European School of Instrumentation
in Particle & Astroparticle Physics

European Scientific Institute

DETECTOR TECHNOLOGIES

Lecture 2: gazeous detectors

Principle of operation

Proportional counters and beyond

Jean-Marie Brom (IPHC) – brom@in2p3.fr

Gazeous detectors : Principle of operation

E. Rutherford and H. Geiger (1908) "An electrical method of counting the number of α particles from radioactive substances," Proceedings of the Royal Society (London)

1. A charged particle is passing trough a gazeous medium : loss of energy

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$T_{max} = \frac{2\,m\,\beta^2}{1-\beta^2}$$

Ex : proton 1 GeV/c^2

T_{max} = 1.2 MeV

K = 4 π N_A r_e^2 m_e = 0.3071

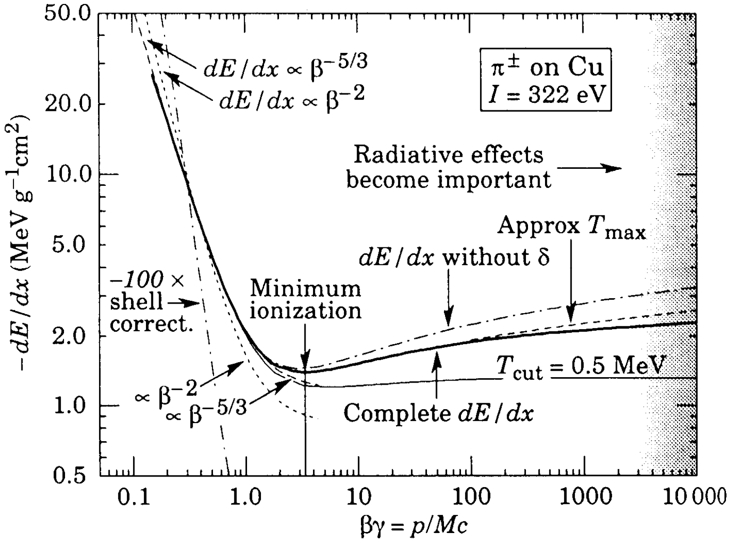
A, Z : atomic mass and number relative to the medium

N_A : Avogadro's number

T_{max} : maximum possible energy transferred to an electron in the medium

z : charge of the incoming particle

β, γ : relatives to the particle



Gazeous detectors : Principle of operation

2. $\boldsymbol{Ei}$: Ionization Energy corresponds to the energy required to remove a single electron from a single atom (or molecule).

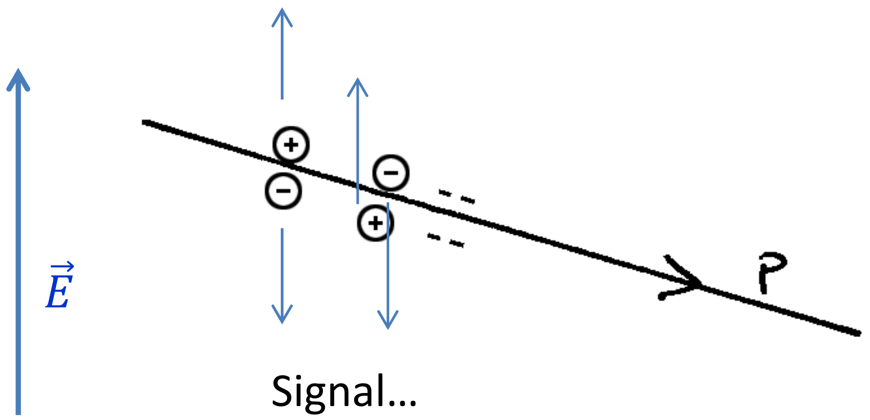
Approximation : $E_i \approx 16\, Z^{0.9}$

3. **If** $T_{max} > E_i$ One or more pairs electron – ion is created

Gas	E_i (eV)	$\frac{dE}{dx}$ (MeV)	N pairs /cm
H2	15.4	4.03	5.2
O2	15.2	1.69	22
Ne	21.6	1.68	12
Ar	15.8	1.47	29.4
Xe	12.1	1.23	44
CO2	13.7	1.62	34
CH4	13.1	2.21	16
DME	10.0	1.85	55

4. If exists an electrical field :

Electrons (and ions) are drifting …

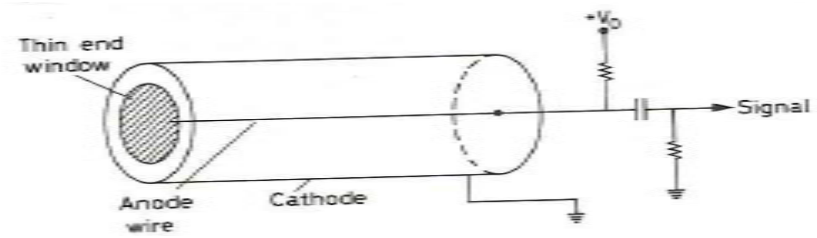


Signal…

Gazeous detectors : Principle of operation

First example : Geiger-Muller counter

Idea from Hans Geiger in 1913 – Developpement with Walther Muller in 1928



Radial Electrical field : $E(r) = \frac{V_0}{r \ln\frac{r_a}{r}}$

r_a = anode radius
r = counter radius

Signal collected $V = \frac{N_e}{C}$

Example :
r = 1 cm
Gas : Argon
particle = MIP → 120 pairs
C = 10pF
Signal : 2 µV

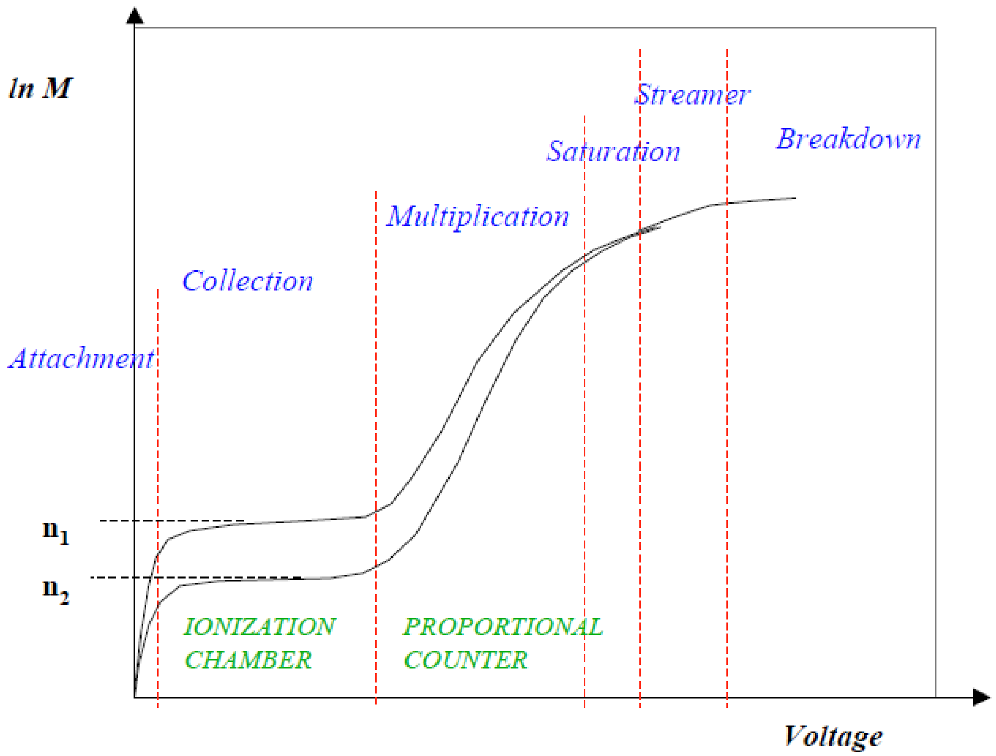
Where $C = \frac{2\pi\varepsilon}{ln\frac{r_a}{r}}$

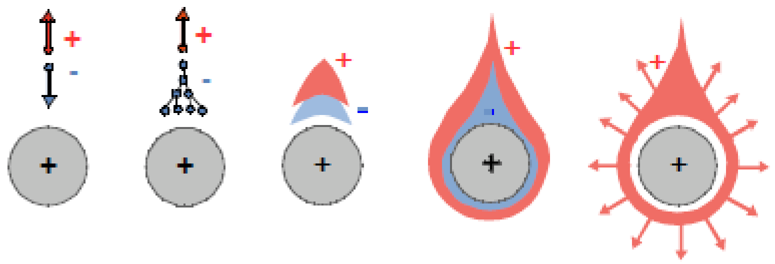
Extremely weak signal… (One electron = 10^{-9} Coulomb…)

But : what can append to the electrons (and ions) during the drift before collection ?

It depens on the Electrical Field (applied voltage)

Gazeous detectors : Principle of operation



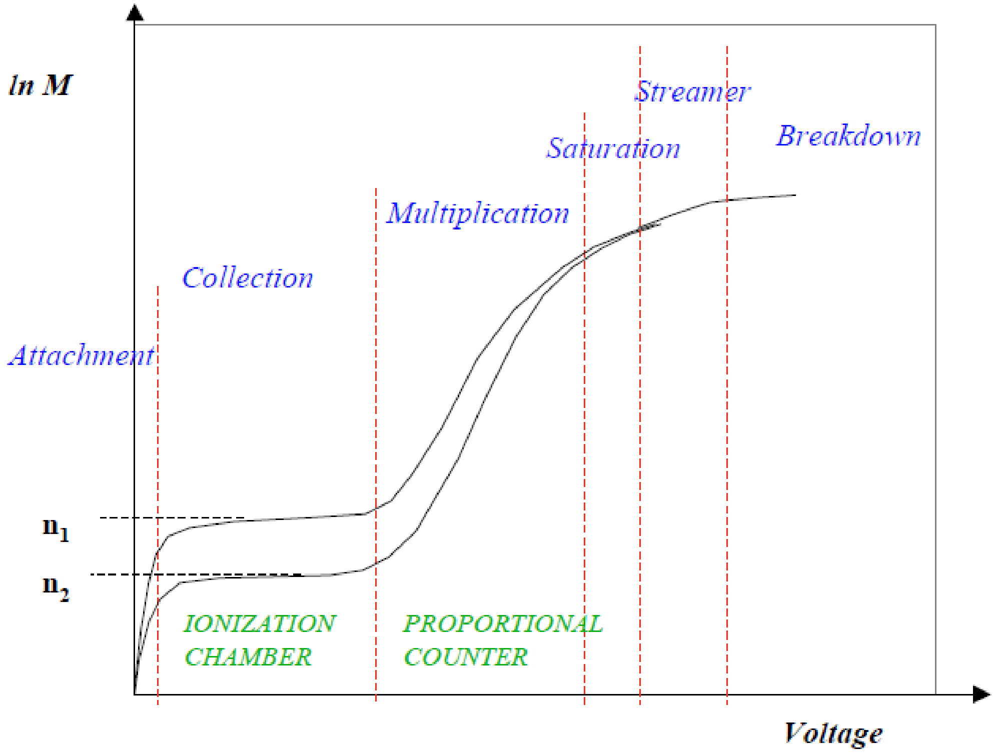


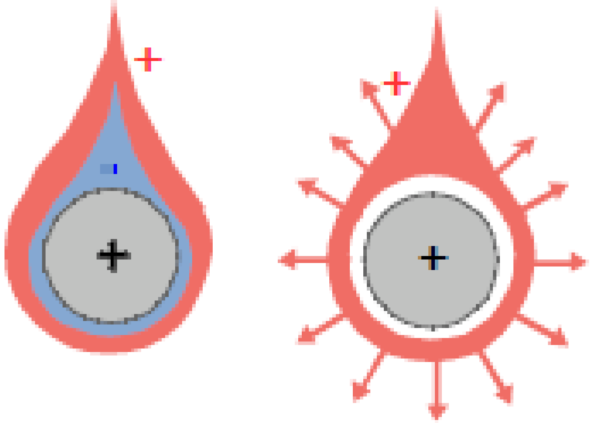
Attachement : E is less than the ion proper field
e^- - ion recombination - almost no signal

Collection - Ionization chamber : All e^- are drifting towards the anode.
Weak signal (typically 1 e^- for 30 eV)

Multiplication - proportionnal regime : E big enough for accelerating e^- above E_i
Production of secondary e^- … Avalanche

Gazeous detectors : Principle of operation





Saturation and Streamer mode - Geiger-Muller regime :

Electronic avalanche amplified by desexcitaion of ions

Saturation of the signal.

Loss of proportionnality

Breakdown : Continuous discharges between anode and cathode… Ultimate destruction…

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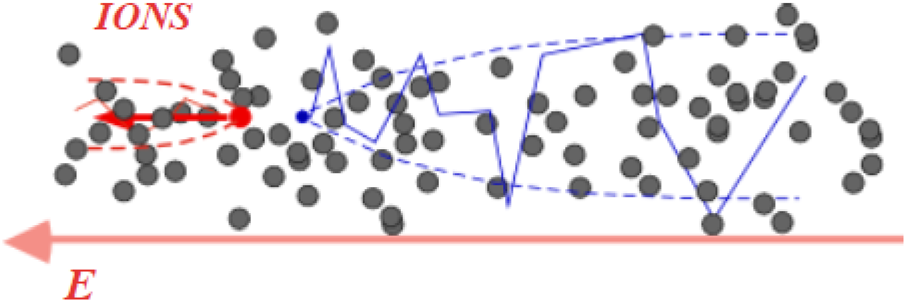
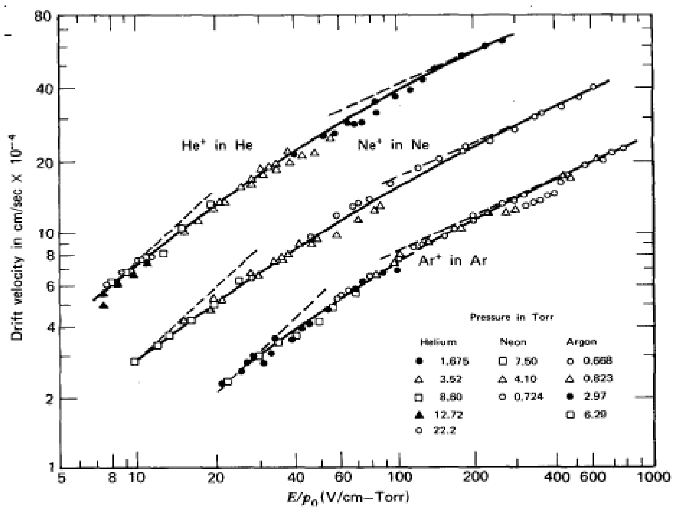
Transport of electrons and ions in the gas :

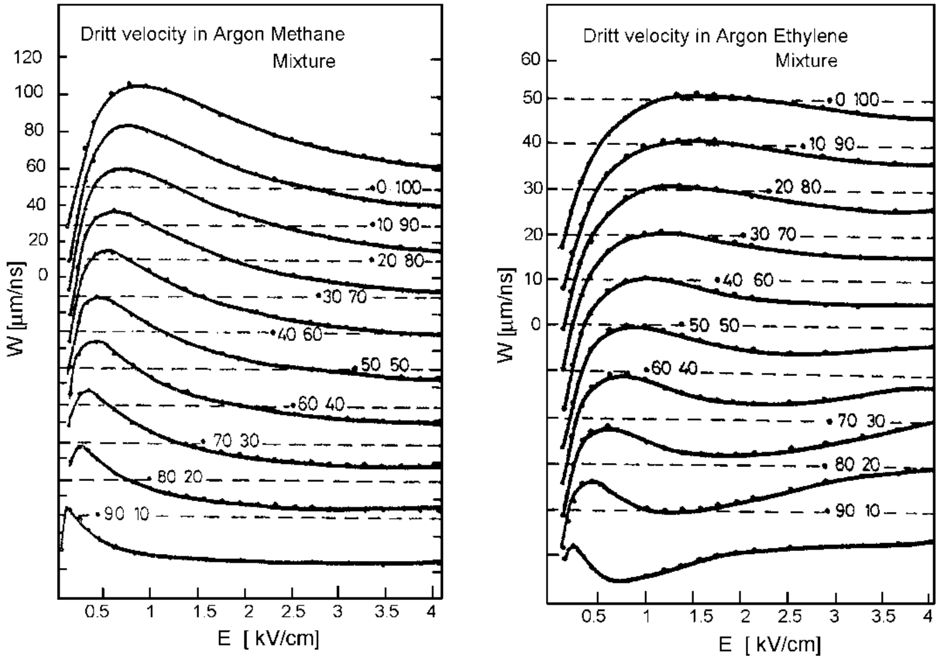
With an electric field, electrons and ions are accelerated along the field lines. Their movement is interrupted by collisions (mean free path…) which limit the maximum average velocity.

This drift velocity is low compare to the thermal velocity.





Ions



The ion collection time is determinant !

Electrons

Choice of gas : Of course, ionization exists in any possible gas.

- Maximum gain (primary electrons)
- Applied voltage as low as possible
- Avalanche with a good proportionnality
- Drift velocity as high as possible

A good compormise : Noble gas (Ar, Xe, Ne...) :

For example : Argon : 30 primary electrons
Possible gain $10^3 – 10^4$
e – drift velocity : 100 µm/nsec. at E = 1kV/cm

Limitation : Noble gas have an high excitation energy (typically 10-12 eV). Excited atoms formed in the avalanche desexicte giving photons which can ionize, causing further avalanche… … Possible discharges.

Solution : the quencher

Gas	E_i (eV)	$\frac{dE}{dx}$ (MeV)	N pairs /cm
H2	15.4	4.03	5.2
O2	15.2	1.69	22
Ne	21.6	1.68	12
Ar	**15.8**	**1.47**	**29.4**
Xe	**12.1**	**1.23**	**44**
CO2	13.7	1.62	34
CH4	13.1	2.21	16
DME	10.0	1.85	55

Quencher : one has to add a polyatomic gas in order to absorb
the photons created either by multiple collisions or molecule dissociation
Usually CH4, CO2, CF3, C2H4 ….

With a mixture of Noble gas – Quencher, one can achieve gains up to 10^6 - 10^7

Magic Gas : 70% Ar, isobutane 29.6%, Fréon 0.4% .

Problem : after dissociation, the organic molecules will polymerize on the anode.
→ Loss of efficiency
→ Need gas circulation

One has to add another agent….
(alcohol…)

One of the BEST possible choice :
DME : Dymethylether CH_3OCH_3
No polymerization
Good gain (10^6)
But it is a solvant !

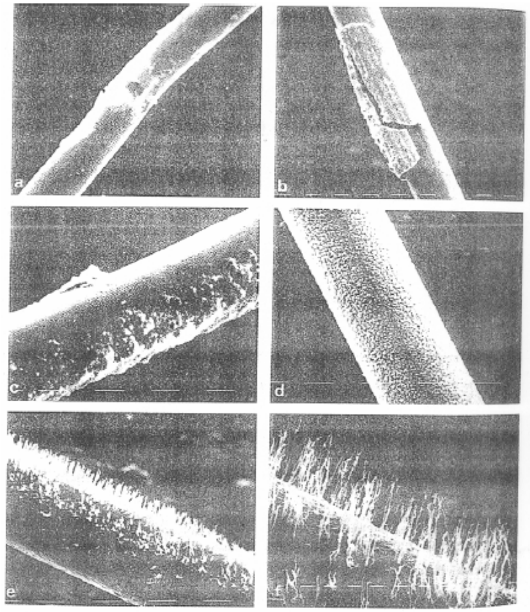


Fig. 4.31. Deposits on anode wires: (a) – $Ar+C_2H_6$; (b) – $Ar+C_2H_6$ + methylal; (c) – $Ar+CO_2$; (d) – perspex chamber; (e, f) – chambers with G10 fiber-glass and a cold trap (Adam 1983)

Basic requirement for a gas detector : determination of particle trajectories

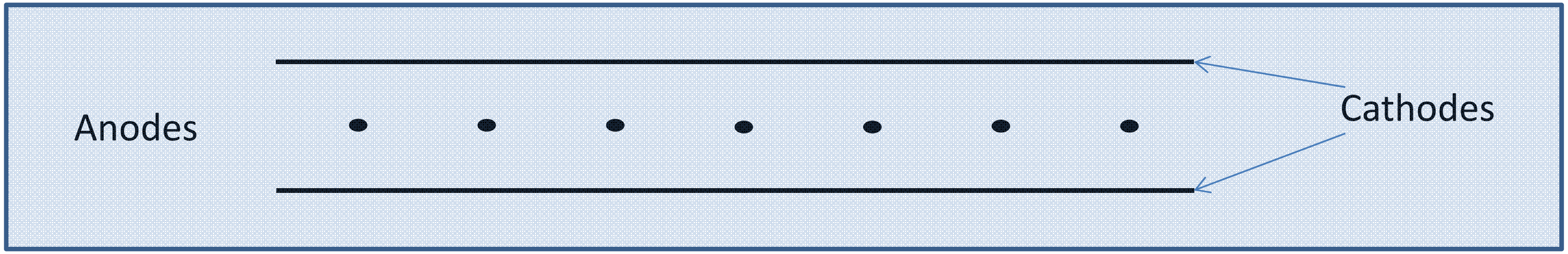
Recipe for a Gas detector

- **Thin** (minimization of de/dx, does not perturb the particle trajectory)
- **Maximum gain** (choice of gas)
- **Stability** (High Voltage, choice of quencher)
- **Choice of material** (to avoid polymerization)
- **Precision**

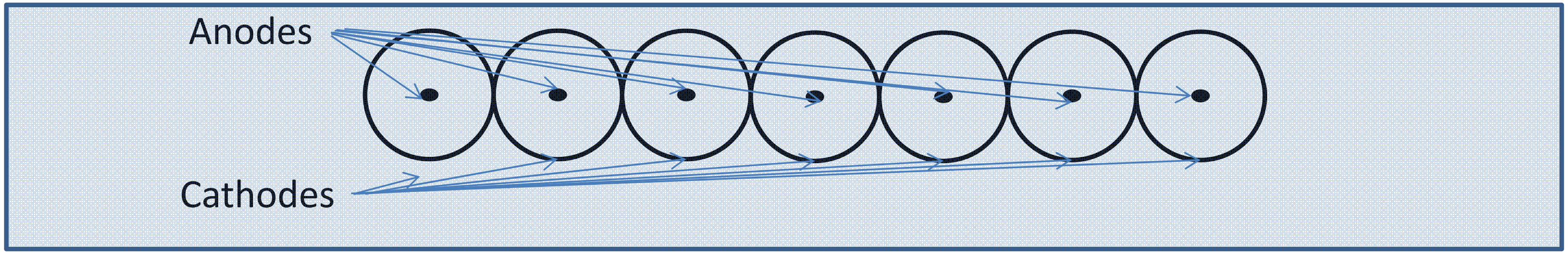
Evolution from **GM counter** to **Multiwire Proportional Chamber (MWPC)**

G. Charpak and all., 1968

An array of closely spaced anode wires in the same volume

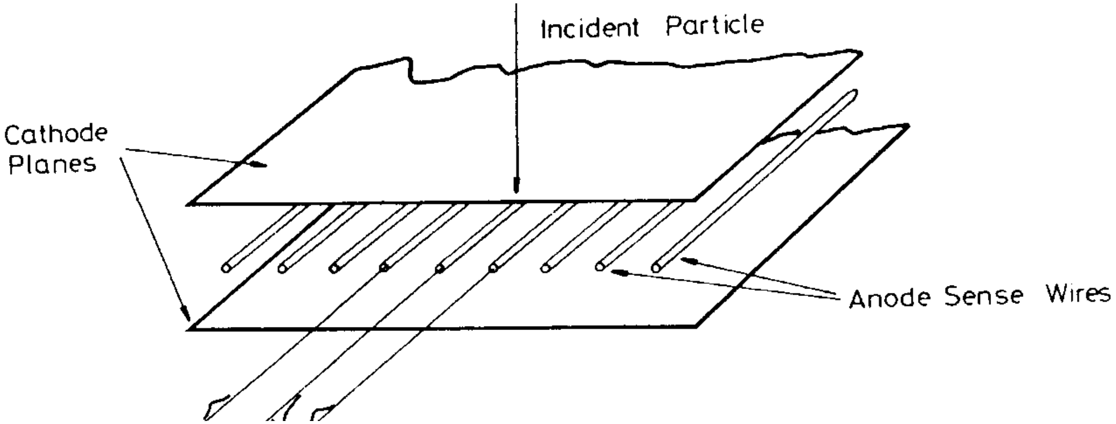


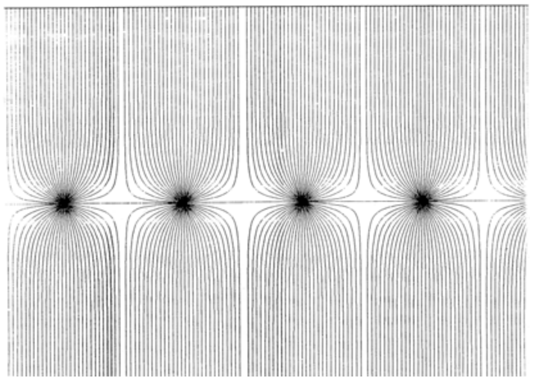
Is equivalent to

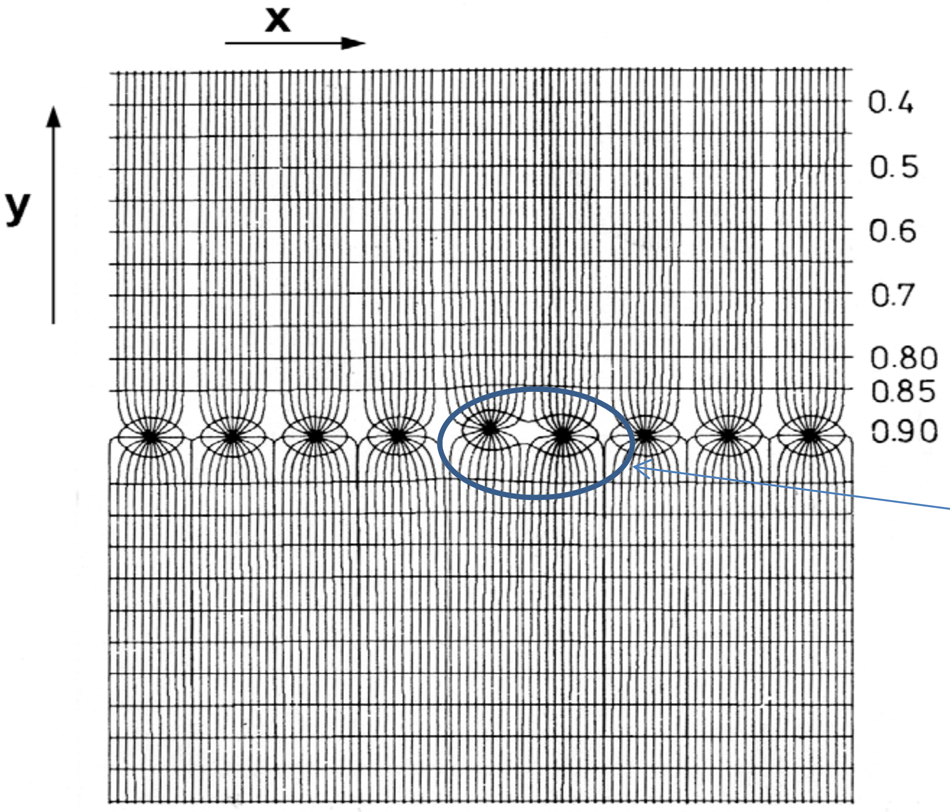


An array of proportional counters tubes

Gazeous detectors : MWPC





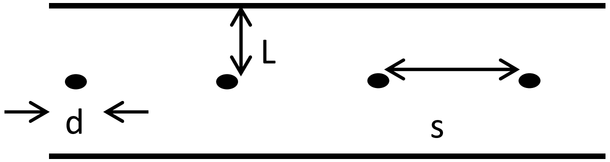


Classical figure of
electrical field disturbed by a
misplaced anode wire

Signal : as seen for the GM proportional counter : Signal $V = \frac{N_e}{C}$ $C = \frac{2\pi\varepsilon}{ln\frac{r_a}{r}}$

For an MWPC chamber
(L >> s >> d)

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



Spatial résolution :

The charges due to the particle passing in the gas are distributed over more than one anode. The spatial resolution of a MWPC is the variance of this distribution .

$$\boxed{\boldsymbol{\sigma = \frac{a}{\sqrt{12}}}}$$

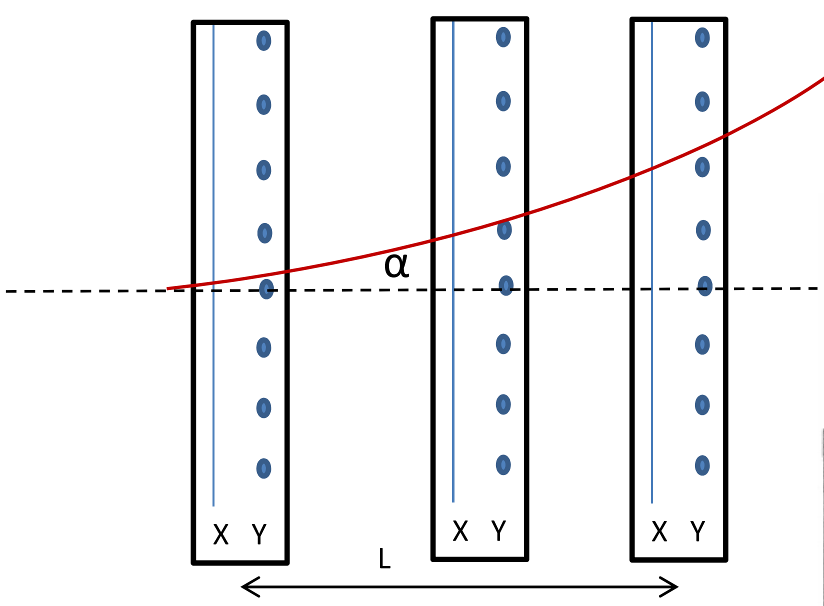
Typically ≈ 200 µm

Signal formation time : depends on the drift time for electrons (typicaly 50 nsec)
Dead time : depends on the drift time for the ions (typicaly 200 nsec)

Gazeous detectors : MWPC limitation s

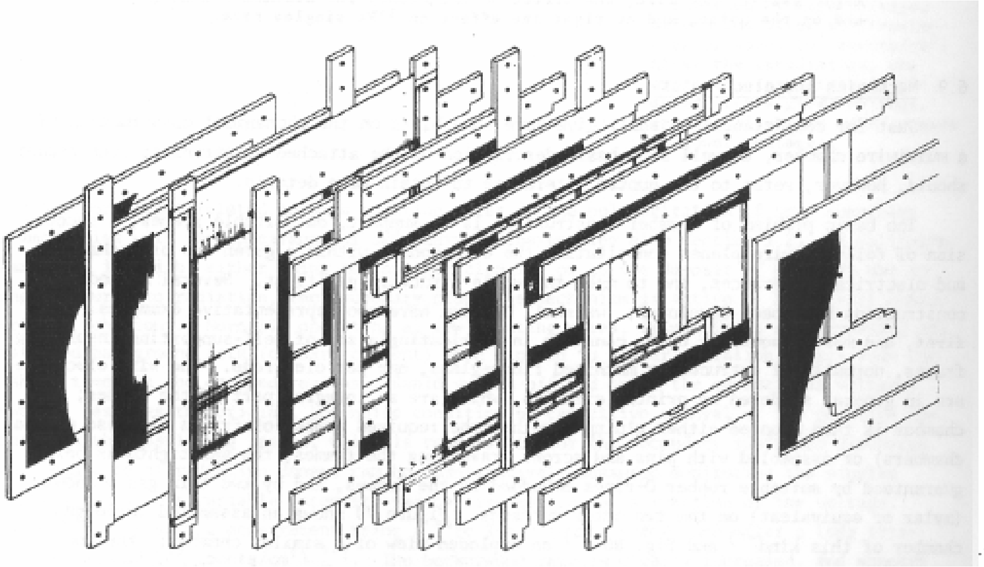
Limitation 1 : Typically : anode spacing of the order of 1-1.5 mm
(Résolution ≈ 200 – 500 µm)
In order to improve the spatial résolution : closer anodes ?
Does not work. Instabilities due to electrostatic forces anode-anode.

Limitation 2 : MWPC can measure only one coordinate.
A second MWPC ?
X-Y coordinate with a second anode row



Precision : $\Delta \alpha \approx \frac{1}{L} \sigma$

One can reduce the wire spacing…
Or increase L (dimensions…)



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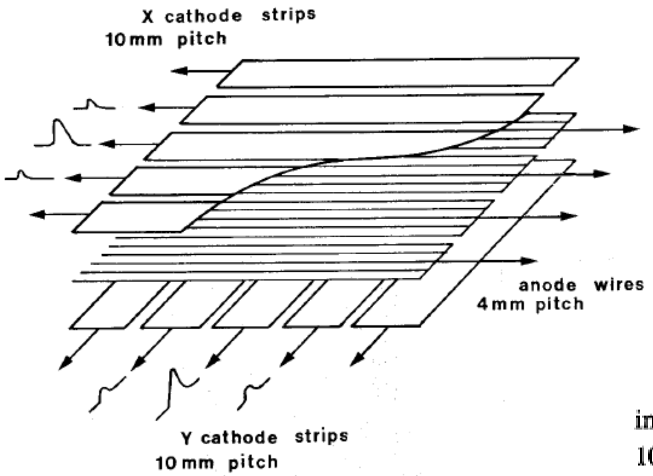
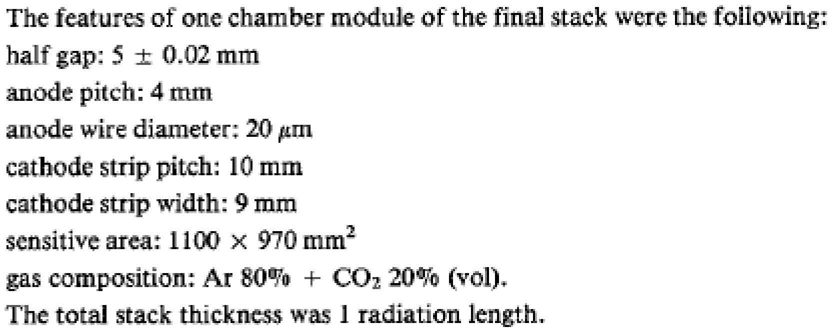
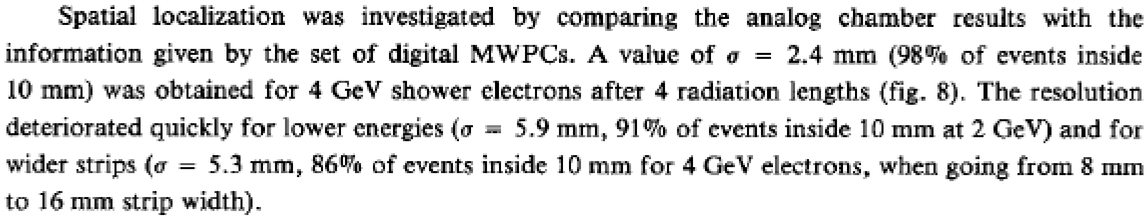
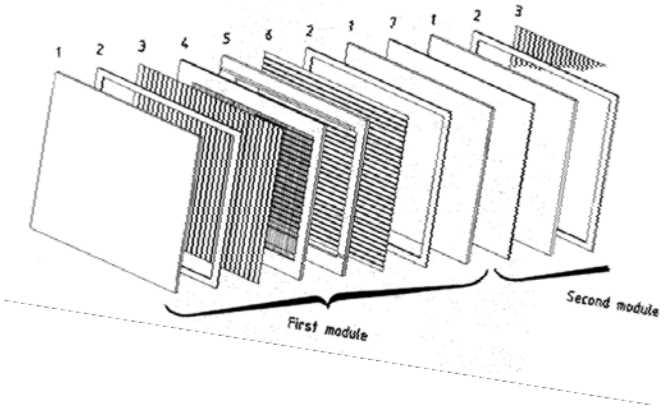
Gazeous detectors : MWPC evolution

Cathode read-out chamber : One anode plan
Segmented cathode plan
Analog read-out



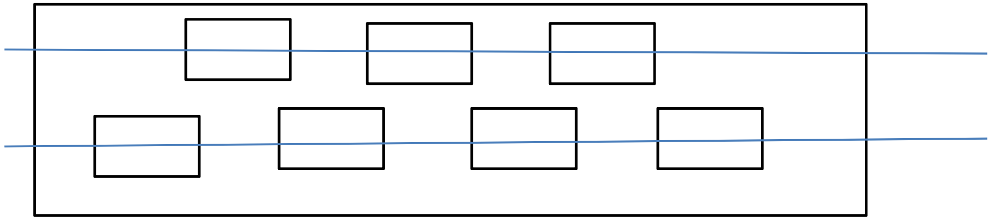

The features of one chamber module of the final stack were the following:
half gap: 5 ± 0.02 mm
anode pitch: 4 mm
anode wire diameter: 20 μm
cathode strip pitch: 10 mm
cathode strip width: 9 mm
sensitive area: 1100 × 970 mm^2
gas composition: Ar 80% + CO_2 20% (vol).
The total stack thickness was 1 radiation length.


Spatial localization was investigated by comparing the analog chamber results with the information given by the set of digital MWPCs. A value of $\sigma = 2.4$ mm (98% of events inside 10 mm) was obtained for 4 GeV shower electrons after 4 radiation lengths (fig. 8). The resolution deteriorated quickly for lower energies ($\sigma = 5.9$ mm, 91% of events inside 10 mm at 2 GeV) and for wider strips ($\sigma = 5.3$ mm, 86% of events inside 10 mm for 4 GeV electrons, when going from 8 mm to 16 mm strip width).

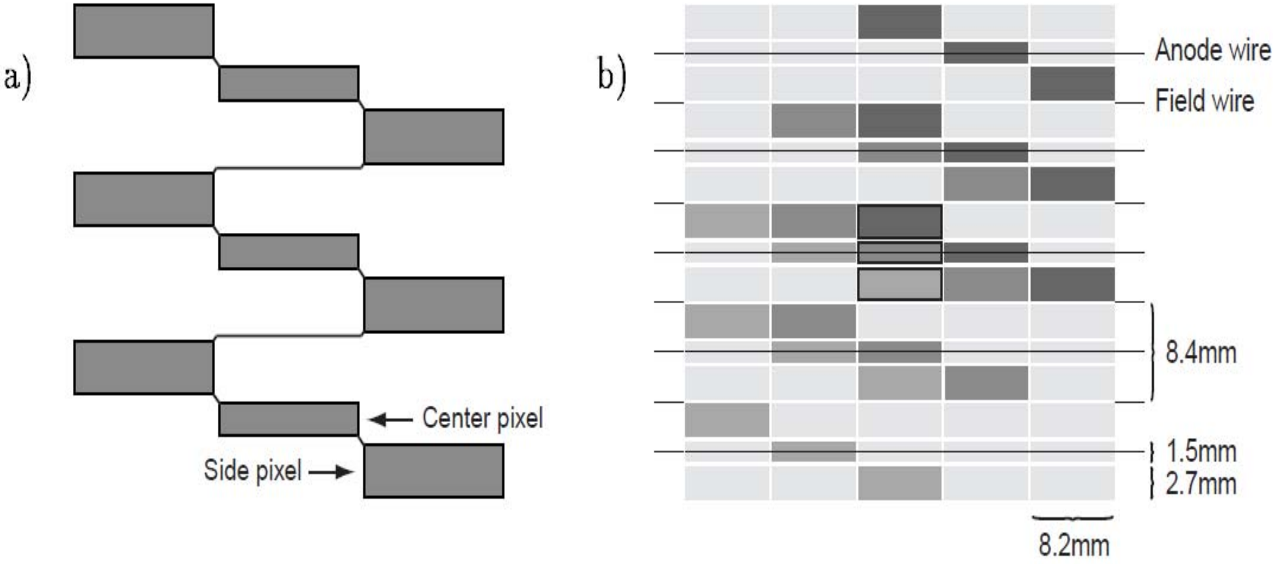


Experiment R704 (CERN) 1981 - 1985

Direct 2-D detector : Pad chambers
cathode segmented in pads



Needs a lot of electronics

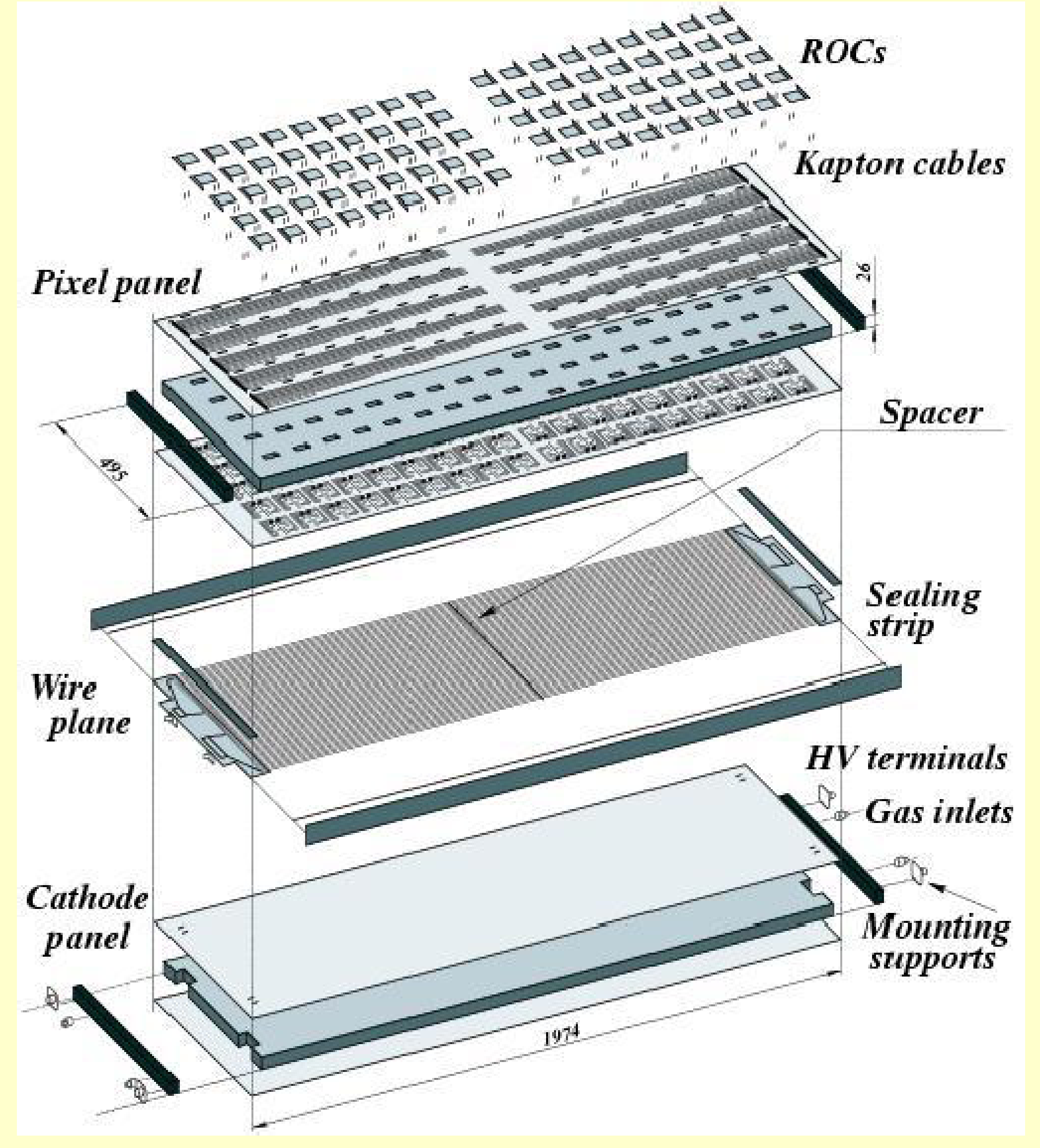


Pads regrouped in cells

PHENIX

Gazeous detectors : Pad chambers

PHENIX at RHIC



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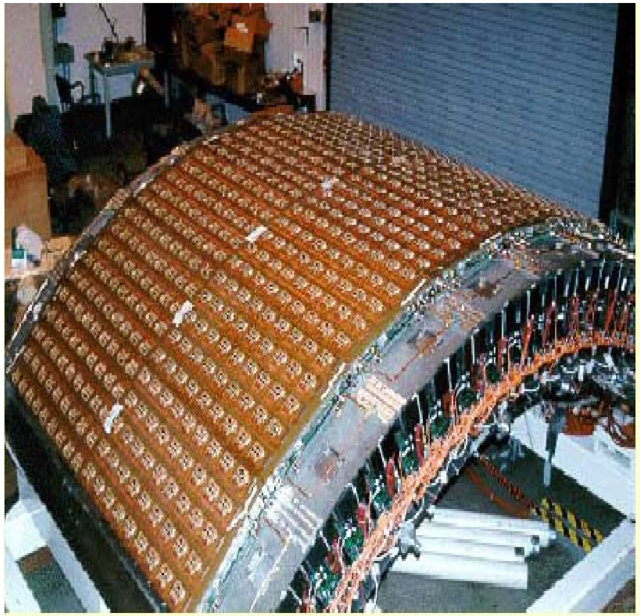
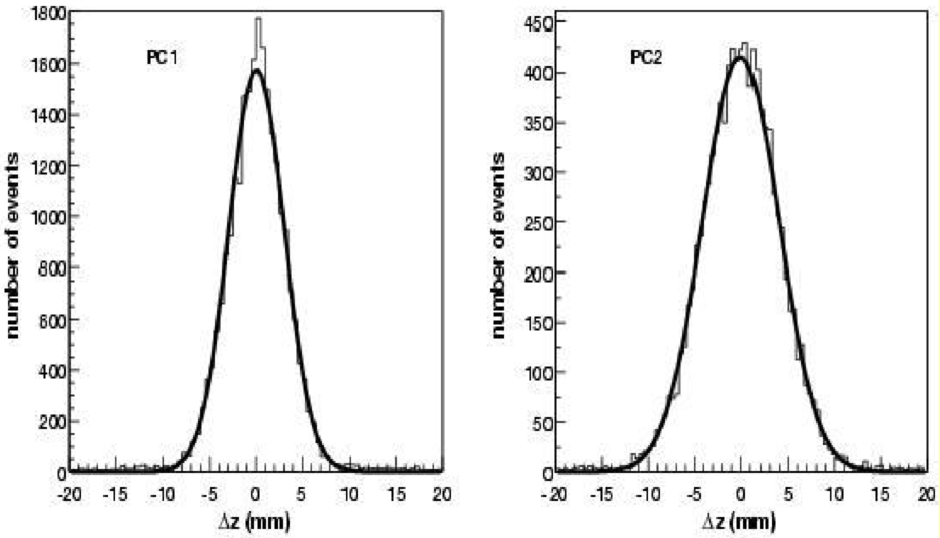
Gazeous detectors : Pad chambers





chamber	Wire dist (mm)	Z-resol. (mm)	Perp res (mm)	Rad. Thickn.
PC1	8.4	1.7	2.5	1.2%
PC2	13.6	3.1	3.9	2.4%
PC3	16.0	3.6	4.6	2.4%

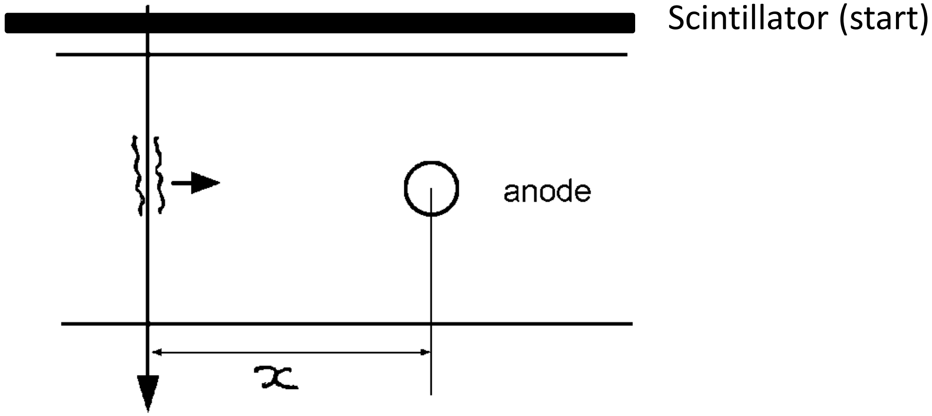
Gazeous detectors : Drift Chambers

A drift chamber is a particle tracking detector that measure the drift time of ionization electrons in a gas to calculate the spatial position of ionizing (charged) particle. Similar to MWPC, but with a better accuracy.

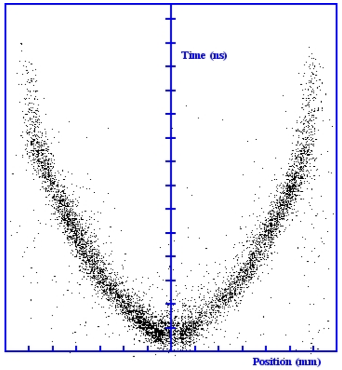
Measure of the position of the particle by mesuring the drift time of the electrons

Need : Precise knoweledge of drift velocities

Precise timing (trigger)



$X = Vd \, \Delta t$



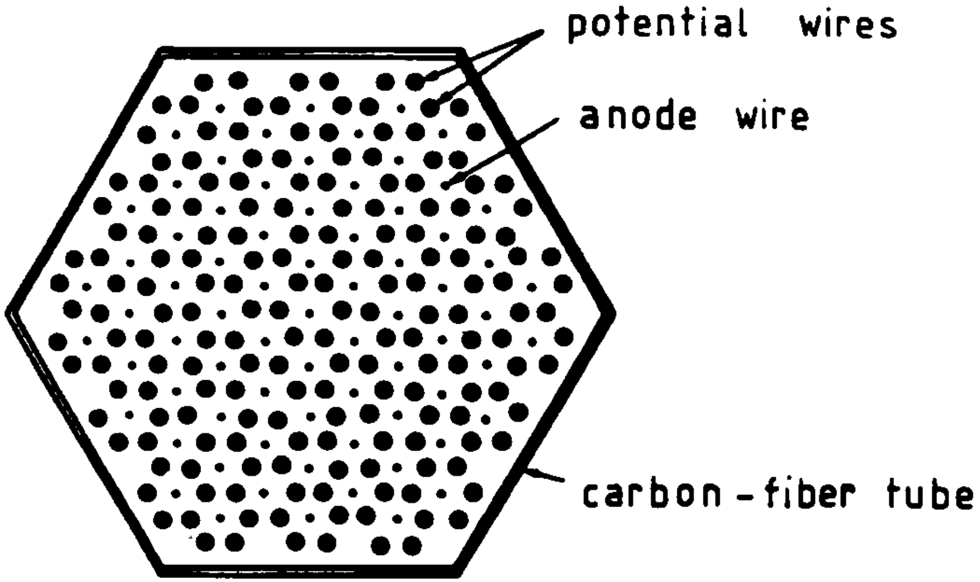
SPACE-TIME CORRELATION
(RIGHT-LEFT AMBIGUITY)

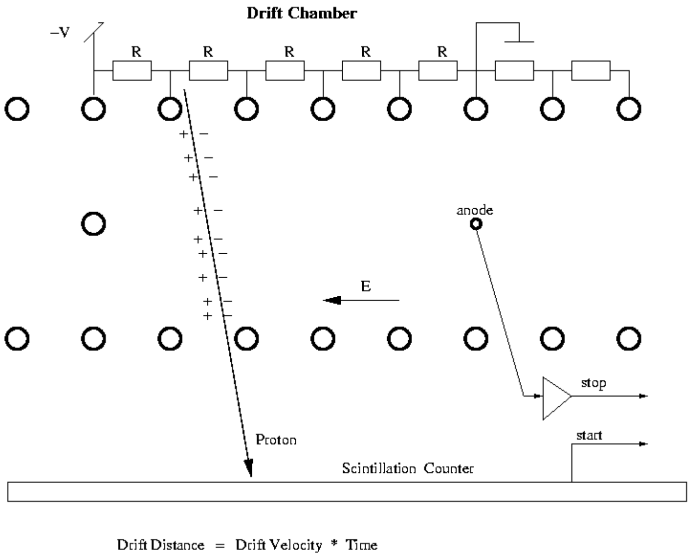
Possible resolution down to 50 µm

Gazeous detectors : Drift Chambers

Main limitation : non-uniformity of the field (non uniformity of the drift time)

Solution : defining a cell (basic unit of field)





PHENIX (RHIC) Drift Chambner

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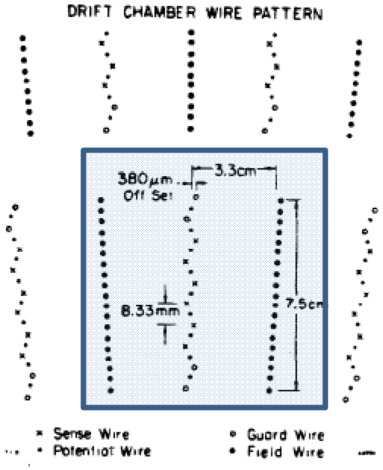
Gazeous detectors : Drift Chambers

MarkII big Drift Chamber



1 cell = 7.5 cm x 6.6 cm

12 layers
Lenght : 2.3 m
Radius : 1.6 m
5732 sense wires (anodes)
31104 potential wires
Gas mixture : 89% Ar, 10% CO2 ,1% methane
Gain : 2 10 ^{4}
Drift filed : 900 V/m
Spatial resolution : ≈ 150 μm

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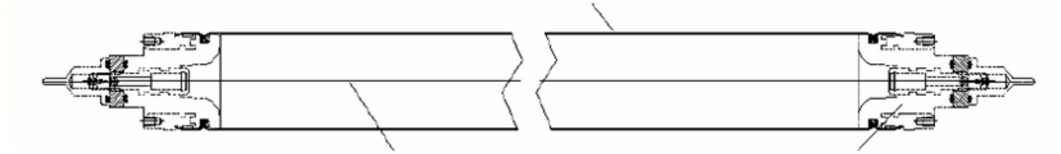
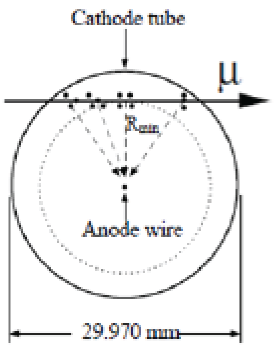
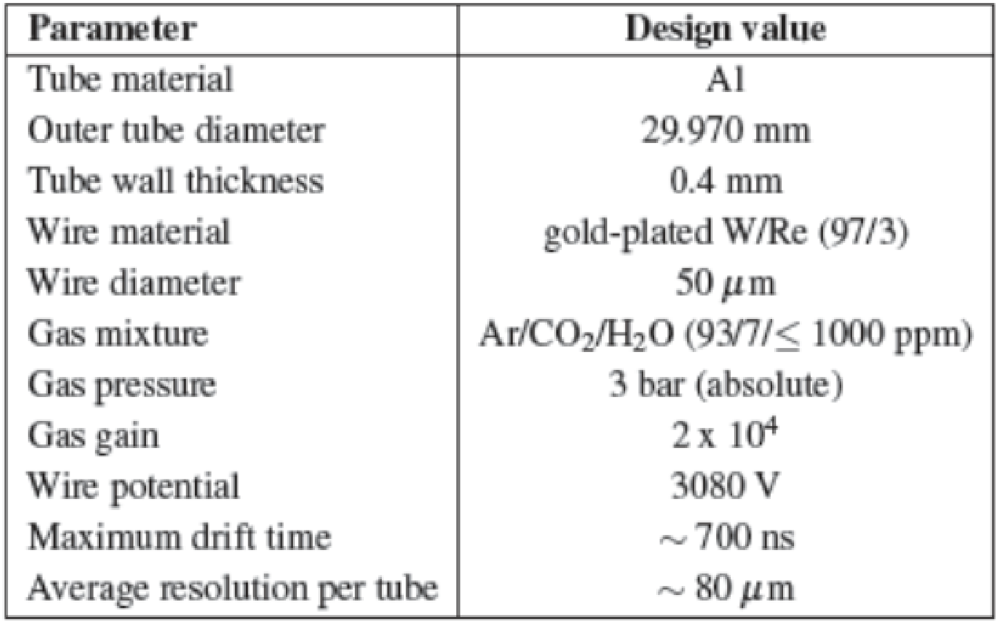
ATLAS DRIFTS TUBES (MUON SPECTROMETER)

370 000 tubes

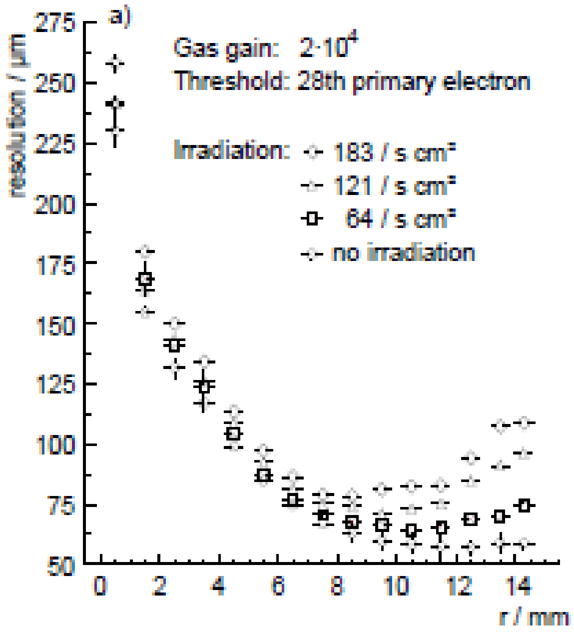
Surface 5500 m ^{2}







Parameter	Design value
Tube material	Al
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold-plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain	2 x 10^4
Wire potential	3080 V
Maximum drift time	$\sim$ 700 ns
Average resolution per tube	$\sim$ 80 μm



Max couting rate : 20 Hz / m

Gas leak < 10 $^{-8}$ Bar.l / sec.

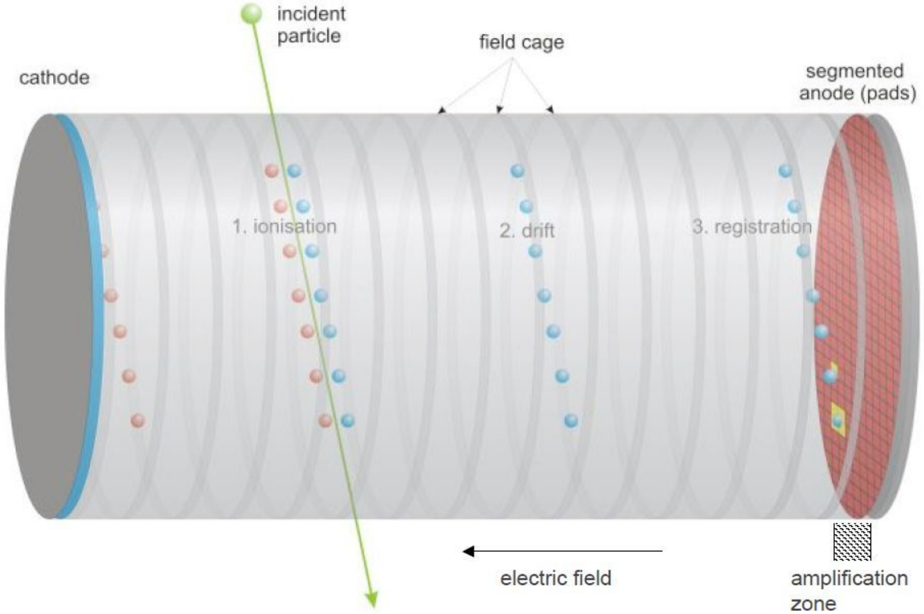
Wire tension tolerance 17g

Wire position tolerance : 25 µm

Gazeous detectors : Drift Chambers

TPC : « The best of the best evolution »

Combination of a Drift Chamber and a MWPC (Pad chamber)



Position (X and Y measurements)

Drift time (Z measurement)

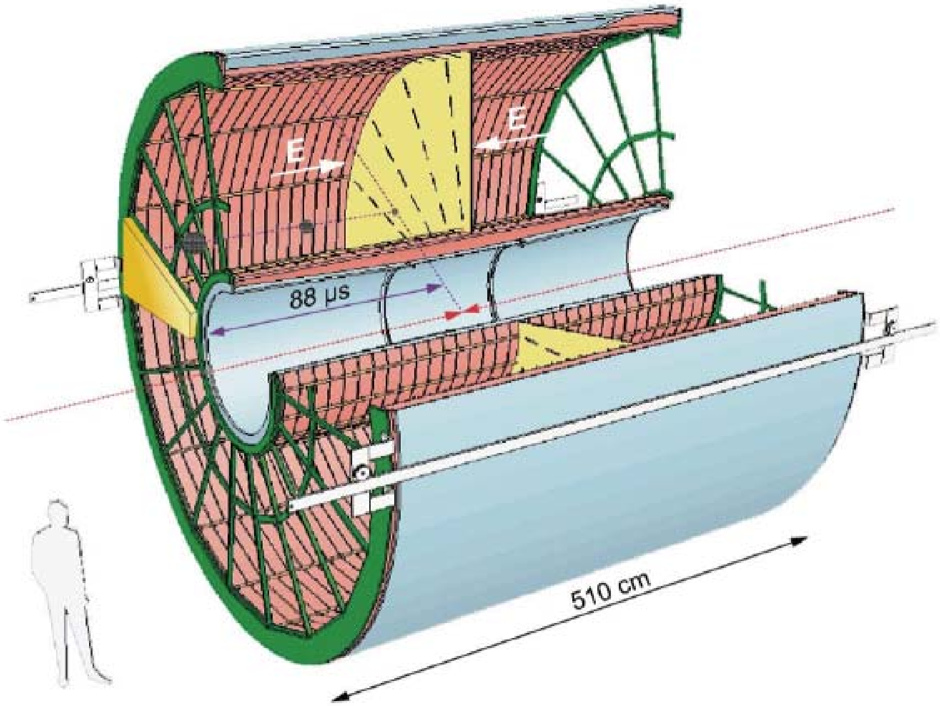
Huge (and empty) drift volume

Multi channels (read out pads)

Drift volume full of ions

→ séparation for the avalanche region

Gazeous detectors : Time Projection Chambers – The ALICE TPC at LHC



Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 µs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

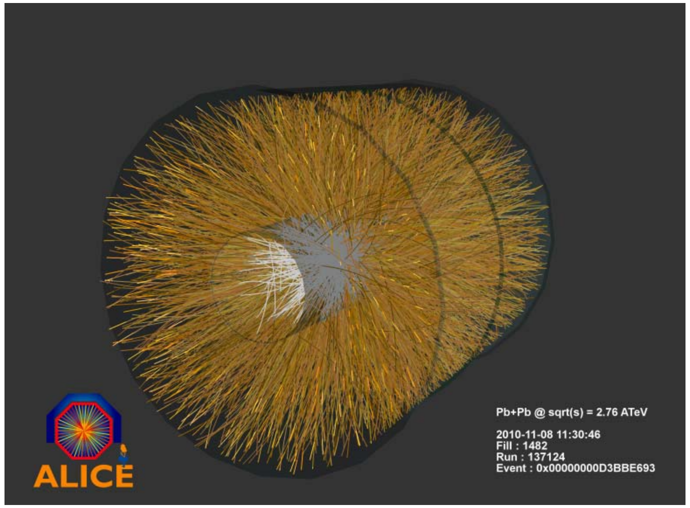
Gain: > 10^4
Diffusion: σ_t = 250 µm
Resolution: $\sigma \approx$ 0.2 mm

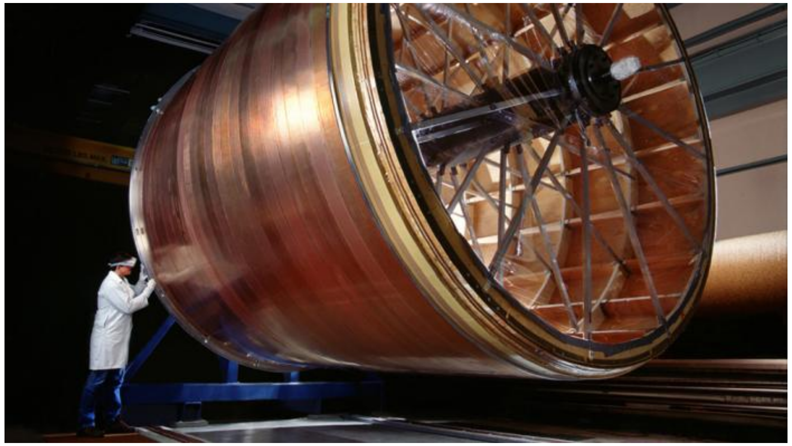
σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

Magnetic field: 0.5 T

Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K





Gazeous detectors : Time Projection Chambers – The ALICE TPC at LHC

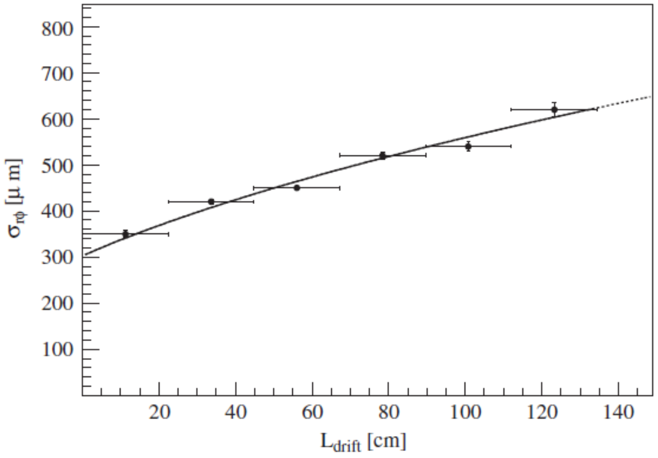


Fig. 6. Space point resolution in pad direction (momentum plane) as a function of drift length. Solid line shows the fit and dashed line the extrapolation.

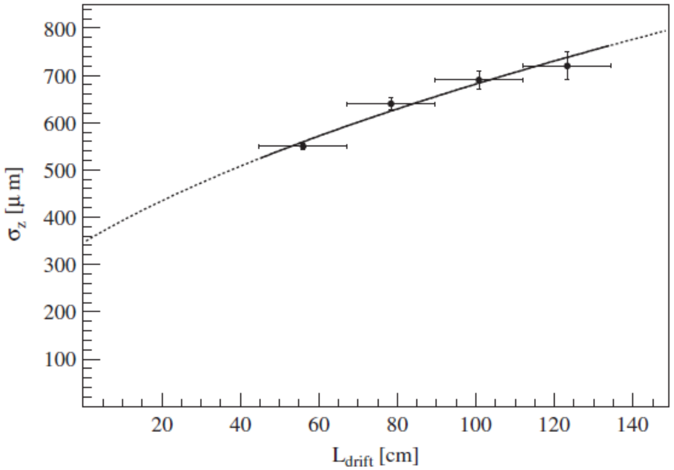
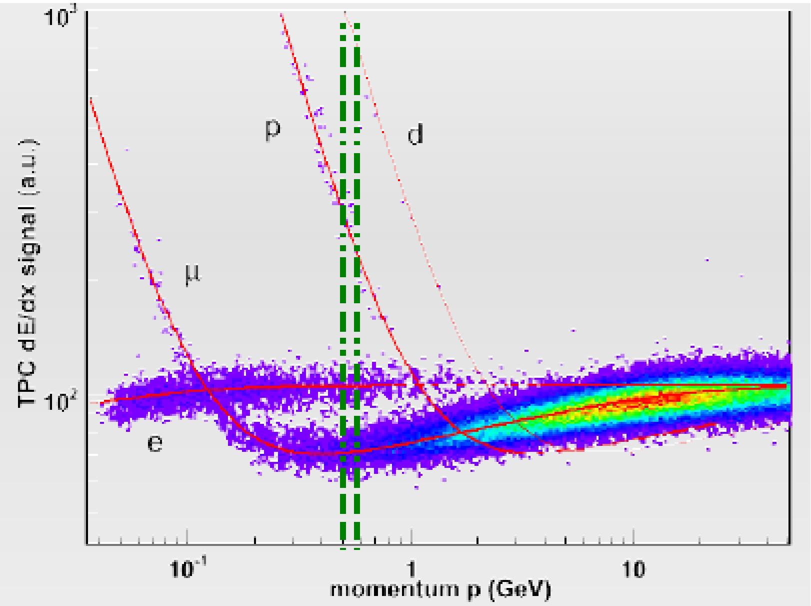


Fig. 7. Space point resolution in drift direction as a function of drift length. Solid line shows the fit and dashed line the extrapolation.



	Experiment	Monte Carlo
$\sigma_{r\phi}$ (μm)	800 ± 80	900
σ_z (μm)	900 ± 100	900

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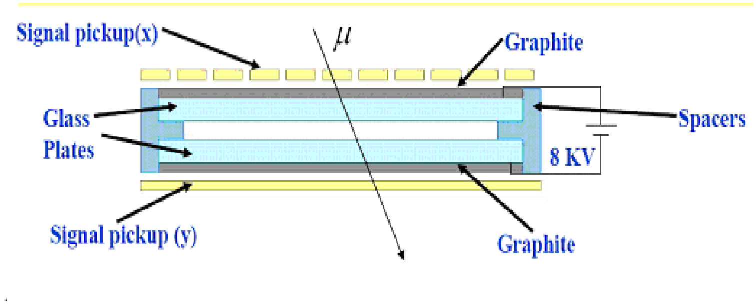
RPC : Thin (2 mm) drift volume sandwiched between

Two highly resistive (2.5 10^{10} Ω.cm) plates

Simple – inexpensive – fast (used as rigger)

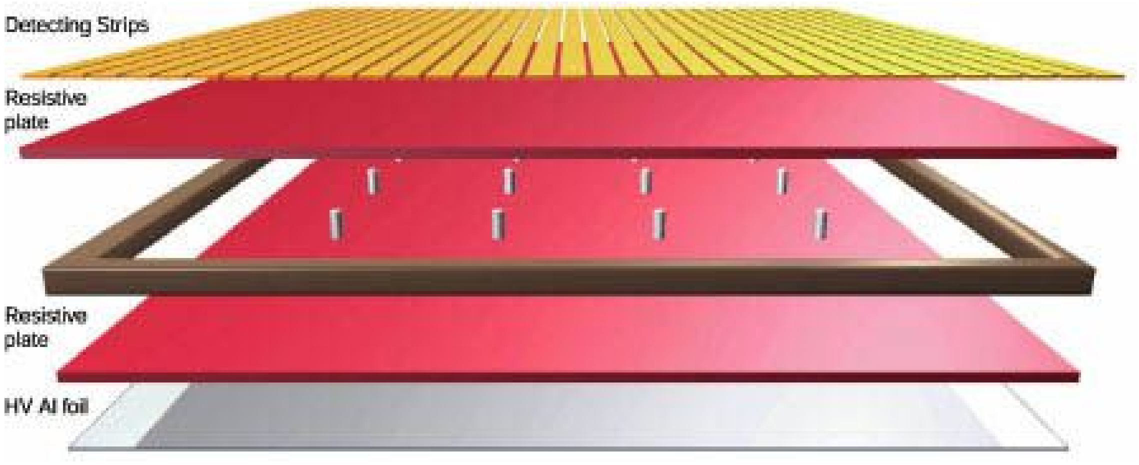


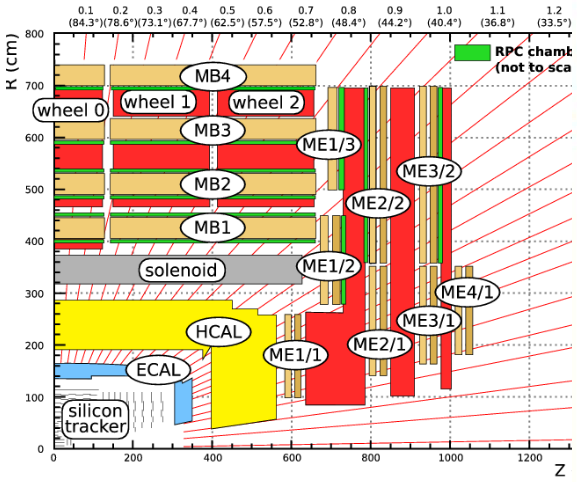
Thin drift volume and High field

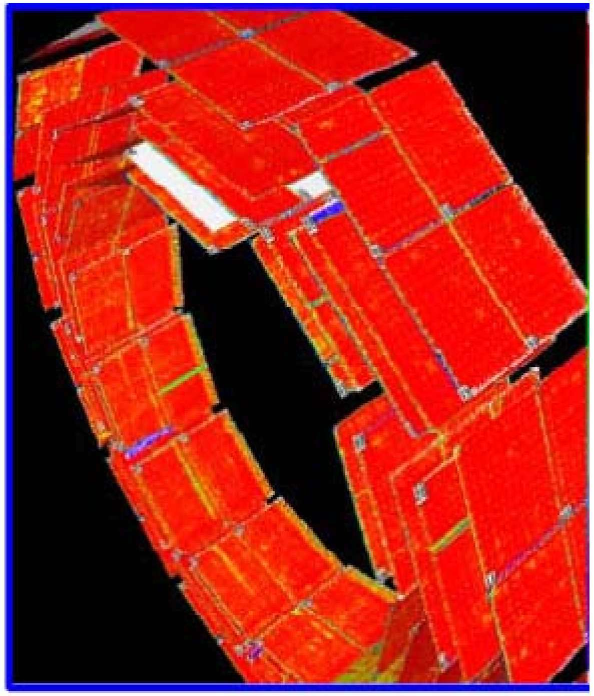
Works usually in streamer mode
Large signal, but slow (100 nsec)

At LHC : in avalanche mode
Lower signal, but fast (1-10 nsec)

Gazeous detectors : Resistive Plate Chamber for CMS - LHC







Resistive plates : 1 10^{12} Ω.cm
Gas mixture :
C2H2F4 (92.5 %)–C4H10 (4.5%) – SF6 (0.3%)
HV : 8.5 – 9.7 kV

RPC efficiency > 97%
Rate capability > 1 KHz/cm2
Operation efficiency plateau > 400V
Time resolution < 3ns
Cluster size < 3
Dead time should be few nano seconds

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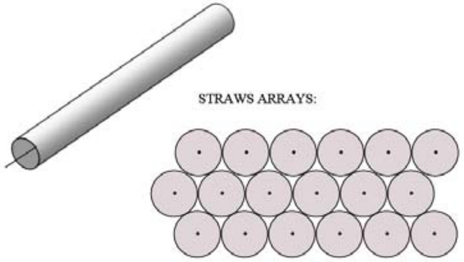
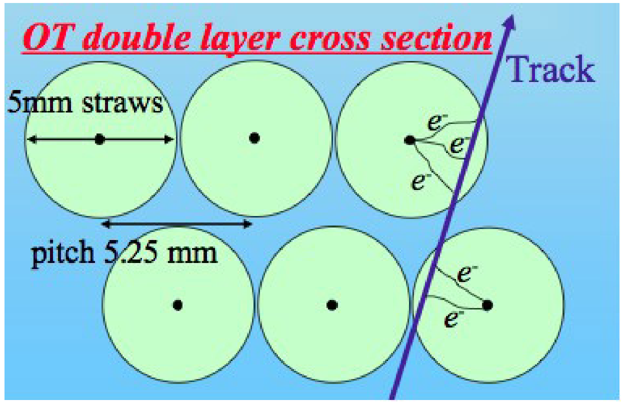
SWPC : Single Wire Proportional Chamber
Single proportional counter in an array

- Cheap and simple to build
- Capable of withstanding very high fluxes





Straw Chambers : the ATLAS read-out system for the Transition Radiation Tracker

Gazeous detectors : MicroStrips Gas Detector

MSGC : following an idea of Oed (1989) :

A MWPC where the wires are replaced by strips deposited on an insulating substrate (glass)

High field : gain ≈ 10^{4}

Spatial resolution : σ ≈ 20 µm

Dead time ≈ 10^{-5} sec.

(Short distance for the ions)

Gas : Ar – DME / Ne - DME

Gazeous detectors : MicroStrips Gas Detector

MWPC	MSGC
anode spacing : 1-3 mm	anode spacing 200 µm

Rate capability comparison
MSGC seems to be well adapted
to high fluxes of particles (LHC)

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Gazeous detectors : MicroStrips Gas Detector

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Gazeous detectors : MicroStrips Gas Detector

Surface charging : Bulk or surface resistivity of the
support material is modified by irradiation (flux)
Choice of support (special glass or doping)

Ageing : Polymerization due to construction material
(DME is a solvant)
Choice of non-sovable material in DME

Discharges: Possible with higher flux or low energetic particles
Certain with dust (short between anode and cathode (50 µm)

Gazeous detectors : MicroStrips Gas Detector

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Gazeous detectors : Gas Electron Multiplier

GEM (on a MSCG) : préamplification at ≈ 100 µm above the substrate
kapton foil (copper coated) with amplification holes

Discharge probability
using single, double
and triple GEMs

Gazeous detectors : MSGC + GEMs

Compass

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Gazeous detectors : Micromegas

Micromegas : (G. Charpak and Y.Giomataris – 1992) is similar to a MSGC+GEM and a drift chamber. The cathode is a mesh at 100mm from the anodes (strip depsited on a substrate)

Impossible d'afficher l'image.

Gazeous detectors : Micromegas

Limitation : Mesh spacers (loss of acceptance)

Prototype (1997)

Gazeous detectors : Micromegas

Compass
Set of 12 plates 40x40 cm ^{2}

T2K / TPC
Set of 12 plates 40x40 cm ^{2}

Gazeous detectors : Aging problems

Example : The GE1/1 project for CMS :

Adding CF_4 to the « classic Ar/CO_2 mixture to increase the time response (5 nsec)

Effect : dissociation of CF_4 leads to HF (hydrofluoric acid) which etch the copper…

Example :
Etching of the GEM
Holes (GE1/1 project)

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Gazeous detectors : « New » Aging problems

In future machine (HL-LHC, FCC…) at very high Luminosity, the particle flux will degrade the performances of the detectors.

One has to test the irradiation effects !
But simulation is « impossible »….

Example :
Gain versus irradiation
(corresponds to 10 years of
Operation at CMS

Impossible d'afficher l'image.

Gazeous detectors : Conclusions

Conclusion :

- Evolution of gaseous detectors : MGD (Micro Gap Detectors)
  - GEM
  - Micromégas
- Main problem for these detectors :
  - Cleaningness
  - Long term operation

EASY TO DESIGN

COMPLICATED TO BUILD

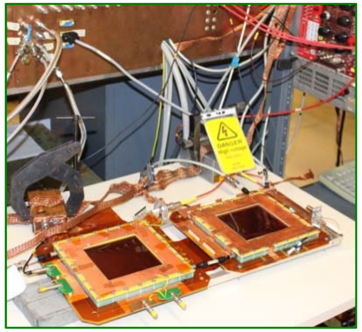
DIFFICULT TO OPERATE ON A LONG TERM BASIS

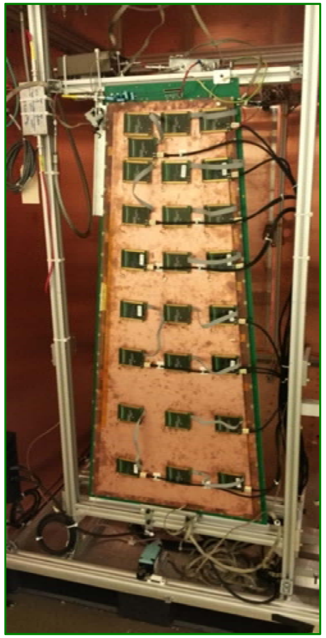
R&D on Big GEM Chambers : a nice nightmare !

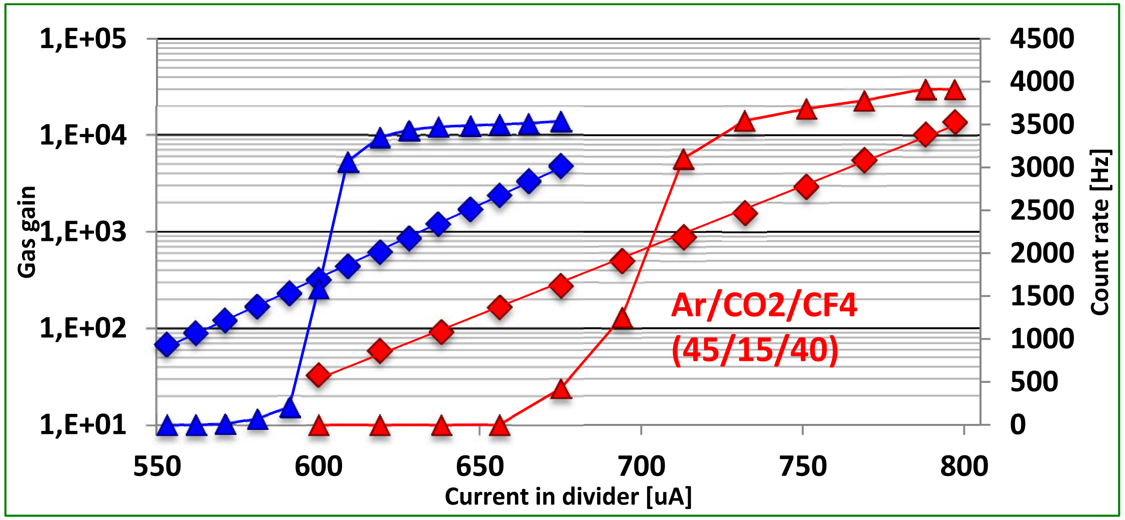
R&D on Big GEM Chambers : 1. DEFINING THE PARAMETERS

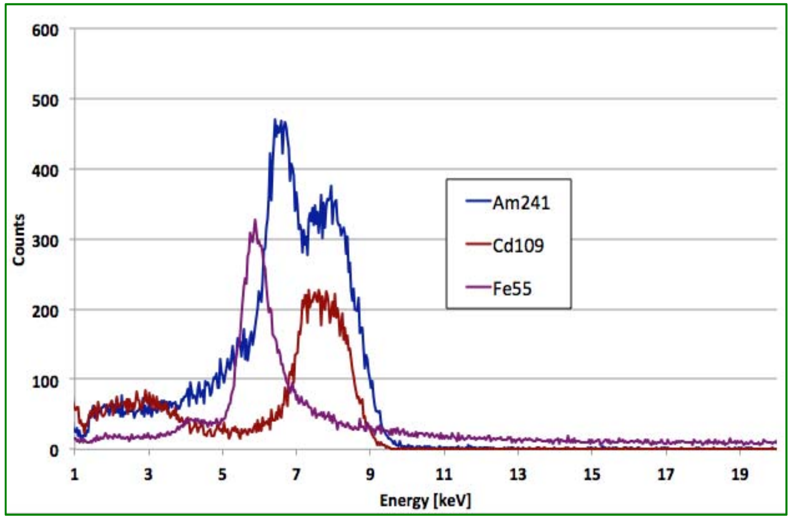
Extensive study on GEM detectors :

- Basic operation with Xray sources
- Calibration tests with different :
  - gas mixtures
  - GEM geometries
  - HV power systems
  - sizes of detectors
- Defining the best configuration









R&D on Big GEM Chambers : 2. VERIFYING THE PARAMETERS

Advanced measurements and characterization:

- General understanding on GEM technology
- Comparison with past measurements
- Charging up effects (short-term stability)

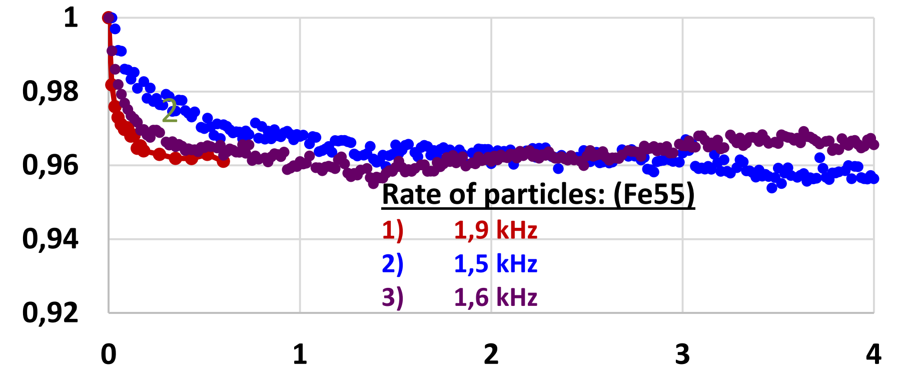
5-10 % after 1 hour

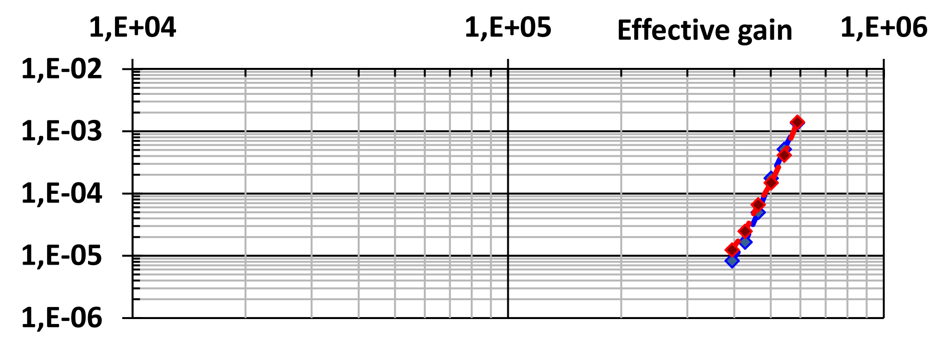
- Discharge probability

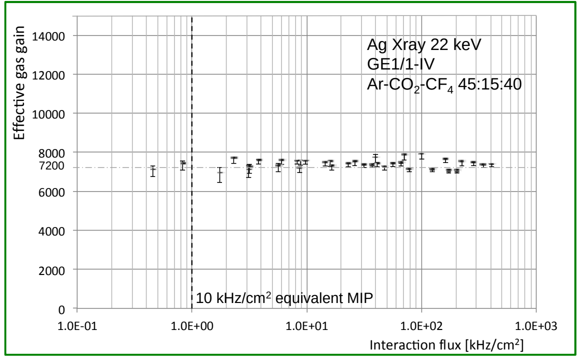
< 10^{-12} at a gain of 10^{4}

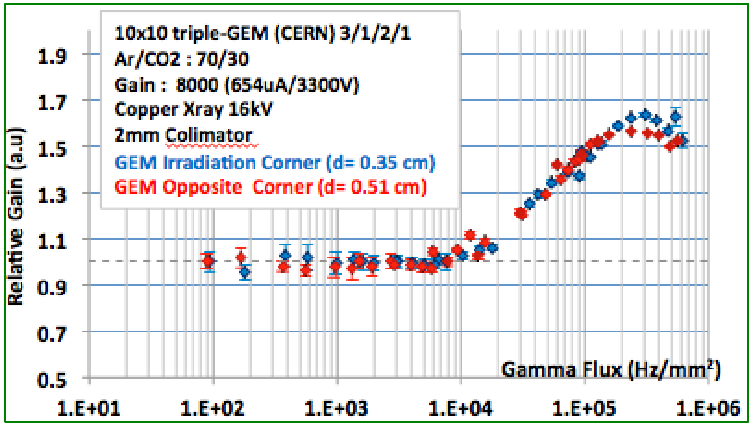
- Rate capability

No gain loss up to 1 MHz/mm²









R&D on Big GEM Chambers : 3. BEAM TESTS

Detectors performences :

- Intense beam of charged particles
- All generations tested in different config.
  And B field.
- Characterization of the beam and comparison with the detector response
- Information about :
  - Efficiency
  - Space resolution
  - Time resolution
- Characterization of new electronics and DAQ systems

σ_x < 300 µm (digital readout)

Detector efficiencies above 98%

R&D on Big GEM Chambers : 4. LONG TERM TESTS…

Aging Test at CERN GIF

- ^{137}Cs source 566 GBq
- Gamma emission 662 keV

R&D on Big GEM Chambers : 5. AGING TESTS

Outgassing Study :

- **select “clean” materials to prevent self-contamination and increase longevity**
- **9 materials already tested / 8 approved**