since $\alpha \neq \text{cte} \Rightarrow A = \frac{n}{n_0} = \exp \left[\int_a^{r_C} \alpha(r) dr \right] \quad \text{Gain} \quad A \approx k e^{CV_0}$

$\left\{ \begin{array}{l} \text{Valid when the applied} \\ \text{voltage is “above” the} \\ \text{proportional zone: } A \\ \text{varies like } \exp.(V_{\text{anode}}). \end{array} \right.$

- α should be measured for all gas (modelling by Rose and Korff).
Above a gain of the order of $\sim 10^8$, there is a spark (**this is the *Raether* limit**).

- Voltage where the avalanche starts depend on gas (mixture) and is of the order of $\sim 10^4$ 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

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Ionisation in gas

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

Quencher / gain variation

δ -ray

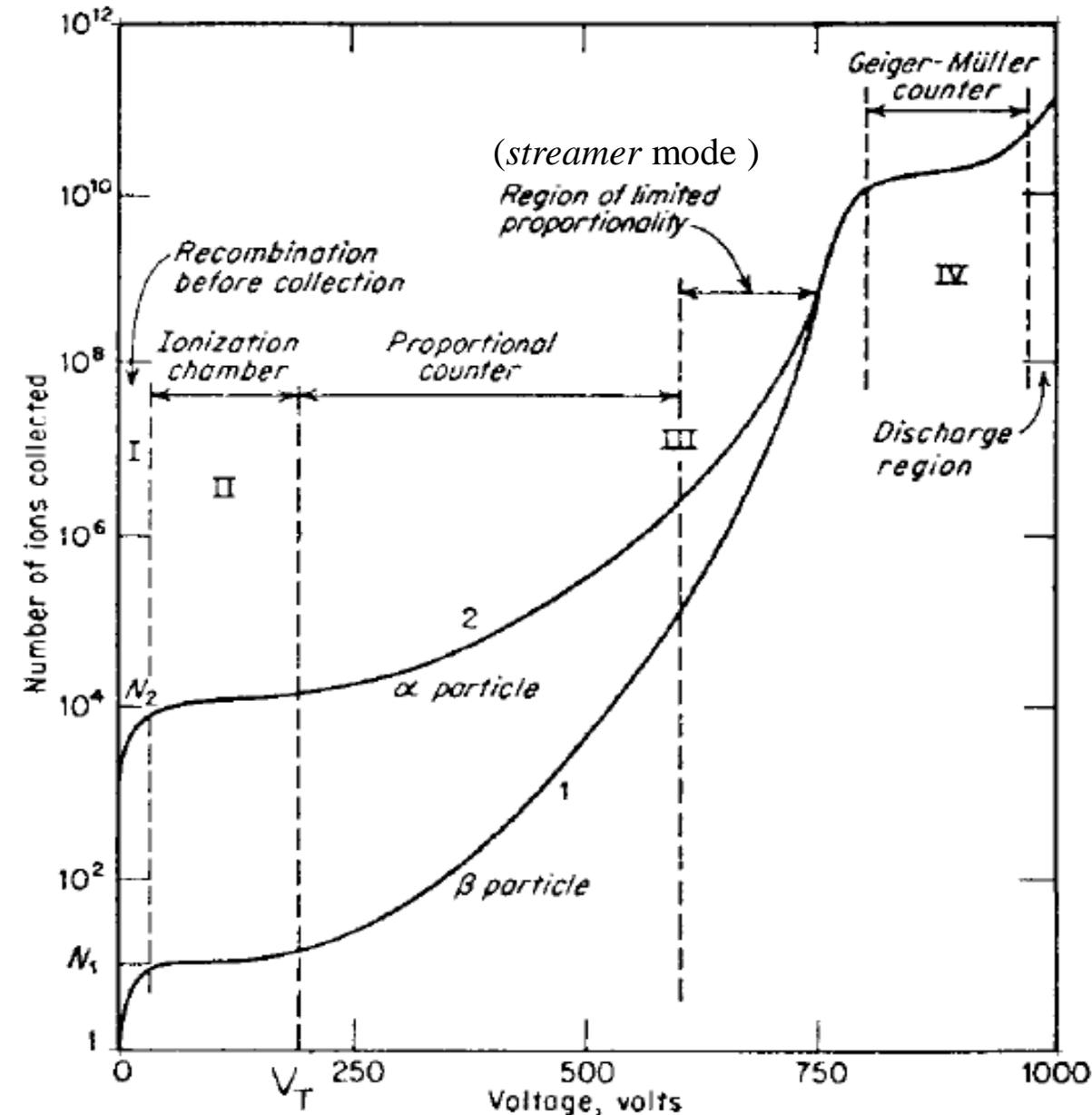
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drift chambers, TPC, *straw* (pailles)

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 \nearrow 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 $\sim 10^{10}$.

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

Geiger-Müller principle

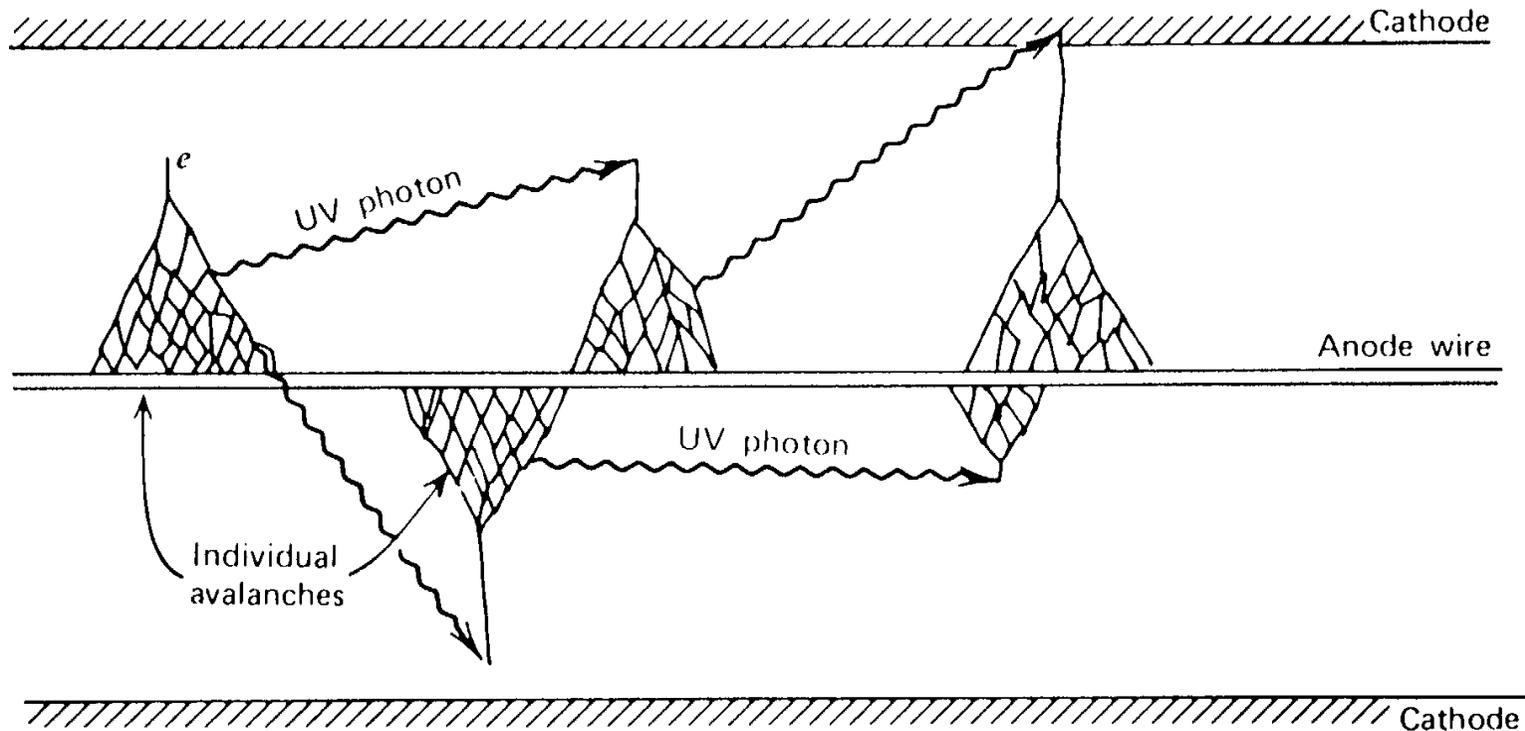
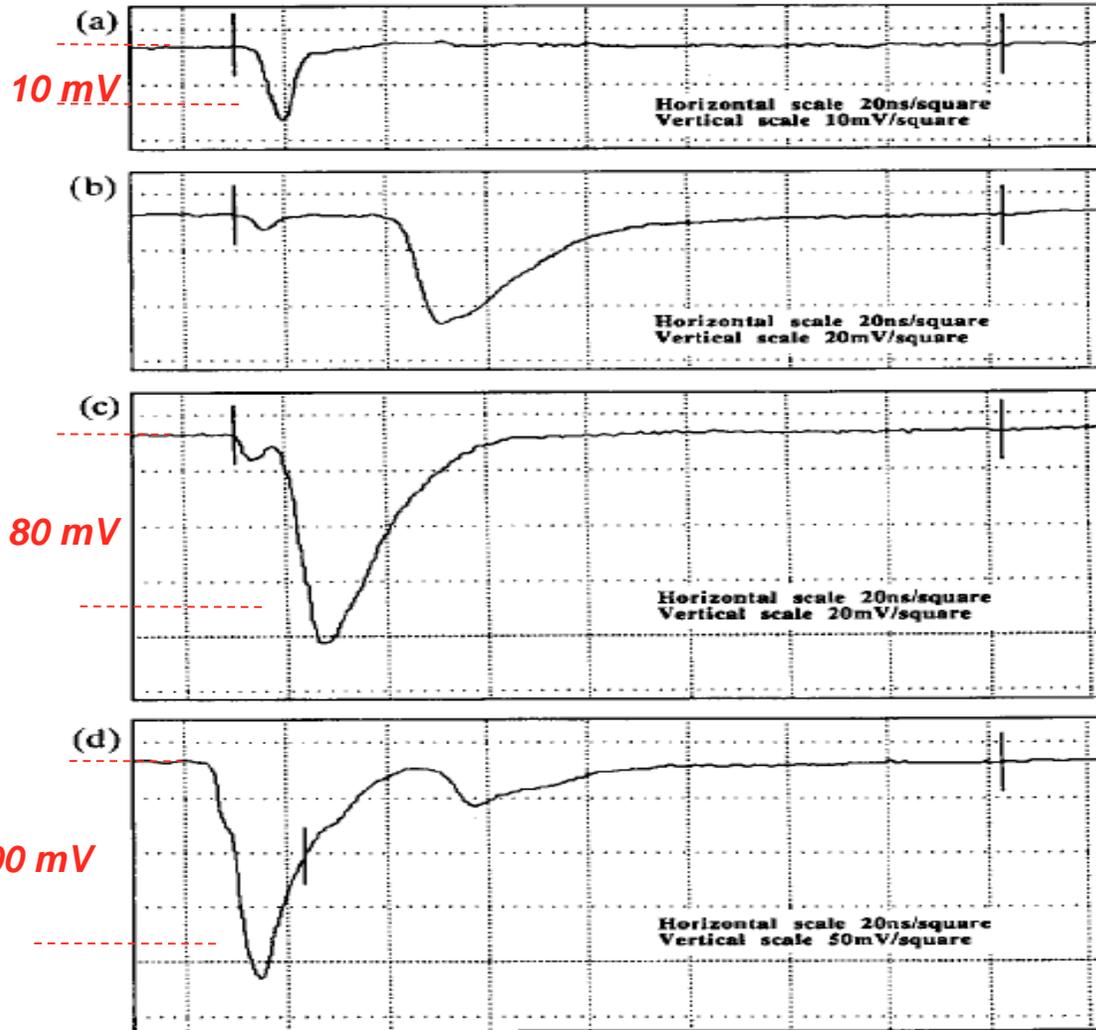


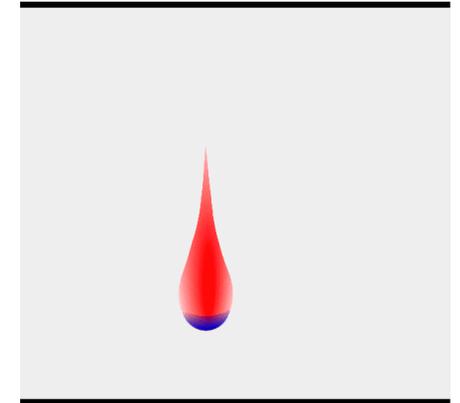
Figure 7-1 The mechanism by which additional avalanches are triggered in a Geiger discharge.

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

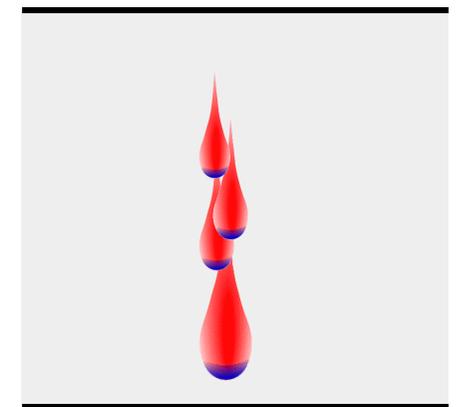
Avalanche in *streamer* mode



NORMAL AVALANCHE



STREAMER



Avalanche simulation



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

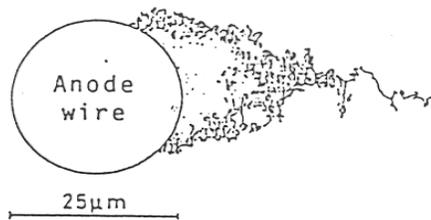


Fig. 6 Two dimensional display of a simulated electron avalanche.

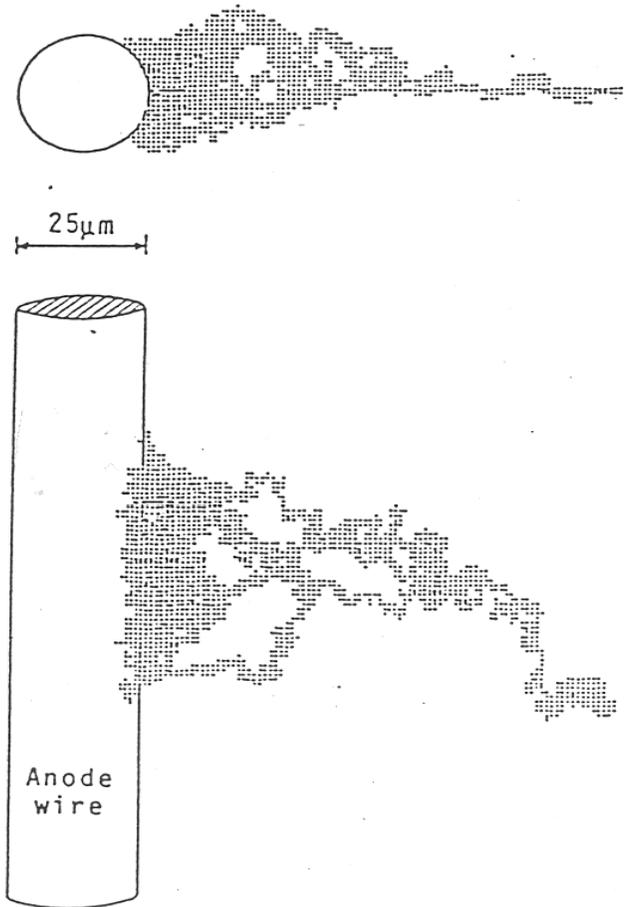


Fig. 7 Two dimensional displays of a simulated electron avalanche. Shading shows the density of electrons in the avalanche.

(Townsend avalanche)

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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... (see F.Sauli, 1977)
- “Magic gas” : 70% Ar, isobutane 29.6%, Freon 0.4% . High gains possible.

Problems induced by quencher gas

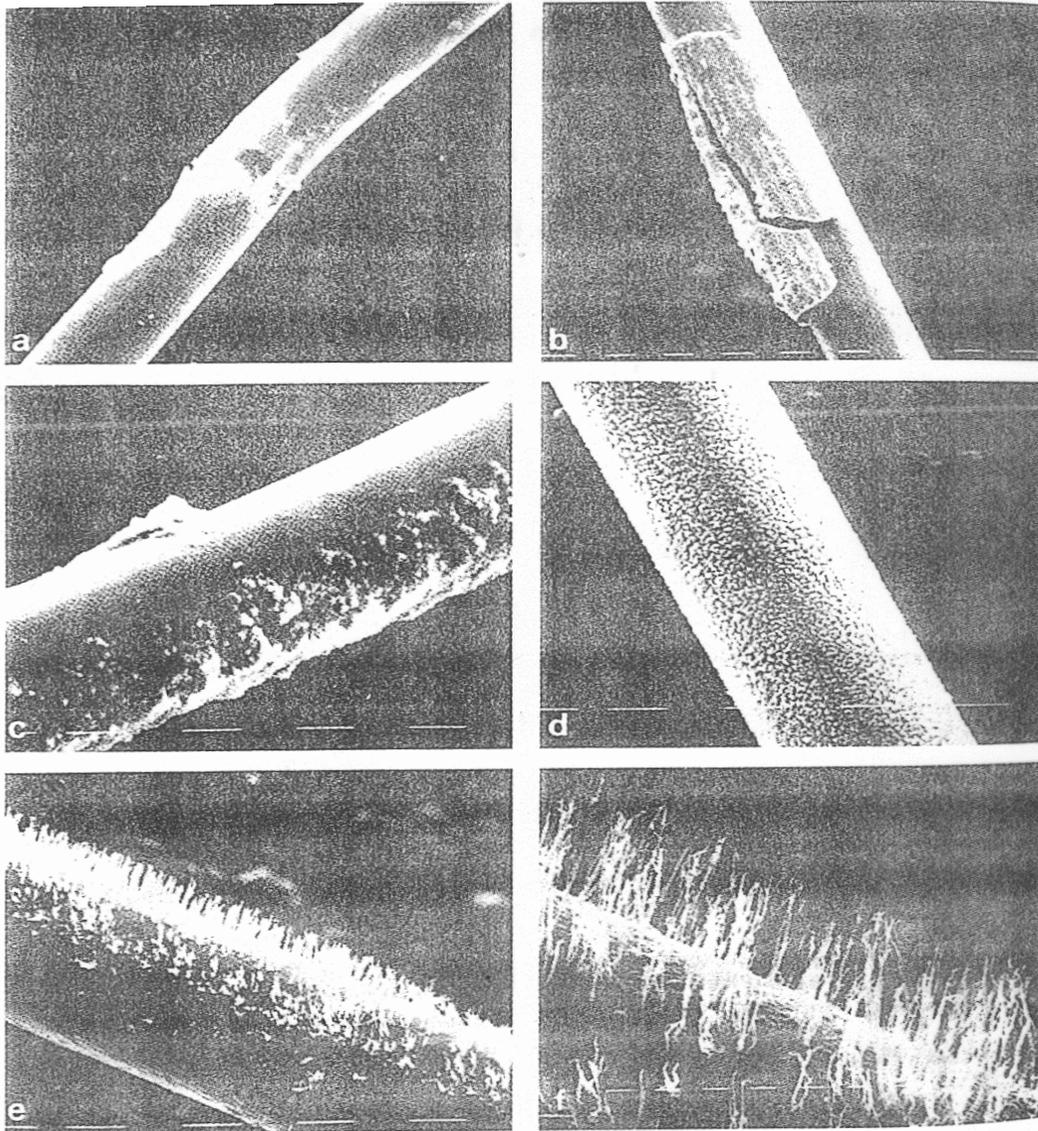


Fig. 4.31. Deposits on anode wires: (a) – Ar + C₂H₆; (b) – Ar + C₂H₆ + methylal; (c) – Ar + CO₂; (d) – perspex chamber; (e, f) – chambers with G10 fiber-glass and a cold trap (Adam 1983)

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

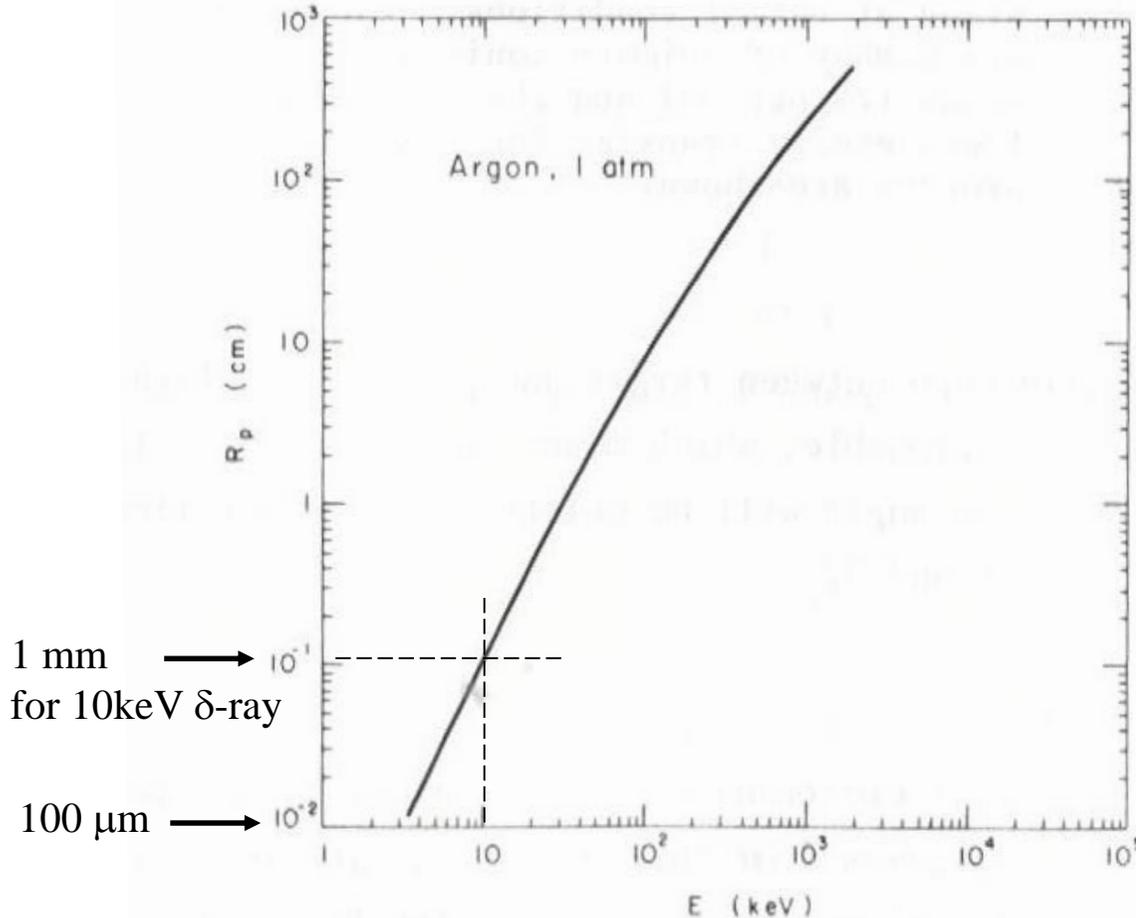


Fig. 5 Range of electrons in argon, at normal conditions as a function of energy, deduced from measurement in light materials⁸⁾

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

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

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

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

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

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

Up to now, what do we learned?

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

Noble gas do not “attach” e- but to a certain extend, O₂ and H₂O 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 ~ 1 cm/m (a magnetic field $B \parallel E$ decrease the transverse diffusion)

etc, etc...

We still have to see practical applications to this “theory”!!

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

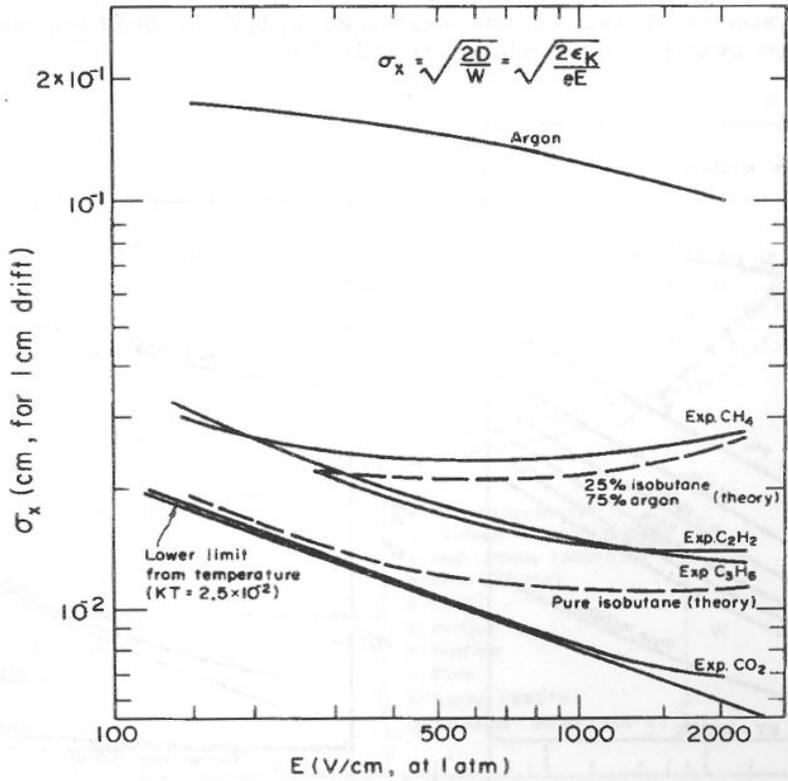


Fig. 35 Computed and experimental dependence of the standard deviation of electron diffusion from the electric field for 1 cm drift, in several gases at normal conditions²⁵⁾

Order of magnitude: drift over 1m $\Rightarrow \sigma \approx 1$ cm

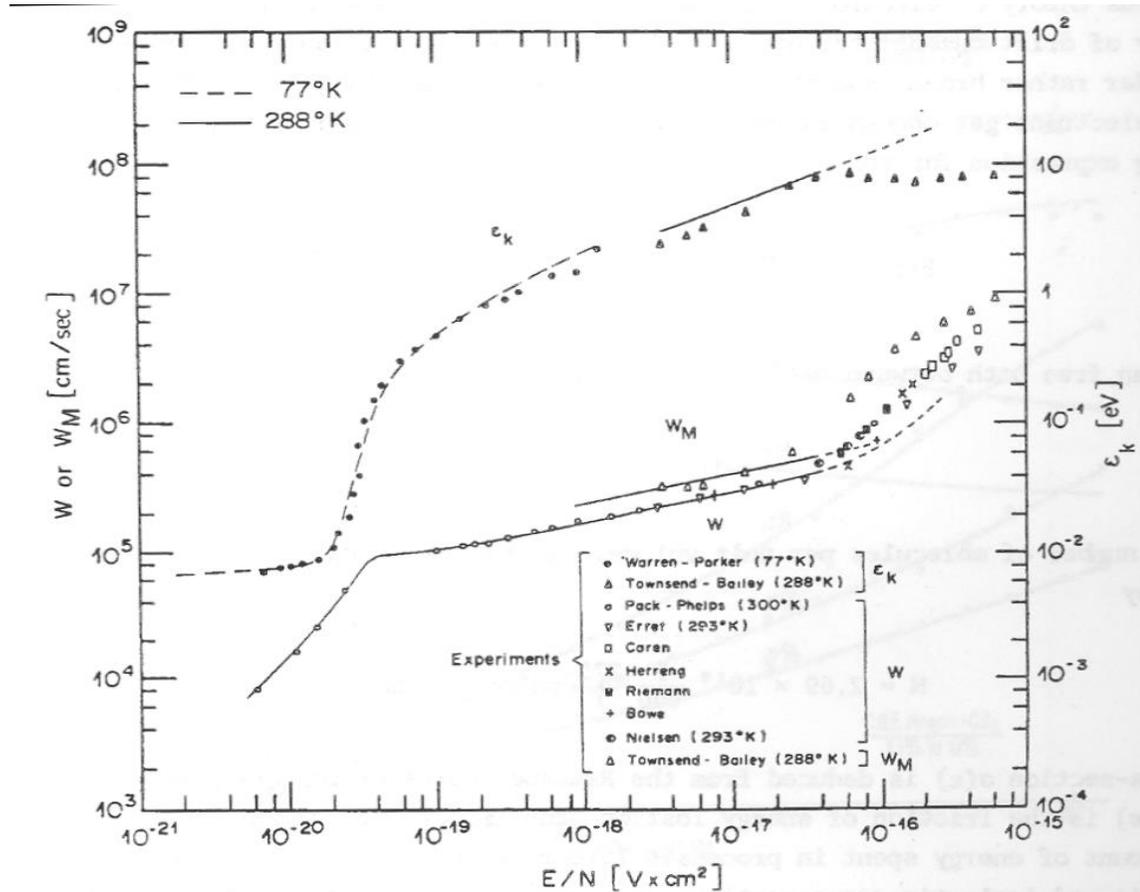
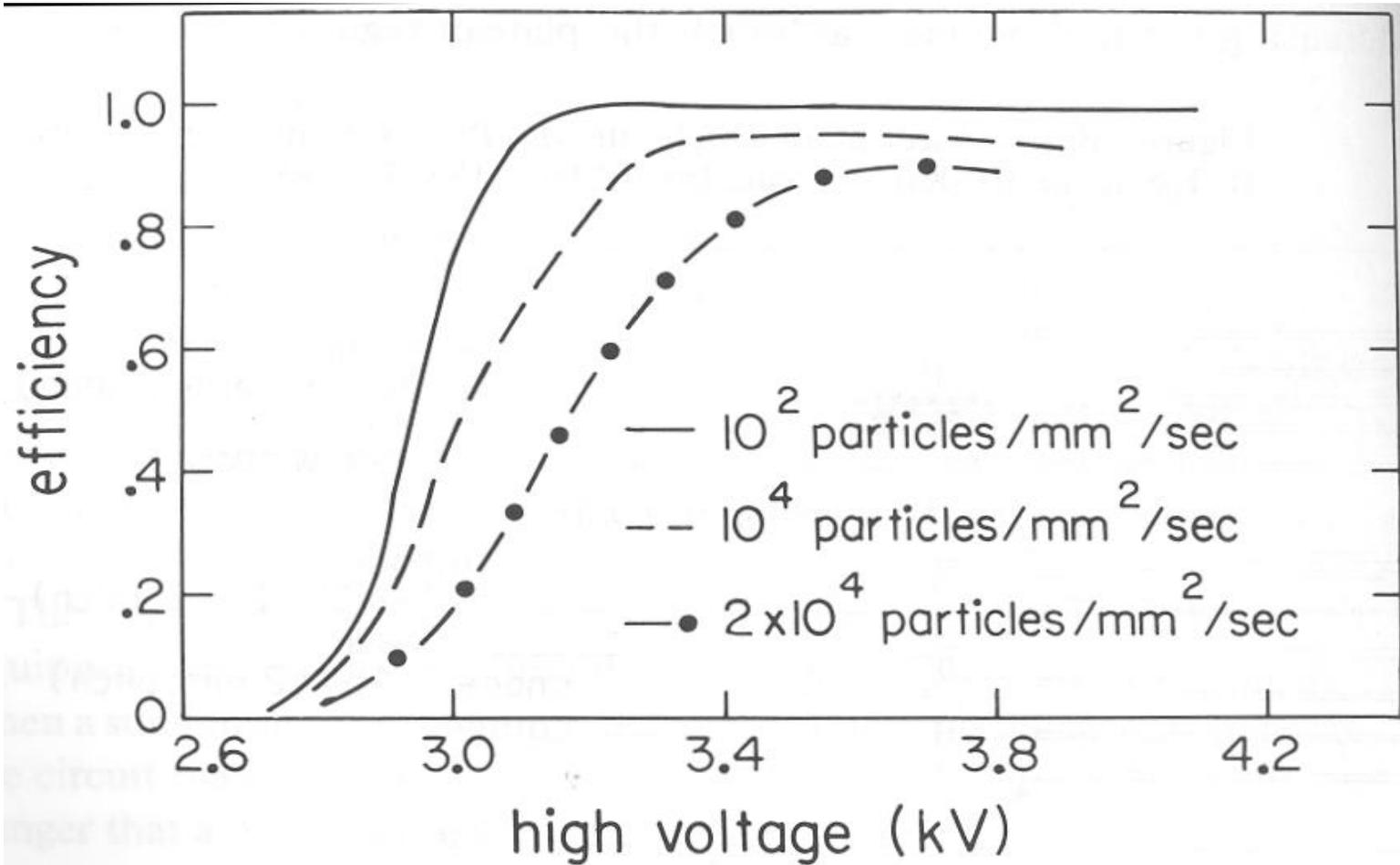


Fig. 31 Comparison of measured and computed drift velocities and characteristic energy for argon²⁶⁾

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:

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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!

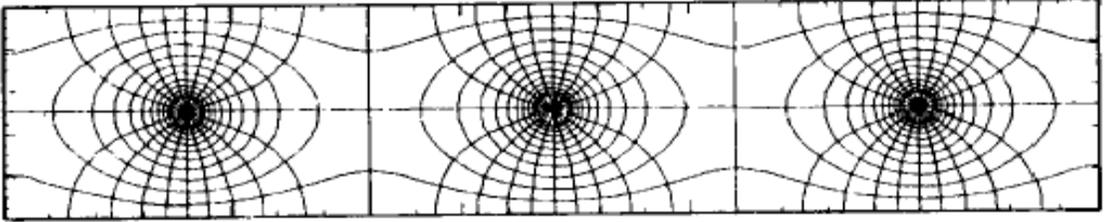
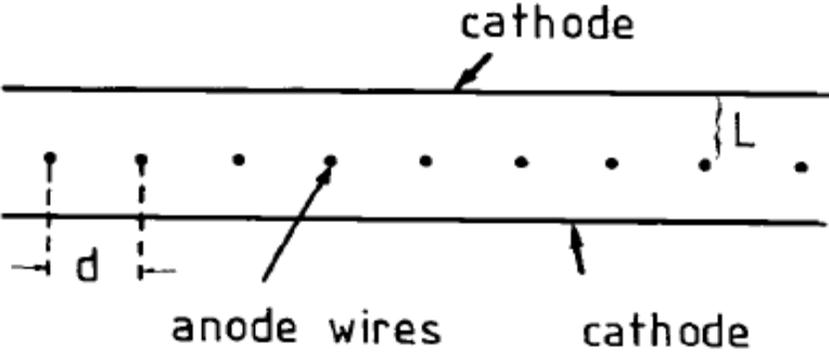
Few examples of gaseous detectors (including some information on diffusion in gas):

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

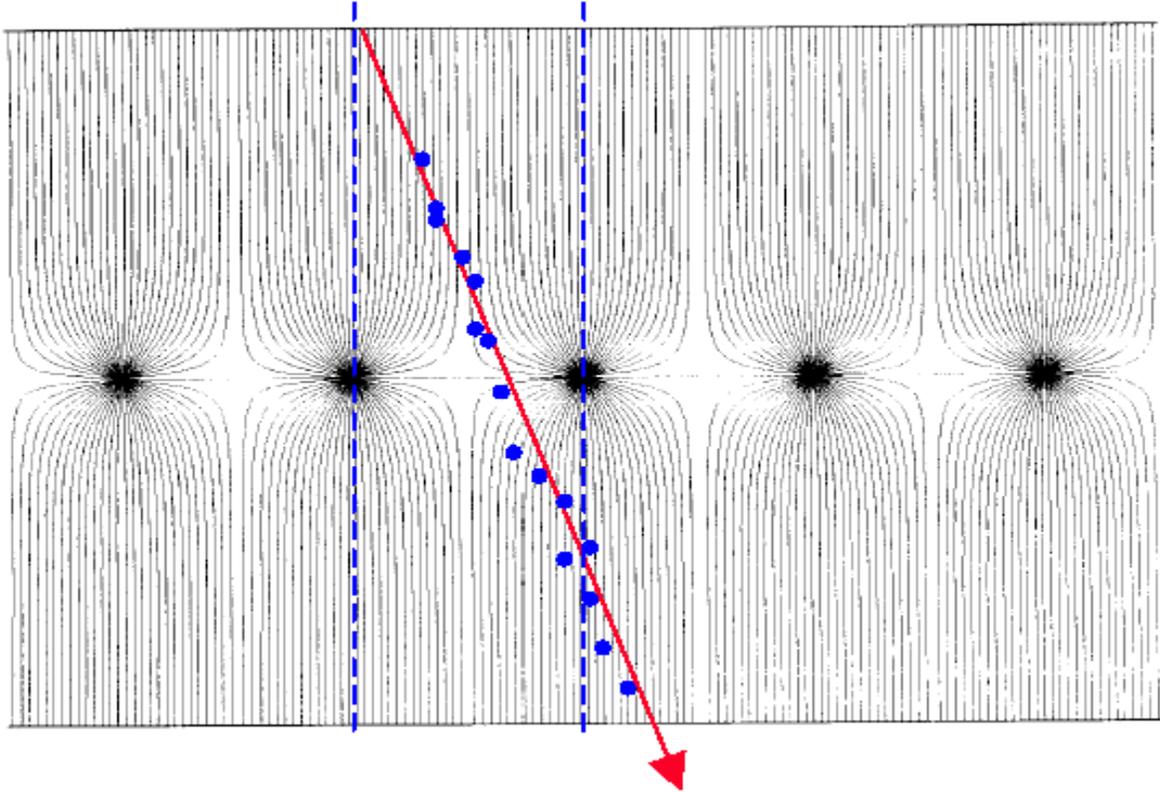
conclusion

Multi-Wire Proportional Chamber (MWPC)

G.Charpak
F.Sauli



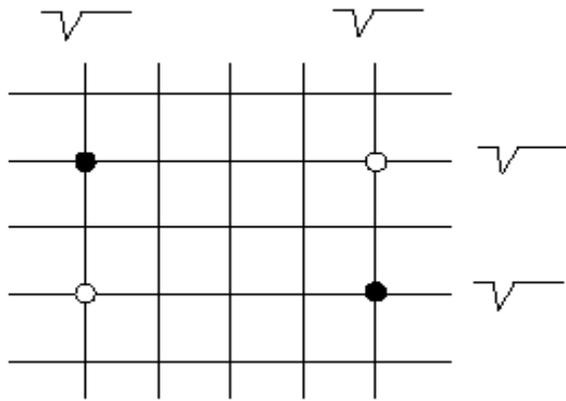
field lines and equipotentials around anode wires



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

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

Several measurements with one detector



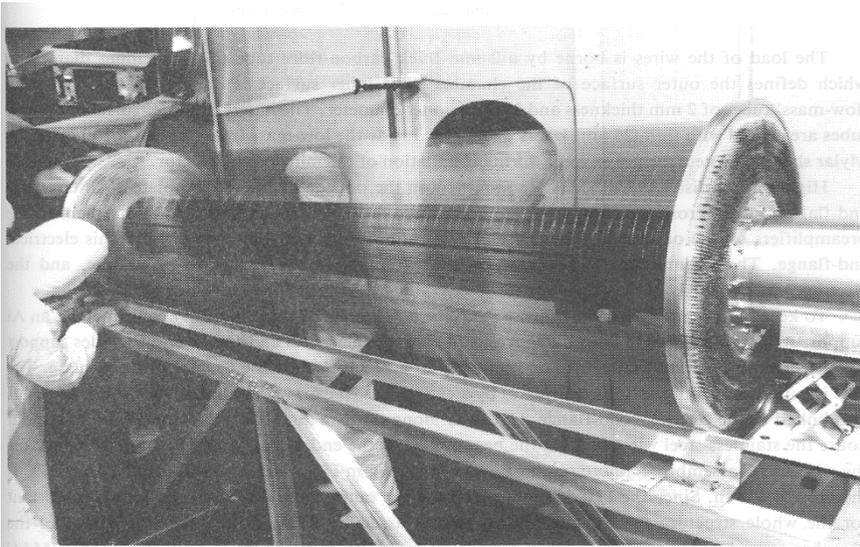
Simple solution:

two planes of crossing wires (90°). Because of ambiguities only possible if the multiplicity is not too high (otherwise combinatorial 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:

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

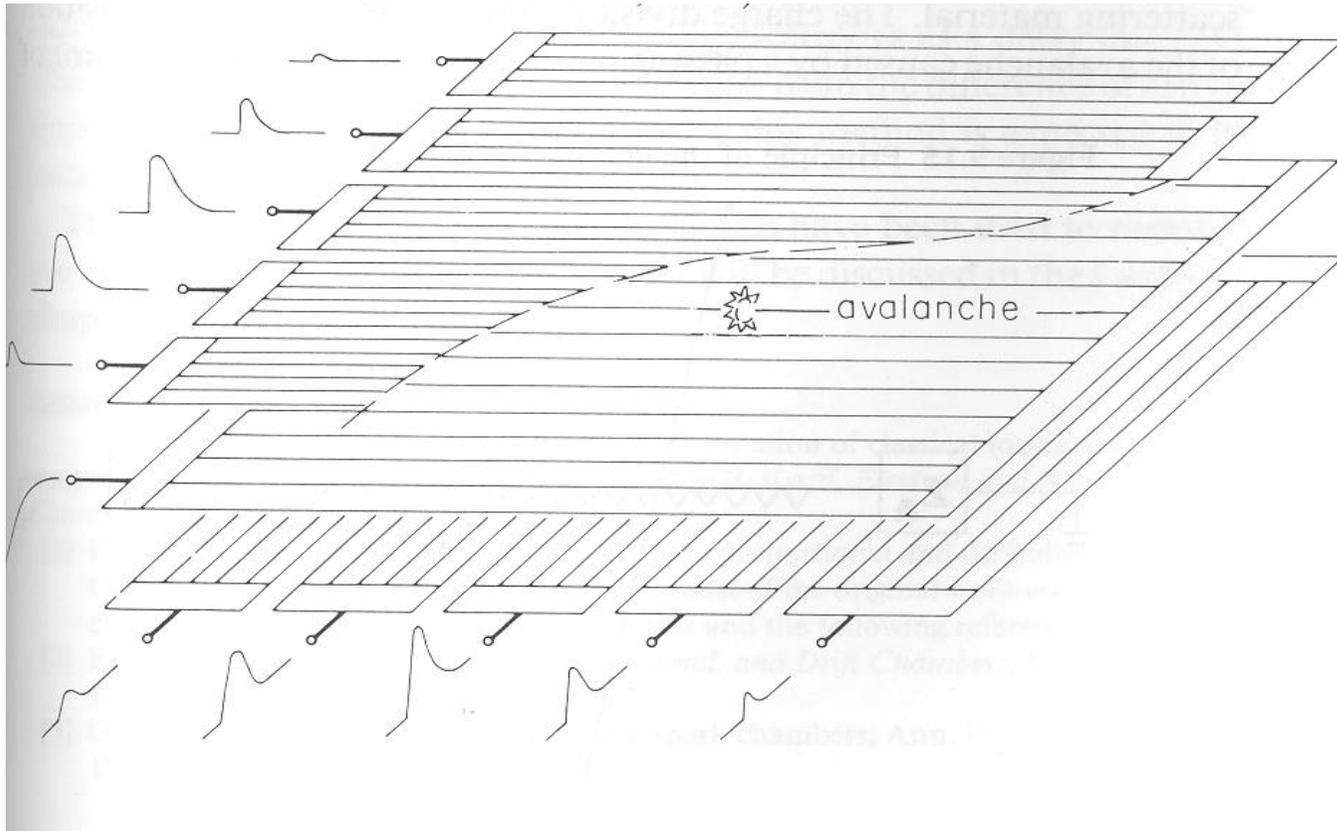
with σ =wire section (mm²), T=stretching (kg)

Tungsten: $s_g \sim 300 \mu\text{m}$

for $L=5\text{m}$ and $\varnothing=100 \mu\text{m}$, $T=350\text{g}$

Deformation (!) if: $T_c/\sigma > 200$ to 400 kg/mm² for W^{63}

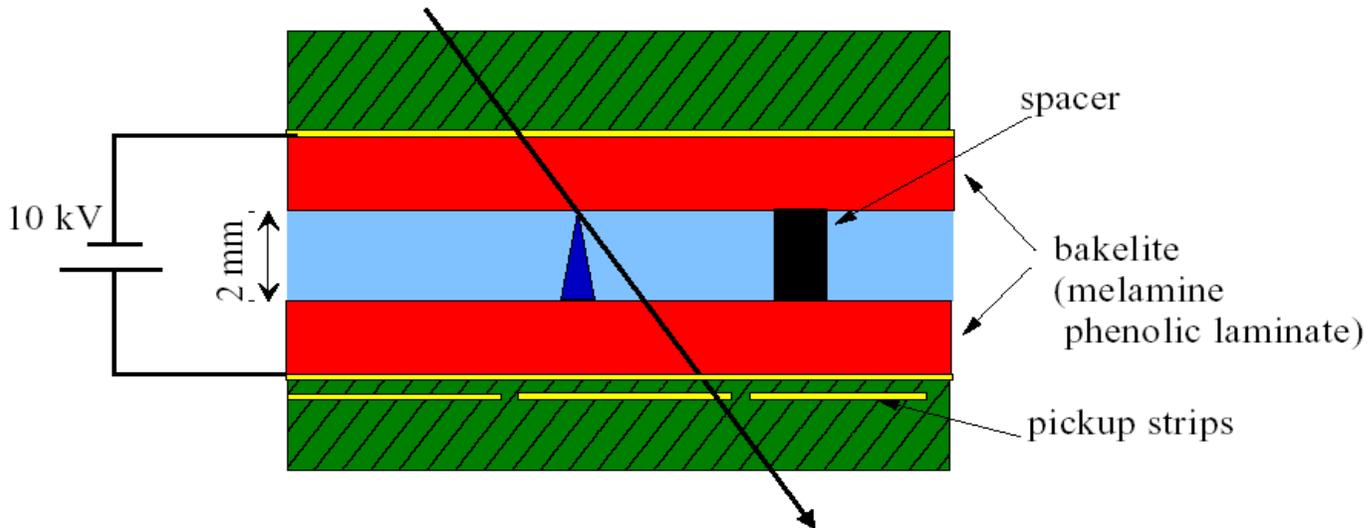
Other possible solution



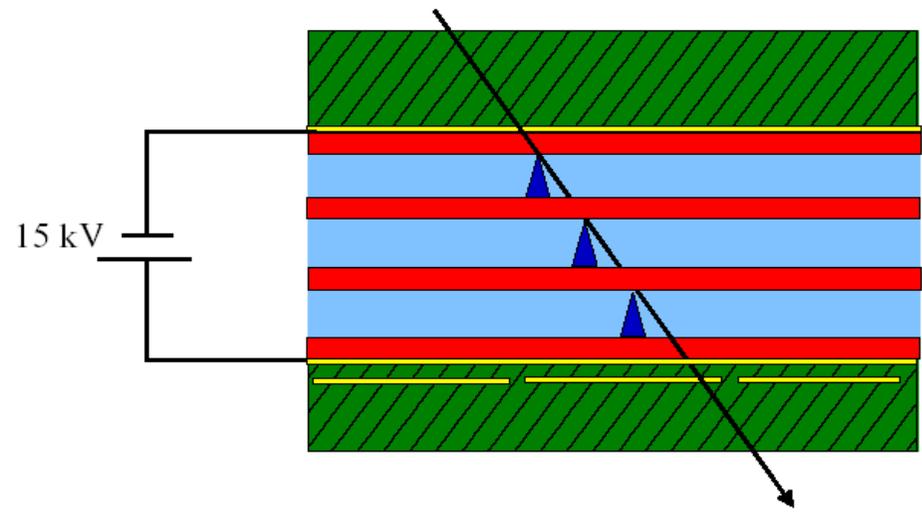
One divide cathode planes in strips, each, readout individually

No wires !!

Resistive Plate Chamber (RPC)



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



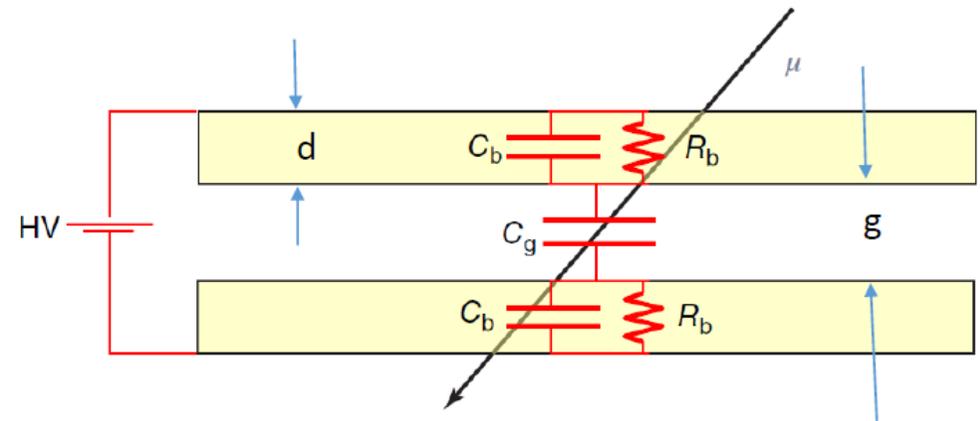
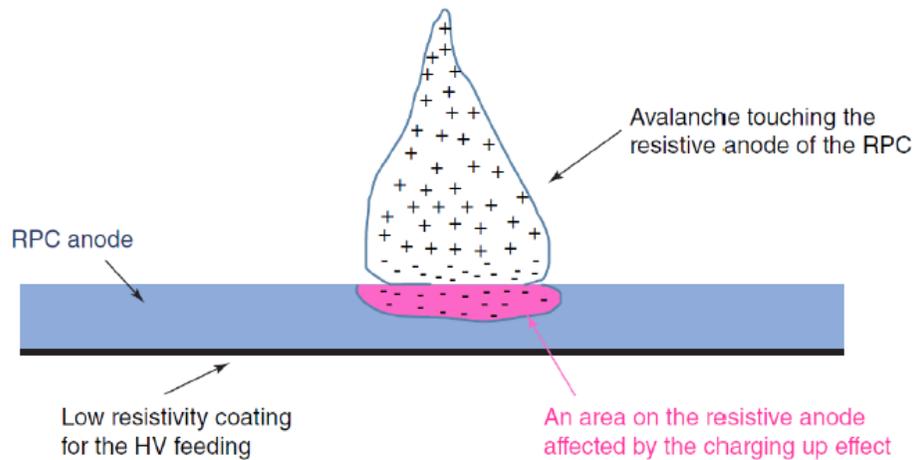
No more wires (pillars to maintain space)

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



$$\tau = 2R_b \left(\frac{C_b}{2} + C_g \right) = 2\rho_b \frac{d}{S} \left(\frac{1}{2} \epsilon_0 \epsilon_r \frac{S}{d} + \epsilon_0 \frac{S}{g} \right) = \rho_b \epsilon_0 \left(\epsilon_r + 2 \frac{d}{g} \right)$$

Could be useful for RD51 community

Micro-Strip Gaz Chamber (MSGC)

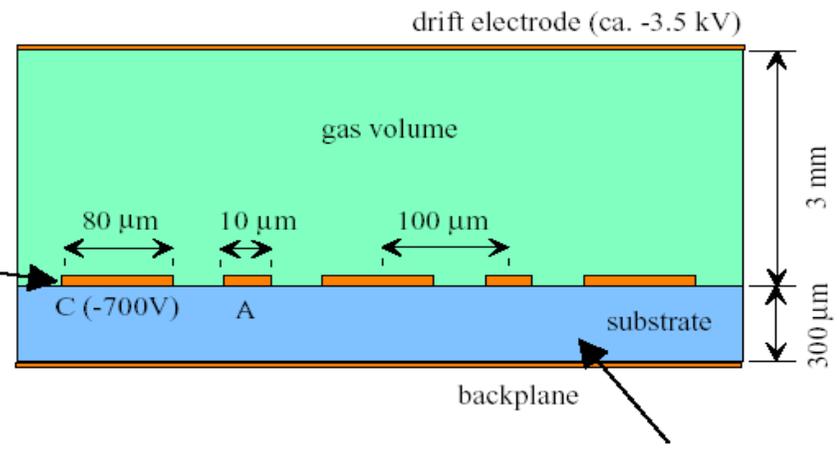
Considered by CMS experiment,
but aging problems...(replace by Si)

Ar:DME 50:50

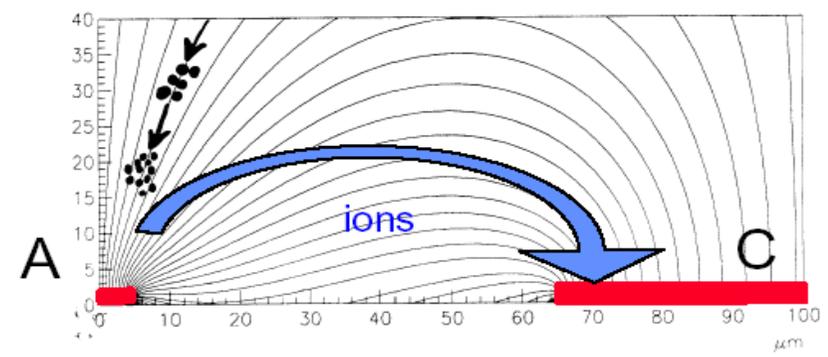
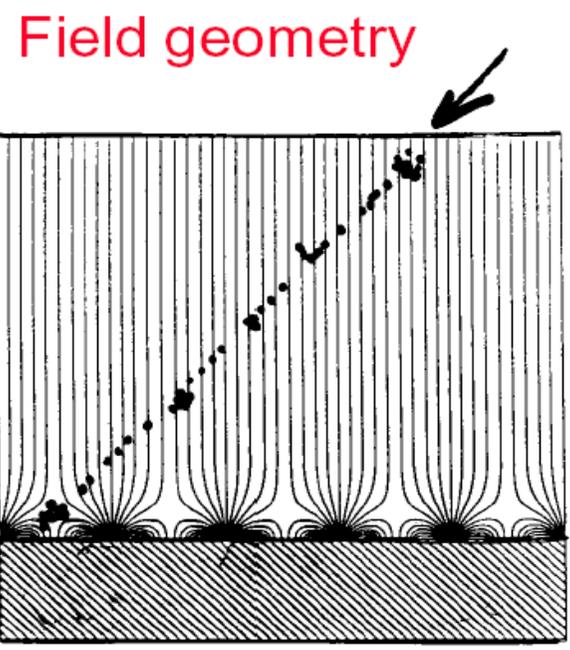
Resolution ~30 to 40 μ m

Gain <10000

Gold strips
+ Cr underlayer



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

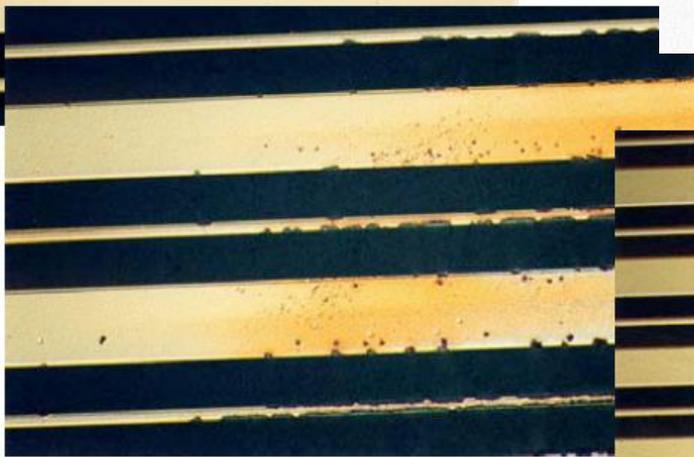
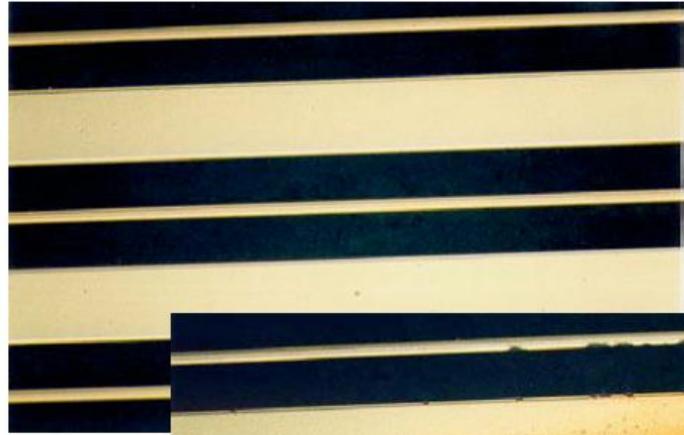


Fast ion evacuation \rightarrow high rate capability
 $\approx 10^6 /(\text{mm}^2 \cdot \text{s})$

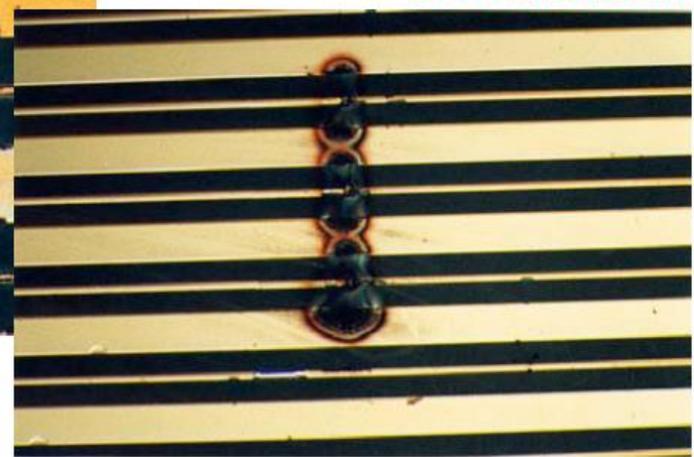
Micro-Strip Gaz Chamber (MSGC)

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

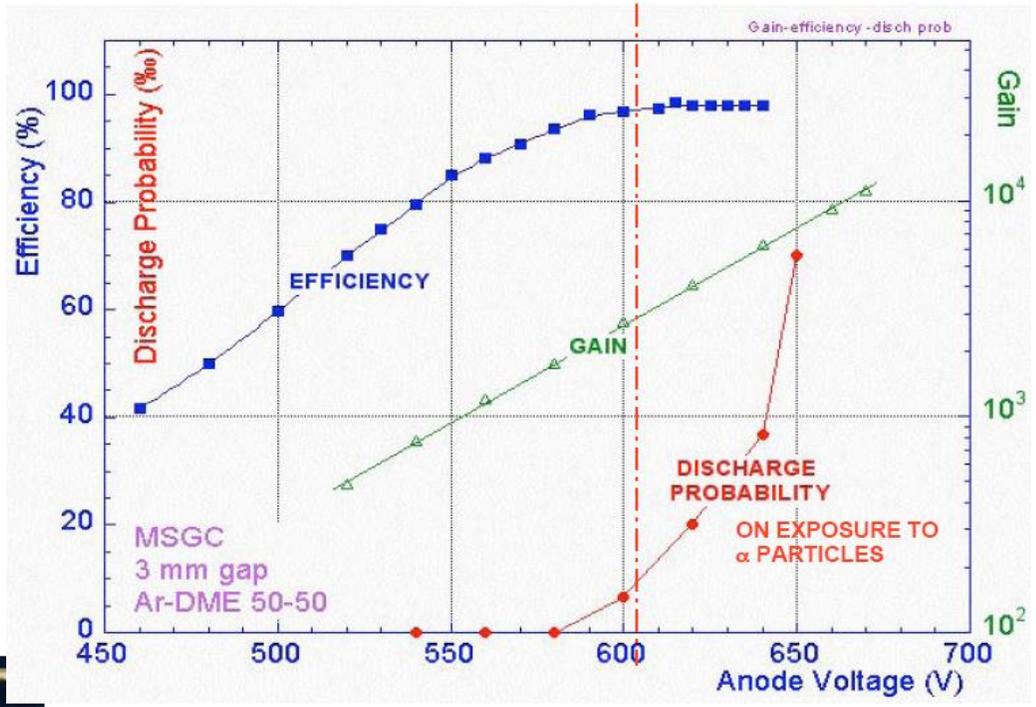
MSGC DISCHARGE PROBLEMS:



MICRODISCHARGES



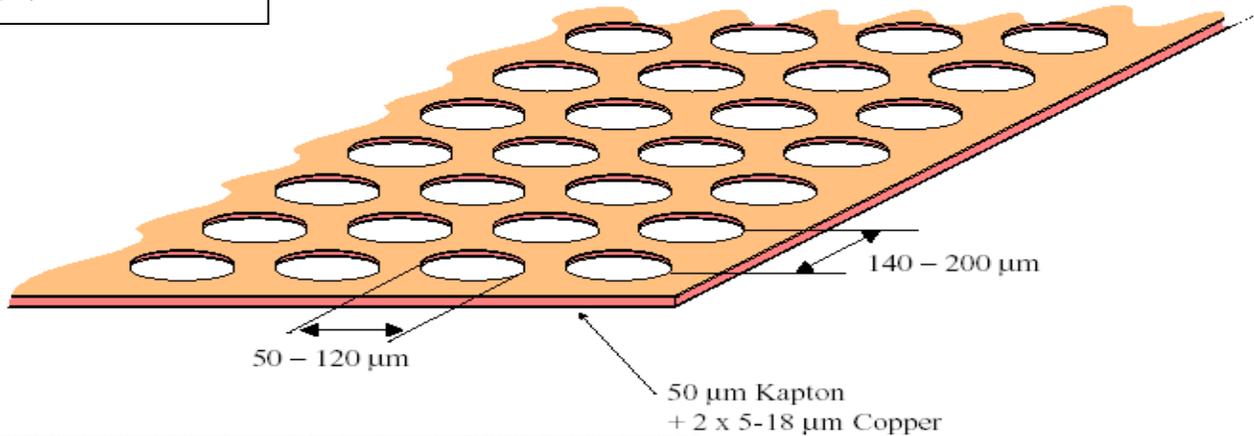
FULL BREAKDOWN



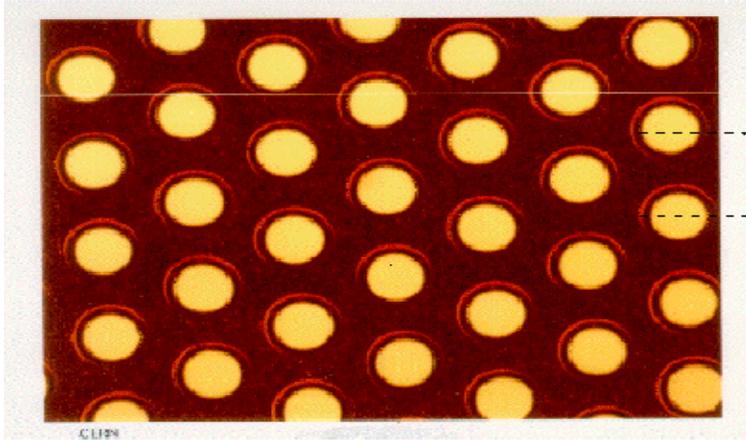
Signal zone (drift zone) and amplification zone are separated!

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

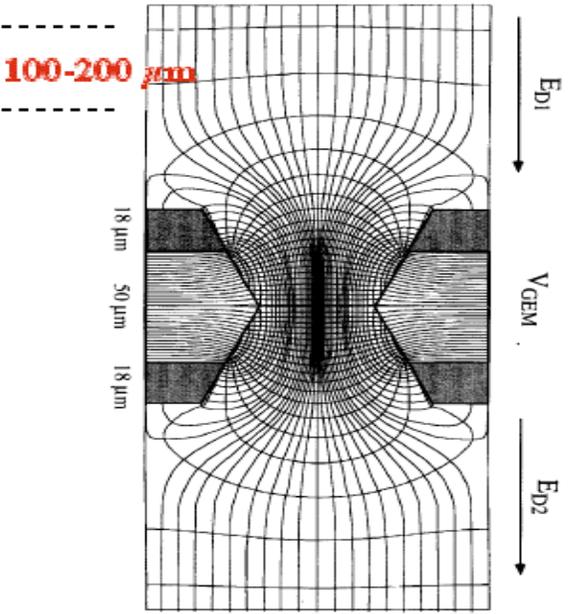
Gaz Electron Multiplier (GEM)



Kapton = isolant



Micro photo of a GEM foil



amplification gap of $\sim 2\text{mm}$ \Rightarrow signal width $\sim 20\text{ns}$

Limitations:
shorts in one "hole"
 \Rightarrow short on the full area

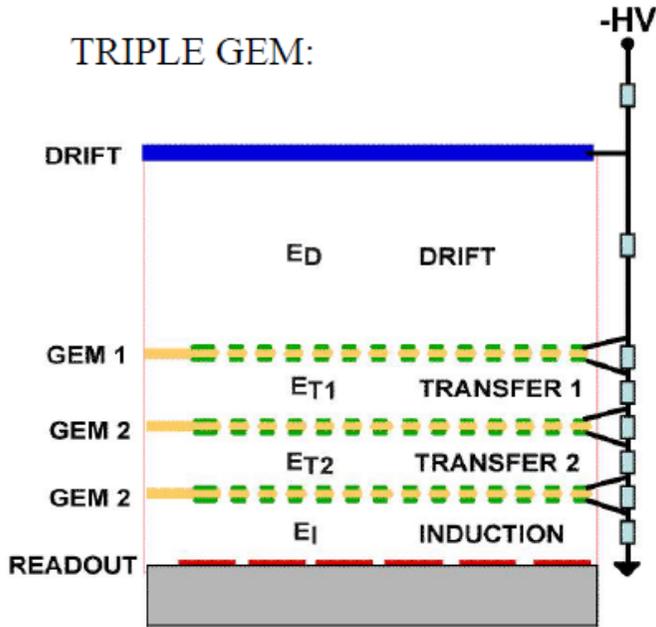
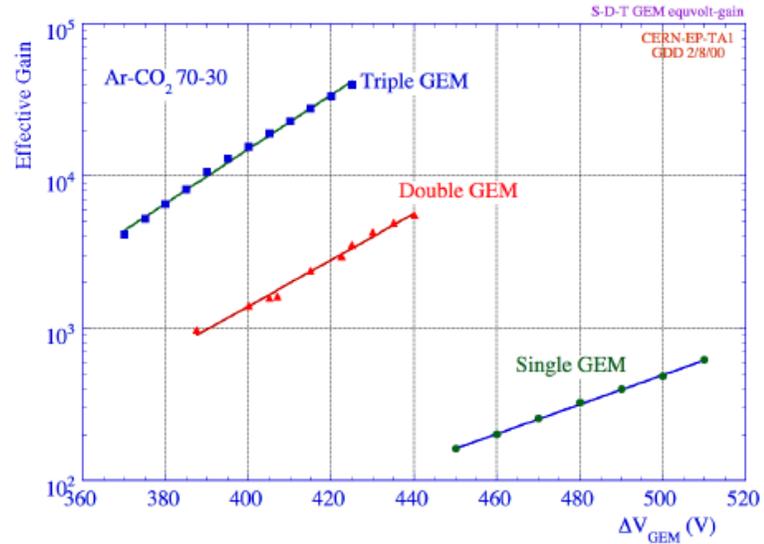
Gain limitation?

Gaz Electron Multiplier (GEM) (multi-stage)

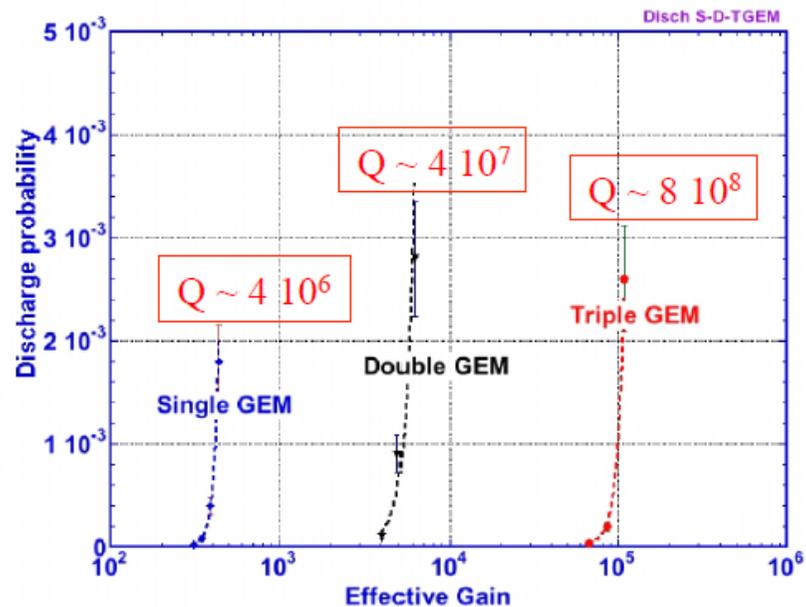
(multi-stage)

Construction complexity?

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



DISCHARGE PROBABILITY VS GAIN:

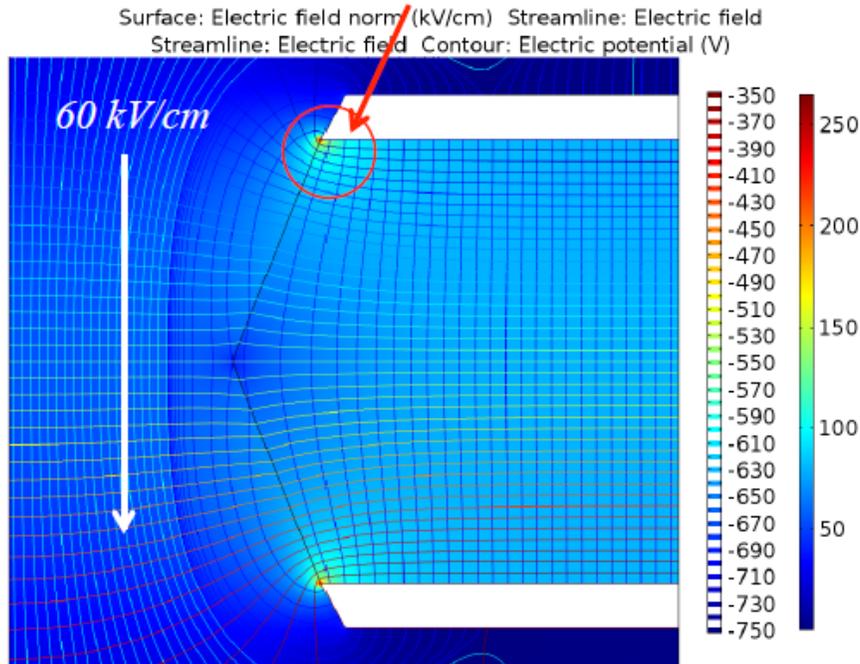


COMPUTED FIELD NEAR THE CATHODE RIMS IN GEM

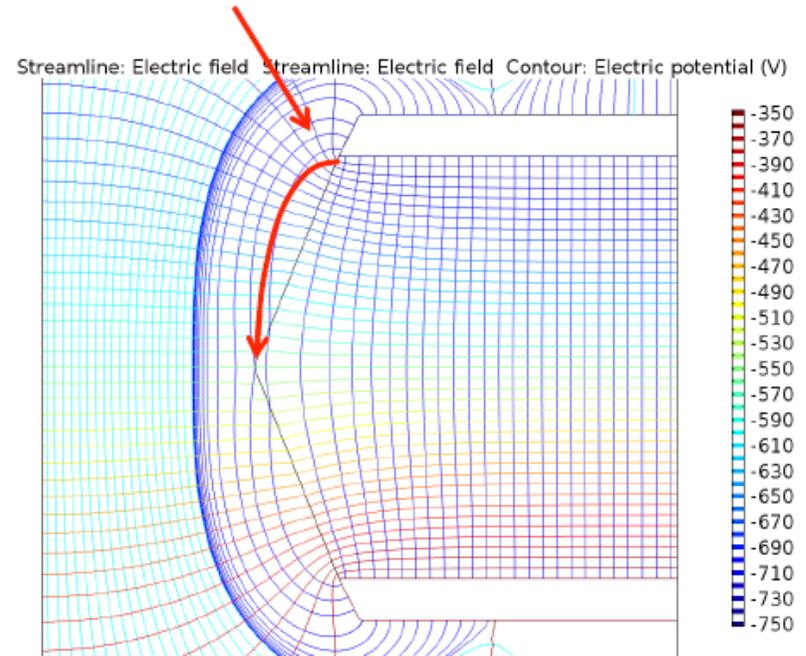
$$V_{\text{GEM}} = 375 \text{ V} \quad V_{\text{T}} = V_{\text{I}} = 3.5 \text{ kV/cm}$$

Filippo Resnati, Personal communication today

160 kV/cm



FIELD EMISSION
AND/OR
IONIZATION

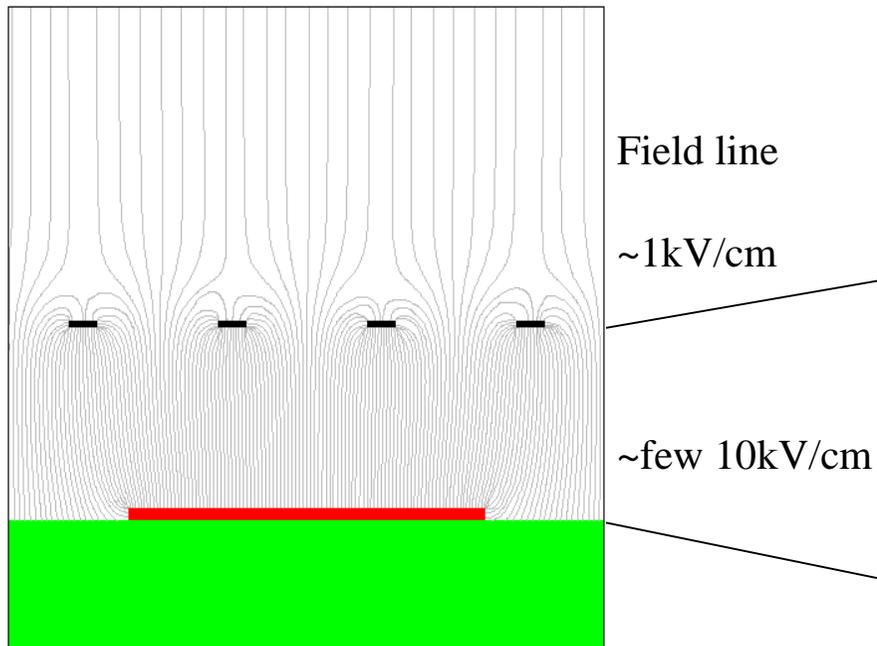
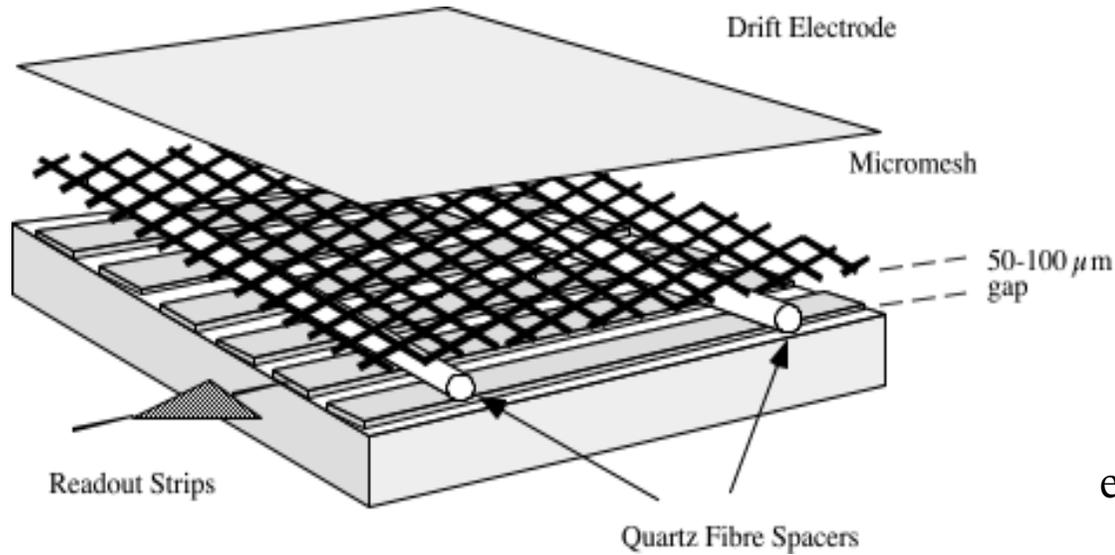


WAITING FOR A DEDICATED FULL GAIN CALCULATION “A LA MSGC”

MicroMegas

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

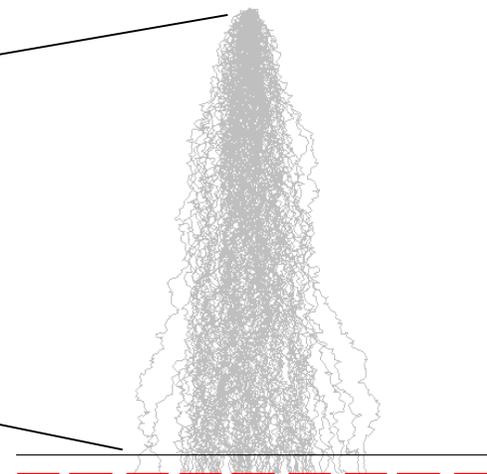
In few years, many improvements in these detectors construction: mainly using industrial lithography process.



e- trajectory in the amplification zone.

e- are scattered, so ions will be catch by the grid -micromesh- (they go back).

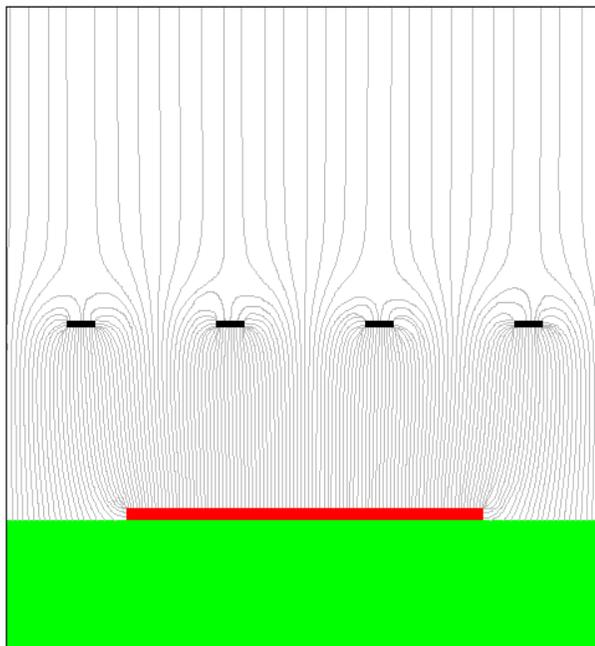
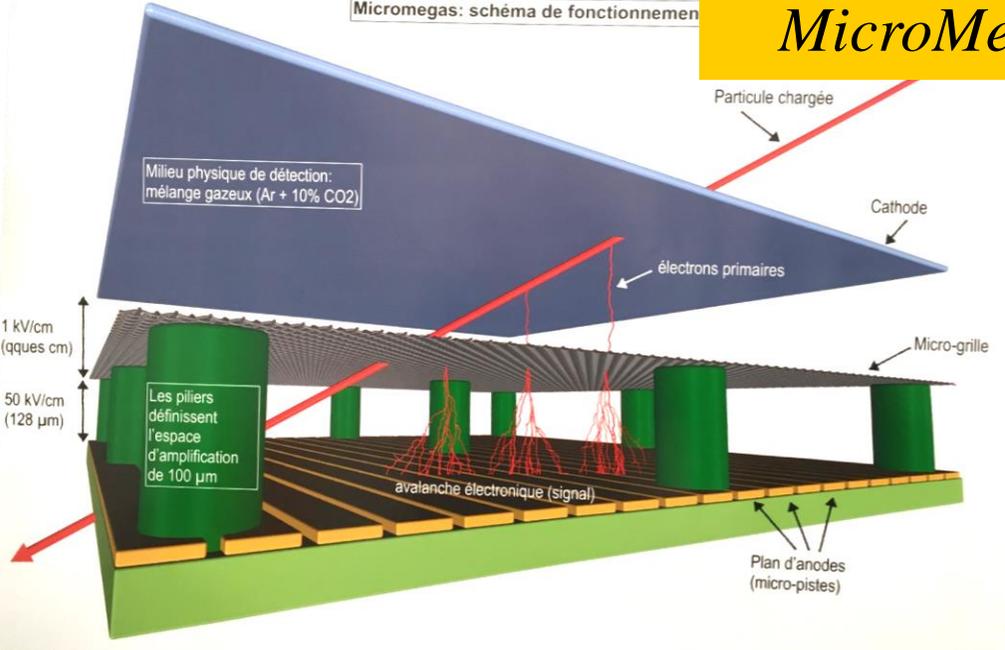
Ions disappeared in about $\sim 100\text{ns}$



Micromegas

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

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



Field line

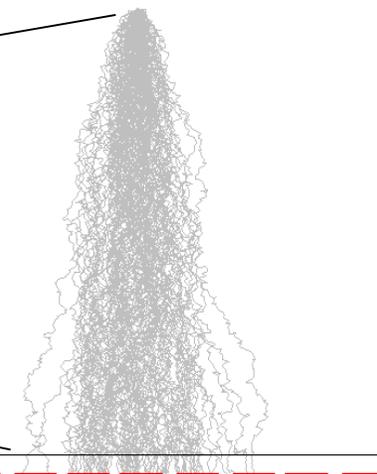
~1kV/cm

~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



Micromegas: schéma de fonctionnement

Drift gap of ~5mm => possibility to do a micro-TPC track reconstruction

Milieu physique de détection: mélange gazeux (Ar + 10% CO₂)

Charged particle

Cathode

électrons primaires

1 kV/cm (qqes cm)
50 kV/cm (128 μm)

Les piliers définissent l'espace d'amplification de 100 μm

mesh

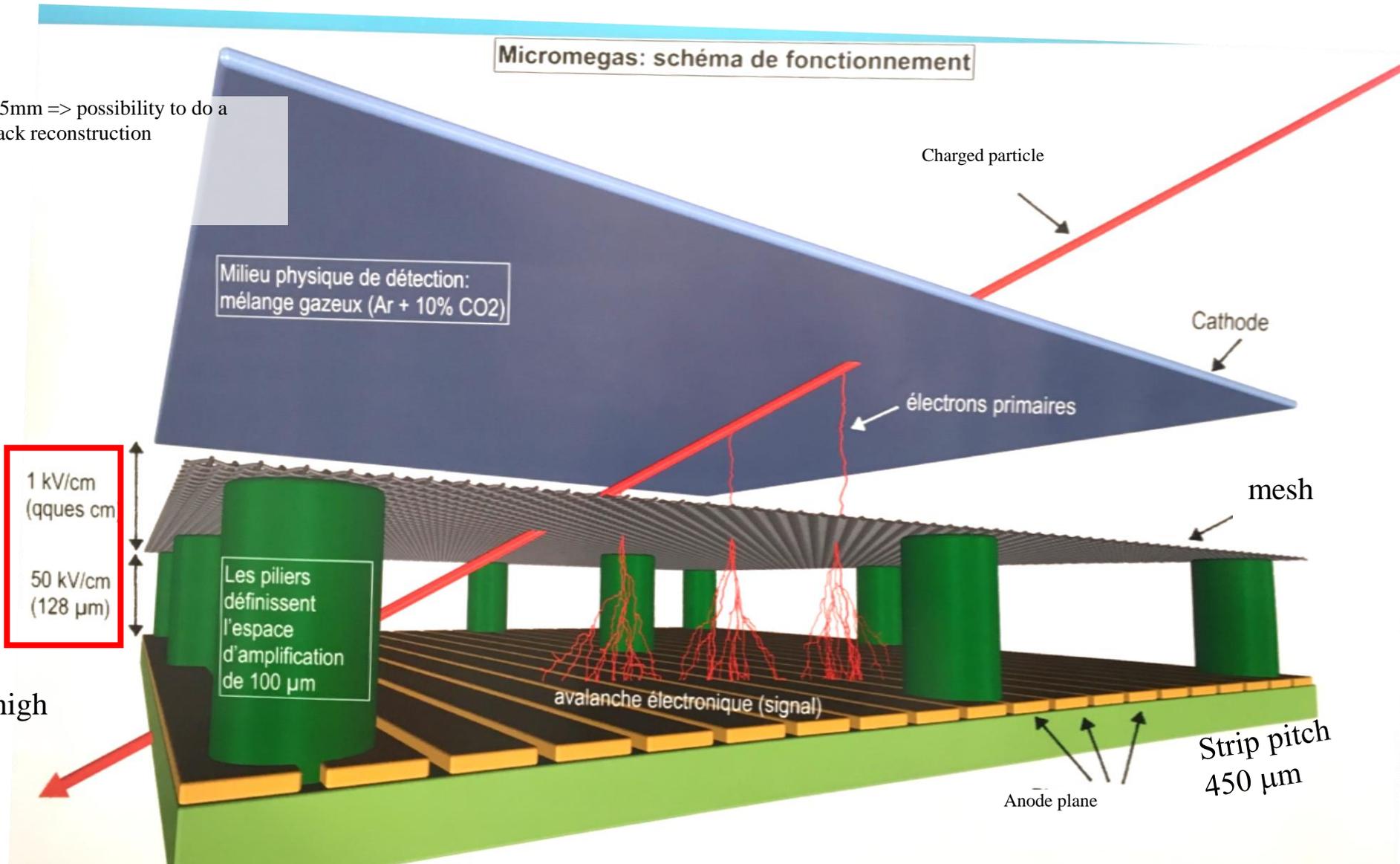
Pillars 128 μm high

avalanche électronique (signal)

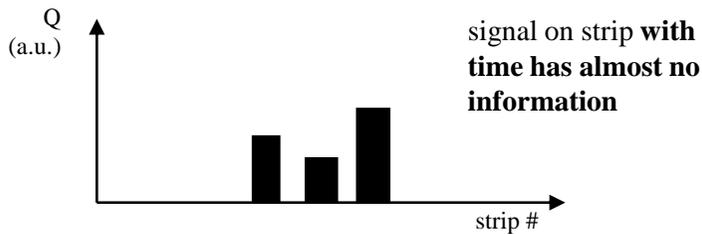
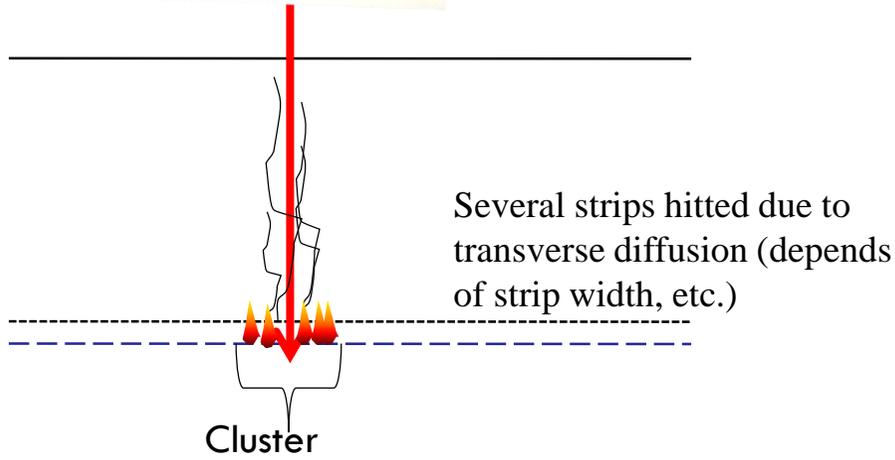
Anode plane

Strip pitch 450 μm

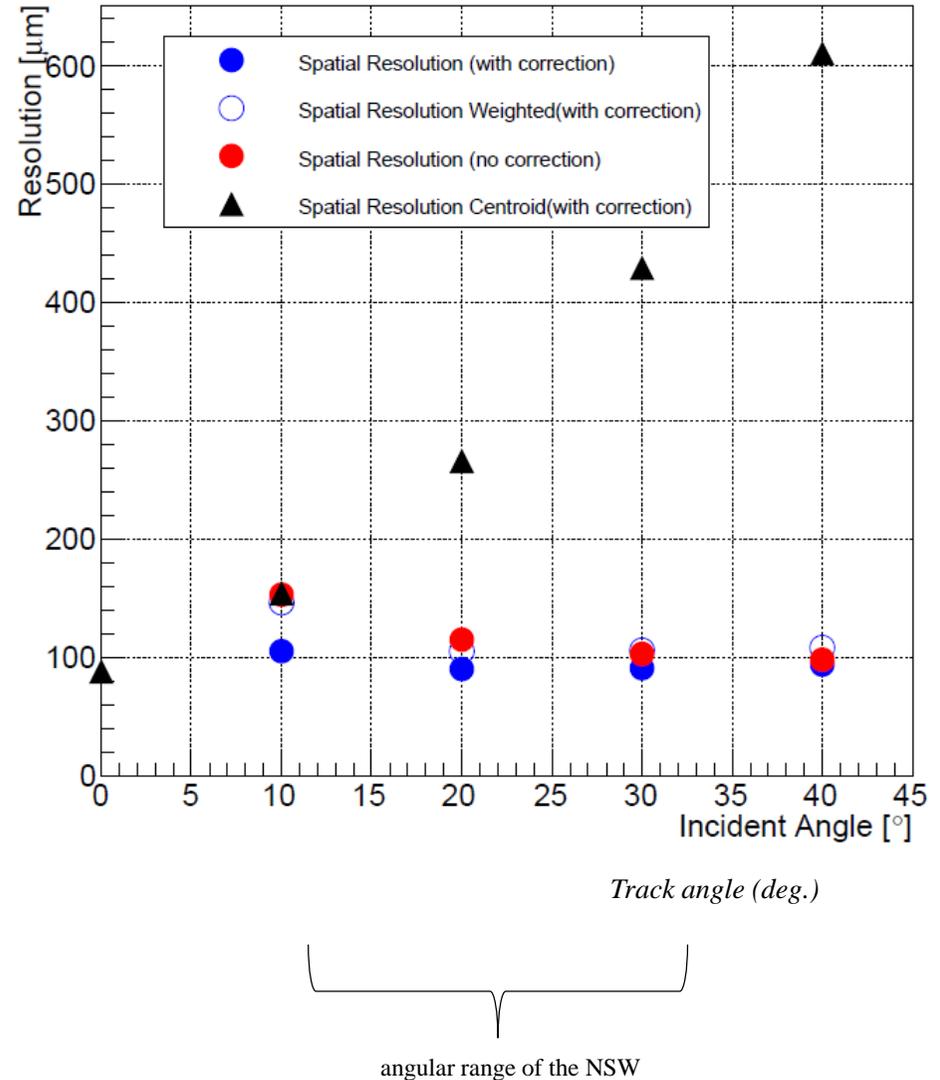
Not shown : resistive strip (HV) + insulator layers on top of strips plane



Micromegas (micro-) TPC mode

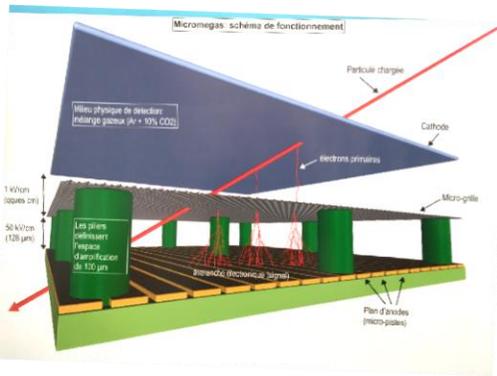


microns

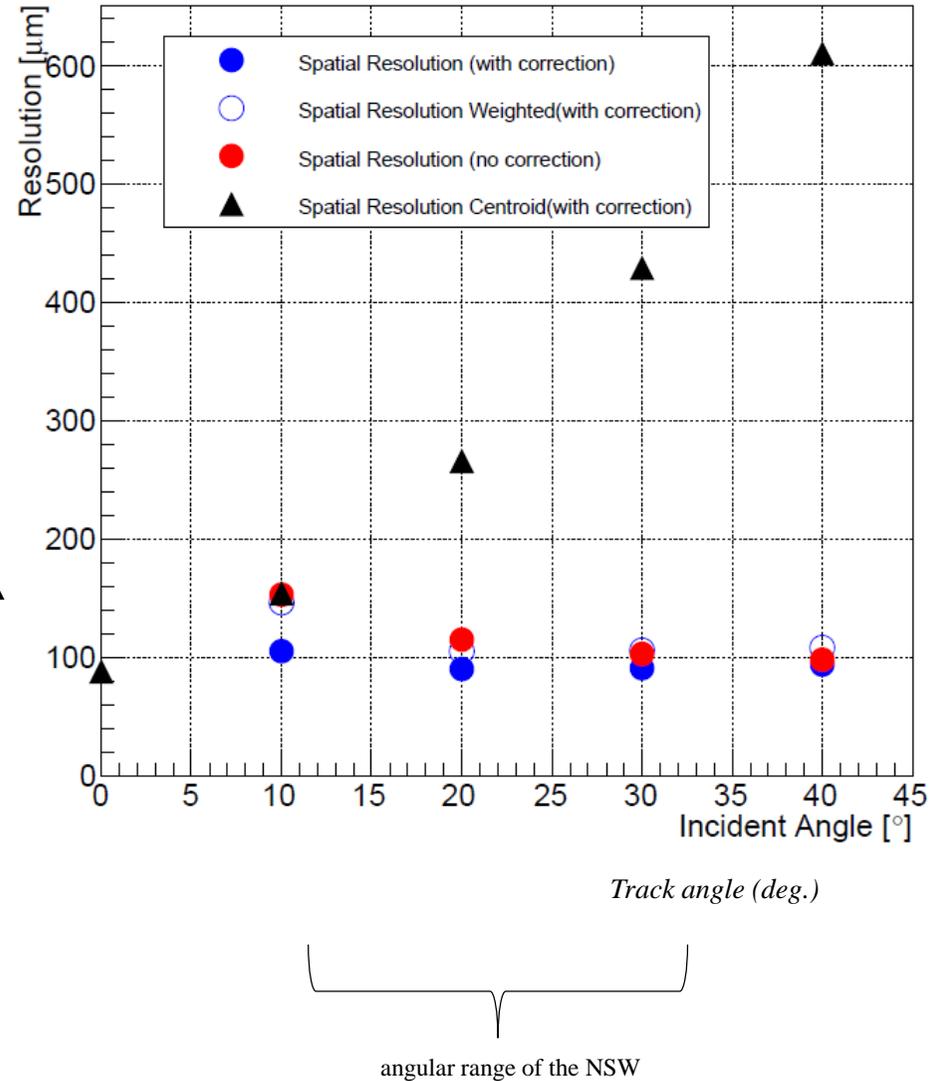
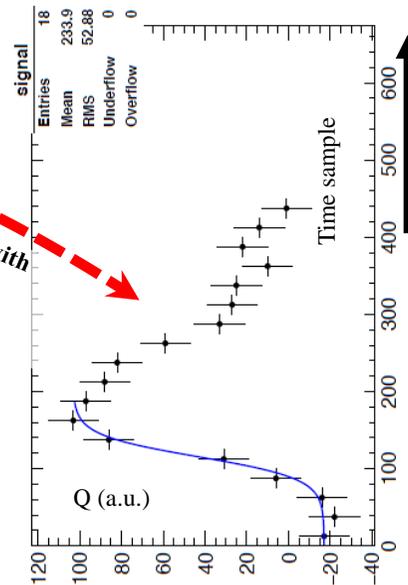
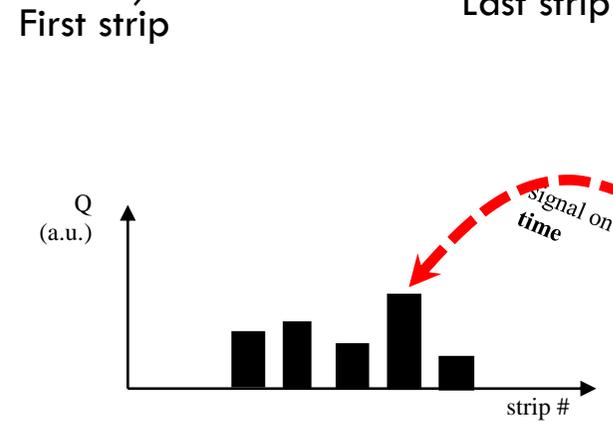
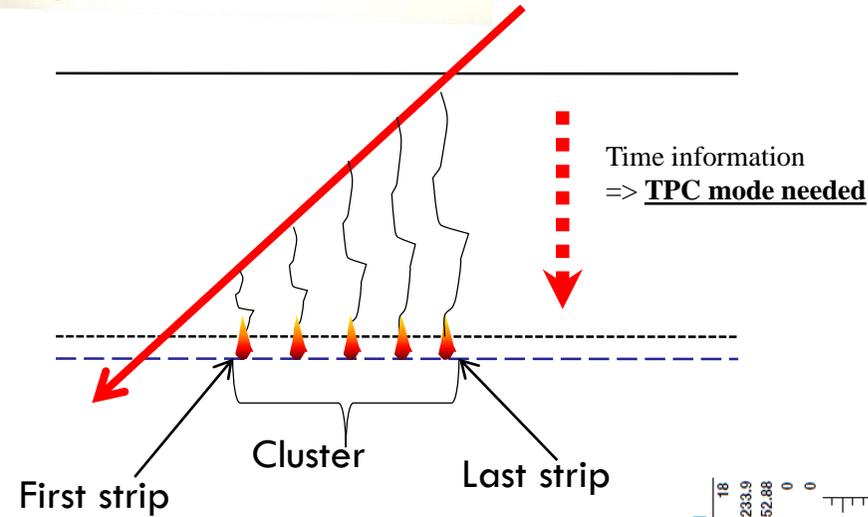


In MM gaz, ~1 ionization cluster each ~200 microns of track.

Micromegas (micro-) TPC mode

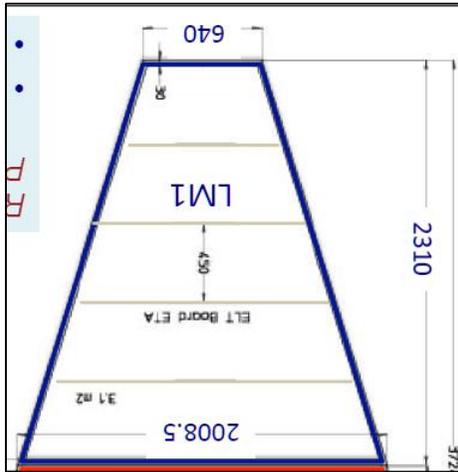


microns

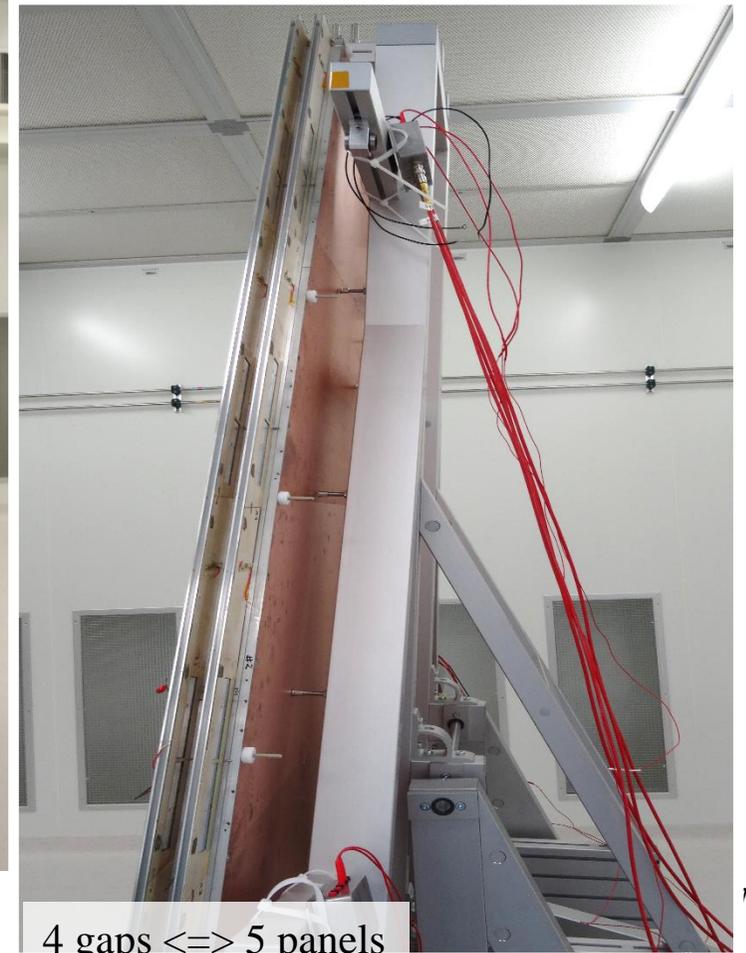


In MM gaz, ~1 ionization cluster each ~200 microns of track.

Micromegas 4 gaps chamber/module when finished

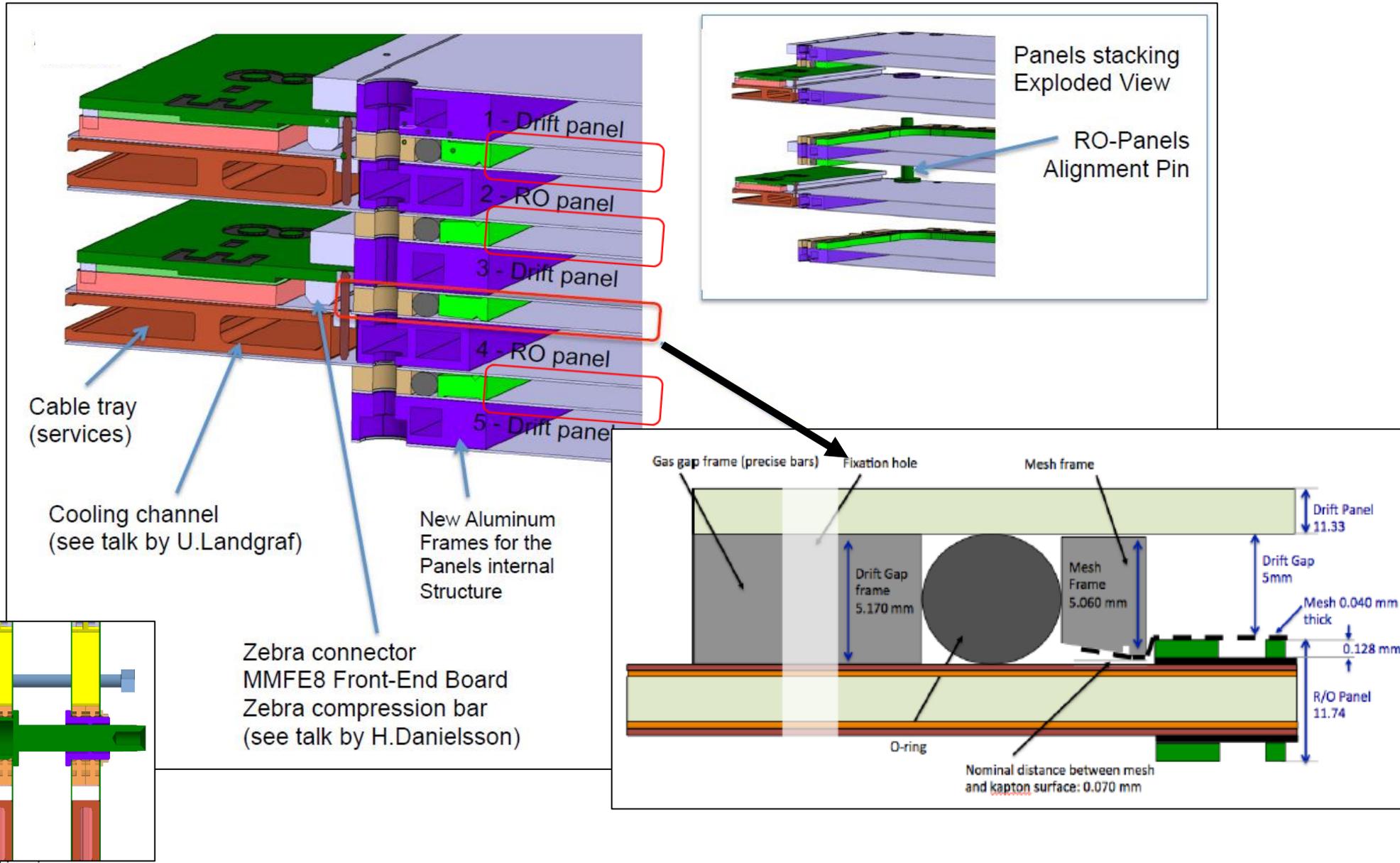


2.3 x 2.0 ~3 m²
(h x L)



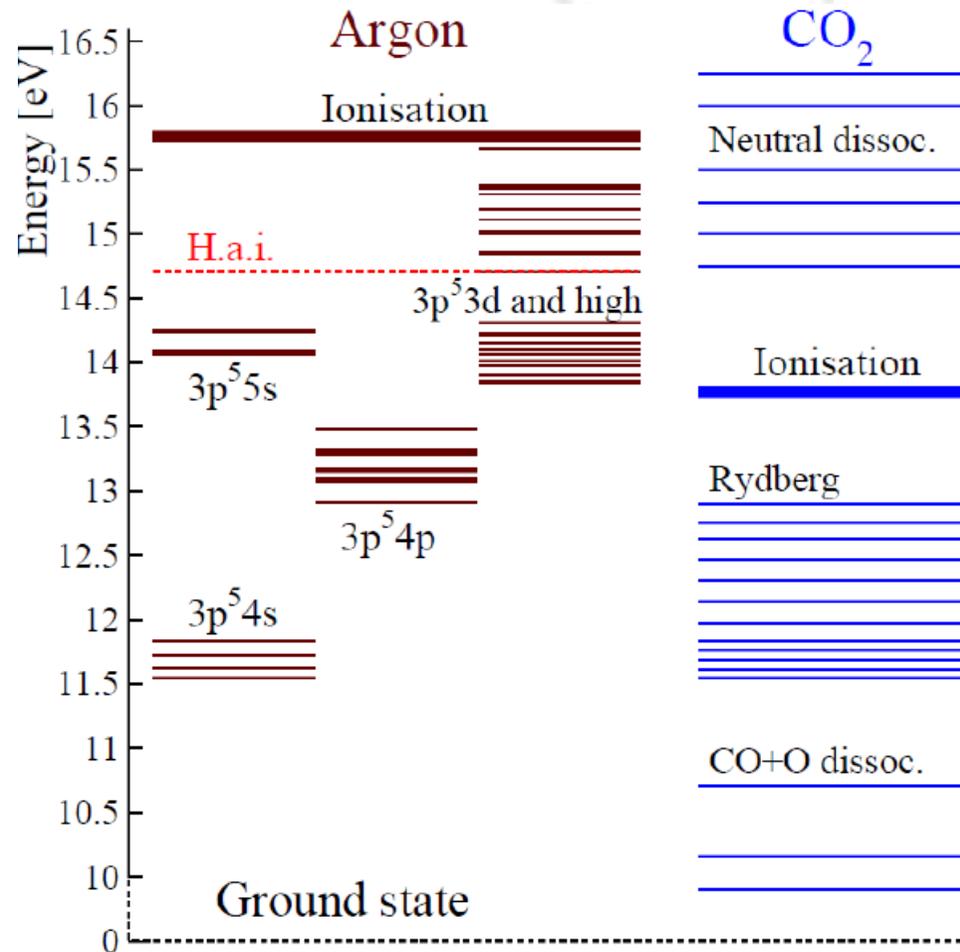
4 gaps \Leftrightarrow 5 panels

Micromegas detector design (physicist and engineer work)



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)

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

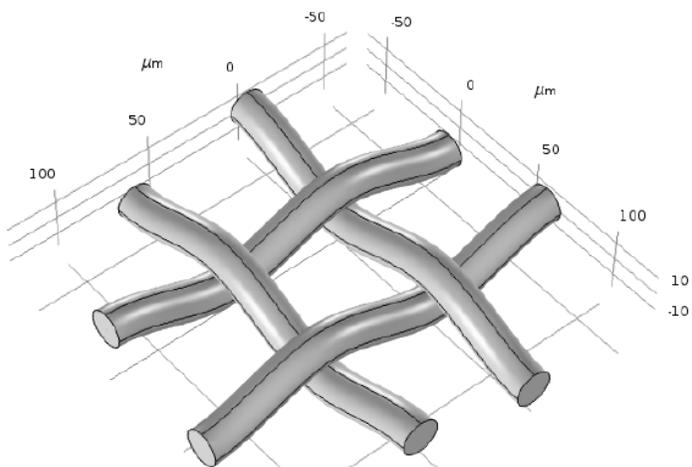
- ❖ Townsend coefficients (α), production frequencies of the ionisations and excitations calculated with **Magboltz**
- ❖ r_{Pen} : Penning transfer rate

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

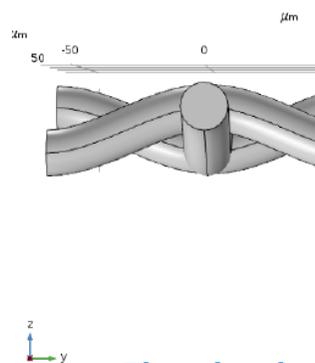
$$G_{total} = G / (1 - \beta G)$$

on the YZ plane, through a wire

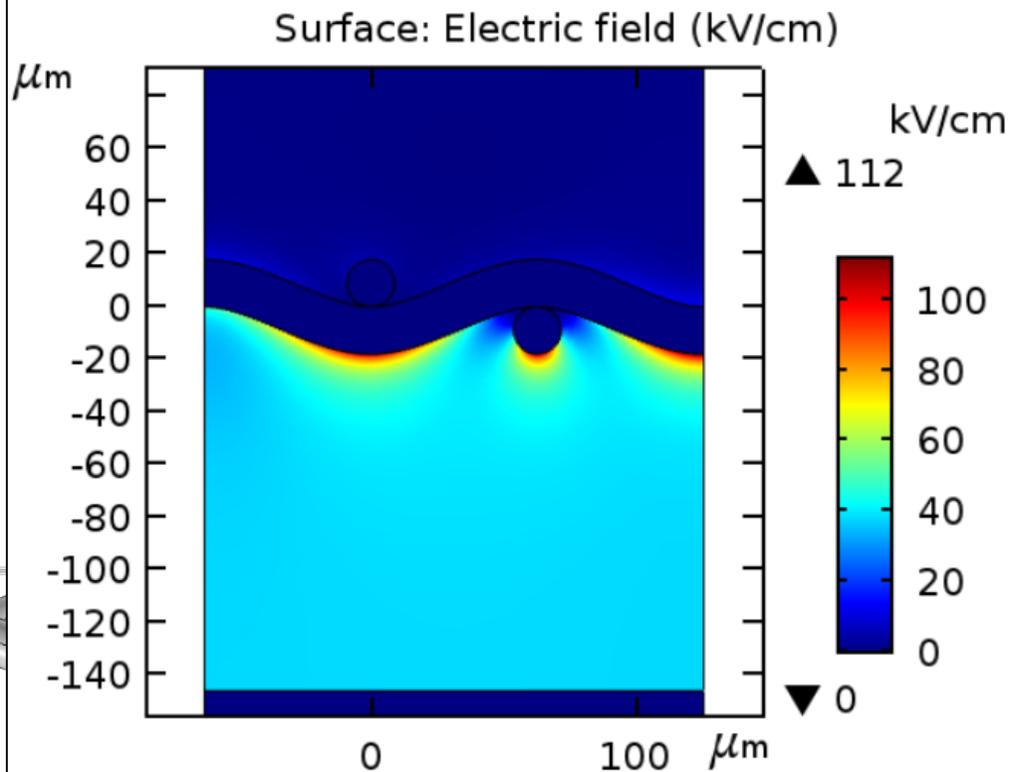
18/45 Standard Woven :



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



The wires have



the maximum field is 112 kV/cm

the drift gap, amplification gap
are the same

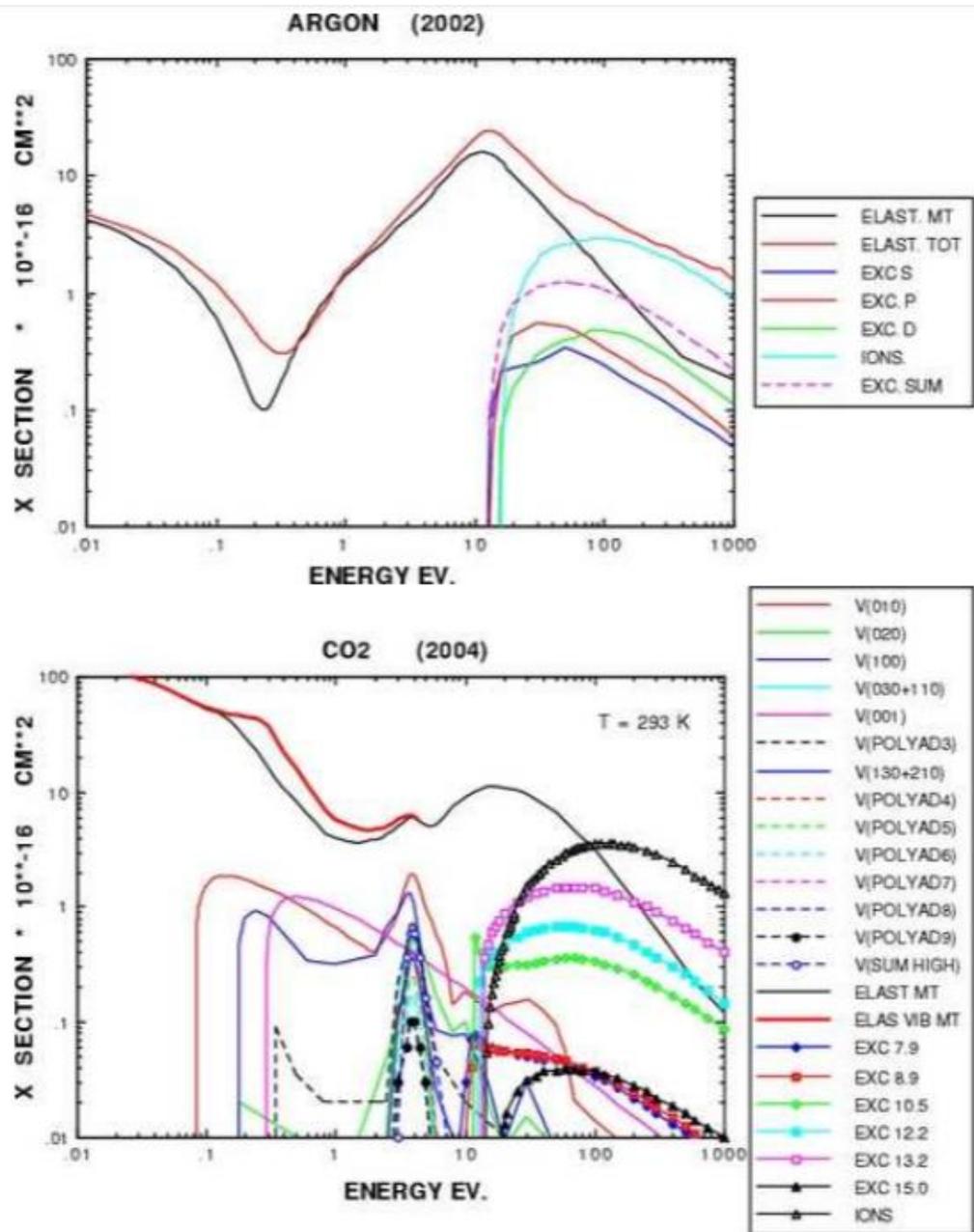
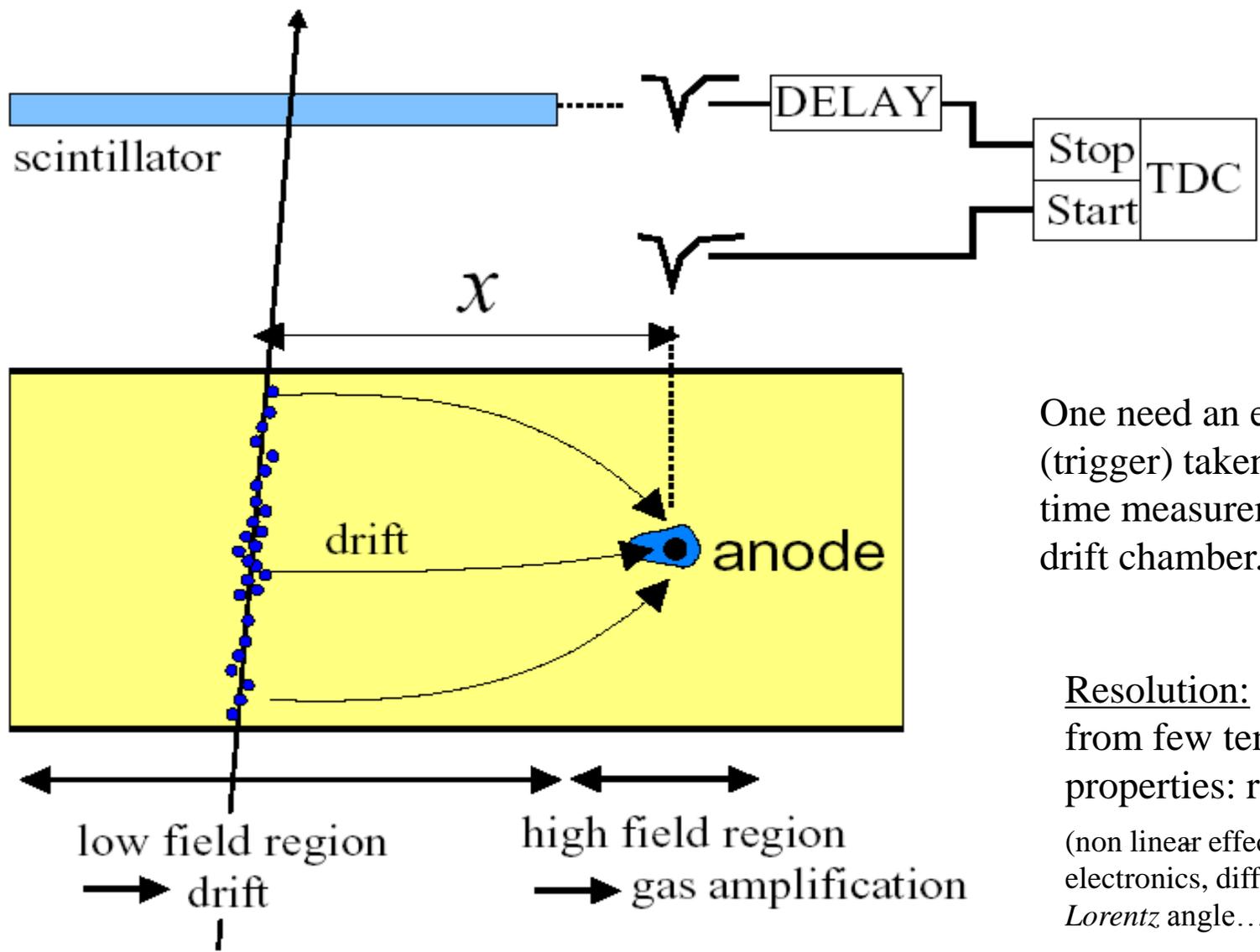


Figure 7: Cross Section of argon and carbon dioxide as a function of energy. These graphs are taken from the Magboltz 7.1 database for gas properties.

Drift chambers



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

Resolution:
 from few tenths 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 $\sim 1\mu\text{s}$)

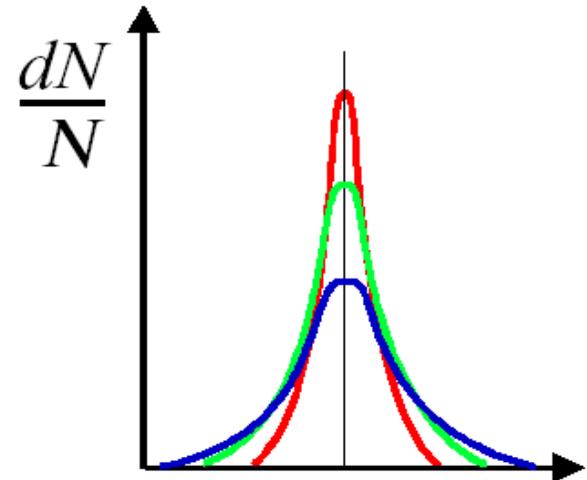
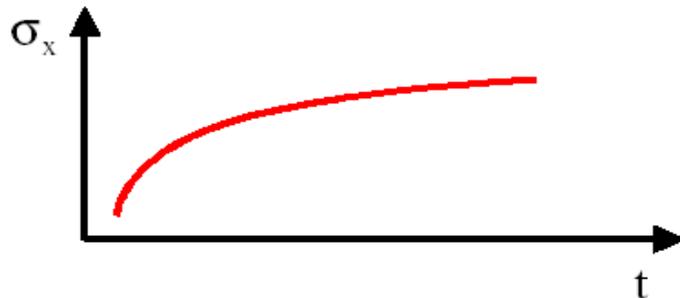
Diffusion and drift

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

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

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 $\Rightarrow \sigma \approx 1$ cm

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

Diffusion and drift

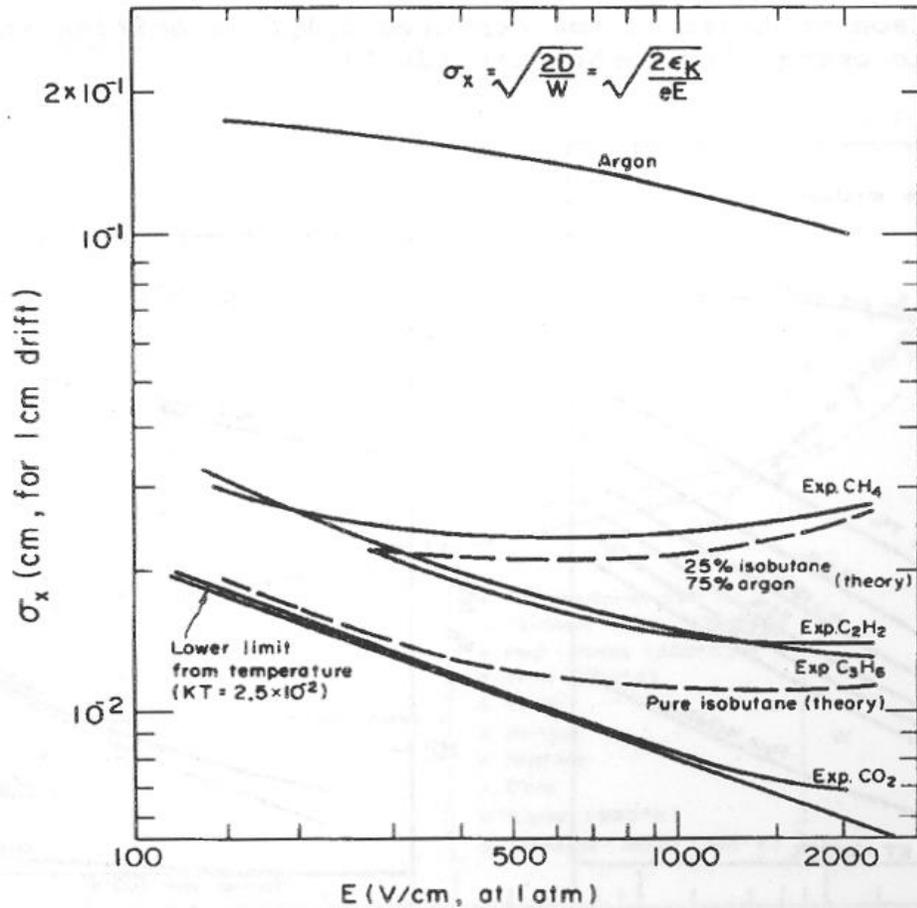
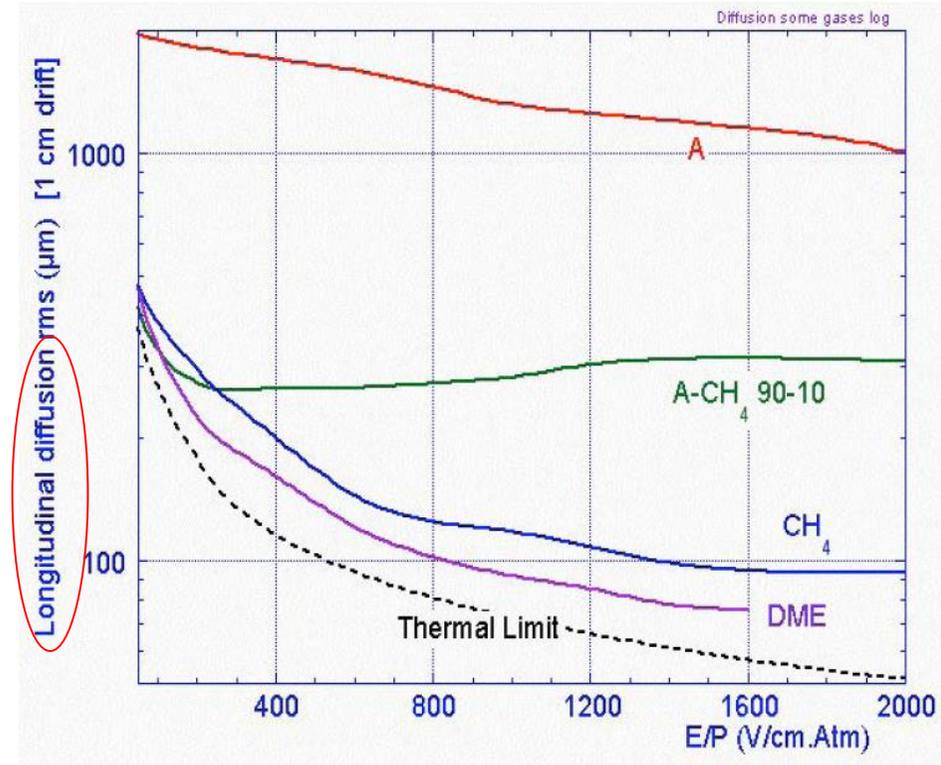


Fig. 35 Computed and experimental dependence of the standard deviation of electron diffusion from the electric field for 1 cm drift, in several gases at normal conditions²⁵⁾



Order of magnitude of *transverse* diffusion:

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

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

But in transverse plane, electrons are spinning -following- “around” B field line

=> diffusion coefficient is:

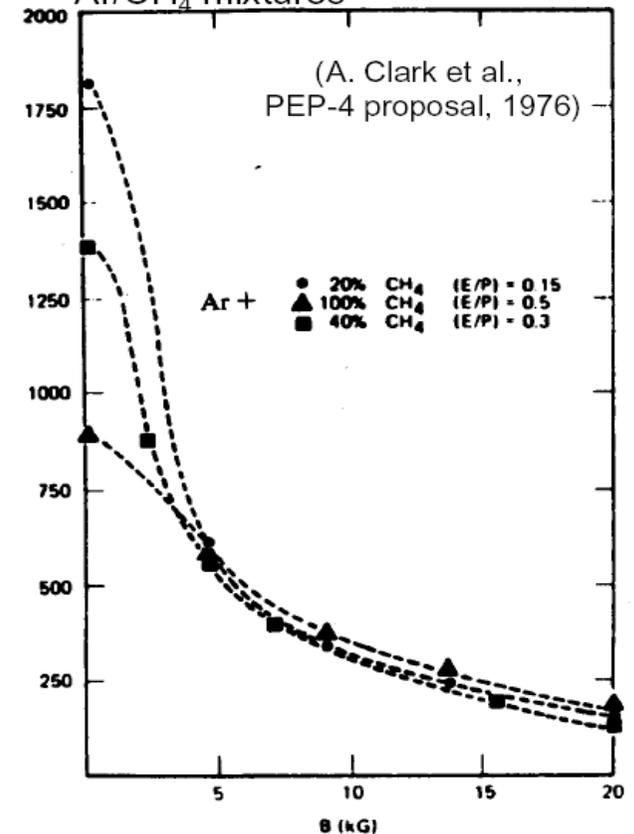
$$D_T(B) = \frac{D_0}{1 + \omega^2 \tau^2}$$

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

with $\omega = eB/m$ cyclotron frequency

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

Transverse diffusion σ (μm) for a drift of 15 cm in different Ar/CH₄ mixtures

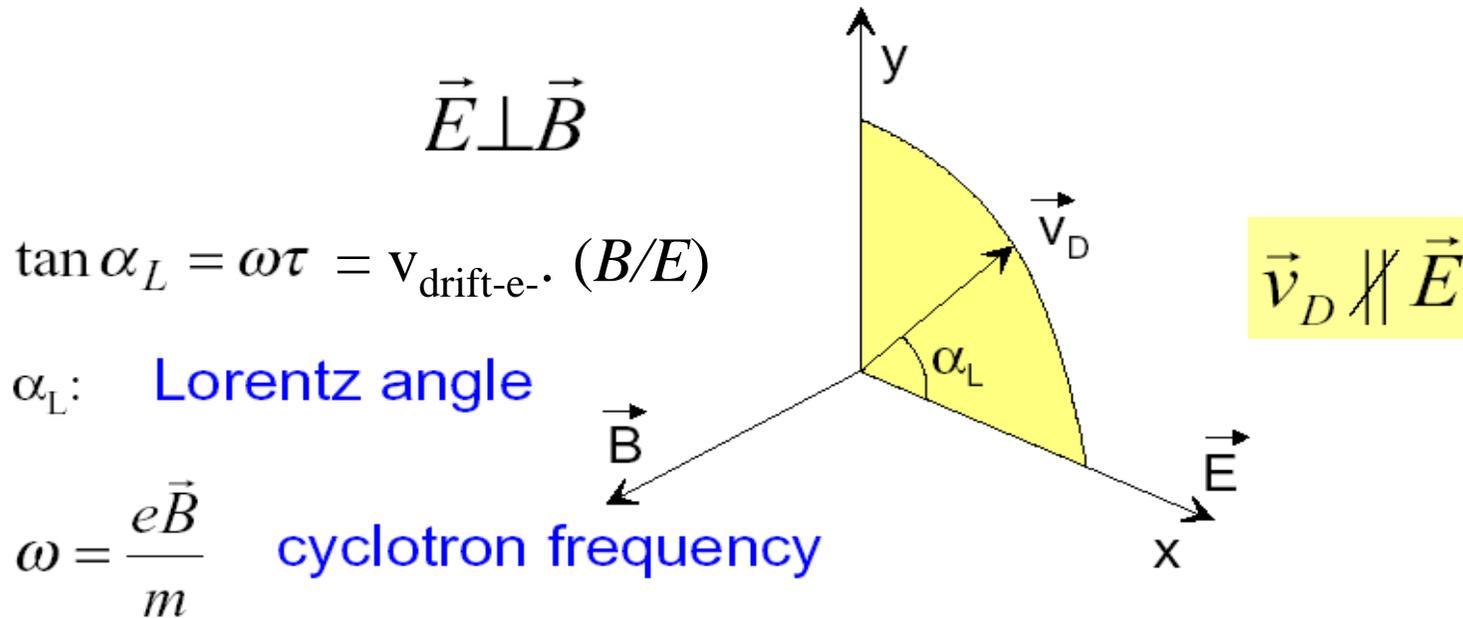


Diffusion and drift

when we have (a E and) B fields

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

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



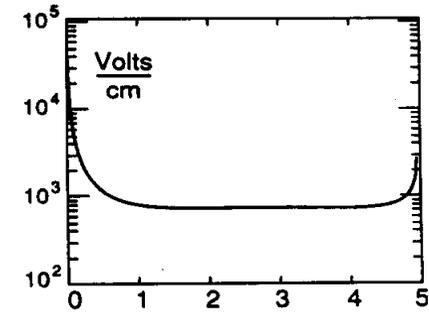
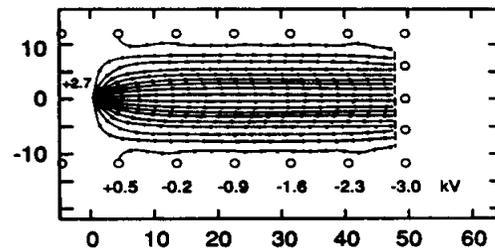
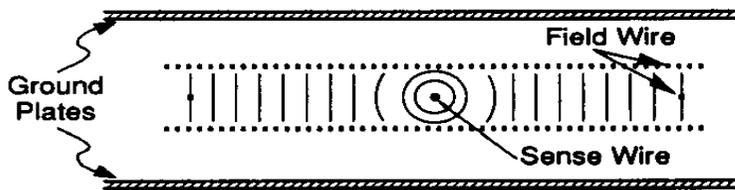
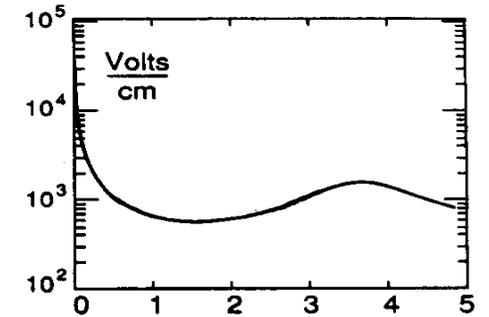
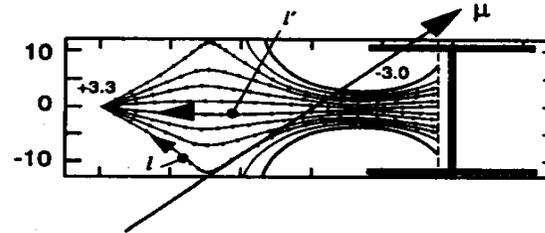
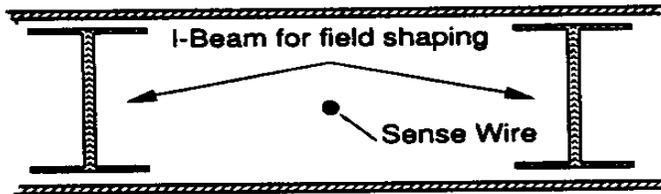
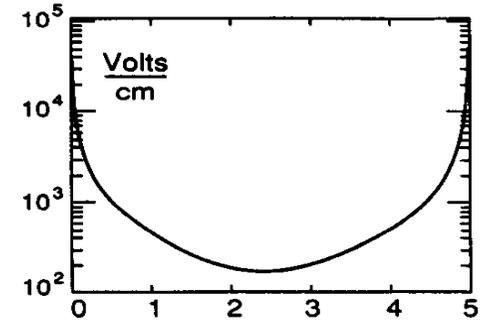
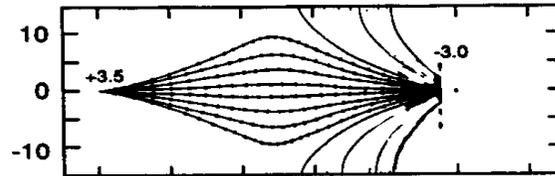
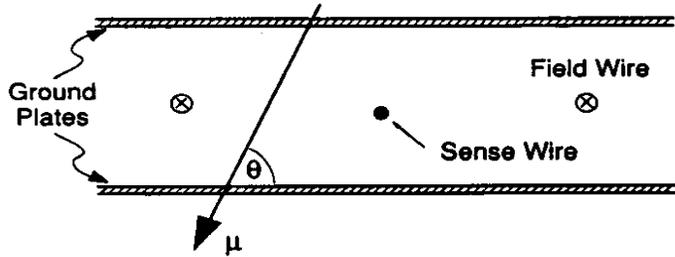
Typical angle ~30 degrees for $B=1$ Tesla and $E=0.5$ kV/cm in Ar: C_4H_{10} :methylal (67:30:3)

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

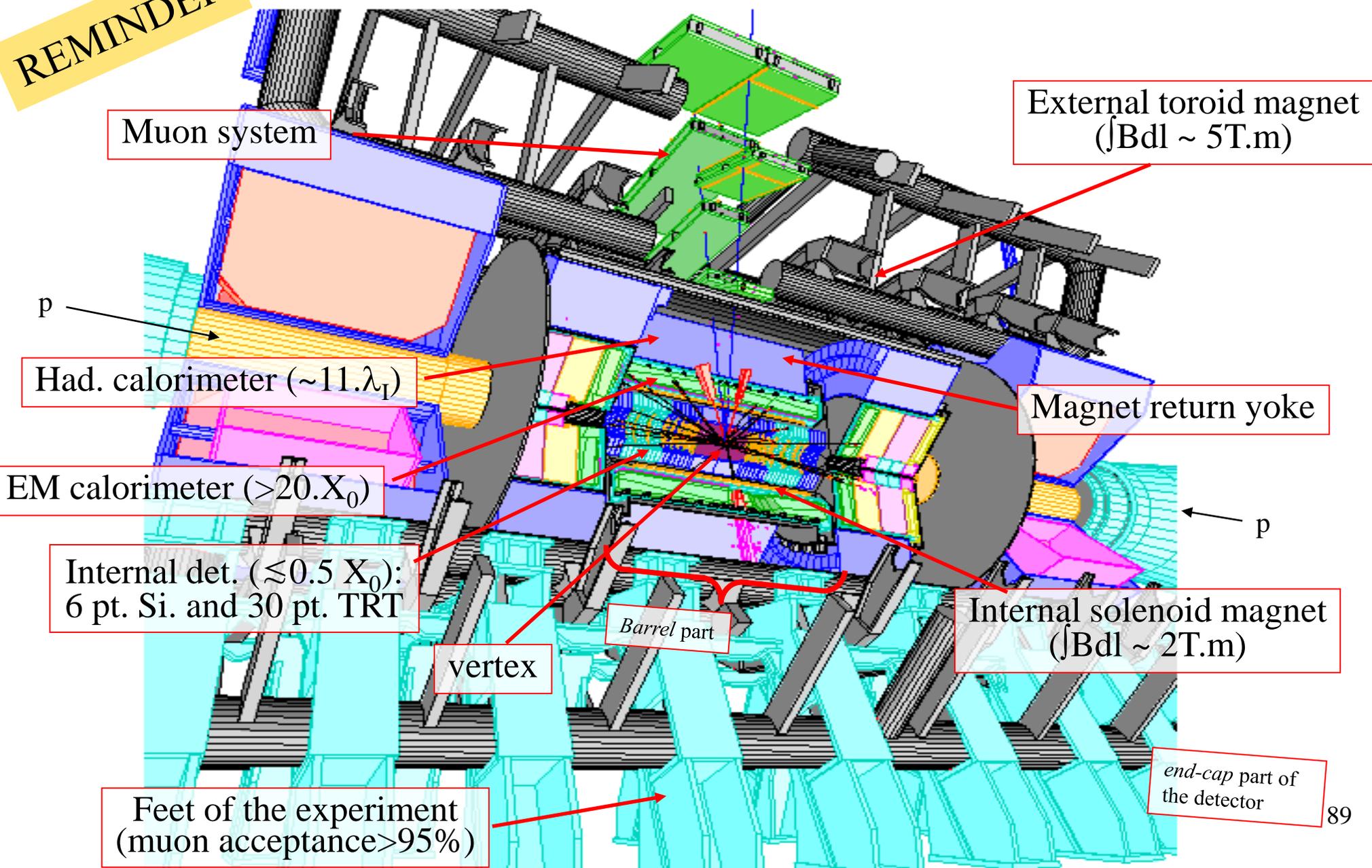


[mm]

[cm]

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

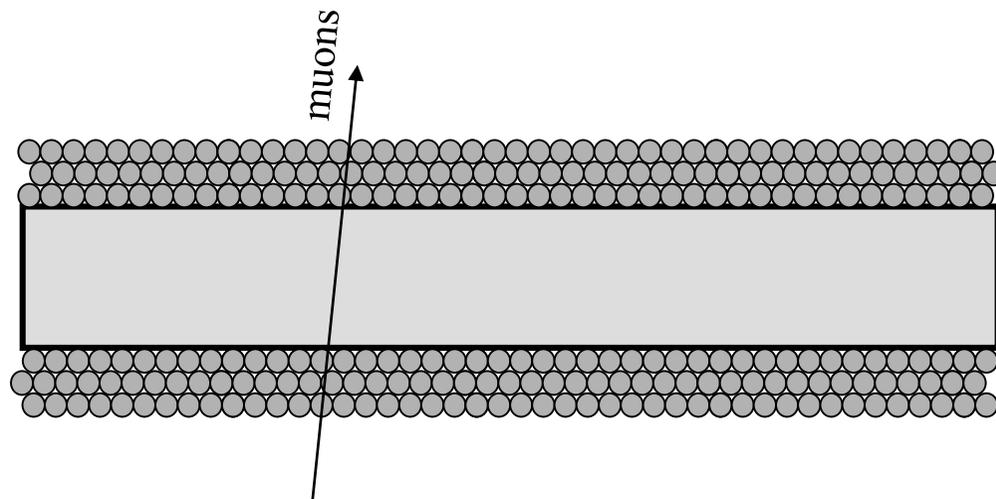
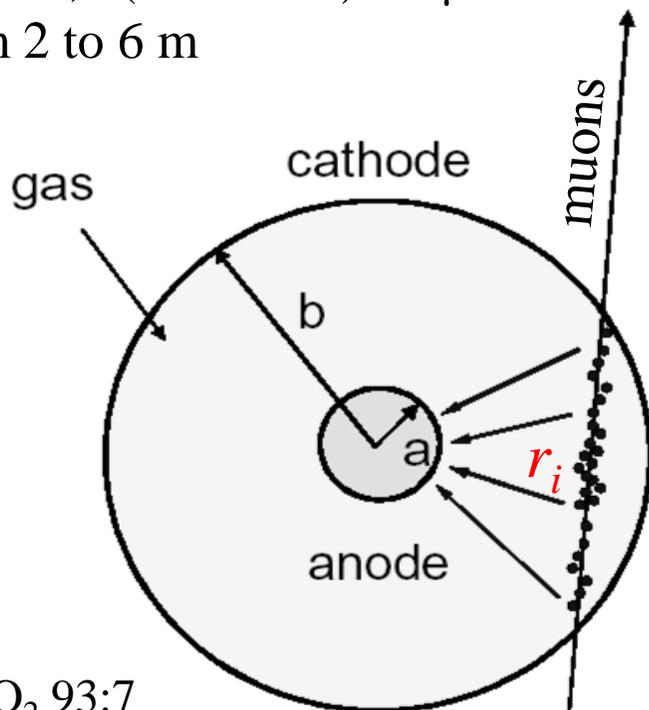
REMINDER



Drift chambers : ATLAS geometry

$b=15\text{ mm}$, $a(\text{anode=fil})=50\mu\text{m}$

L from 2 to 6 m



Ar:CO₂ 93:7

$p = 3\text{ bar} \Rightarrow \sim 3 \times 100\text{ pairs/cm}$ (n_{Total})

$V \sim 3000\text{V}$ (2.10^5 V/cm)

Gain: 2.10^4

Max drift time of e⁻ : 700ns, i.e. “slow” good for *Lorentz* angle limitation

$v \sim 3\text{cm}/\mu\text{s}$ ($=30\mu\text{m}/\text{ns}$)

Centring of wire < 100 μm all along the tube (20 μm at the end-plug)

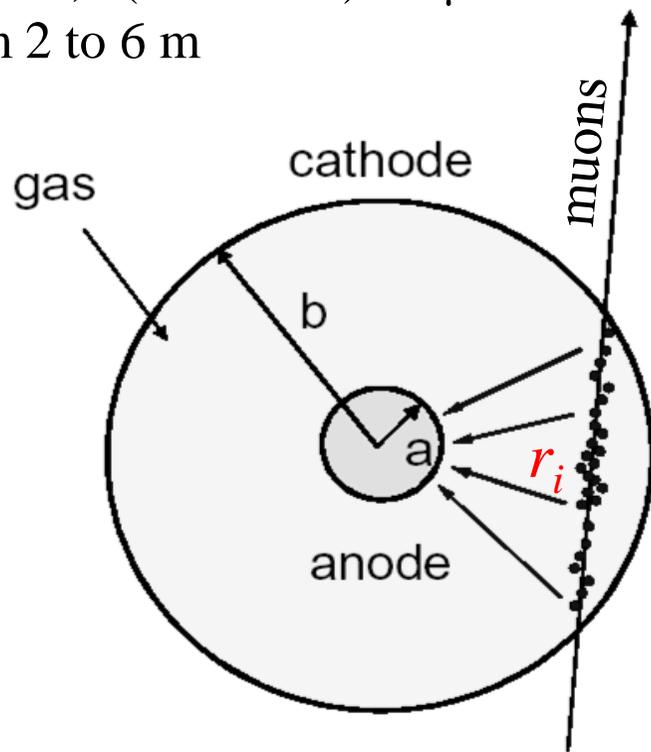
Threshold at the $\sim 25^{\text{th}}$ e⁻

$\sigma \sim 80\ \mu\text{m} / \text{tube} \Rightarrow$ combining tubes of one chamber gives $\sim 50\mu\text{m}$ locally

Drift chambers : ATLAS geometry

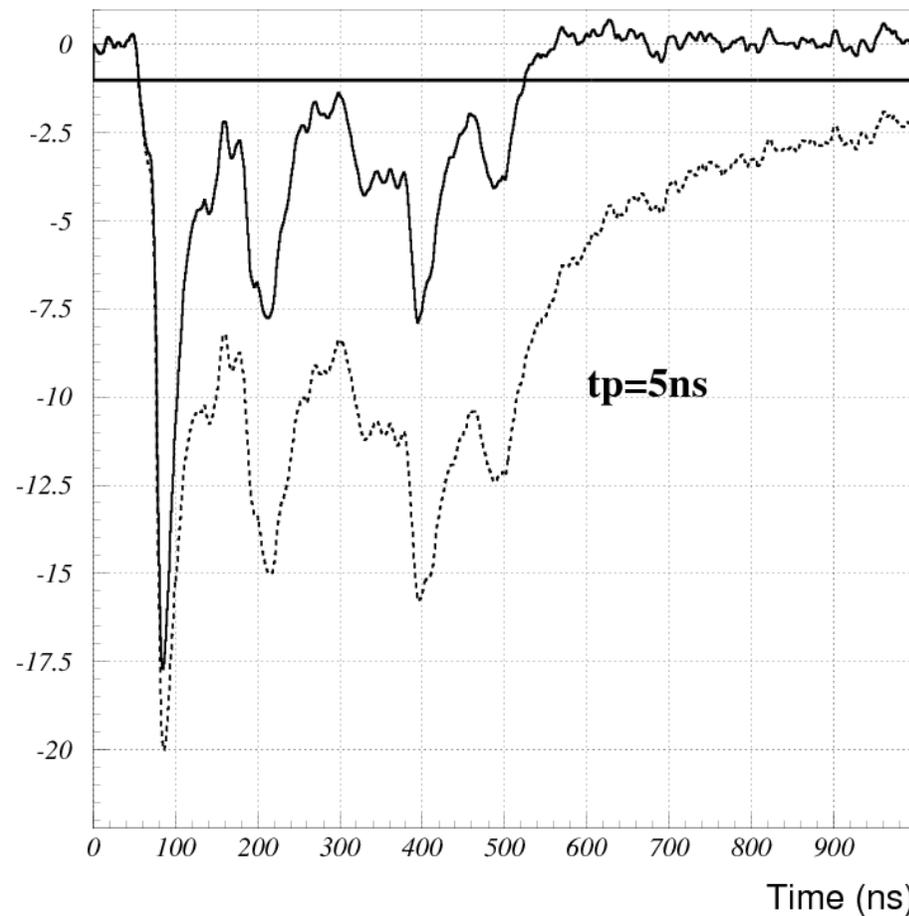
$b=15\text{ mm}$, $a(\text{anode=fil})=50\mu\text{m}$

L from 2 to 6 m



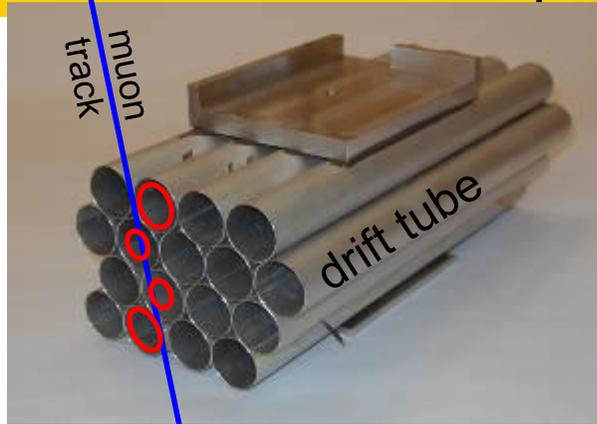
$dE/dx(\mu) = 14\text{ keV}$

i.e. several e- clusters

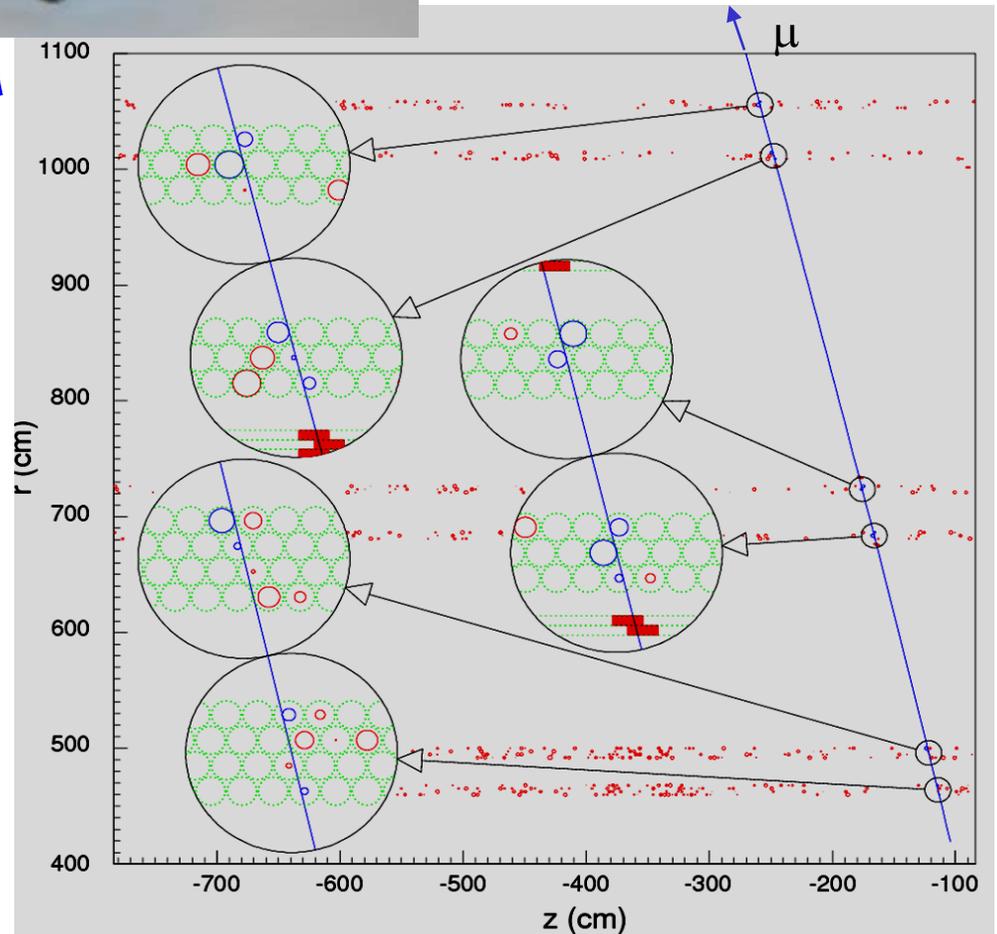
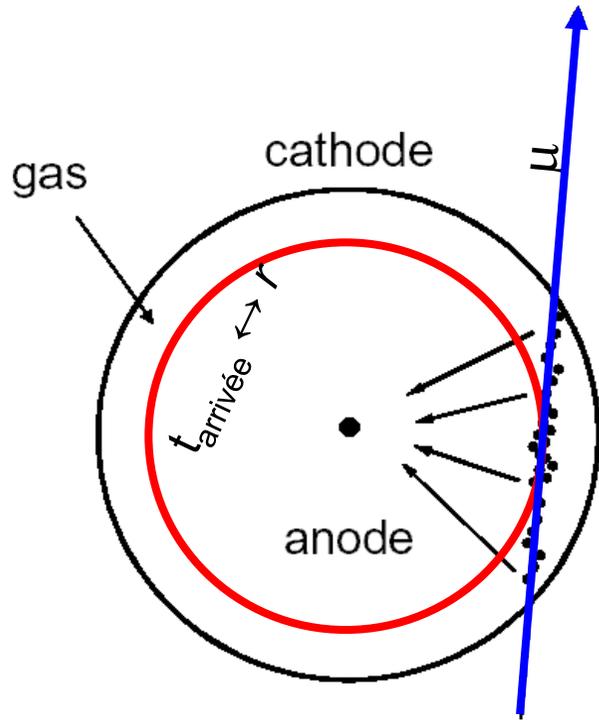


Arrival time fluctuation of each e- cluster on the anode wire

Sag measurement in Atlas muon spectrometer



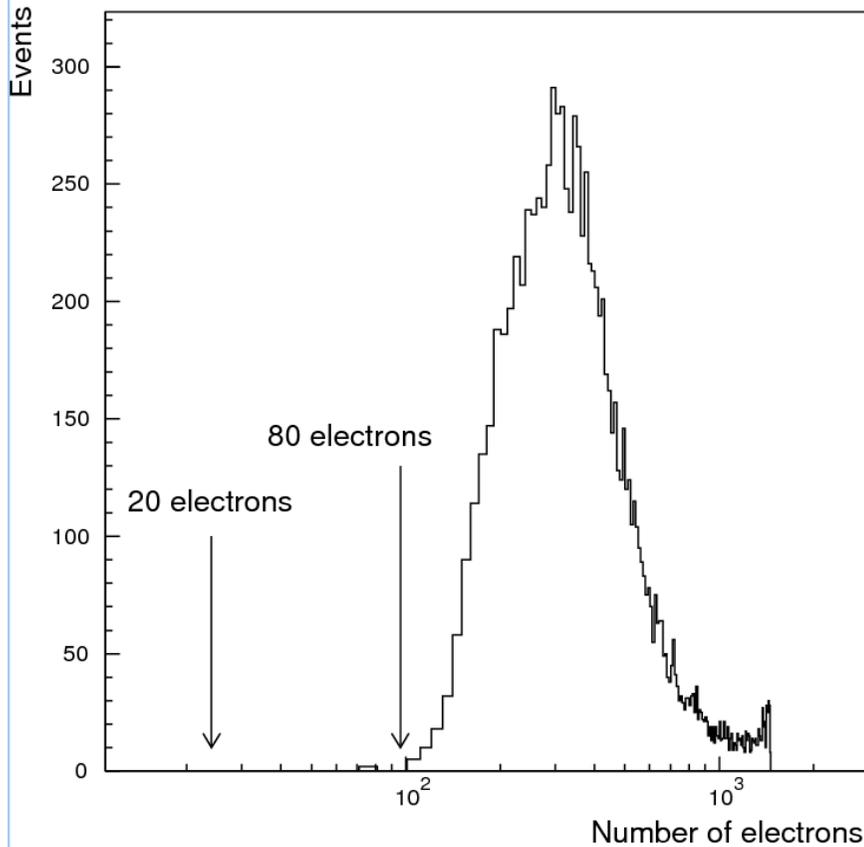
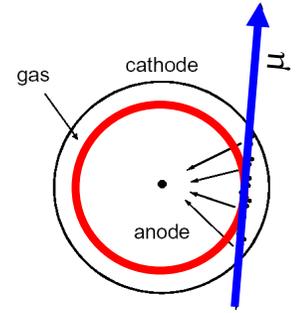
MDT are sensitive to Lorentz angle (in B field), up to 20ns delay over 680ns (not for CSC chambers).



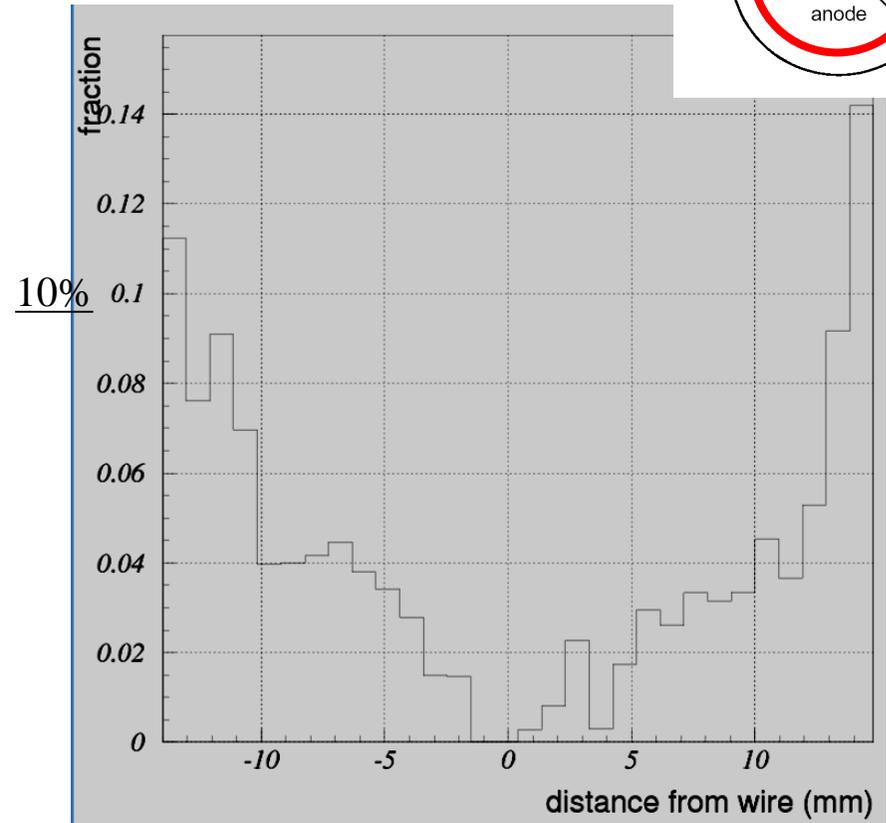
$\sigma \sim 80 \mu\text{m}/\text{tube}$, and combining them by 2×3 or 2×4 tubes within a chamber: $\sigma \sim 60 \mu\text{m}$ locally

Also an angular measurement (vector) $\sim 200 \mu\text{rad}$.
 $\epsilon(\text{tube}) \sim 95\%$ (half from tube wall, half track centred w.r.t. wire)

Drift chambers : ATLAS geometry



Mean # of e- from ionisation ($\langle \rangle \sim 400$)



Inefficiency = $f(\text{radius})$

close to tube walls, because of δ -ray!

Remark: bad resolution for tracks centred on the wire

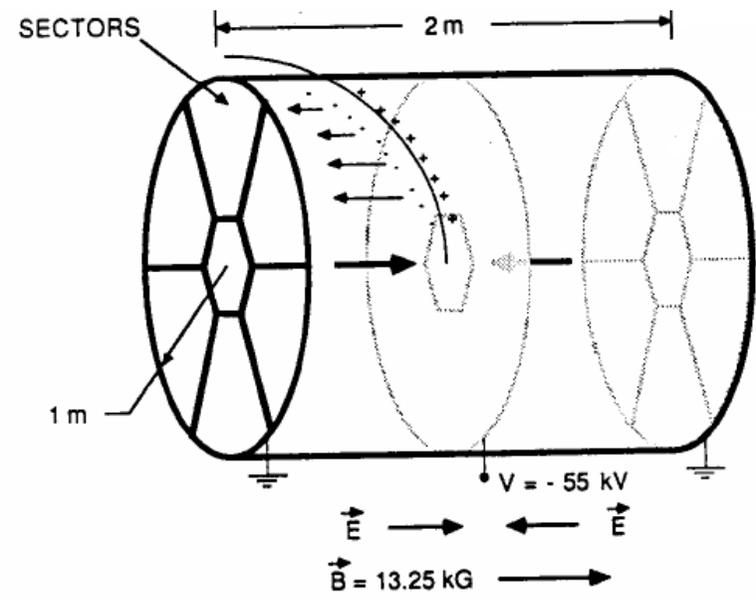
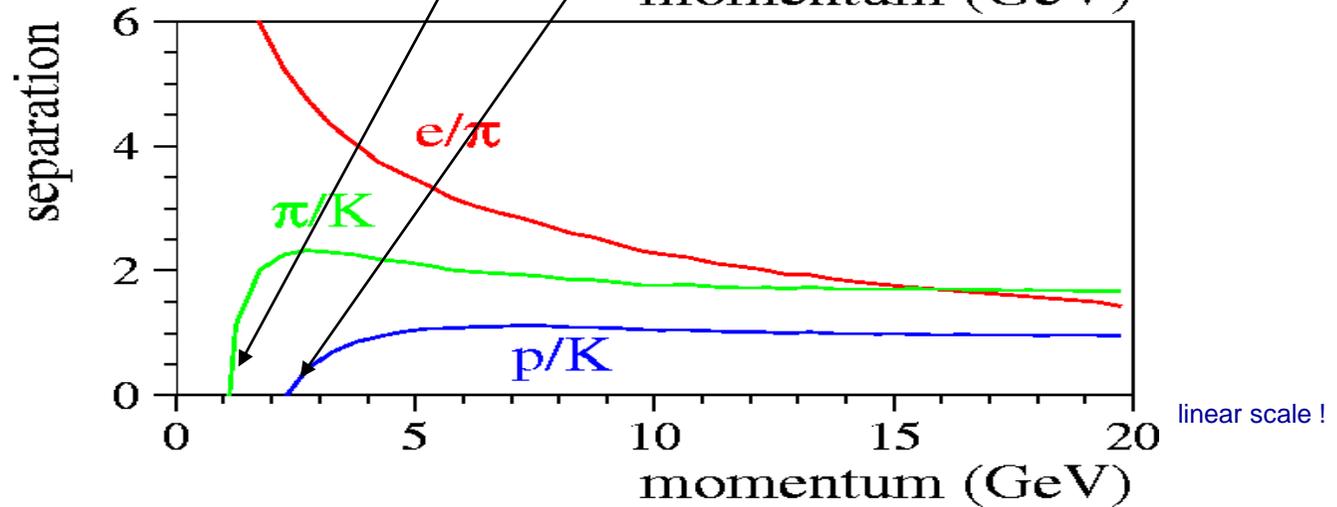
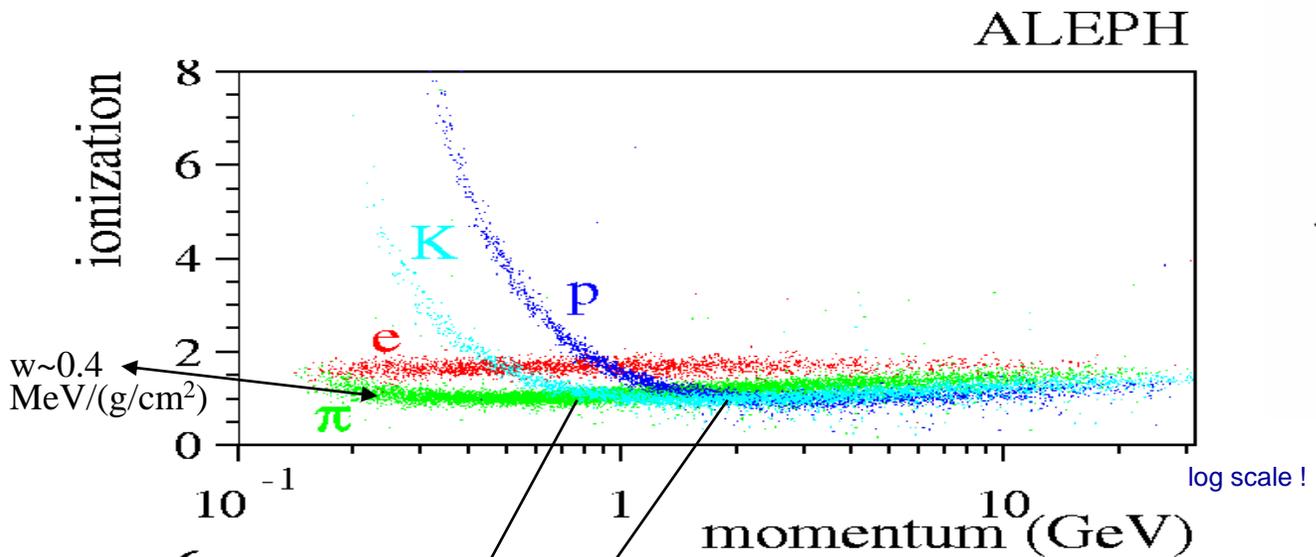
REMINDER

TPC: example of dE/dx measurement

Example: Aleph TPC (gas: Ar/CH₄ 90/10)

N_{samples} : 338, wire spacing 4 mm

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



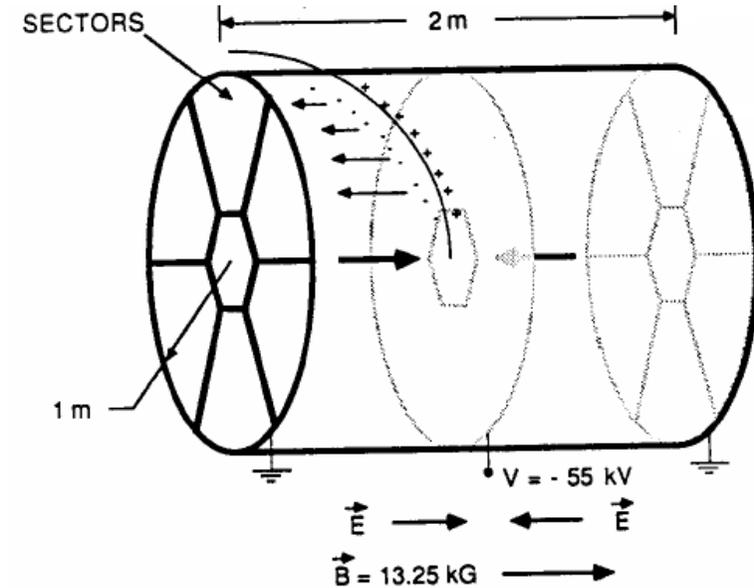
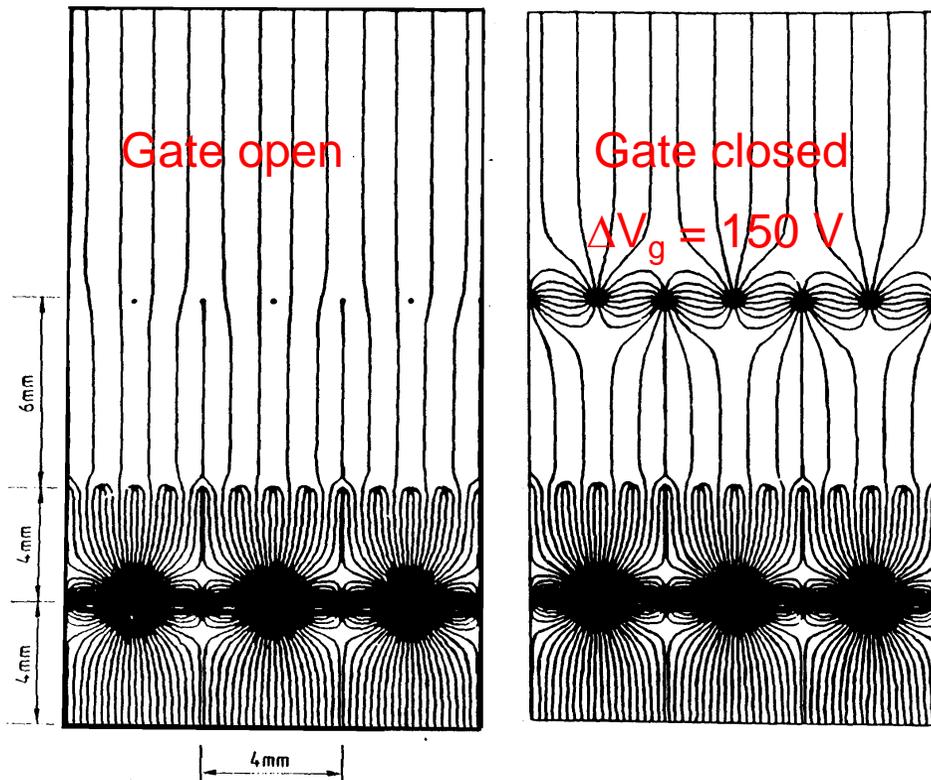
Each track gives ~ 338 measurements for a given particle seen in the detector (Time Projection Chamber –TPC–).

Limiting factor comes from fluctuation “Landau tails”.

TPC: example of dE/dx measurement

Slow detector: $\sim 100\mu\text{s}$

Space charge problem: 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:

>350000 straws of $\varnothing=4\text{mm}$, $L_{\text{max}}=150\text{cm}$

Particle flux: 200 kHz/cm \Rightarrow occupancy $\sim 25\%$

Gas with 3 components: 70% Xe+20% CF₄+10% CO₂ ($\pm 2\%$)

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

CF₄ fast gas (+ plastic foils for trans. radiation)

CO₂ as a *quencher* (auto-limited *streamer* mode, i.e. close to)

$dE/dx_{m.i.p.} \sim 2 \text{ keV}$

Lorentz angle $\sim 30^\circ$ ($B_{\text{solenoid}}=2\text{T}$)

Wire diameter $30\mu\text{m}$ (gain limitation to $4 \cdot 10^4$)

streamer fraction $\sim 7\%$ (if 5% more of Xe \Rightarrow *streamer* event fraction $\sim 2\%$)

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

Wire centring $\lesssim 200\mu\text{m}$

Anode HV: $1570 \pm 30 \text{ V}$ (if higher *streamer* \nearrow)

Maximum collection time $\sim 40\text{ns}$

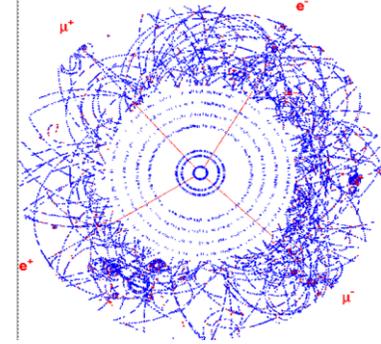
Threshold for drift time measurement at 200 eV (i.e. 8000 e⁻) : $\sigma \sim 150\mu\text{m} \leftrightarrow 8\text{ns}$

Threshold of soft X-ray detection: 6.5 keV.

For $\epsilon_e=90\%$ we get 8% of $\pi \Rightarrow$ rejection > 10

etc, etc...

Heat produced $\sim 400\text{W}$. Cooling using CO₂. Temp. $< 50^\circ$ on electronics



End 2003: new gas! Aging problem of connexions...
70%Xe+27%CO₂+3%O₂

REMINDER

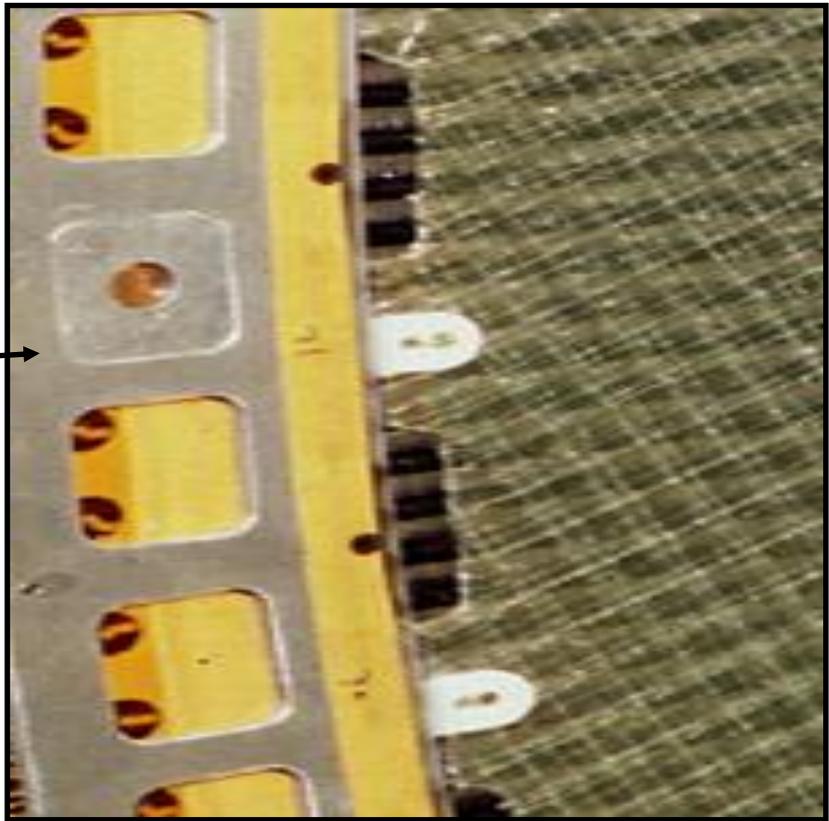
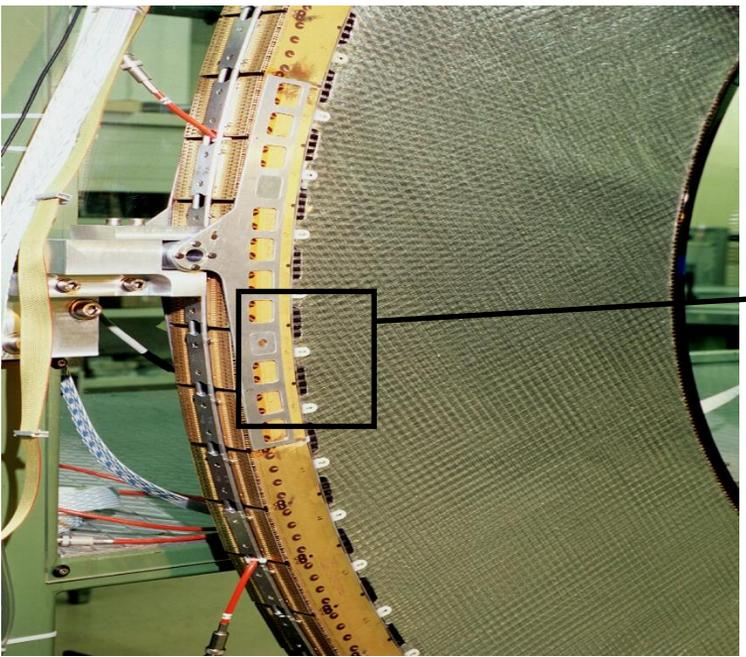
Transition Radiation Detector

Discriminating e/π

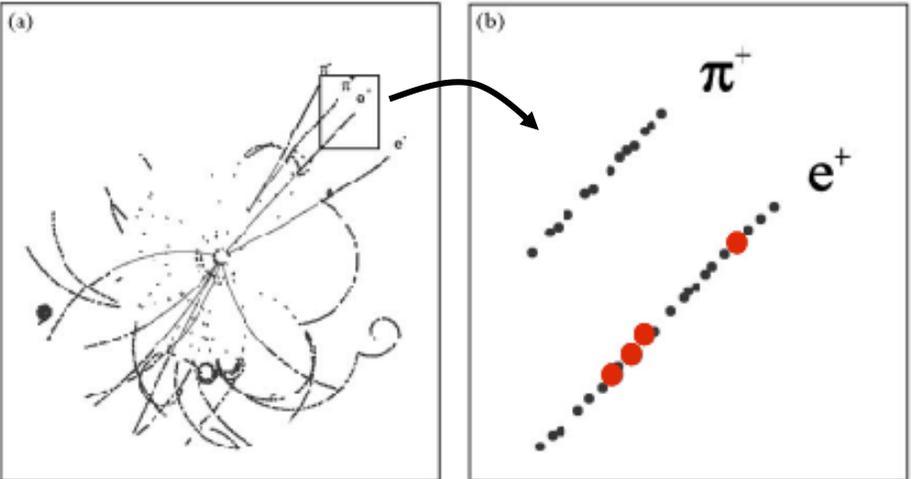
$\theta \sim 1/\gamma$ so $\sim \mu$ -radian for e of about 10 GeV.

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

Soft X-ray emission
associated of few keV.

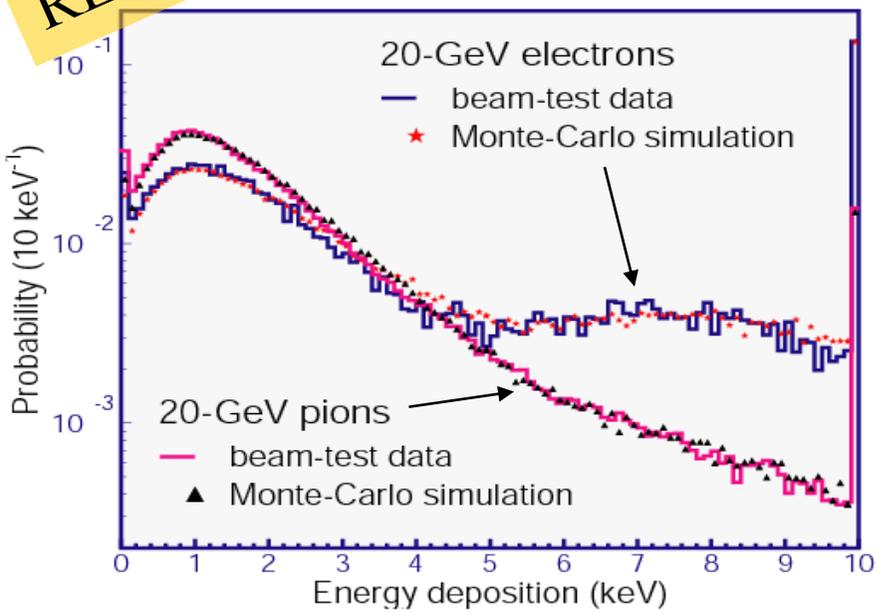


Assembly of plastic foils (reinforced) and straws of 5mm diameter

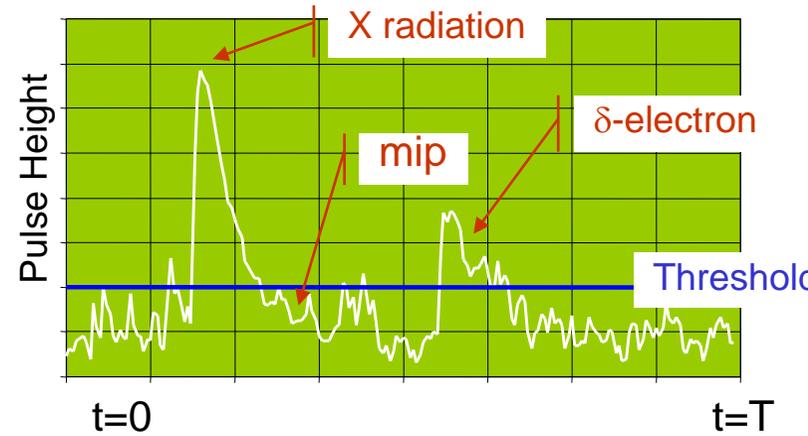


REMINDER

Discriminating π / e thanks to Transition Radiation

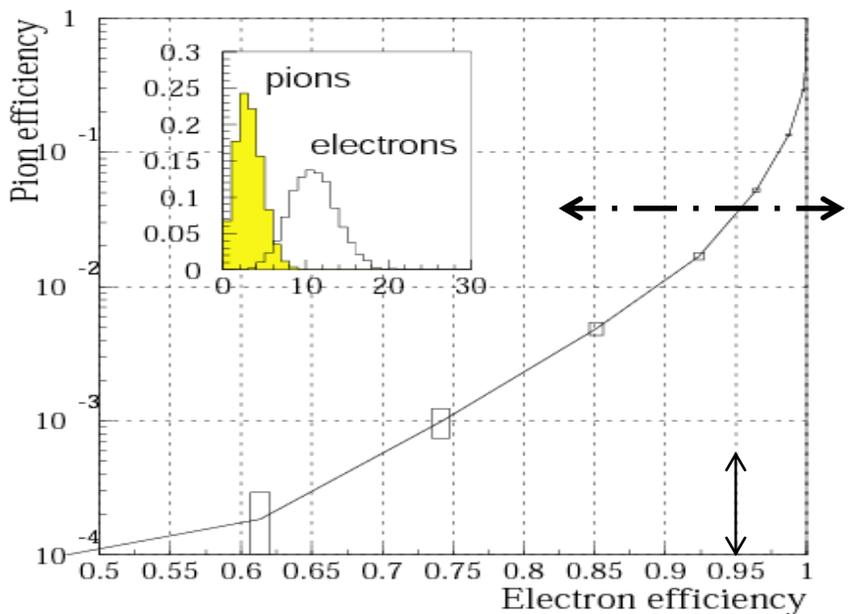


Without plastic foils energy loss is almost the same for π or electrons.



X-ray absorbed in $\sim 1\text{mm}$ (if Argon gas)

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



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

REMINDER

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

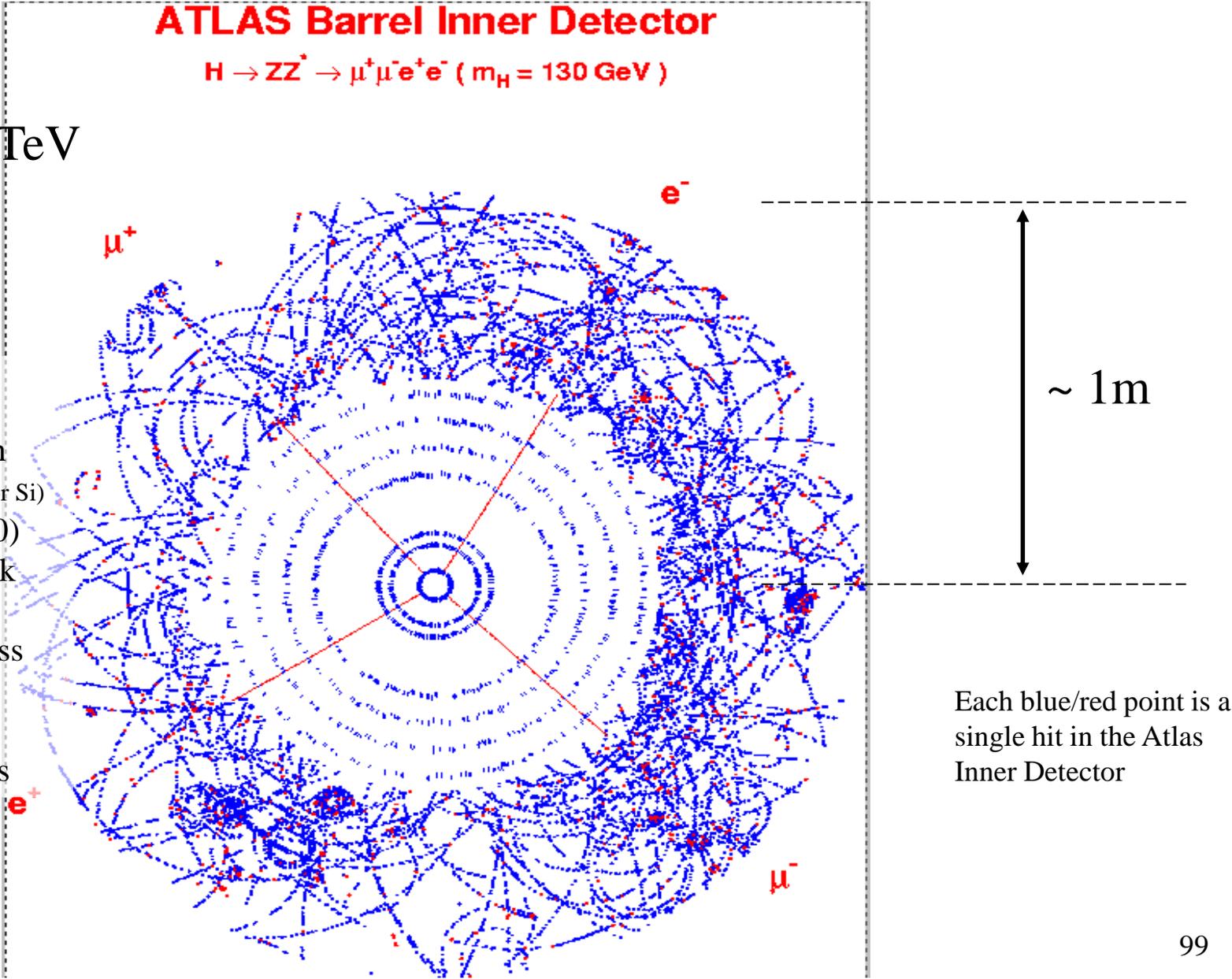
$E_{\text{Center of mass}} = 14 \text{ TeV}$

ATLAS Barrel Inner Detector

$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-e^+e^- (m_H = 130 \text{ GeV})$

We observe that:

- lot of track (~2000), high occupancy (for straw but not for Si)
- curved tracks (B field $\neq 0$)
- $e^+/-, \mu^+/- \sim$ 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



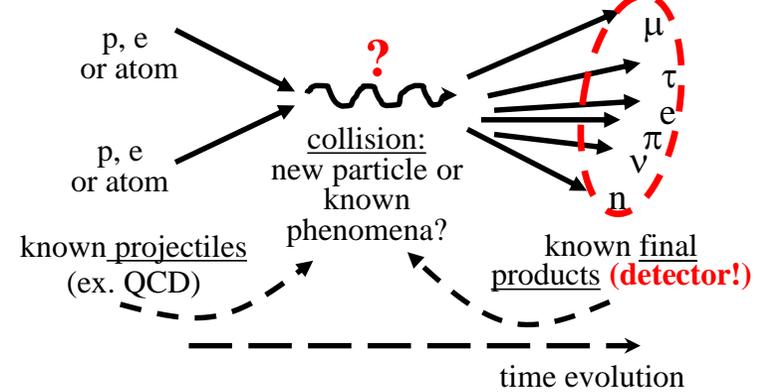
Conclusions

We have seen:

- Signal formation and detection (including fluctuations)
- Velocity(electrons) ~ 100 to $\sim 1000\times$ velocity(ions). Drift time of electrons is ~ 5 cm/ μ s
- 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]	$\sim 175\text{--}450$ 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 ≤ 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.



ACTAR TPC

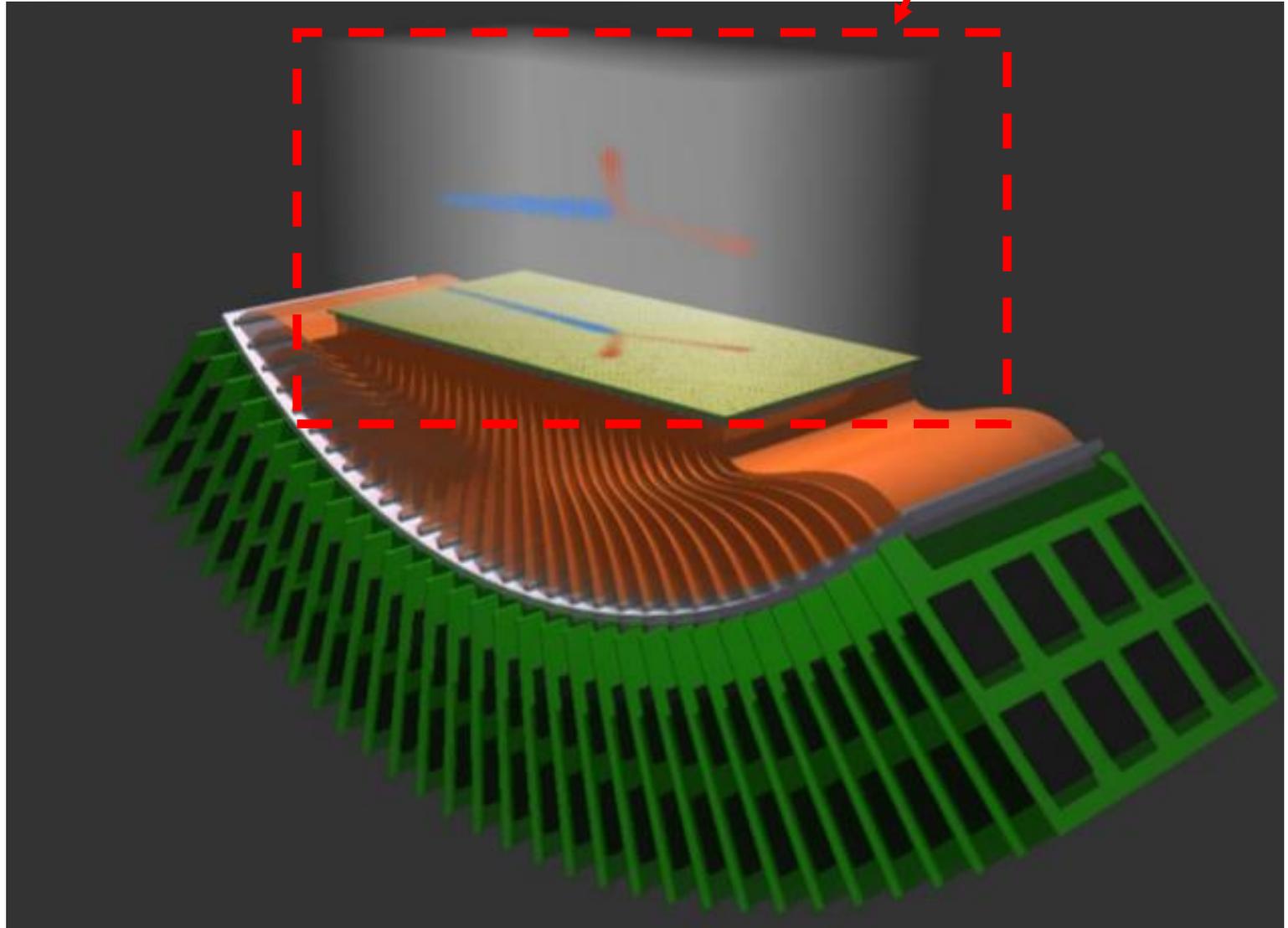
a versatile instrument for nuclear physics

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

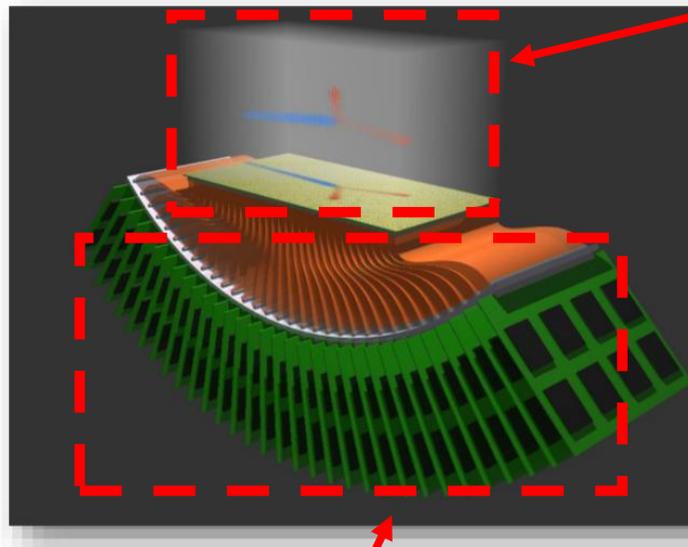


ACTAR TPC

a versatile instrument for nuclear physics

J. Giovinazzo - CENBG
and the ACTAR TPC collaboration

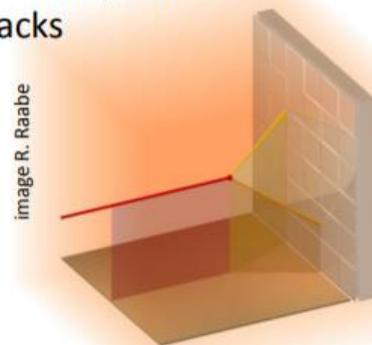
- ▷ what is ACTAR TPC
- ▷ General design
- ▷ Characterization
- ▷ Status



Veresatile detection volume.
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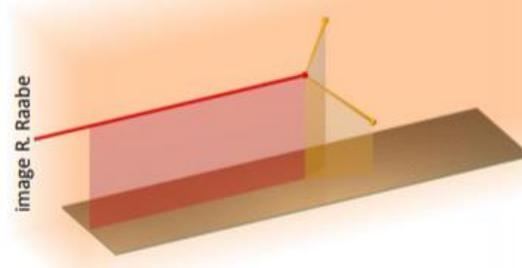
“reaction” chamber

128x128 pads collection plane
large transverse tracks



“decay” chamber

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

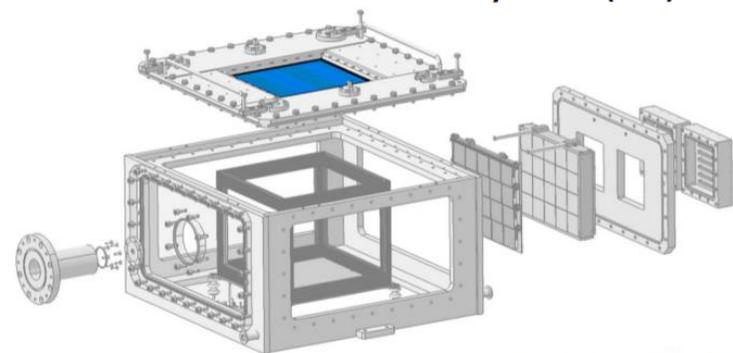


Elongated gas detection volum with 2 readout
area (read from below)

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

ACTAR TPC design: amplification

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

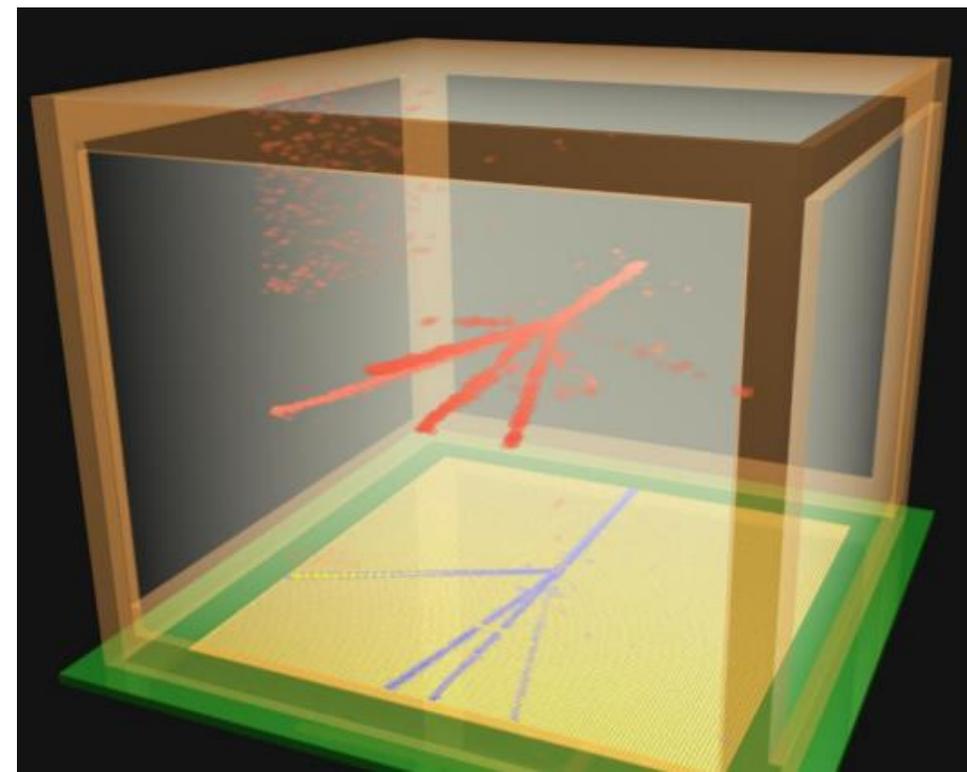


effective calibration

- scan
- electronics chains gain matching

effective calibration

- scan
- electronics chains gain matching

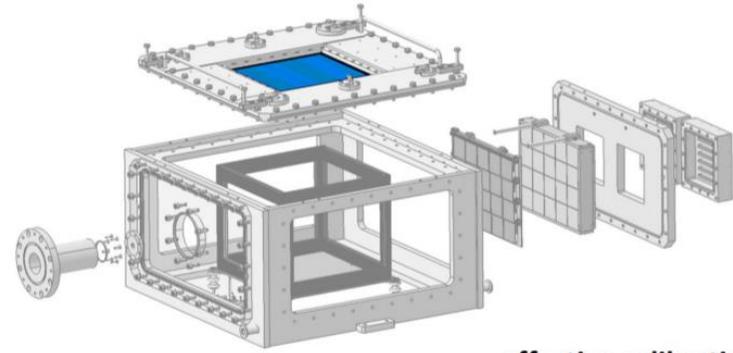


Detector characterization :
i.e. which gain (relatively or better absolutely)

How to do that ?

ACTAR TPC design: amplification

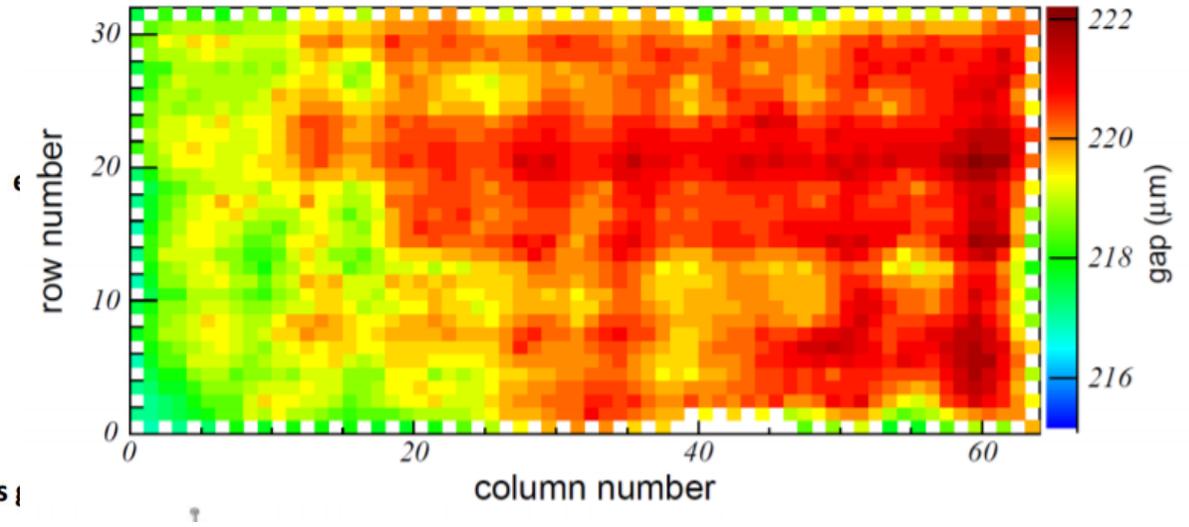
detector scan with collimated X-ray source (^{55}Fe)



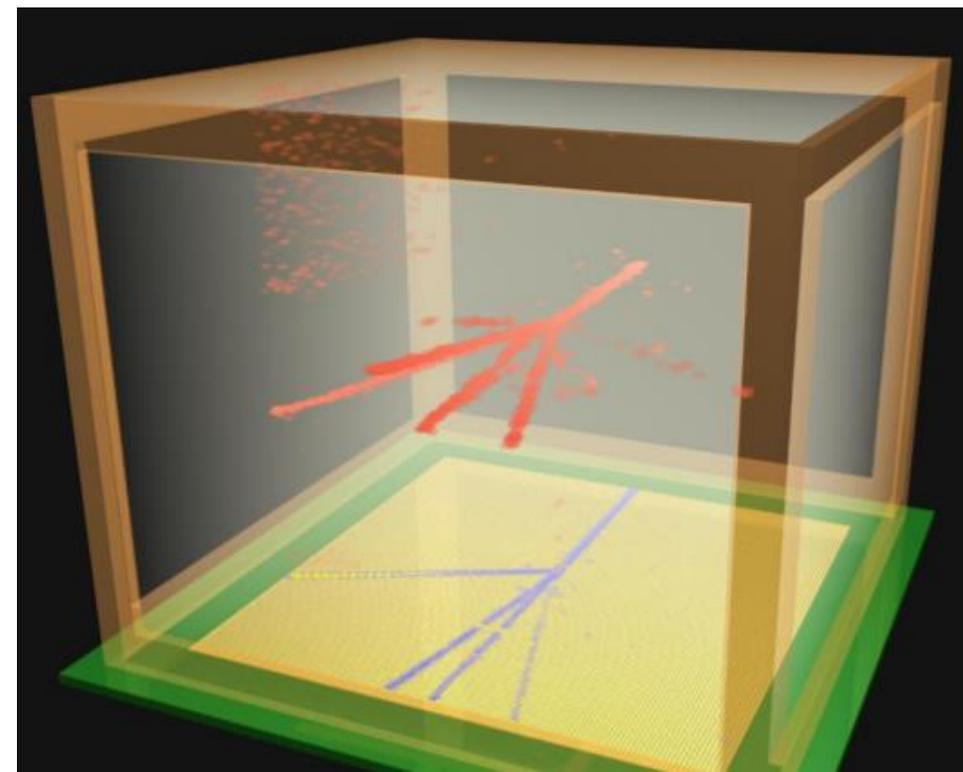
effective calibration

- scan
- electronics chains matching

GANIL scanning table



T. Roger et al., NIM A 895 (2018)



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

How to do that ?

