European School of Instrumentation in Particle & Astroparticle Physics

European Scientific Institute

DETECTOR TECHNOLOGIES

Lecture 1: Generalities

Gazeous detectors

Principle of operation

Proportional counters and beyond

Goal :

Observation and identification of final states (whatever the processus)

A particle is defined by its :

- Mass
- Electrical Charge
- Momentum
- Energy
- Lifetime
- ~~(spin, flavour, color….)~~

A Detector : does not give any measurement.

Gives an information coming after an **interaction** between the **particle** and a **medium,** through **energy deposition**

Energy deposition

- **Limited** (the particle goes almost undisturbed)
  - Momentum
  - Electrical charge (if magnet)
    - → Trajectography
- **Total** (the particle stops)
  - Energy

Various processes :

Ionization (Bethe-Bloch)
Radiation (Bremstrhalung or Transition Radiation)
Scattering (Coulomb or direct)
Particle production (photon)
Cerenkov emission

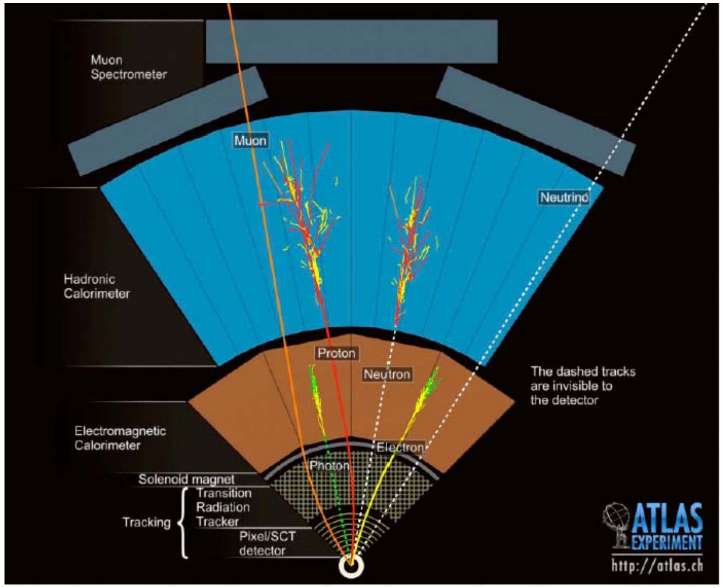
Types of detectors :

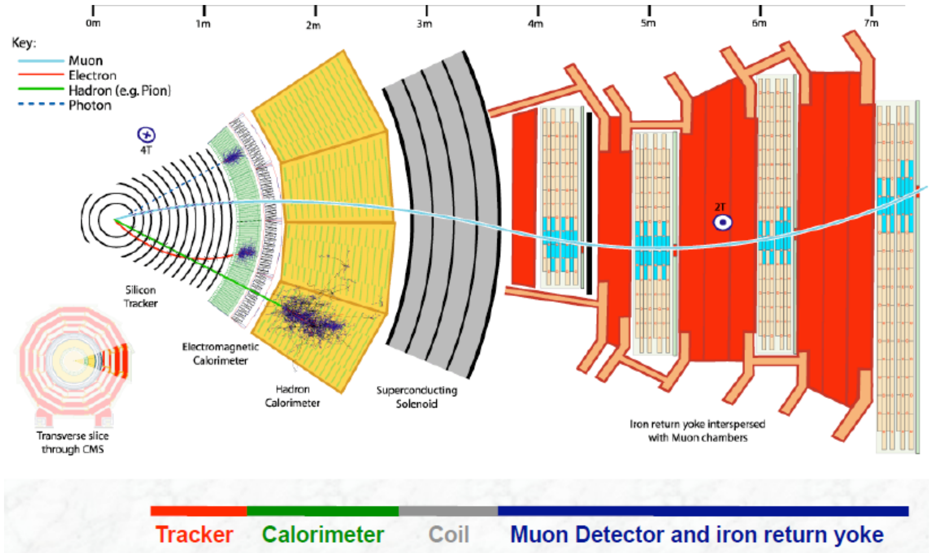
Trackers (position and momentum measurement)

Calorimeters (energy measurement)

Identifiers (identification of various types of particles)

Trigger counters (decision)





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)

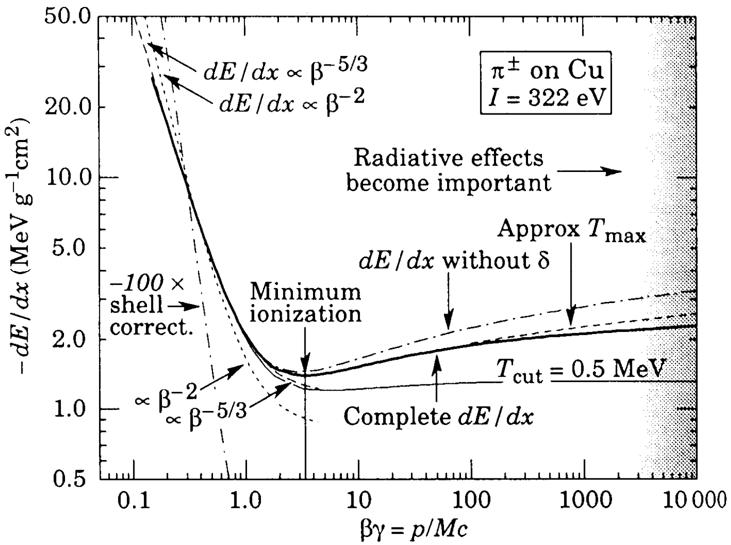
1. A charged particle is passing trough a gazeous medium : loss of energy

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

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

Ex : proton 1 GeV/c²
$T_{max} = 1.2$ MeV

$K = 4\,\pi\,N_A\,r_e^2\,m_e = 0.3071$
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



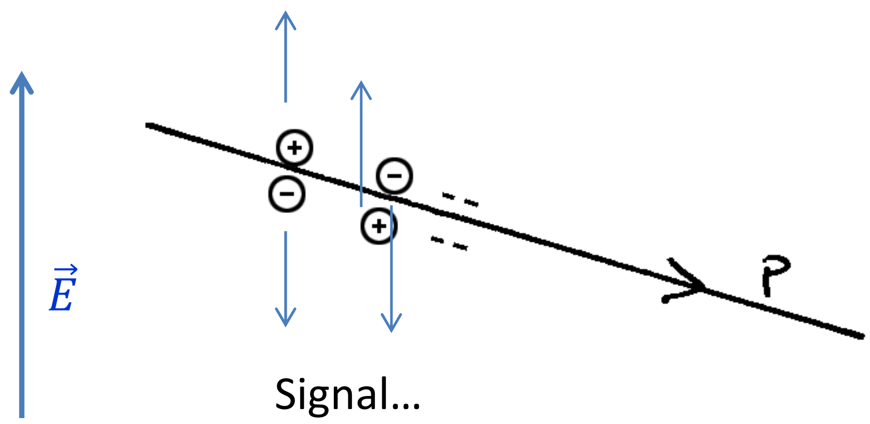
Usually, we have to deal with MIPs
Minimum Ionizing Particles (βγ≈ 3-4)

2. ***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

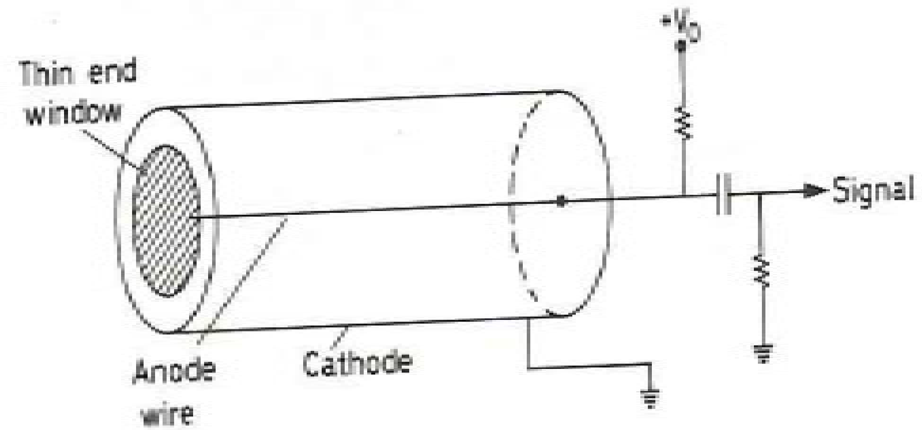
4. If exists an **electrical field** :
Electrons (and ions) are drifting …



Signal…

First example : Geiger-Muller counter

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



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

r_a = anode radius
r = counter radius

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

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

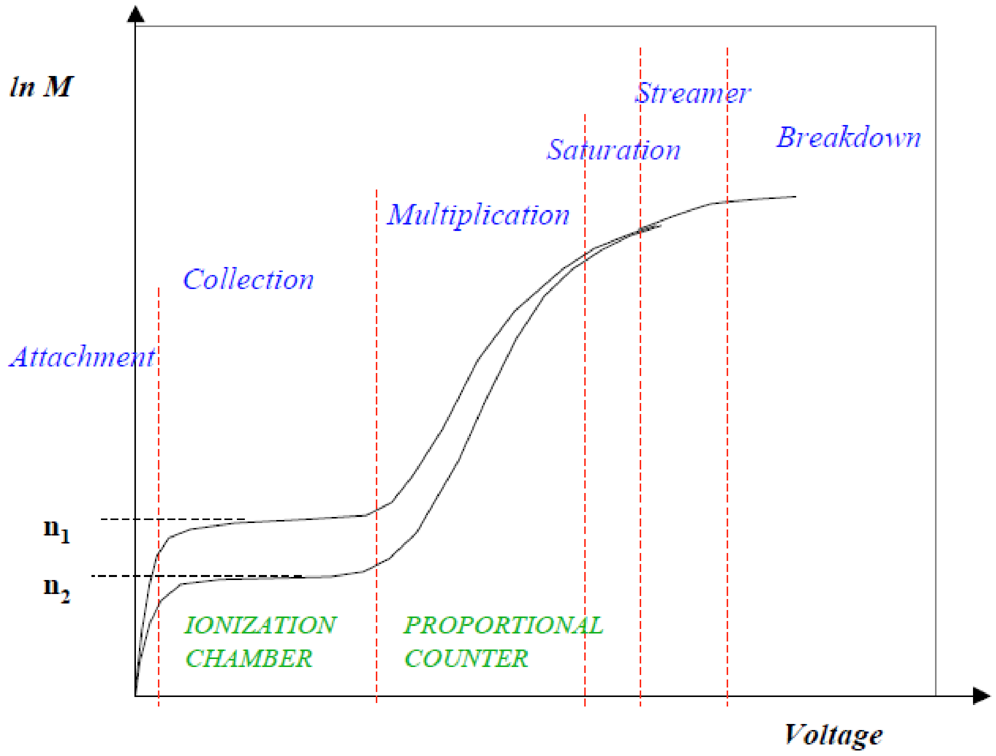
Where $C = \frac{2\pi\varepsilon}{ln\frac{r_a}{r}}$

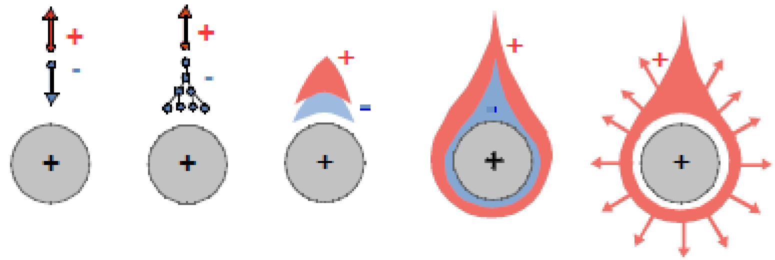
Extremely weak signal… (One electron = 10^{-9} Coulomb…)

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



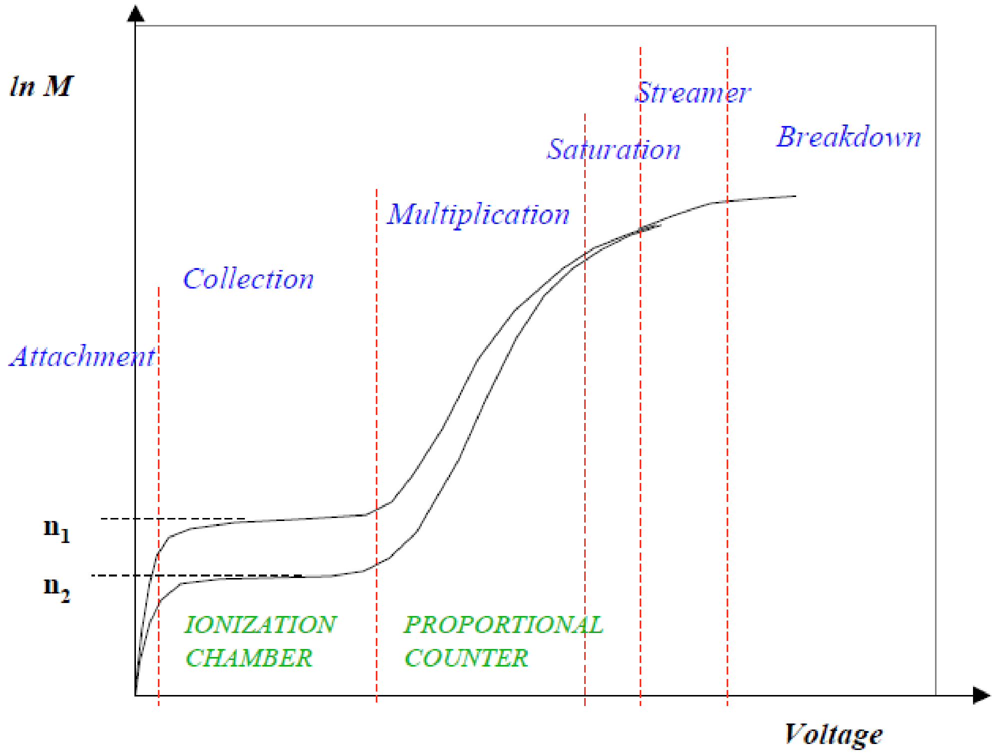


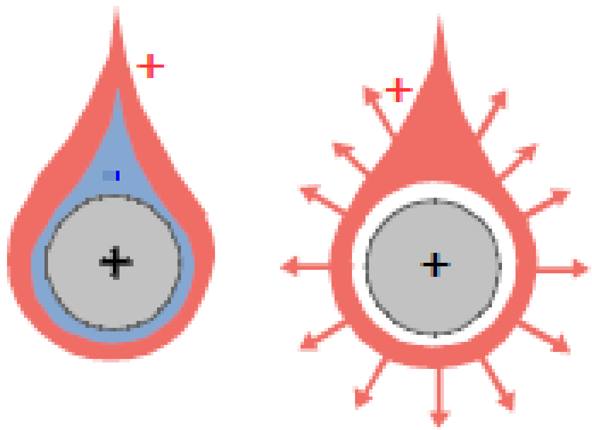
e^- - ion recombination - almost no signal

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
Multiplication factor (Gain) can reach 10^5 - 10^6

Gazeous detectors : Principle of operation





Saturation and Streamer mode - Geiger-Muller regime :

Electronic avalanche amplified by desexcitaion of ions trhu γ (pair creation)

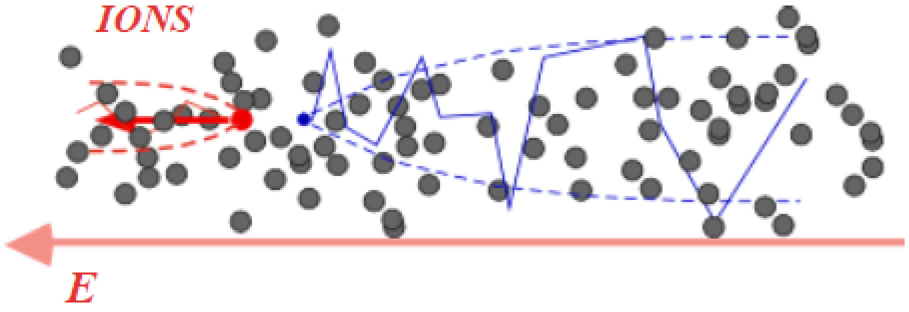
Saturation of the signal.

Loss of proportionnality

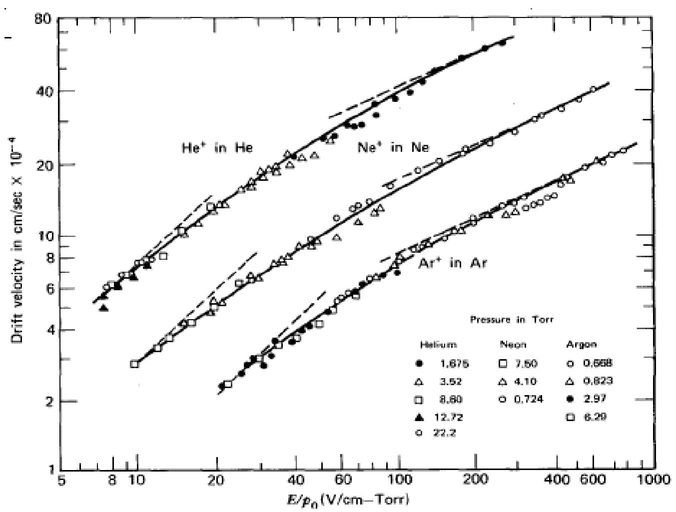
Breakdown : Continuous discharges between anode and cathode… Ultimate destruction…

Transport of electrons and ions in the gas :

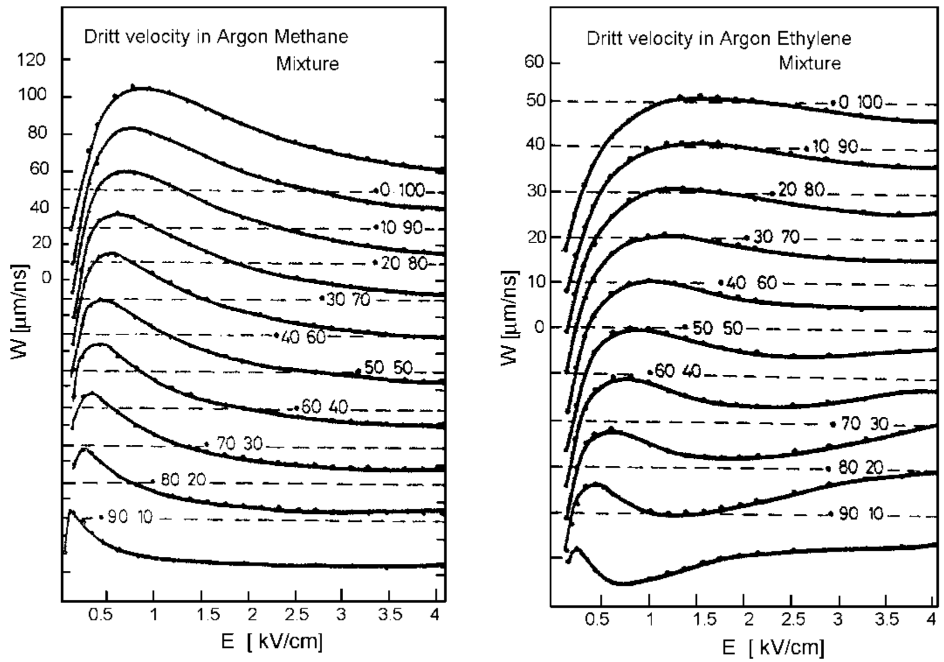
With an electric field, electrons and ions are accelerated along the field lines. Their movement is interrupted by collisions (mean free path…) which limit the maximum average velocity.



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...) :

Example : Argon : 30 primary electrons

Possible gain $10^3 – 10^4$

e – drift velocity : 100 µm/nsec. at E = 1kV/cm

Gas	E_i (eV)	$\frac{dE}{dx}$ (MeV)	N pairs /cm
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DME	10.0	1.85	55

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

Solution : the quencher

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 !

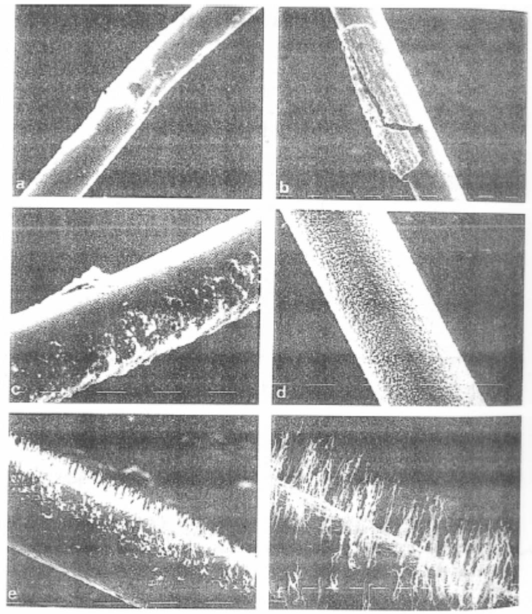


Fig. 4.31. Deposits on anode wires: (a) – $Ar+C_2H_6$; (b) – $Ar+C_2H_5$ + methylal; (c) – $Ar+CO_2$; (d) – perspex chamber; (e, f) – chambers with G10 fiber-glass and a cold trap (Adam 1983)

Basic requirement for a gas detector : determination of particle trajectories

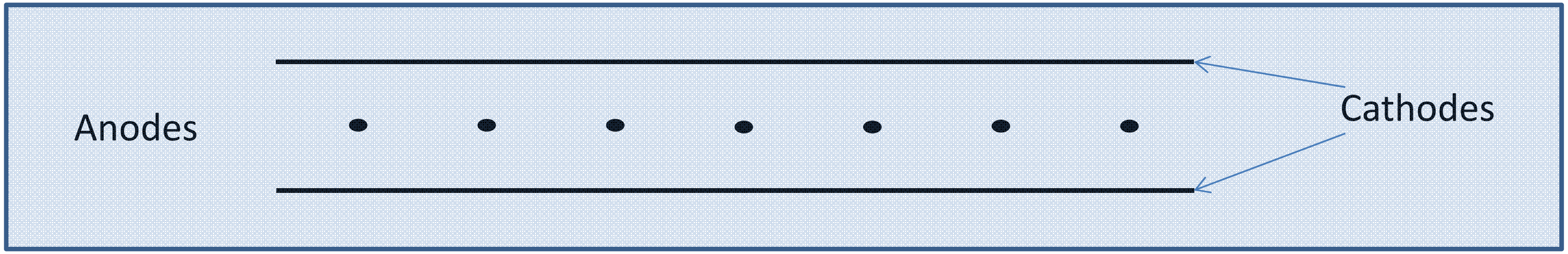
Recipe for a Gas detector

- **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** (by contruction, placement…)

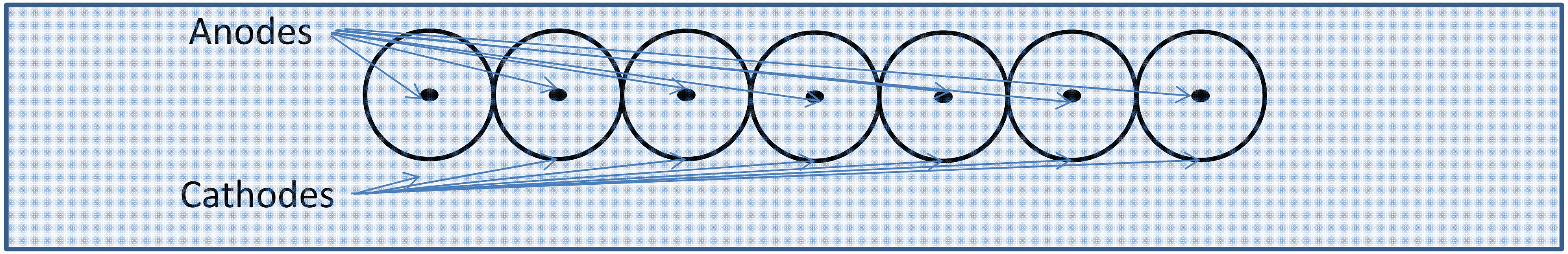
Evolution from **GM counter** to **Multiwire Proportional Chamber (MWPC)**

G. Charpak and all., 1968

An array of closely spaced anode wires in the same volume

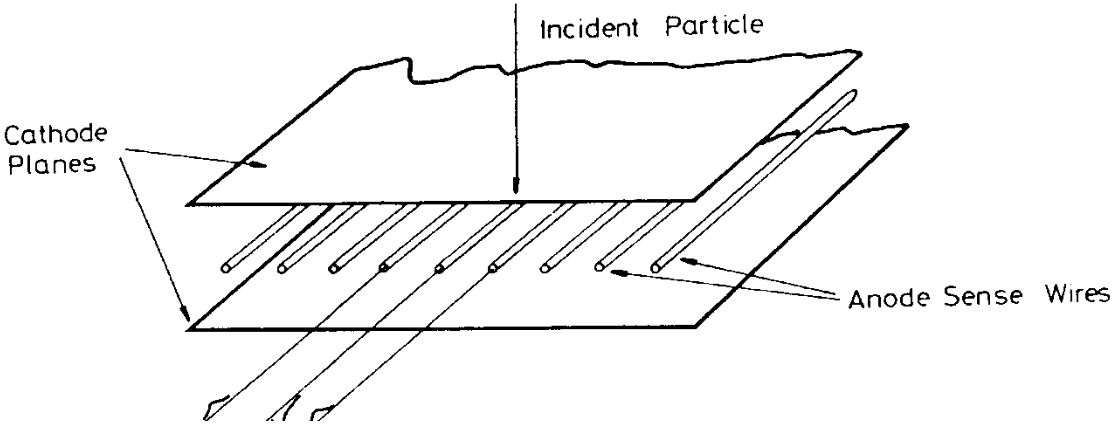


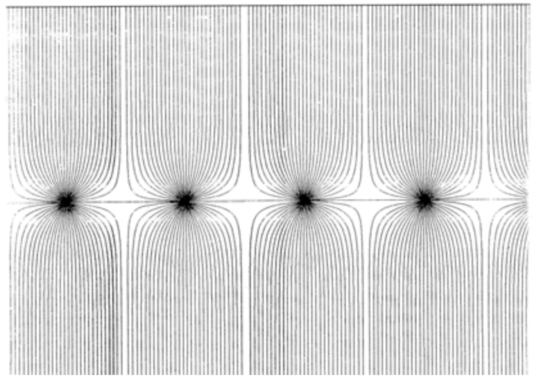
Is equivalent to

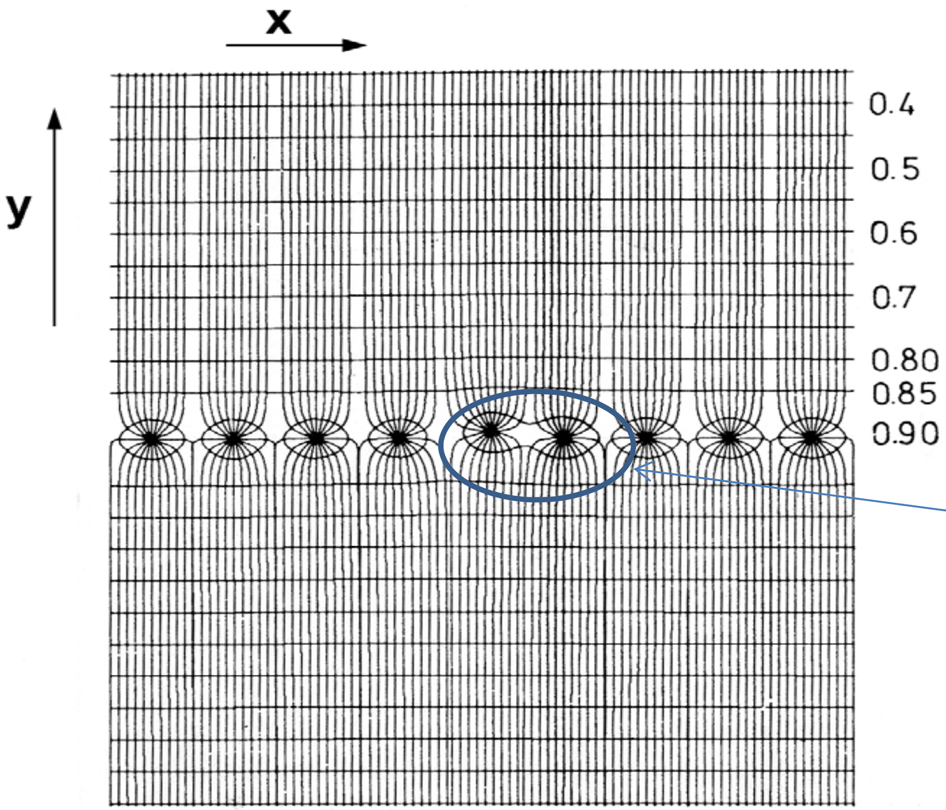


An array of proportional counters tubes

Gazeous detectors : MWPC





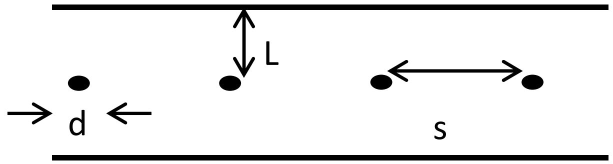


Classical figure of electrical field disturbed by a misplaced anode wire

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)

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



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 .

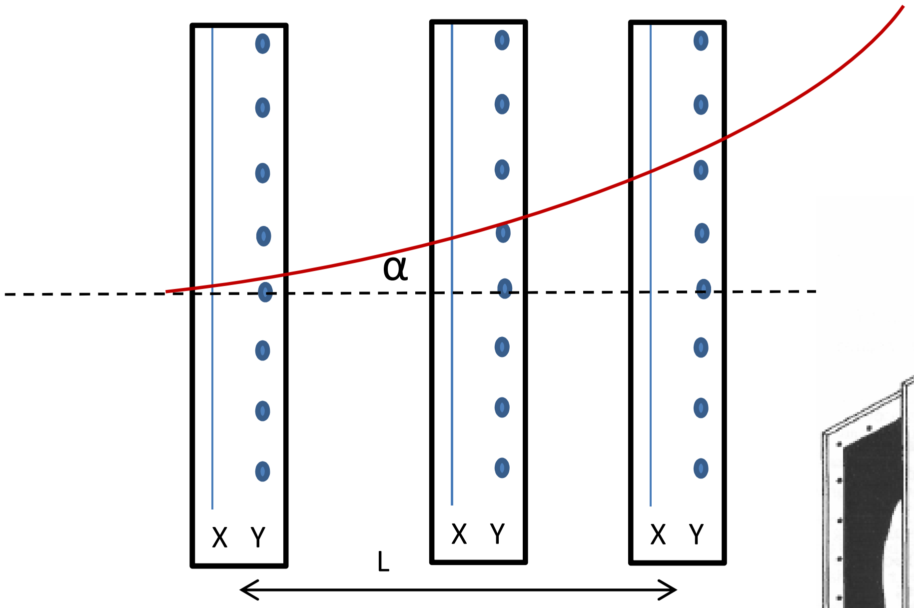
$$\boldsymbol{\sigma = \frac{a}{\sqrt{12}}}$$

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)

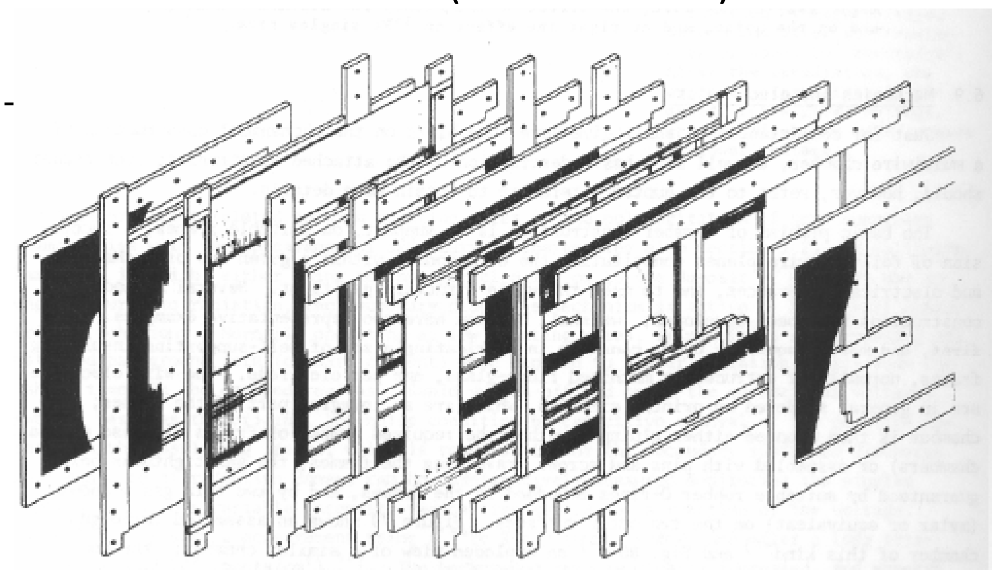
Limitation 1 : Typically : anode spacing of the order of 1-1.5 mm
(Résolution ≈ 200 – 500 µm)
In order to improve the spatial résolution : closer anodes ?
Does not work. Instabilities due to electrostatic forces anode-anode.

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

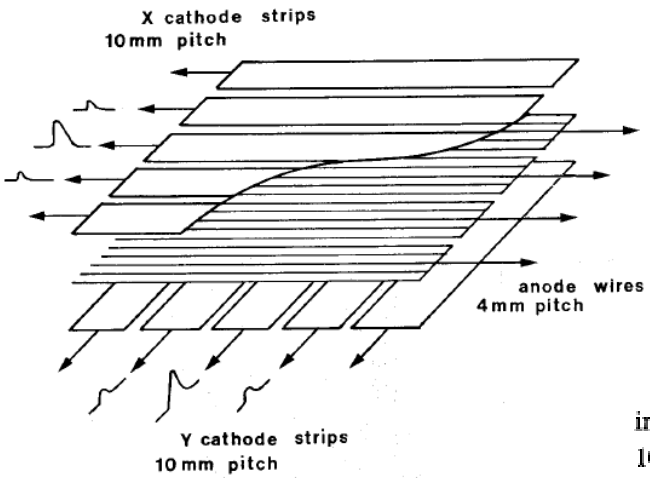


Precision : $\Delta\,\alpha \approx \frac{1}{L}\,\sigma$

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

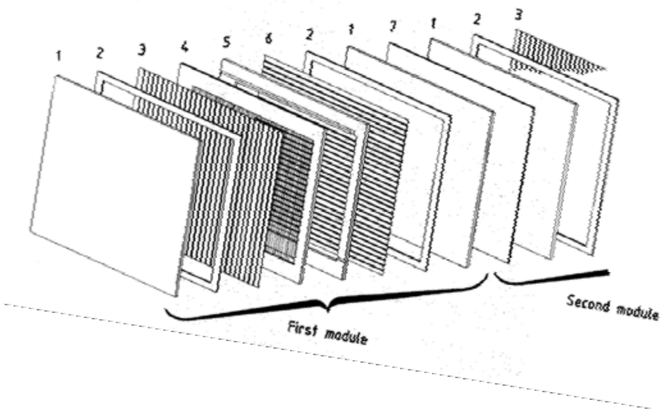


Cathode read-out chamber : One anode plan
Segmented cathode plan
Analog read-out



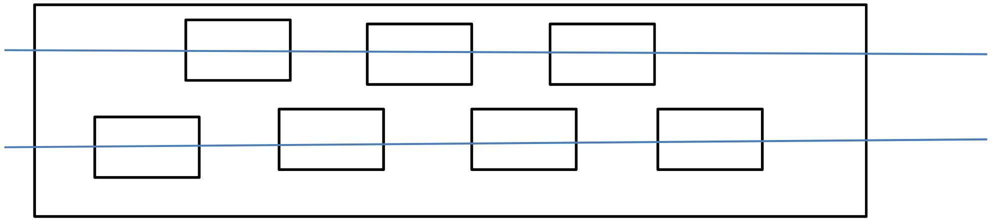
The features of one chamber module of the final stack were the following:
half gap: 5 ± 0.02 mm
anode pitch: 4 mm
anode wire diameter: 20 μm
cathode strip pitch: 10 mm
cathode strip width: 9 mm
sensitive area: $1100 \times 970\ mm^2$
gas composition: Ar 80% + CO_2 20% (vol).
The total stack thickness 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 σ = 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 (σ = 5.9 mm, 91% of events inside 10 mm at 2 GeV) and for wider strips (σ = 5.3 mm, 86% of events inside 10 mm for 4 GeV electrons, when going from 8 mm to 16 mm strip width).



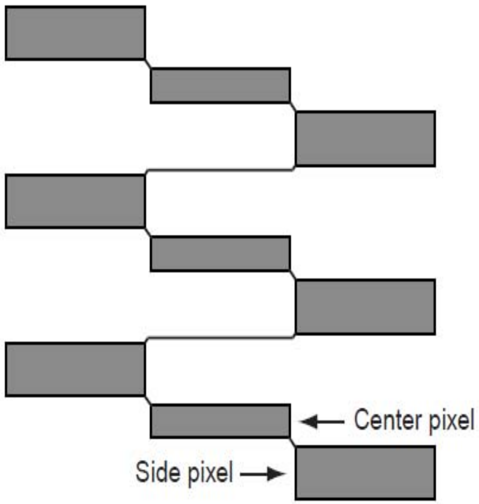
Experiment R704 (CERN) 1981 - 1985

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

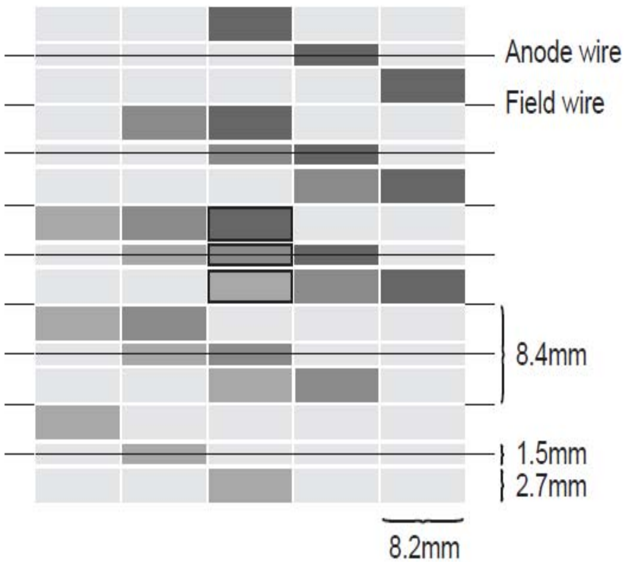


Needs a lot of electronics

a)



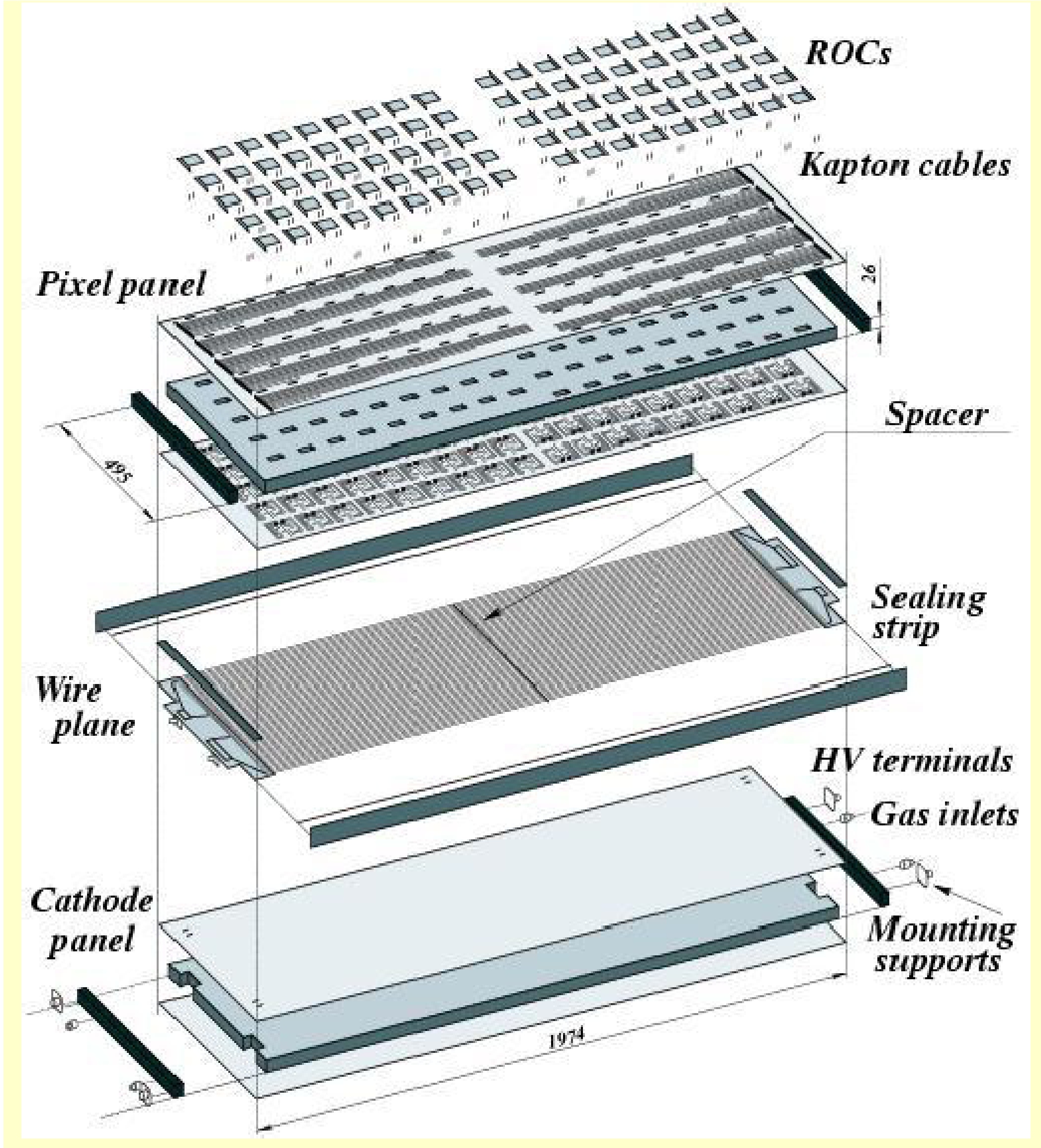
b)



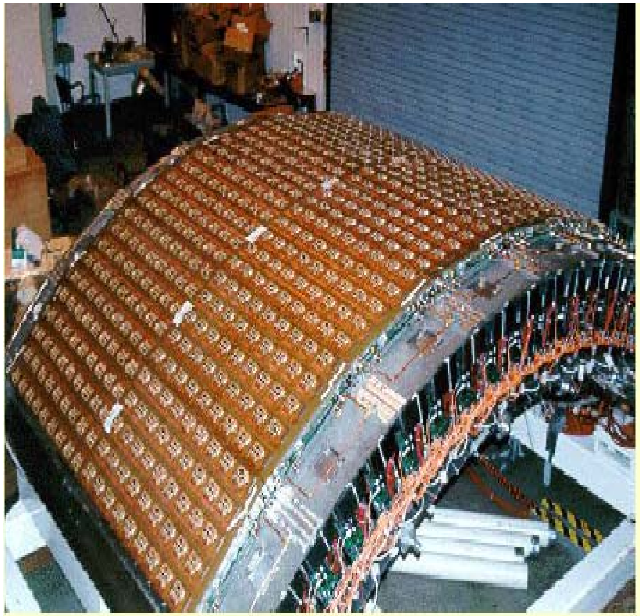
Pads regrouped in cells

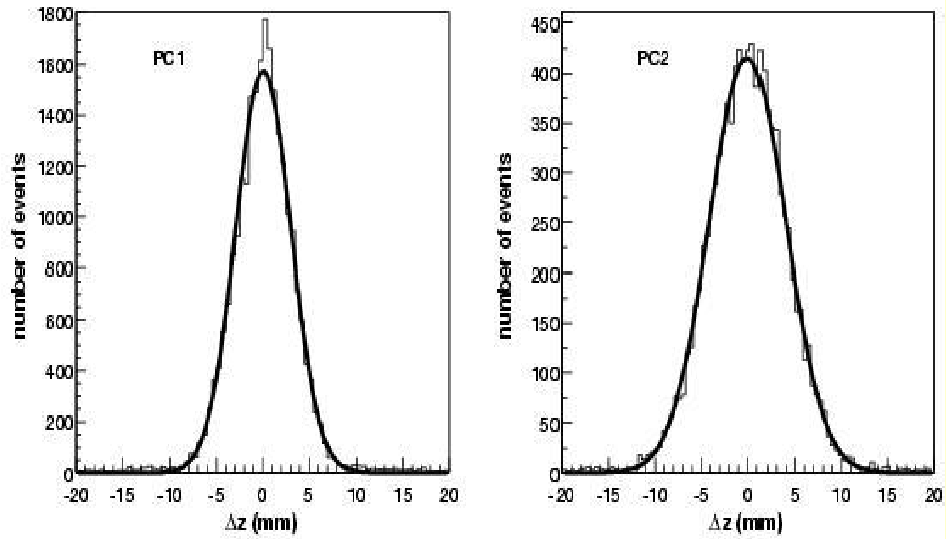
PHENIX experiment

PHENIX at RHIC



Gazeous detectors : Pad chambers





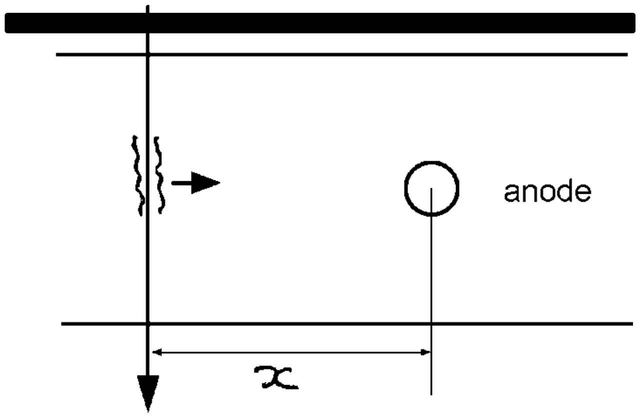
chamber	Wire dist (mm)	Z-resol. (mm)	Perp res (mm)	Rad. Thickn.
PC1	8.4	1.7	2.5	1.2%
PC2	13.6	3.1	3.9	2.4%
PC3	16.0	3.6	4.6	2.4%

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.

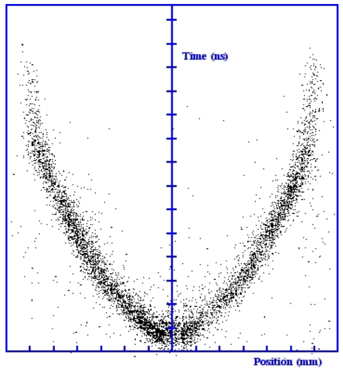
Measure of the position of the particle by mesuring the drift time of the electrons

Need : Precise knoweledge of drift velocities

Precise timing (trigger)



$X = V_d \Delta t$

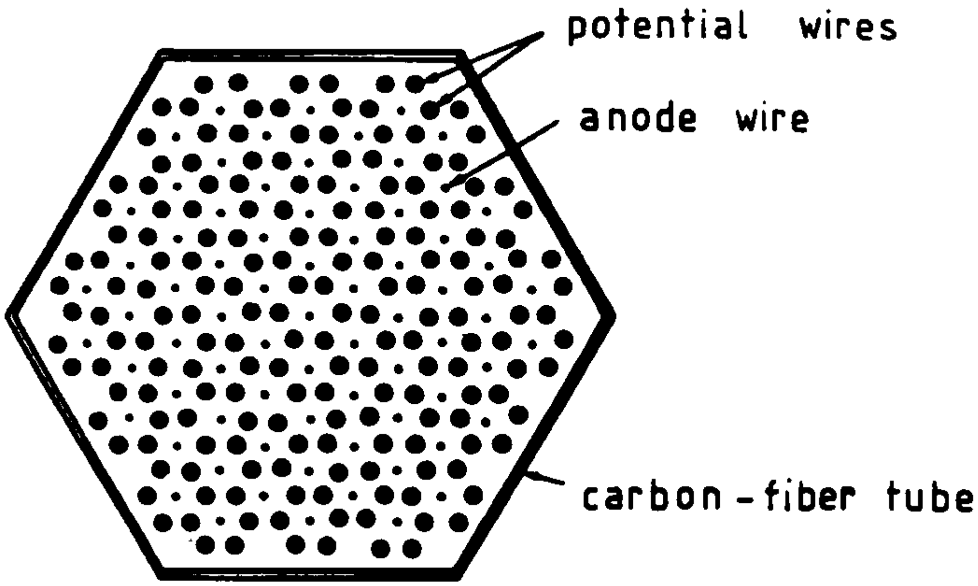


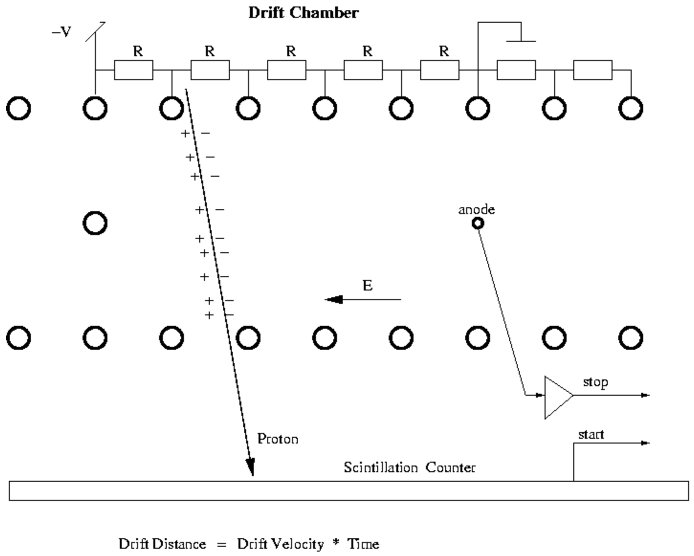
SPACE-TIME CORRELATION
(RIGHT-LEFT AMBIGUITY)

Possible resolution down to 50 µm

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

Solution : defining a cell (basic unit of field)

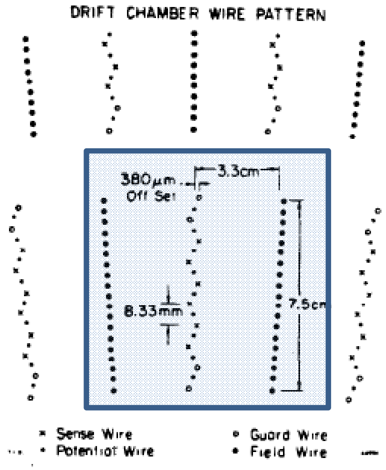




PHENIX (RHIC) Drift Chambner

Gazeous detectors : Drift Chambers

MarkII (1985 – 1990) big Drift Chamber

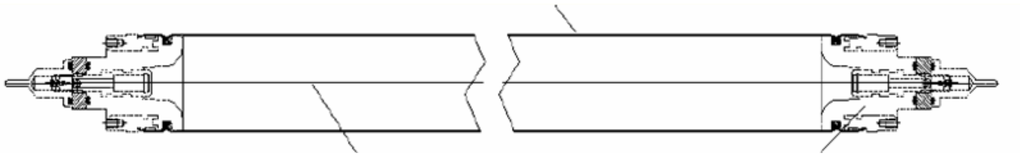


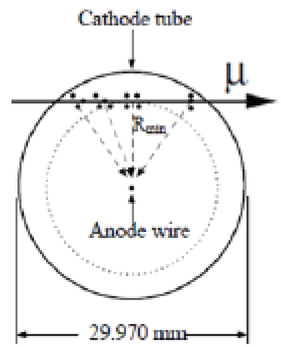
1 cell = 7.5 cm x 6.6 cm

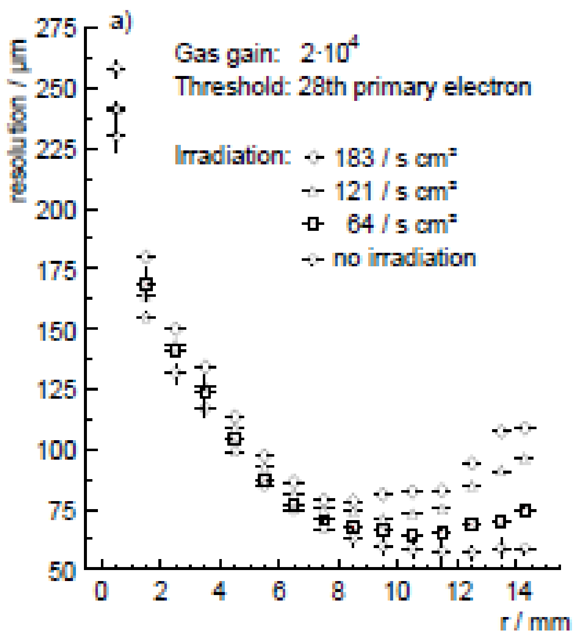
12 layers
Lenght : 2.3 m
Radius : 1.6 m
5732 sense wires (anodes)
31104 potential wires
Gas mixture : 89% Ar, 10% CO_2 ,1% methane
Gain : $2\ 10^{4}$
Drift filed : 900 V/m
Spatial resolution : ≈ 150 μm

ATLAS DRIFTS TUBES (MUON SPECTROMETER)

370 000 tubes
Surface 5500 m ^{2}





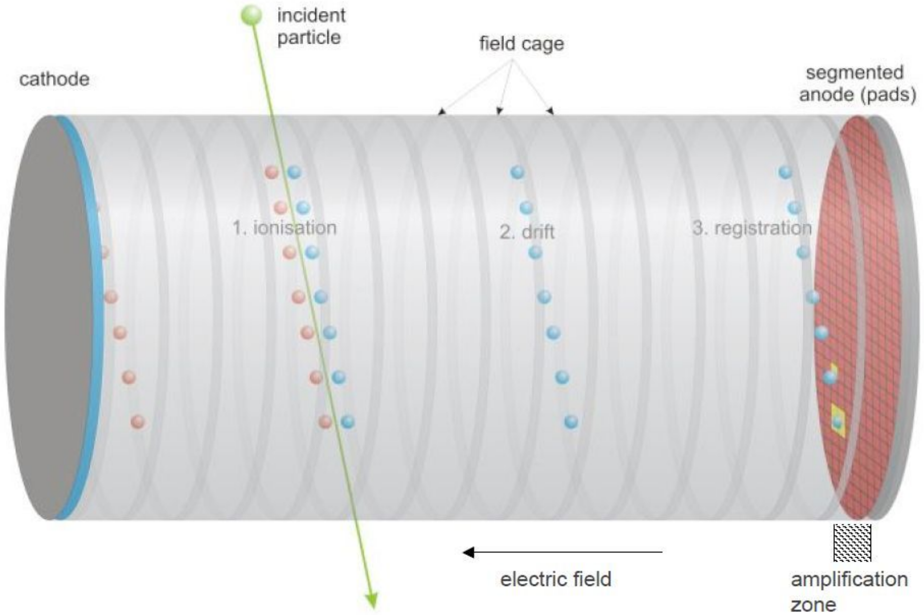


Parameter	Design value
Tube material	Al
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold-plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain	2 x 10^4
Wire potential	3080 V
Maximum drift time	$\sim$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

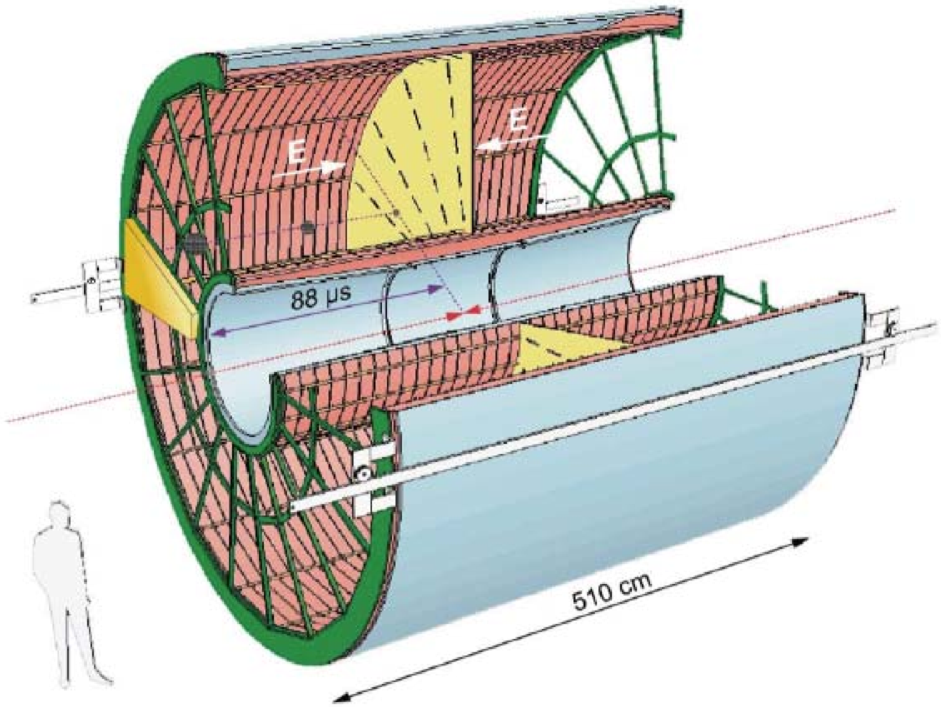


Position (X and Y measurements)

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

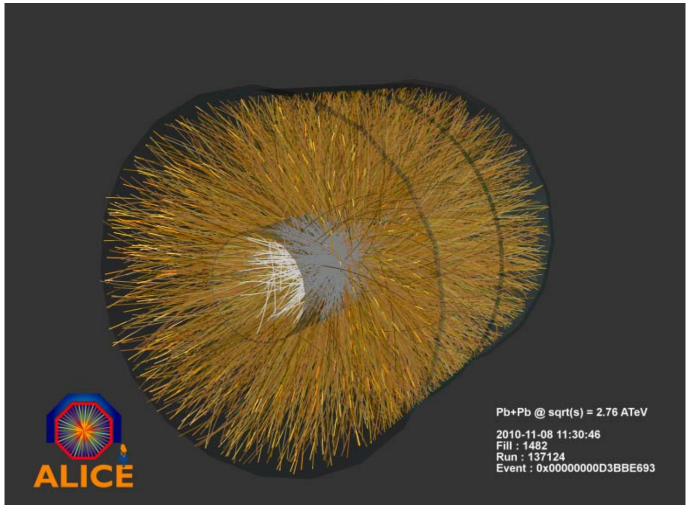
Diffusion: σ_t = 250 µm
Resolution: $\sigma \approx$ 0.2 mm

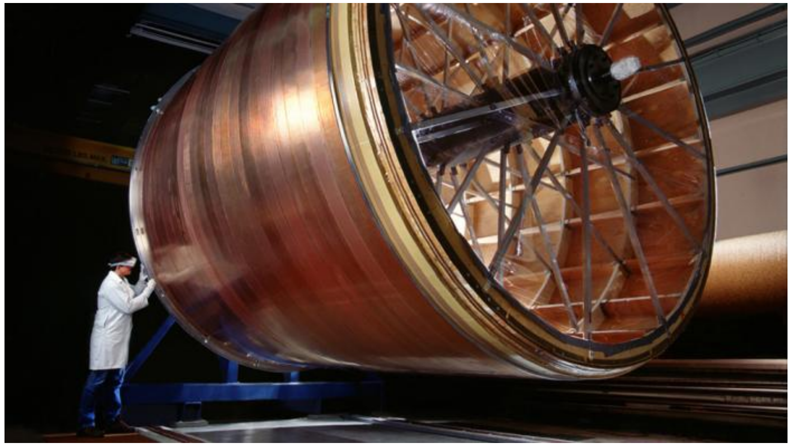
σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

Magnetic field: 0.5 T

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

Temperature control: 0.1 K





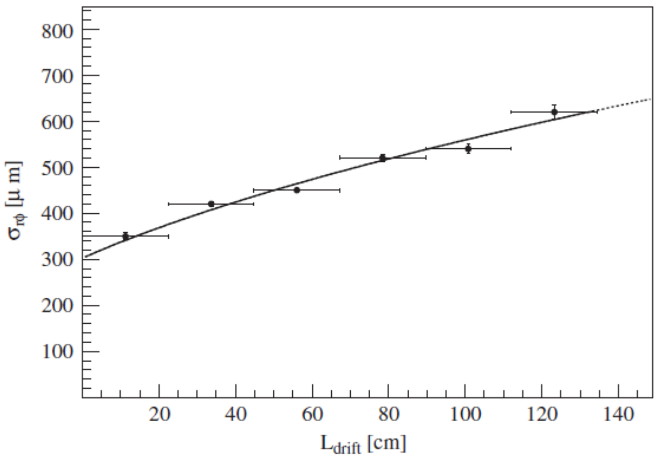


Fig. 6. Space point resolution in pad direction (momentum plane) as a function of drift length. Solid line shows the fit and dashed line the extrapolation.

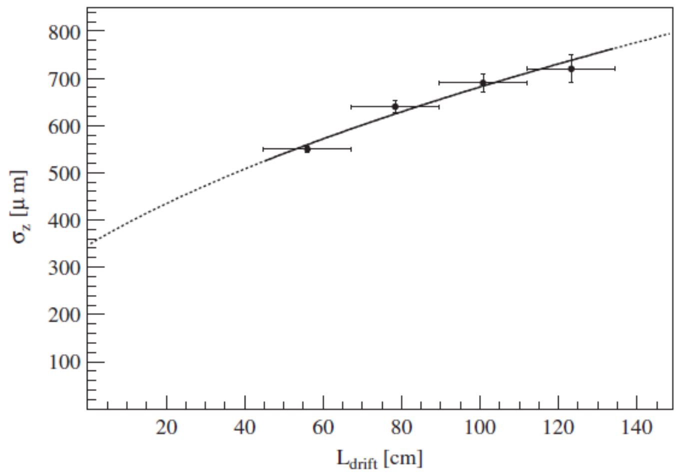
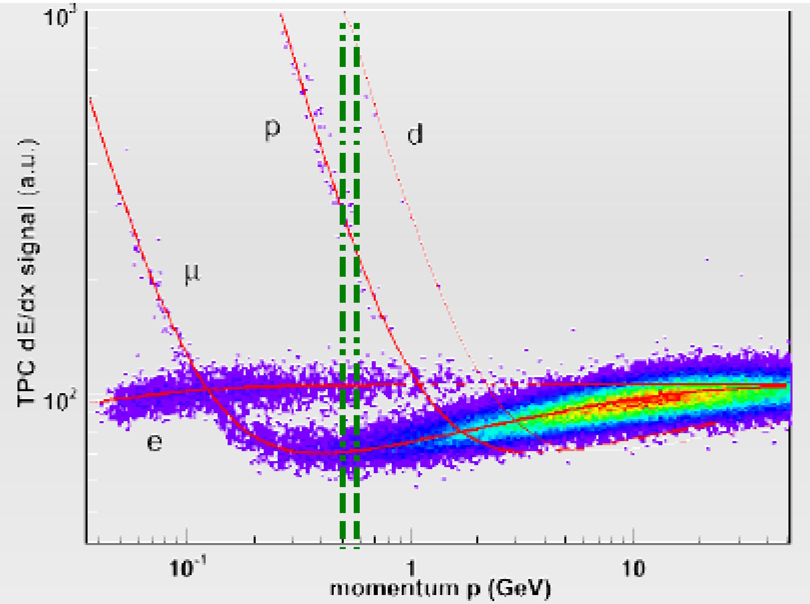


Fig. 7. Space point resolution in drift direction as a function of drift length. Solid line shows the fit and dashed line the extrapolation.

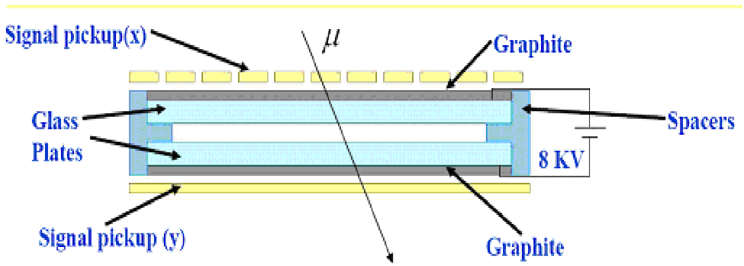


	Experiment	Monte Carlo
$\sigma_{r\phi}$ (μm)	800 ± 80	900
σ_z (μm)	900 ± 100	900

RPC : Thin (2 mm) drift volume sandwiched between

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

Simple – inexpensive – fast (used as trigger)

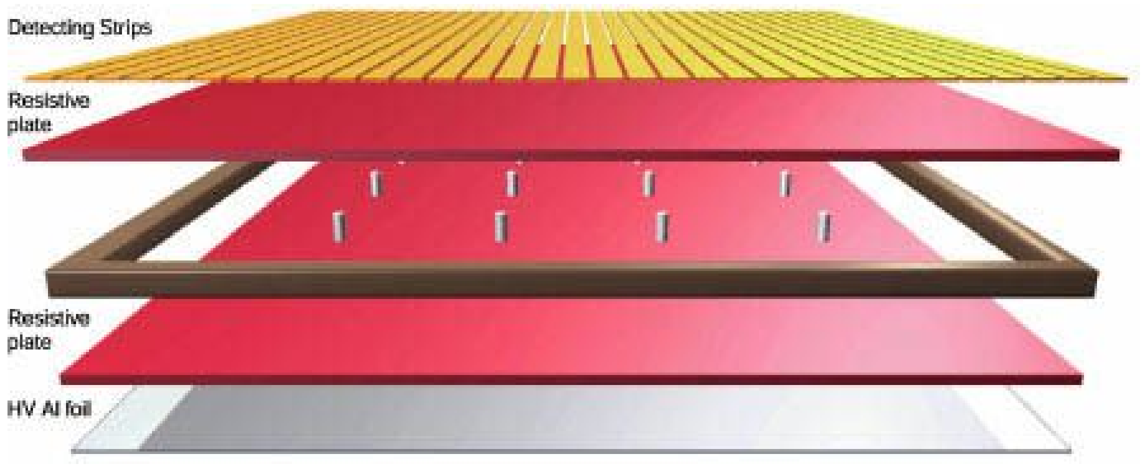


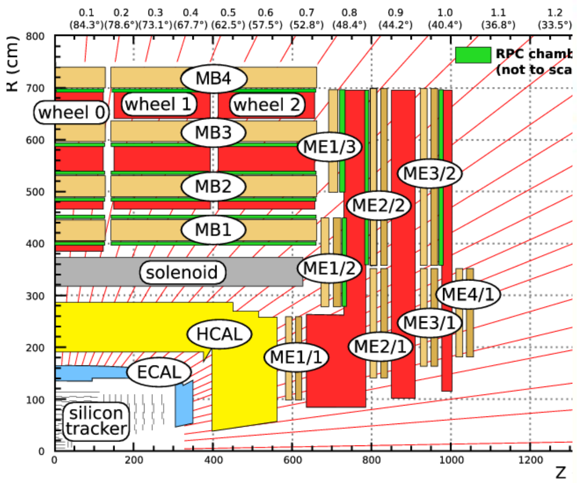
Thin drift volume and High field

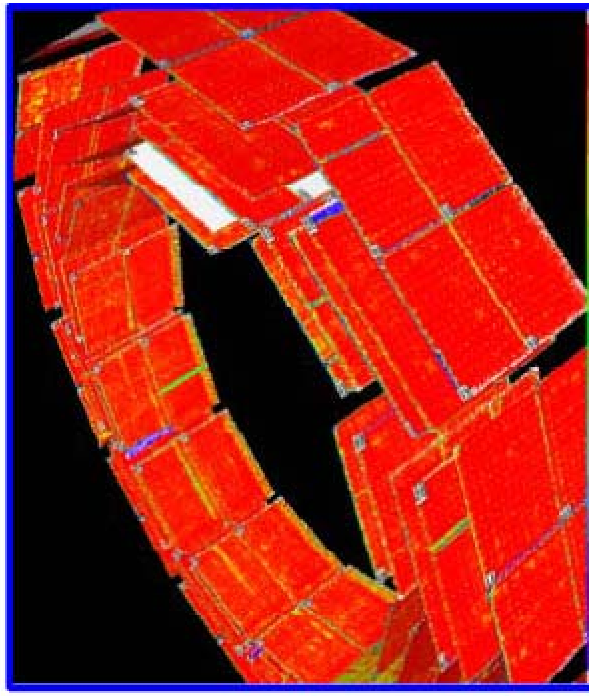
Works usually in streamer mode
Large signal, but slow (100 nsec)

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

Gazeous detectors : Resistive Plate Chamber for CMS - LHC





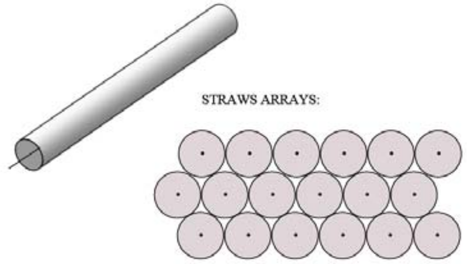


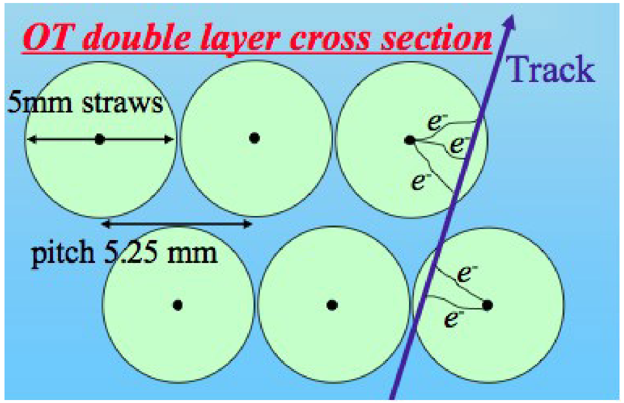
Resistive plates : 1 10^{12} Ω.cm
Gas mixture :
$C_2H_2F_4$ (92.5 %)–C_4H_{10} (4.5%) – SF_6 (0.3%)
HV : 8.5 – 9.7 kV

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

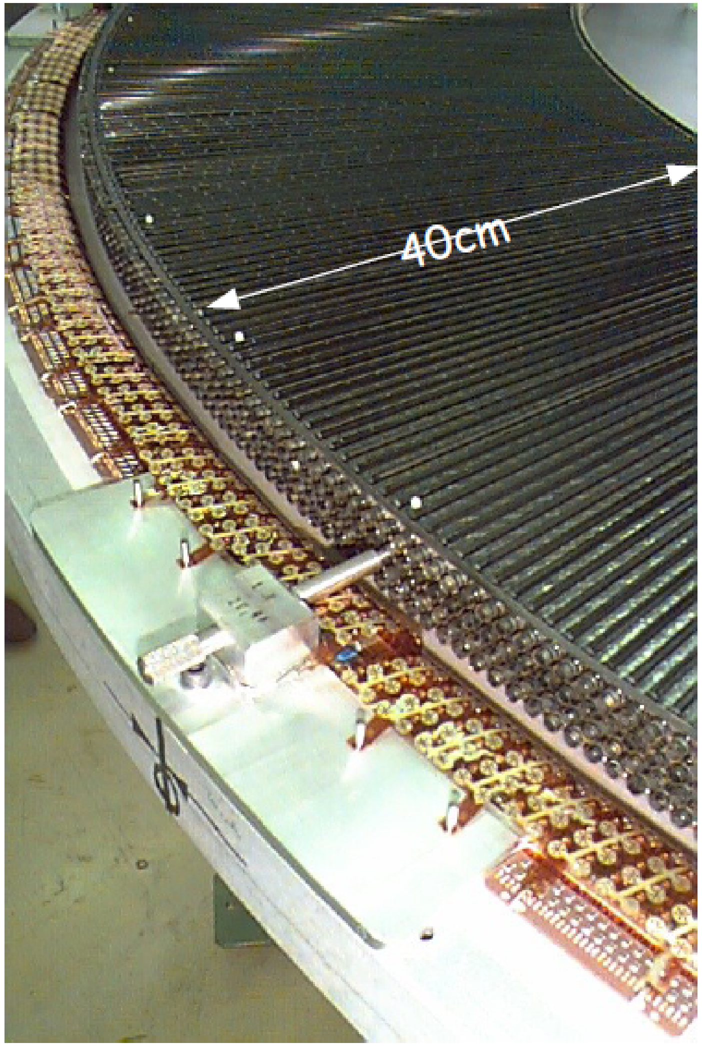
SWPC : Single Wire Proportional Chamber
Single proportional counter in an array

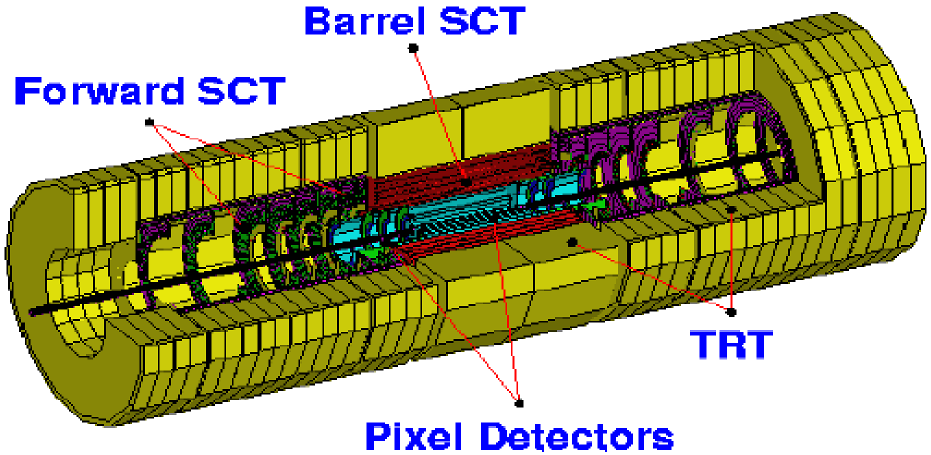
- Cheap and simple to build
- Capable of withstanding very high fluxes





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





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

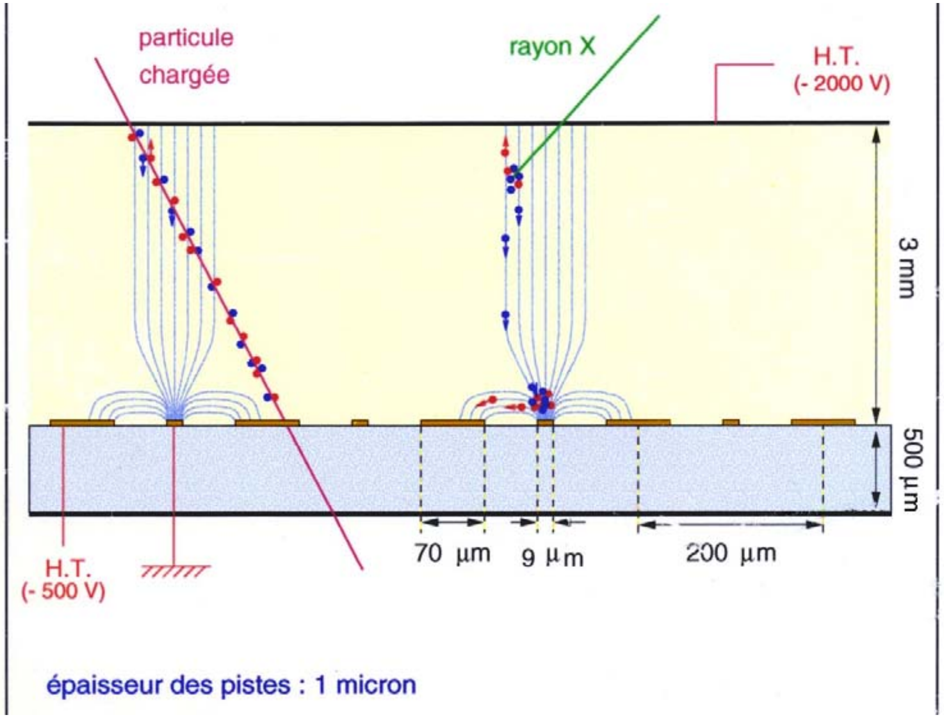
Beam test result:

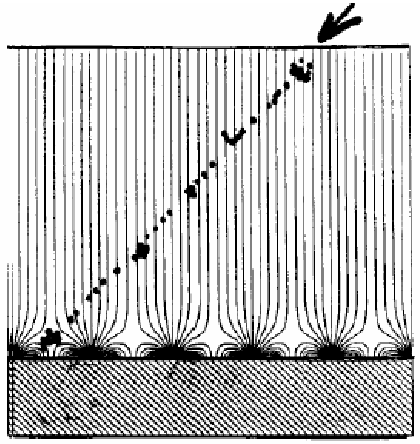
Hit efficiency: 96.7± 0.8%

Drift-time accuracy: 133 ± 4 μm

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

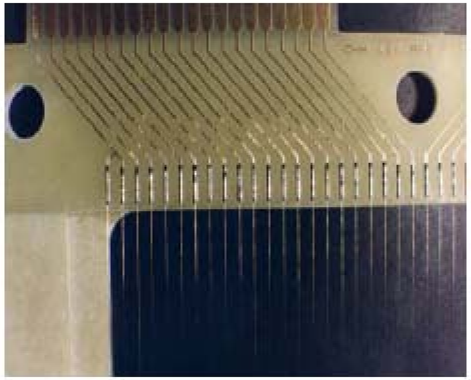
Spatial resolution : $\sigma \approx 20\ \mu m$

Dead time ≈ 10^{-5} sec.

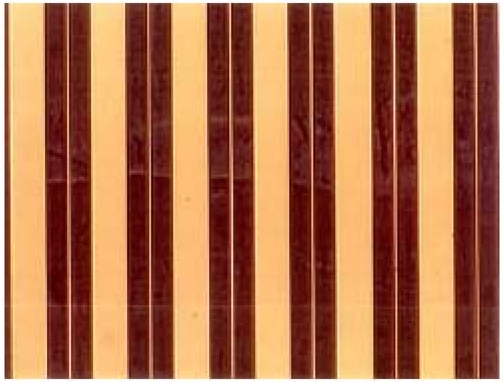
(Short distance for the ions)

Gas : Ar – DME / Ne - DME

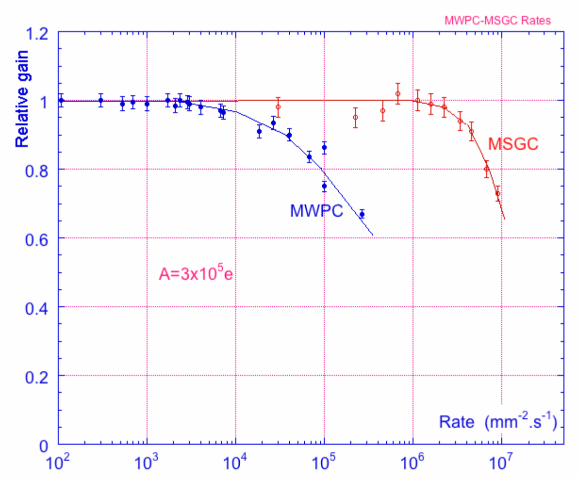
Gazeous detectors : MicroStrips Gas Detector



MWPC
anode spacing : 1-3 mm

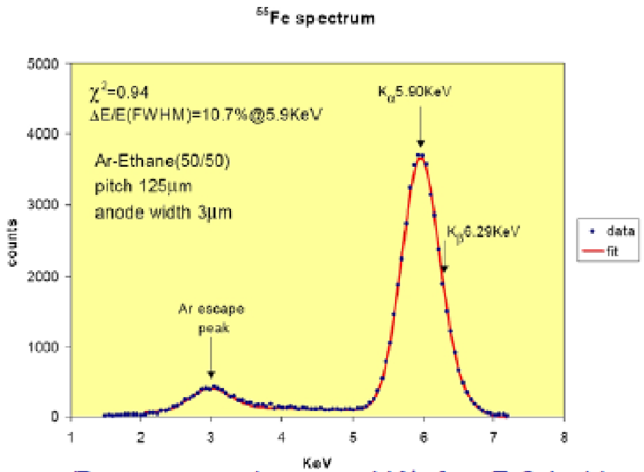


MSGC
anode spacing 200 µm

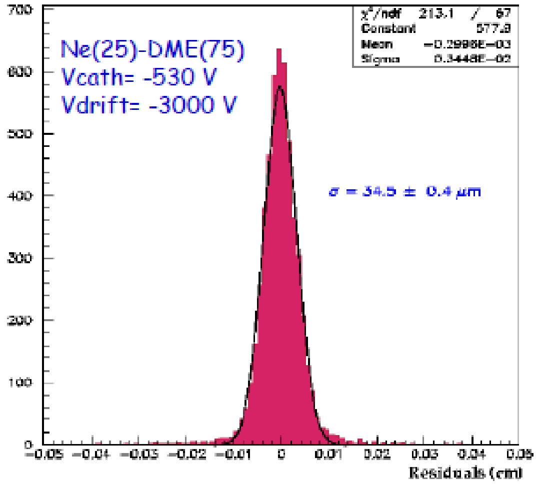


Rate capability comparison
MSGC seems to be well adapted
to high fluxes of particles (LHC)

Gazeous detectors : MicroStrips Gas Detector



Energy resolution ~11% for 5.9 keV



Spatial resolution = 34.5 ± 0.4 μm
2-track resolution ~400 μm

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)

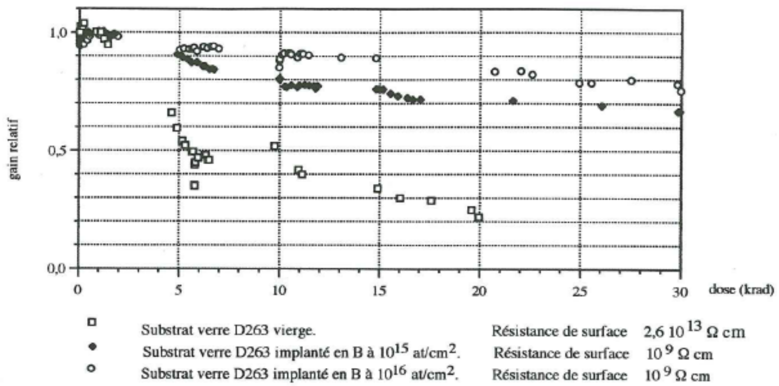
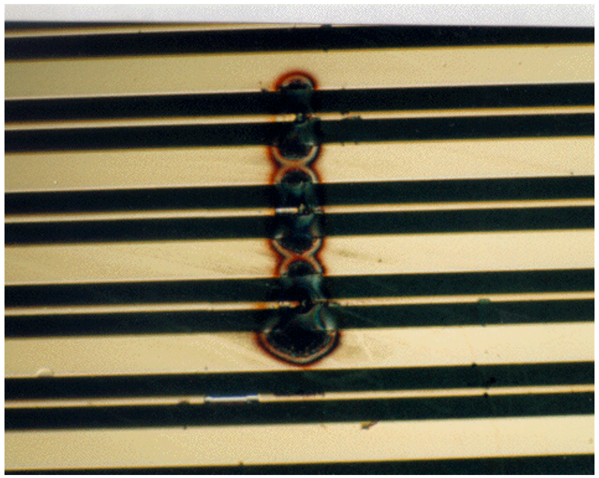
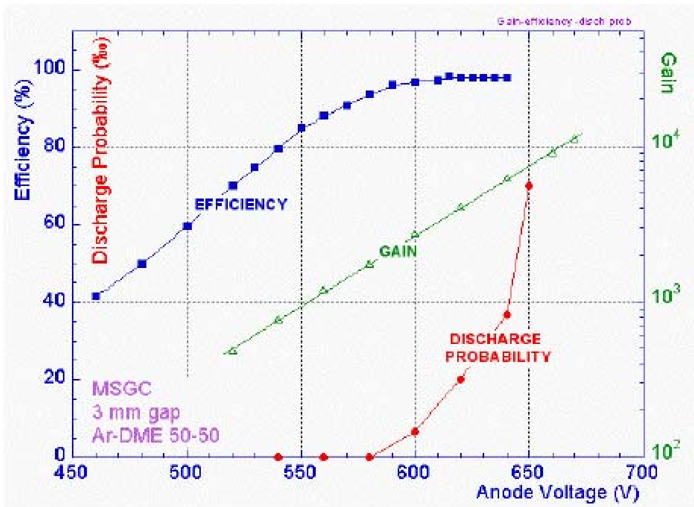


Figure 42:
Evolution du gain d'une MSGC en fonction de la dose d'irradiation pour différents types de substrats.

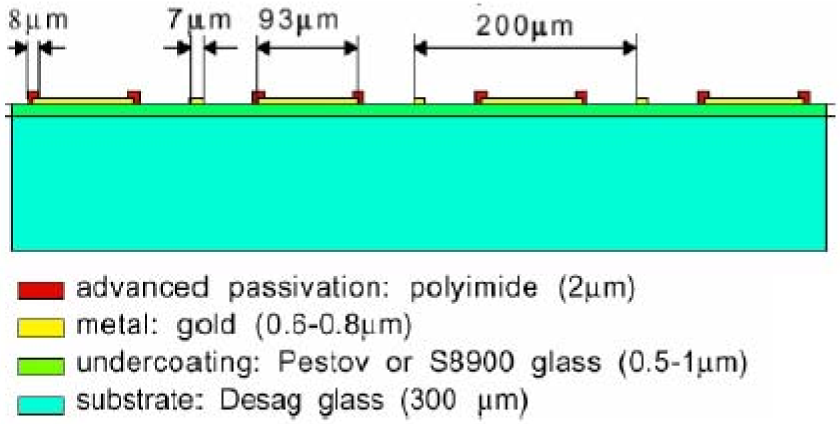
Ageing : Polymerization due to construction material (DME is a solvant)
Choice of non-solvable material in DME

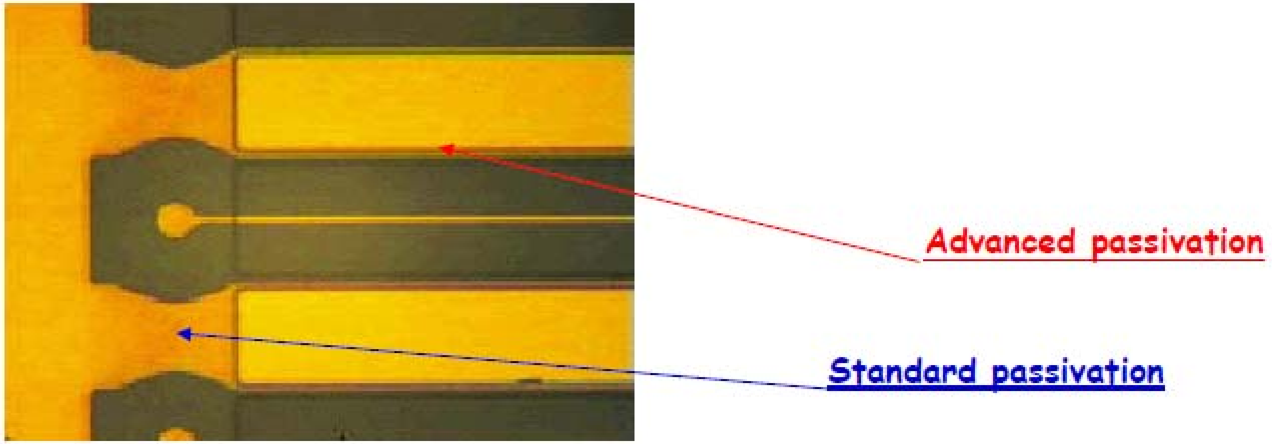
Discharges: Possible with higher flux or low energetic particles
Certain with dust (short between anode and cathode (50 µm)



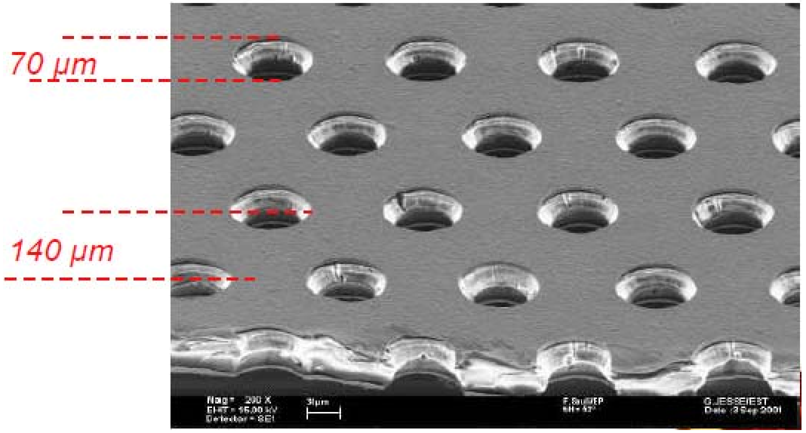


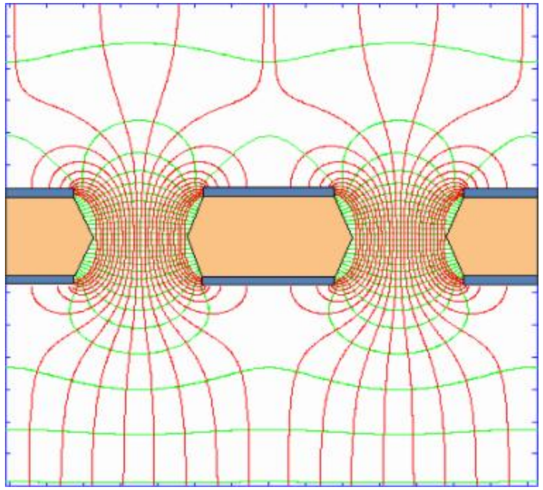
Cathode edge passivation

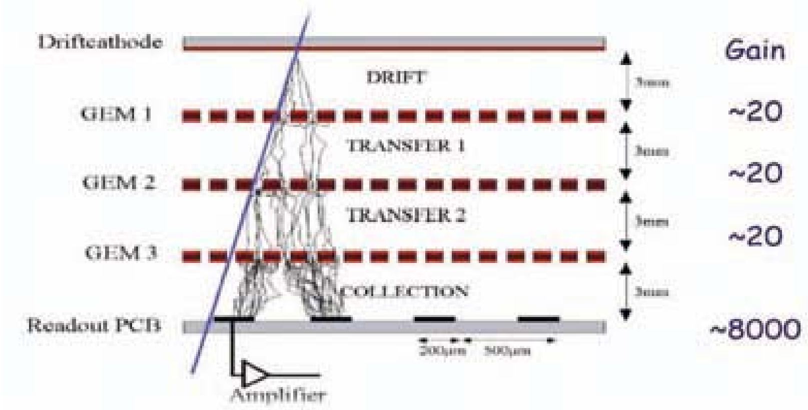


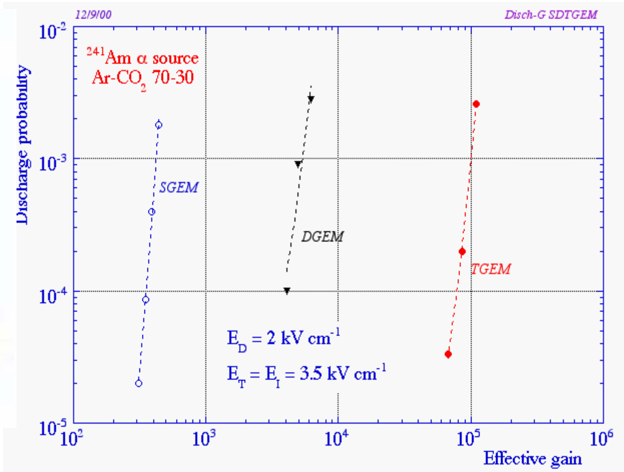


GEM (on a MSCG) : préamplification at ≈ 100 µm above the substrate
kapton foil (copper coated) with amplification holes







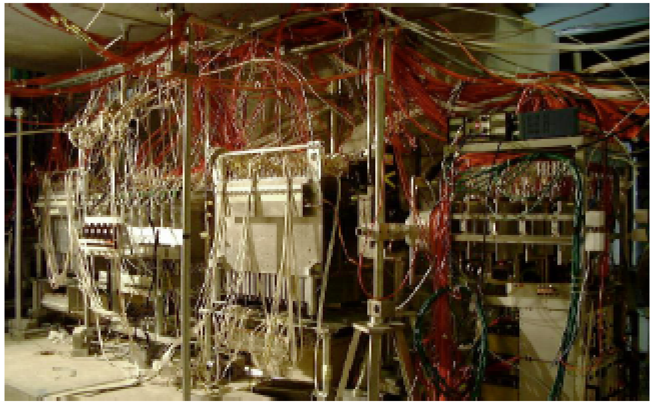


Discharge probability using single, double and triple GEMs

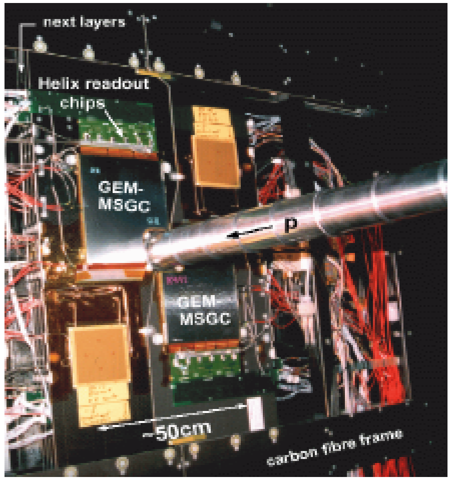
Gazeous detectors : MSGC + GEMs

Compass

MicroStrip Gas Chamber



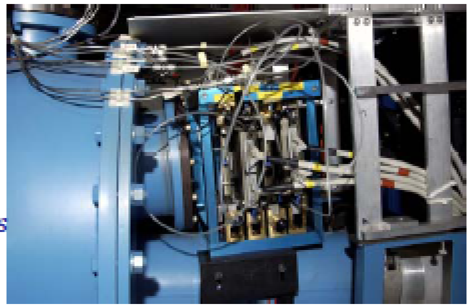
CMS (rejceted)
Advanced passivated MSGC
Telescope of 32 MSGCs tested at PSI in Nov99 (CMS Milestone)



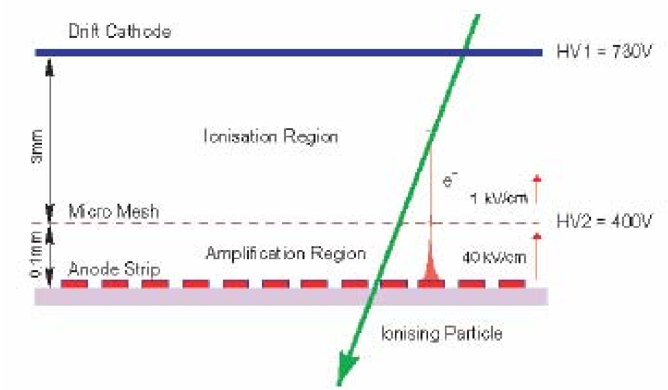
HERA-B Inner Tracker
MSGC-GEM detectors
R_{min} ~ 6 cm
10^6 particles/cm^2•s
300 µm pitch
184 chambers: max 25x25 cm^2
~ 10 m^2; 140.000 channels

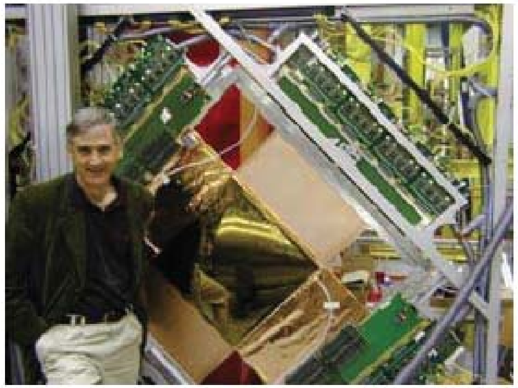
D20 diffractometer at ILL for neutron detection
1D localisation
48 MSGC plates (8 cm x 15 cm)
Substrate: Schott S8900
Angular coverage : 160° x 5,8°
Position resolution : 2.57 mm (0,1°)
5 cm gap; 1.2 bar CF4 + 2.8 bars 3He
Efficiency 60% @ 0.8 Å

DIRAC
MSGC-GEM detectors
Hadron beam
3 10^5 particles/cm^2·s
4 planes; 10x10 cm^2

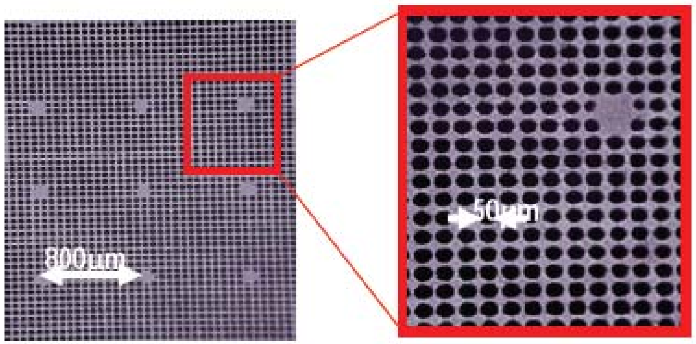


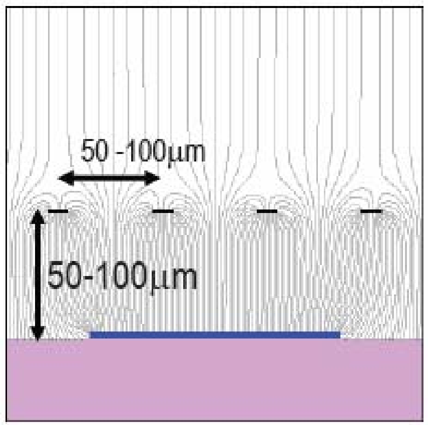
Micromegas : (G. Charpak and Y.Giomataris – 1992) is similar to a MSGC+GEM and a drift chamber. The cathode is a mesh at 100mm from the anodes (strip depsited on a substrate)



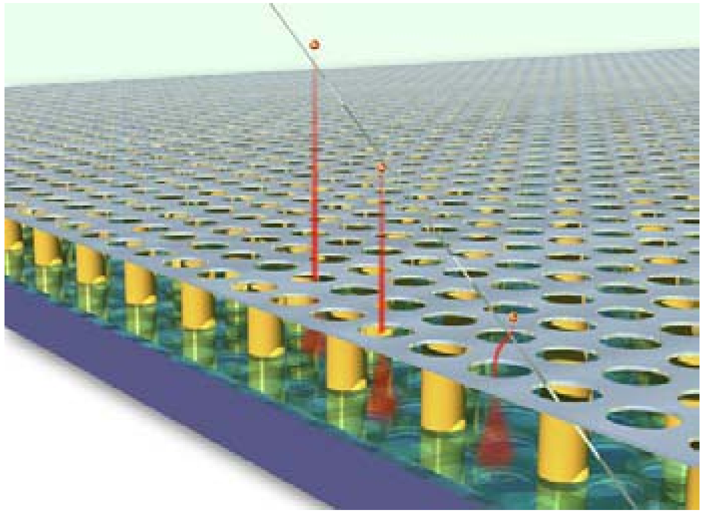


Y.Giomataris et al, NIM A 376 (1996) 29

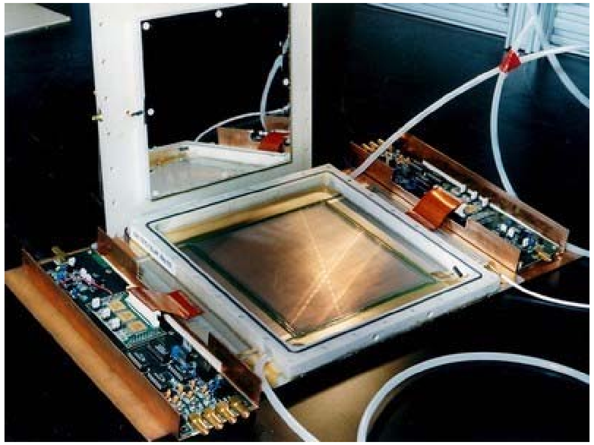




Gazeous detectors : Micromegas

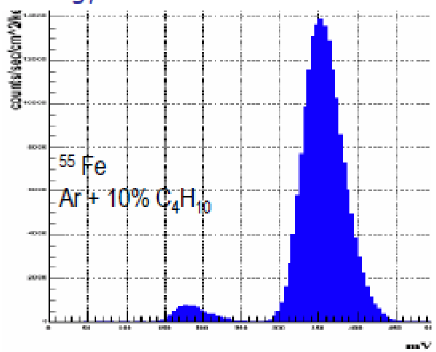


Limitation : Mesh spacers (loss of acceptance)

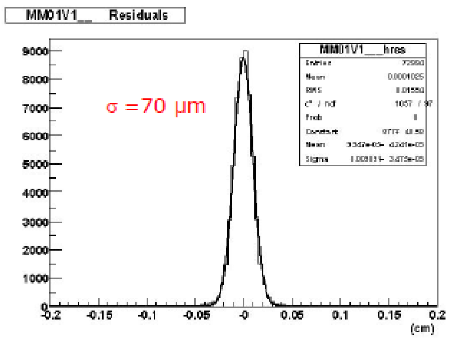


Prototype (1997)

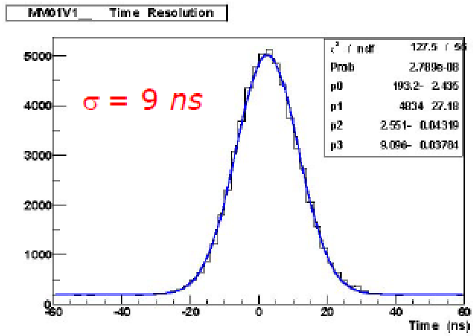
energy resolution ~ 10%



D.Thers et al NIM A 469 (2001) 133



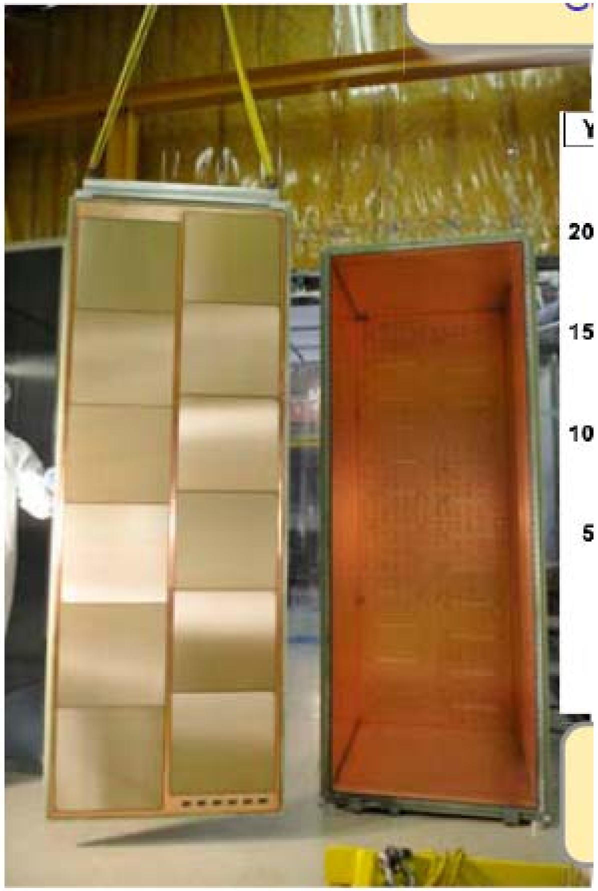
Spatial resolution < 70 μm



Time resolution : 9 ns

Gazeous detectors : Micromegas

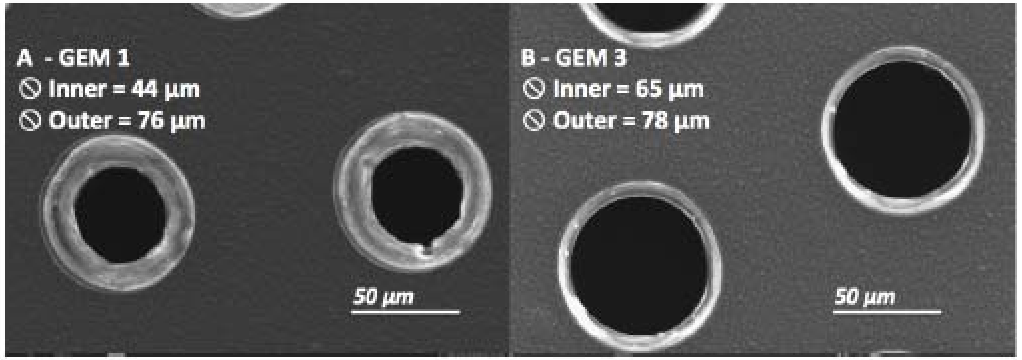
Compass
Set of 12 plates 40x40 cm ^{2}



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

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…

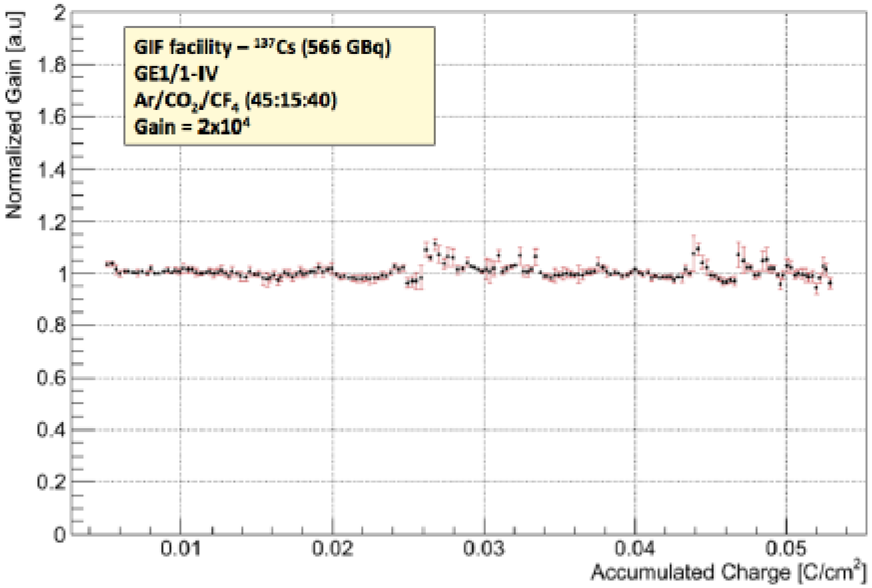
Example :
Etching of the GEM Holes (GE1/1 project)



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



Conclusion :

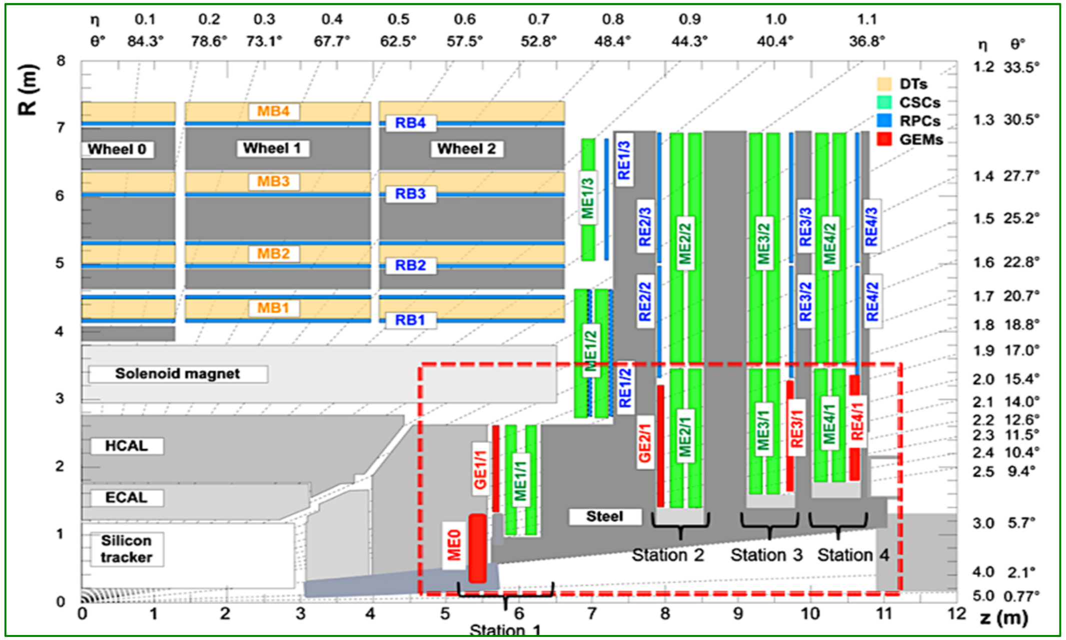
- Evolution of gaseous detectors : MGD (Micro Gap Detectors)
  - GEM
  - Micromégas
- Main problem for these detectors :
  - Cleaningness
  - Long term operation

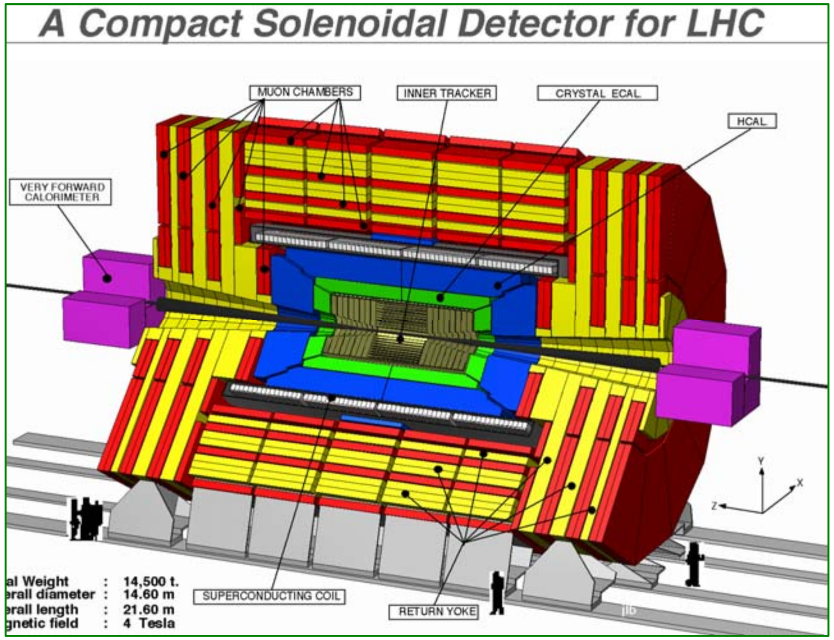
EASY TO DESIGN

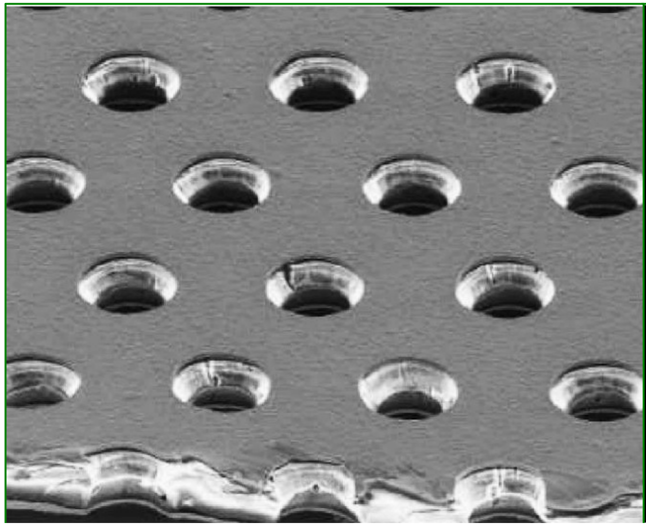
COMPLICATED TO BUILD

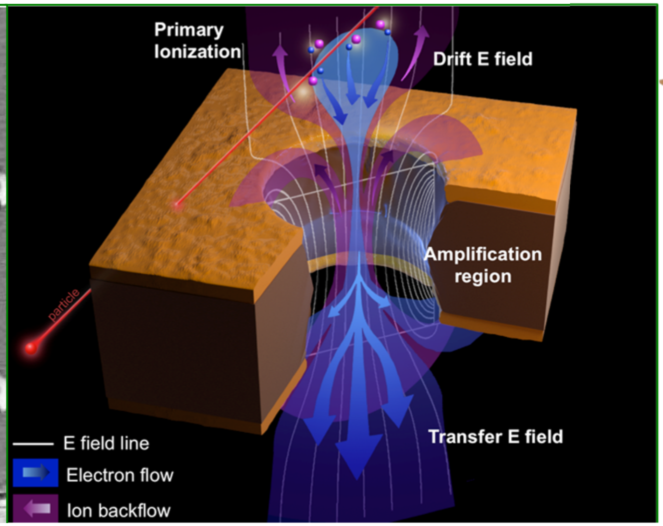
DIFFICULT TO OPERATE ON A LONG TERM BASIS

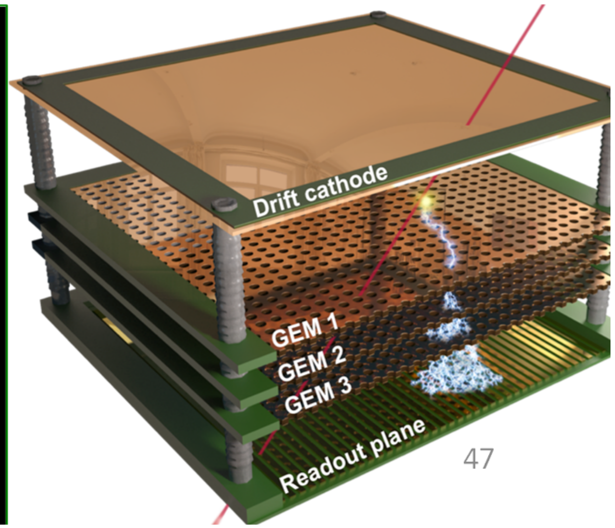
R&D on Big GEM Chambers : a nice nightmare !







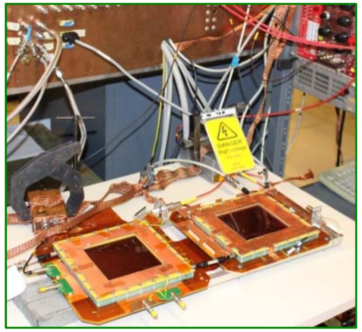


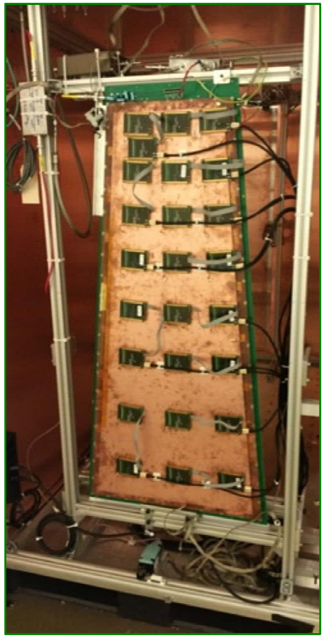


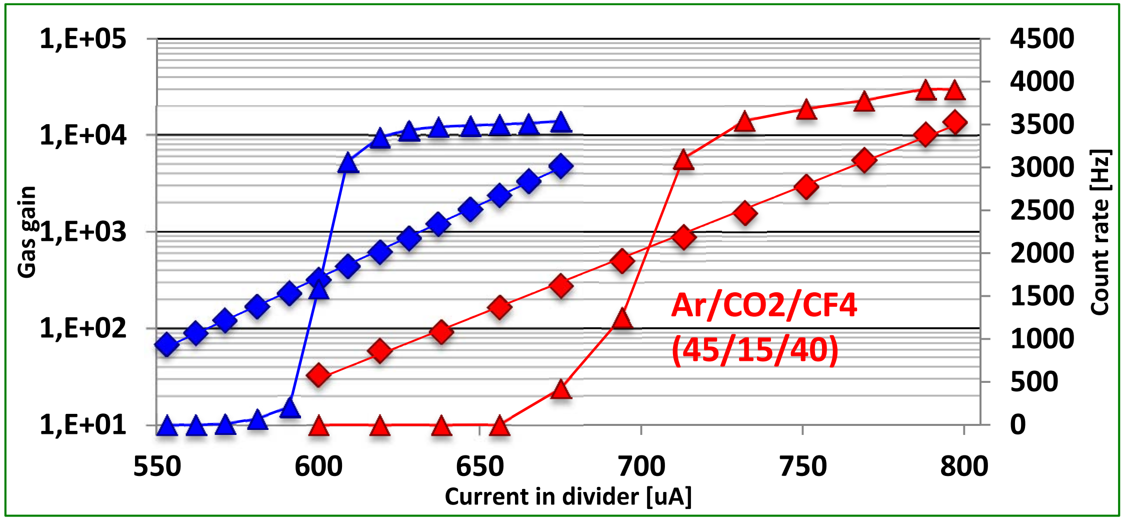
R&D on Big GEM Chambers : 1. DEFINING THE PARAMETERS

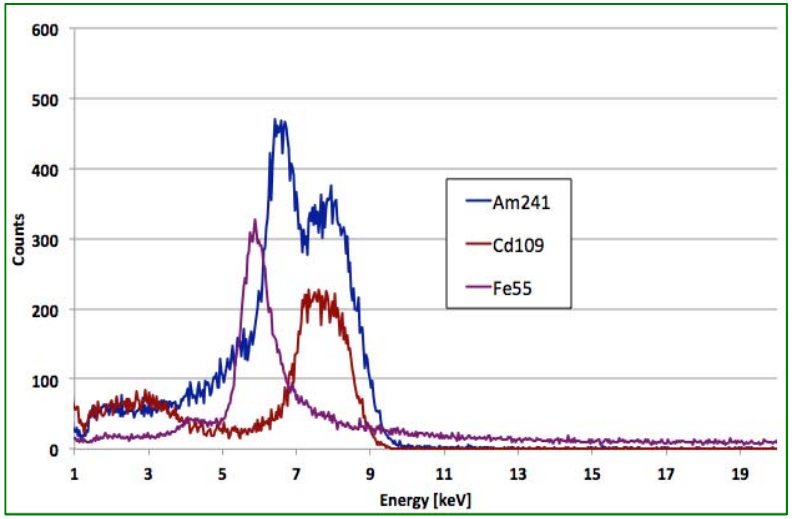
Extensive study on GEM detectors :

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







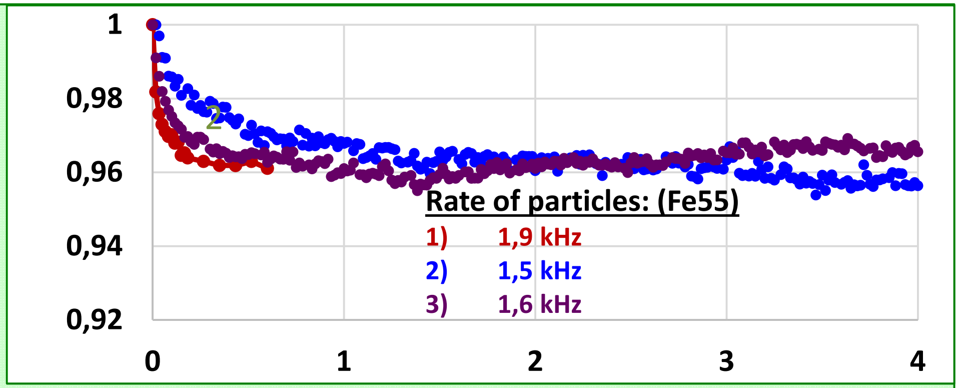


R&D on Big GEM Chambers : 2. VERIFYING THE PARAMETERS

Advanced measurements and characterization:

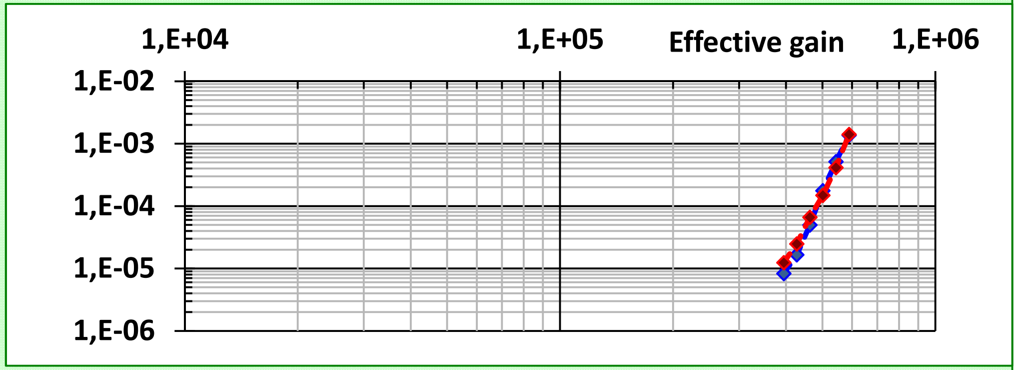
- General understanding on GEM technology
- Comparison with past measurements
- Charging up effects (short-term stability)

5-10 % after 1 hour



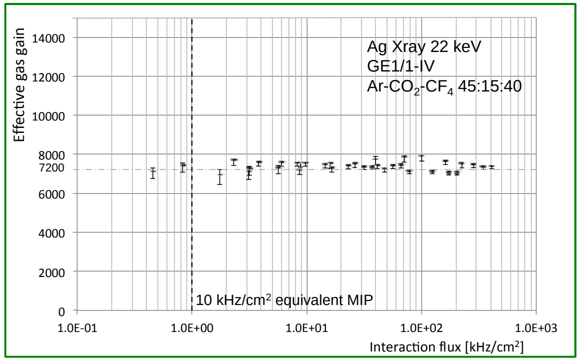
- Discharge probability

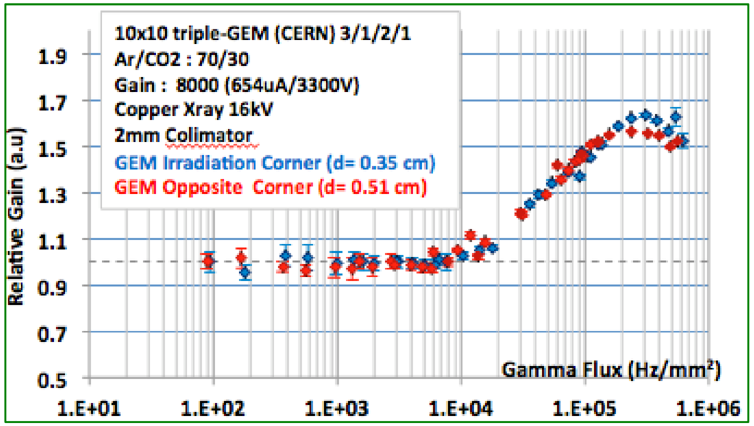
$< 10^{-12}$ at a gain of 10^4



- Rate capability

No gain loss up to 1 MHz/mm²

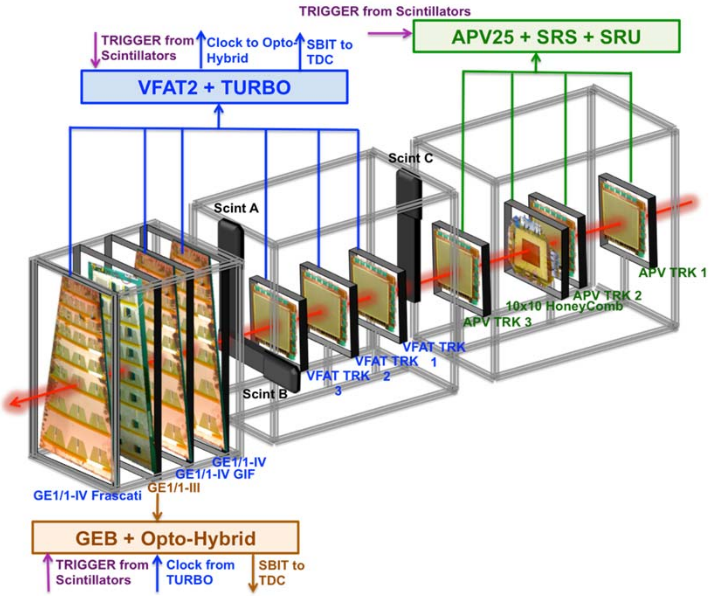


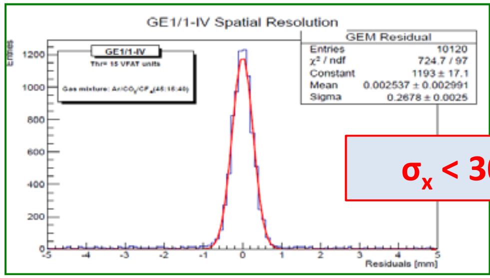


R&D on Big GEM Chambers : 3. BEAM TESTS

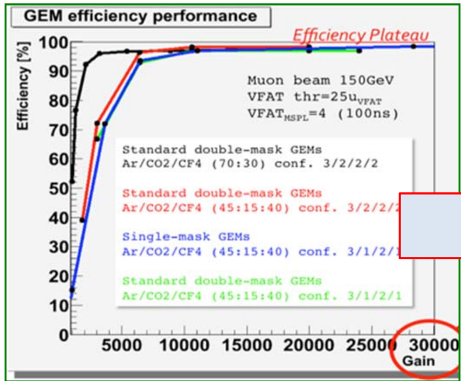
Detectors performences :

- 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



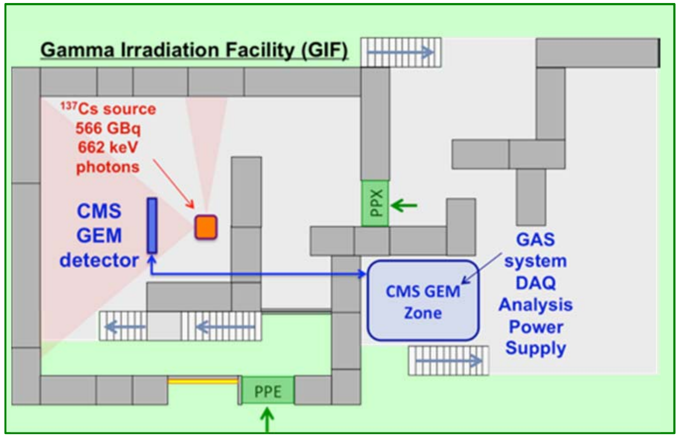


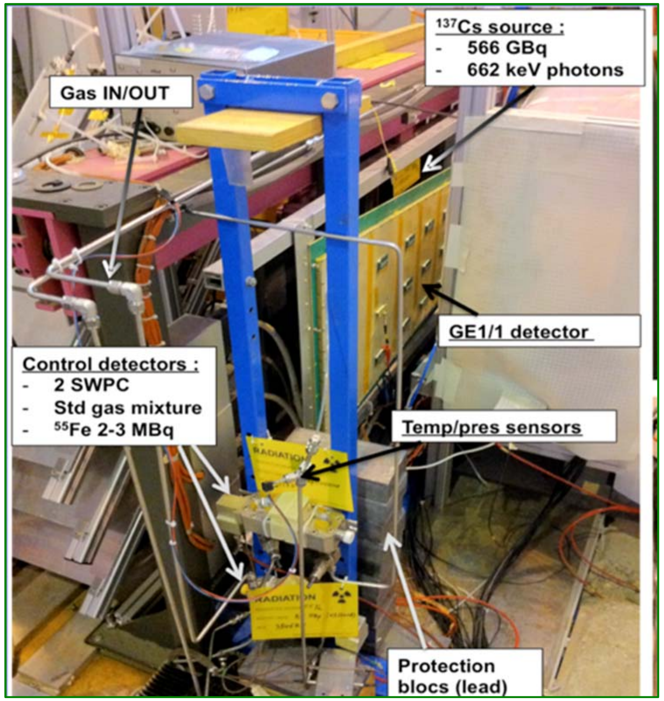
σ$_x$ < 300 µm (digital readout)



Detector efficiencies above 98%

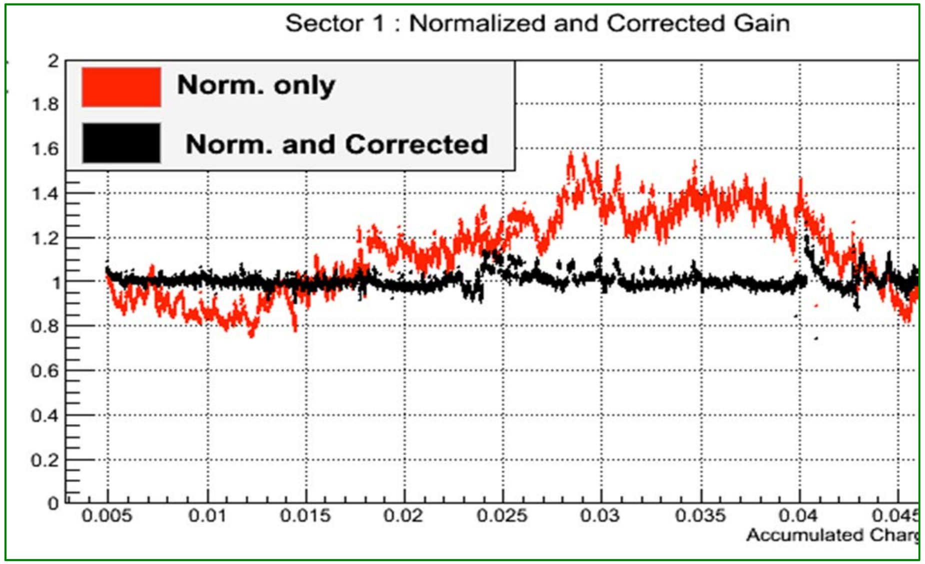
R&D on Big GEM Chambers : 4. LONG TERM TESTS…



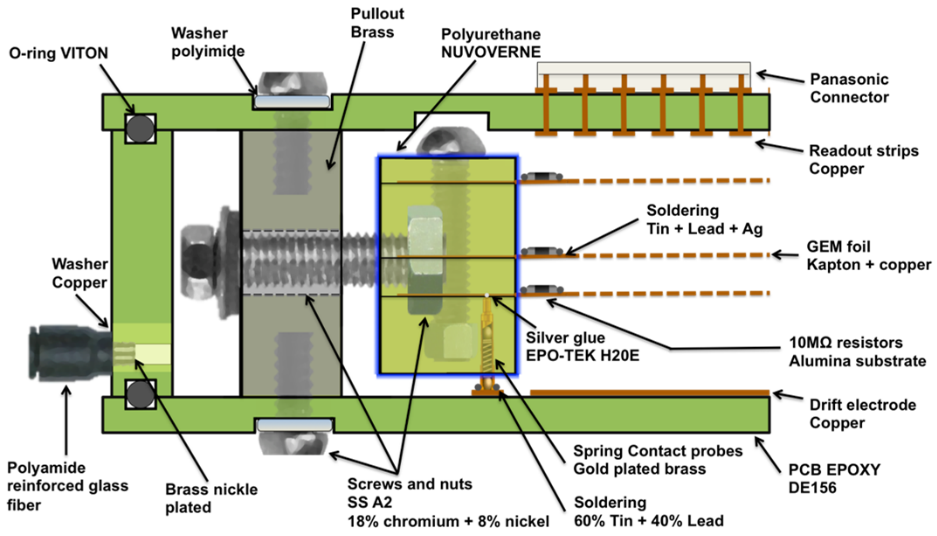


Aging Test at CERN GIF

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



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



<u>Outgassing Study :</u>

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