# Gas Detectors I

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- Introduction
- Gas detector basics
- MPWC
- Drift chambers (LHCb straw detector)
- Micro pattern detectors

# Gas Detectors – A Frontier Technology

**Advantages**

- Cheap large area coverage
- Good spatial resolution
- Fast and large signals
- Good dE/dx resolution
- Good double track resolution
- Many possible detector configurations
- Low material budget – low radiation length

**Challenges**

- Extremely large area detectors needed (ATLAS 5500 $m^2$)
- High mechanical precisions (ATLAS, better than 30 μm)
- Fast readout (25 ns bunch crossing cycle at LHC)
- High rate capability (LHCb Straw Tracker 400 $kHz/cm^2$)
- High radiation dose (charge deposition ~2 C/cm)
- Light construction (LHCb Straw Tracker 9% $X_0$)

# Example: ATLAS Muon Detector

**Monitored Drift Tubes (MDT)**

Muon-Spectrometer provides
**standalone momentum resolution**

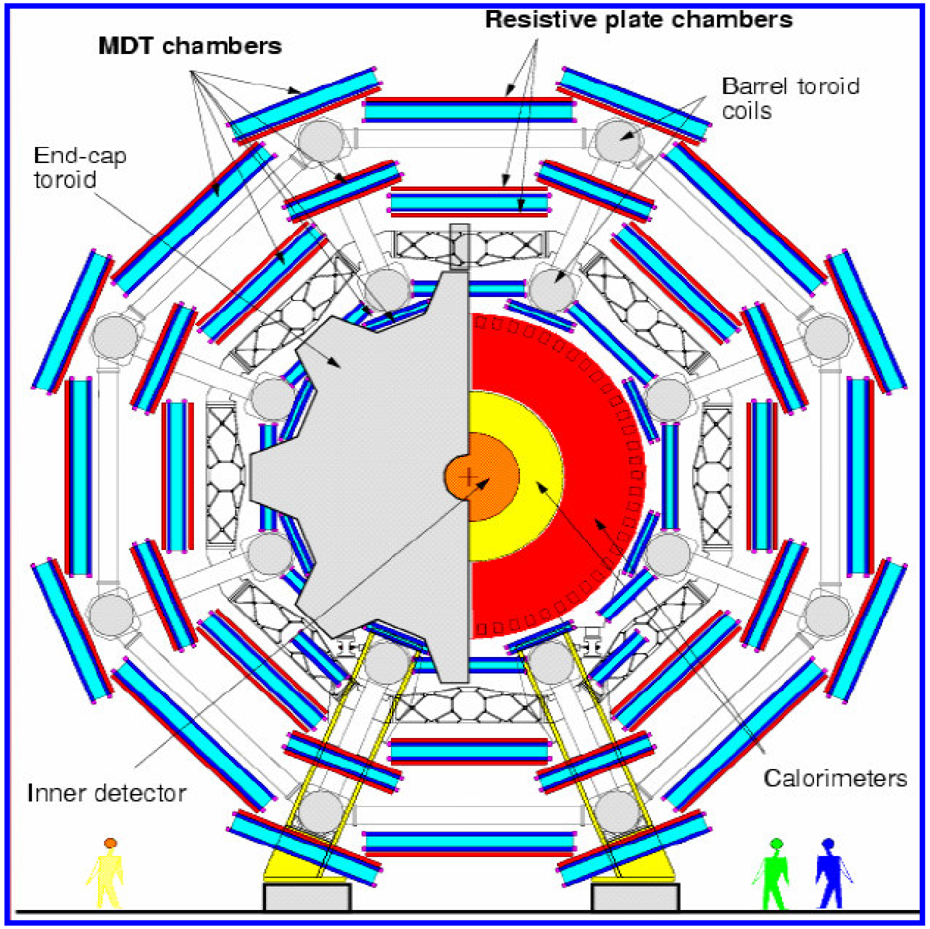
dp/p ~10% at ~1TeV/c

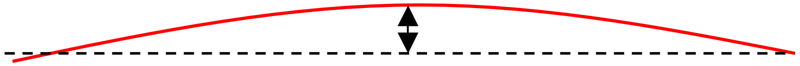
dp/p ~3% at ~100GeV/c

⇒need overall **$ds_{sagitta}$ ~ 50µm**

⇒need low **radiation length≤ 10%**

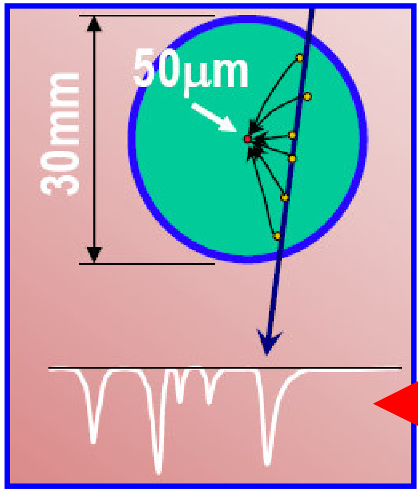
Cover 5500m²



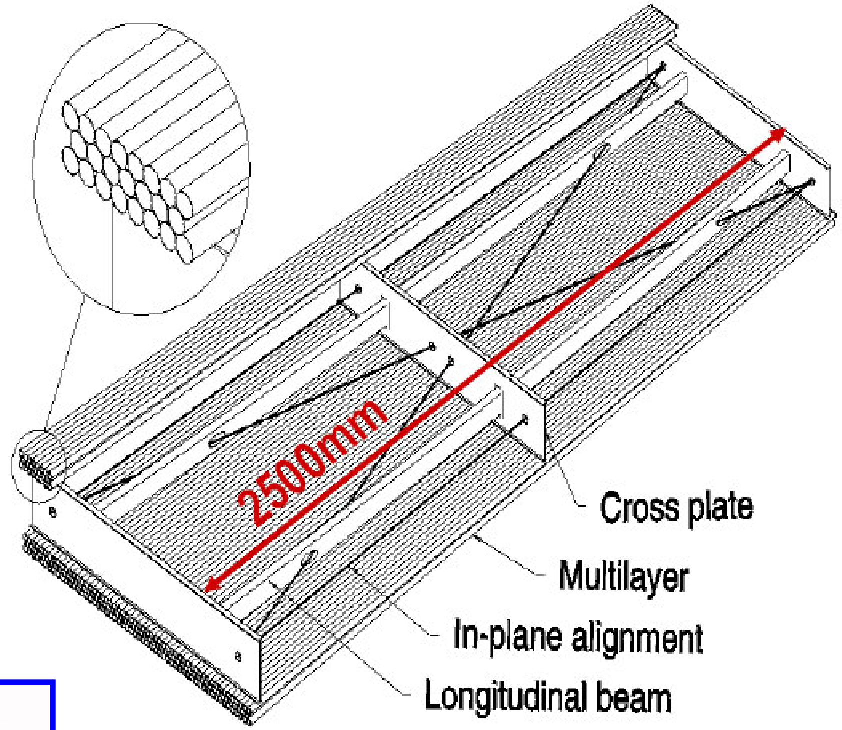



Sagitta s

# ATLAS MDTs




Trigger on first cluster




Single tubes:

$Ar/CO_2$ (93/7%) with 3 bar

**single tube resolution: ~100µm**

Chambers:

2 multilayers with 3 or 4 monolayers

**MDT position resolution $\sigma_{sagitta}$~50µm**

# Gaseous Detectors at LHC

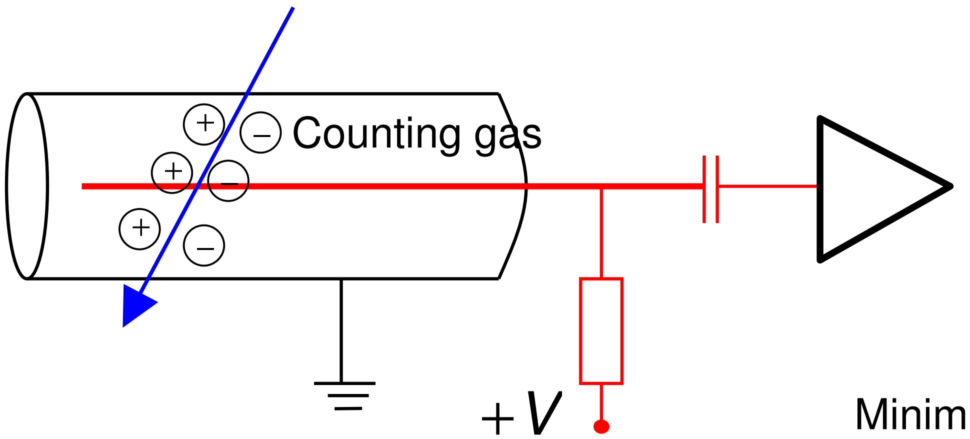
**ALICE:** TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

**ATLAS:** TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

**CMS:** Muon detector (drift tubes, CSC), RPC (muon trigger)

**LHCb:** Tracker (straw tubes), Muon detector (MWPC, GEM)

# Gas ionization by charged particles




Minimum ionizing particle m.i.p

Energy loss dE/dx of charged particles:

- primary ionization
- secondary ionization

Average energy $W_{ion}$ to create e/ion pair

Total number of e/ion pairs for a particle:

$$n_{ion} = \frac{\langle dE/dx \rangle}{W_{ion}}$$ ← Bethe-Bloch

| Gas | Z | $W_{ion}$ [eV] | $n_{ion}$ [$cm^{-1}$] |
|---|---|---|---|
| Ar | 18 | 26 | 94 |
| $CO_2$ | 33 | 33 | 91 |
| $CH_4$ | 10 | 28 | 53 |

For comparison:

Scintillator: energy for photon ~ 100 eV

Si Detector: energy for e/hole ~ 3.5 eV

# Drift of electrons in presence of fields

Motion of charged particles under influence of E and B fields: **Langevin equation.**

**Drift velocity u:**

$$m\frac{d\vec{u}}{dt} = e(\vec{E} + \vec{u} \times \vec{B}) - K\vec{u}$$

"stochastic friction force" due to collisions
m, e = mass and charge of electron

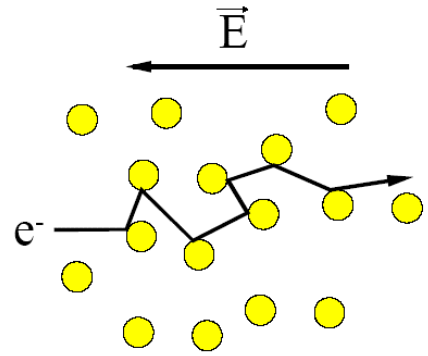
For t>>τ → static situation: $\frac{d\vec{u}}{dt} = 0$

Cyclotron frequency

$$\omega = \frac{e}{m}B$$

Scalar mobility

$$\mu = \frac{e}{m}\tau$$




Mean free path L

Time between collisions:

$$\tau = \frac{L}{c} = \frac{1}{N\sigma \cdot c}$$

instantaneous velocity

One finds: $\tau = \frac{K}{m}$

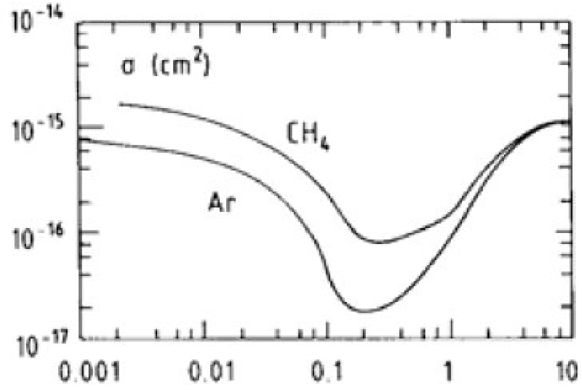
$$\vec{u} = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\,\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

for $\omega\tau \to 0 \quad \vec{u} = \mu\vec{E}$

# Drift velocity

In the microscopic picture one finds for the drifting electrons (energy ε):

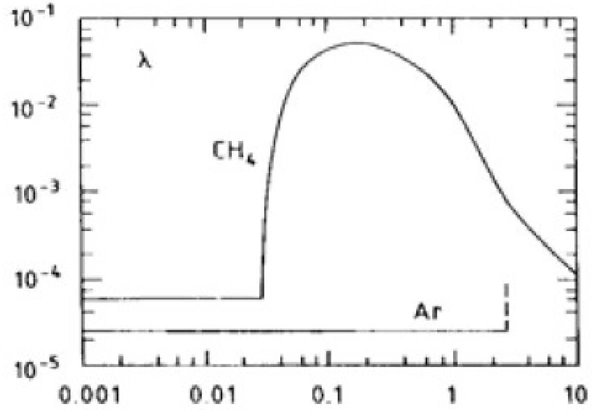
drift $$u^2 = \frac{eE}{mN\sigma}\sqrt{\frac{\lambda}{2}}$$ $$\sigma = \sigma(\varepsilon)$$




ε [eV]

Instant. $$c^2 = \frac{eE}{mN\sigma}\sqrt{\frac{2}{\lambda}}$$ $$\lambda = \lambda(\varepsilon)$$

fractional energy loss




ε [eV]

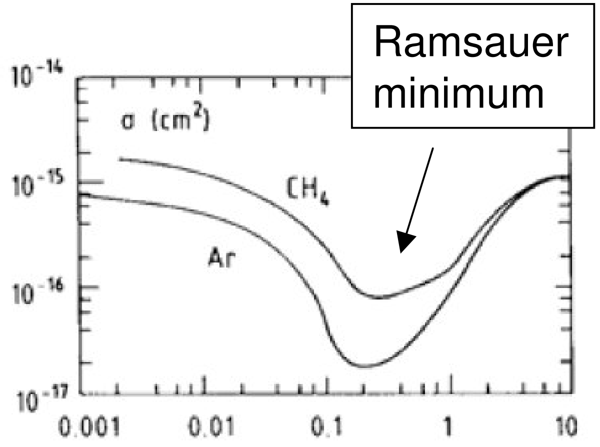
(Energy received from the E field between collisions equal to energy transferred in collisions.)

Elastic collisions: $$\lambda \approx \frac{2m}{M_{gas}} \approx 10^{-4}$$

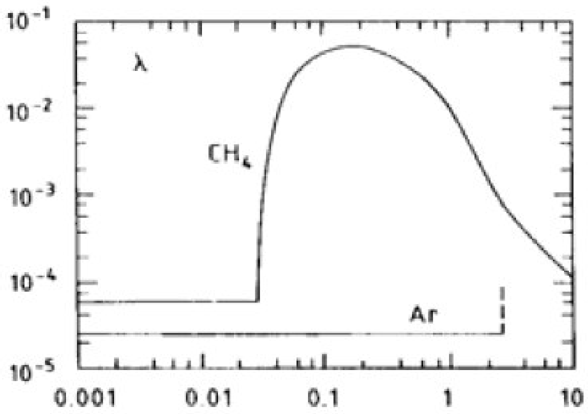
$$u^2 = \frac{\lambda}{2}c^2 \quad \Rightarrow u \approx \frac{c}{100}$$

Drift velocity much smaller than instantaneous velocity

# Fast and slow gases




ε [eV]




ε [eV]

Excitation threshold: Ar at 11.5 eV

$CH_4$ at 0.03 eV

(vibrations+rotations)

- Ramsauer minimum: v is large
- Ar: $\varepsilon_{ionization} >> \varepsilon_{Ramsauer}$

  ➡ $\frac{\sqrt{\lambda}}{\sigma}$ small, i.e. slow gas

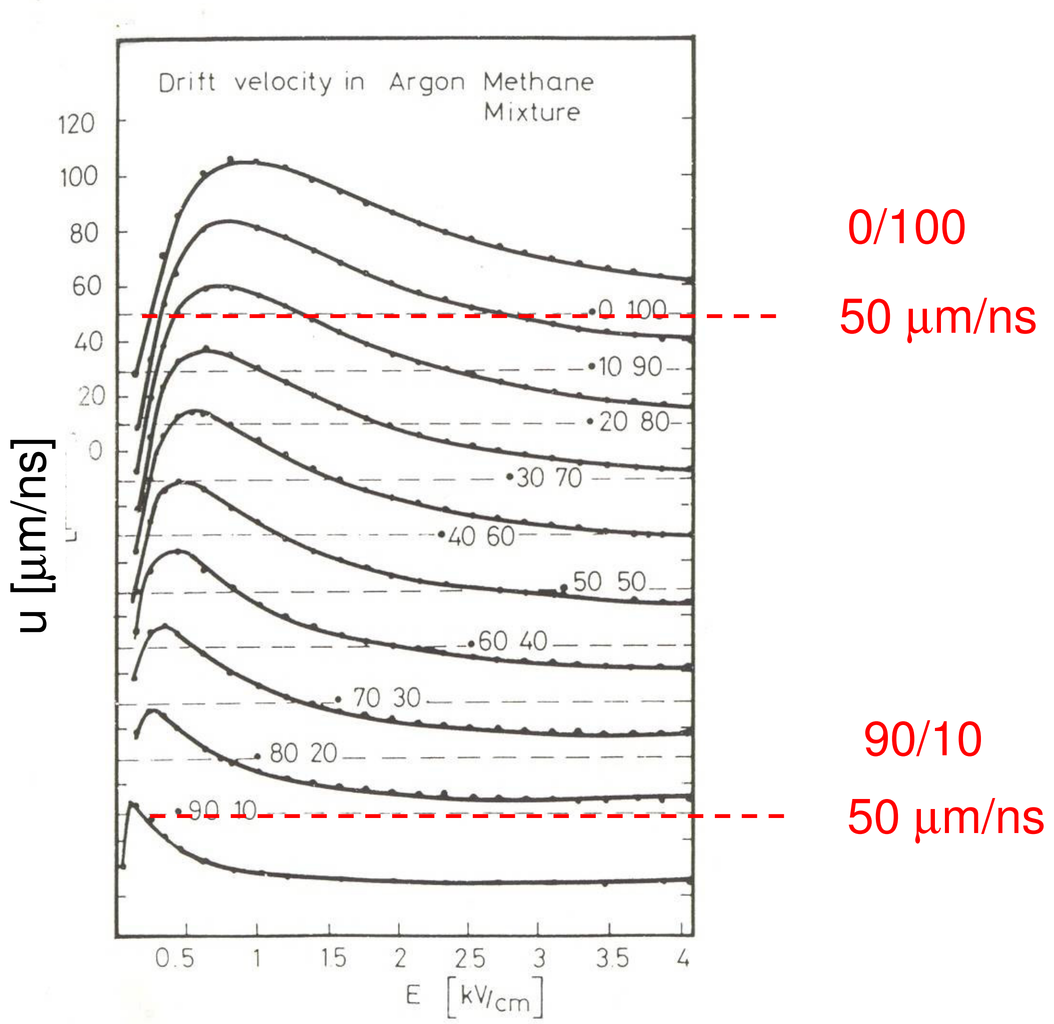
- $CH_4$: $\varepsilon_{exitation} < \varepsilon_{Ramsauer}$

  ➡ $\frac{\sqrt{\lambda}}{\sigma}$ big, i.e. fast gas

- Ar / $CH_4$ mixture

  ➡ Drift velocity u can be tuned

# Drift velocity of $ArCH_4$



# Drift velocity of ions

- Fractional energy loss for ions large:

$$\lambda \approx \frac{2m_{ion}M_{gas}}{(m_{ion}+M_{gas})^2} \approx \frac{1}{2}$$

- Mobility / drift velocity much smaller than for electrons.

$$\mu_{ion} \approx 10^{-4}\mu_e \quad \Rightarrow v_{ion} \approx 10^{-4}u_e$$

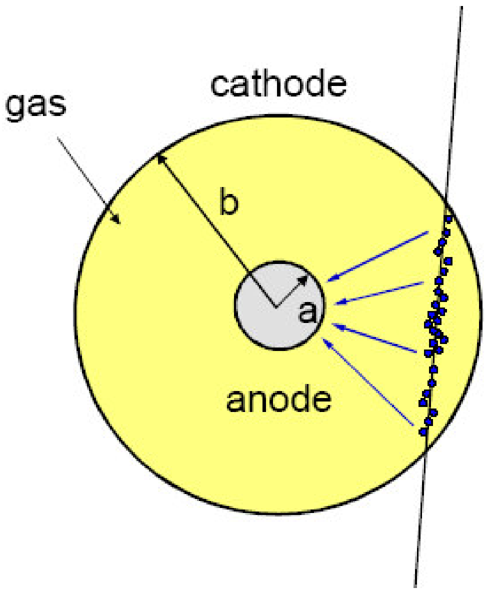
- While for electrons μ=μ(E, Gas, p, T) one finds for ions only little dependence on E:

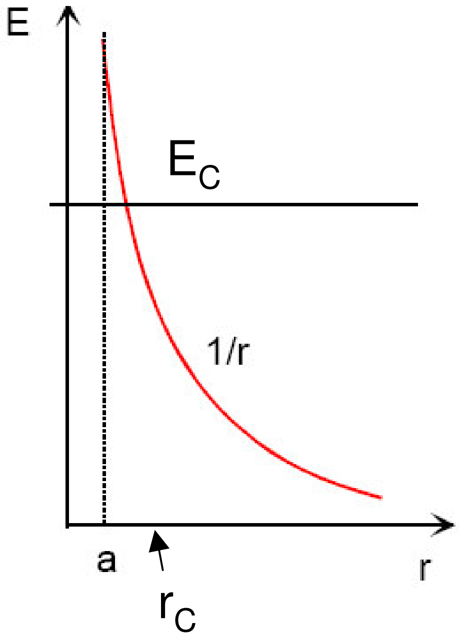
$$\mu(E) \sim \text{const} \quad \Rightarrow v \sim E \quad \text{for small E}$$

$$\mu(E) \sim \sqrt{E} \quad \Rightarrow v \sim \sqrt{E} \quad \text{for large E}$$

| Gas | Ion | μ [cm²/(Vs)] |
|---|---|---|
| Ar | $Ar^+$ | 1.5 |
| Ne | $Ne^+$ | 4.1 |
| Xe | $Xe^+$ | 0.6 |

# Proportional Counter



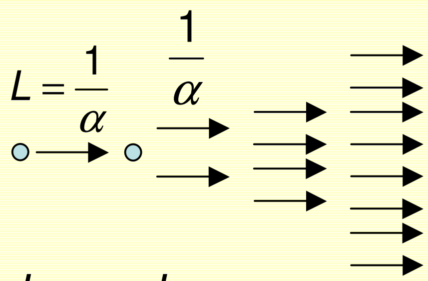




Electrical field:

$$E(r) = \frac{V_0}{\ln(b/a)}\frac{1}{r} = \frac{C'V_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$C' = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ Capacity/length

Gas amplification – avalanche:

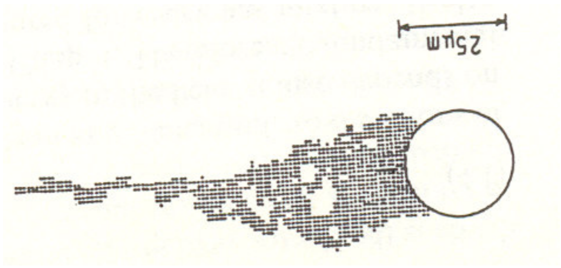



$$\frac{dn_e}{n_e} = \frac{dx}{L} = \alpha\, dx$$

Examples:

- LHCb straw tubes: a=12.5 μm, b=2.5 mm
- ATLAS MDT: a=25 μm, b=15 mm

# Gas amplification




For uniform field

$$n(r) = n_0 \exp(\alpha r) \qquad G = \frac{n}{n_0} = \exp(\alpha r)$$

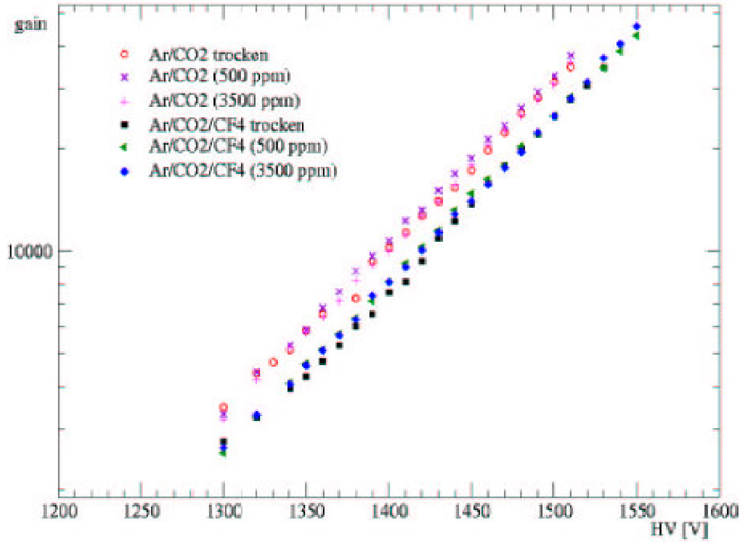
G = gas amplification = $10^4 \ldots 10^5$
(gain)

General case of non-uniform fields

$$G = \exp\left(\int_a^{r_c} \alpha(r)dr\right)$$

α(r) = Townsend coefficient

→ $G = k \exp(C'V)$




(LHCb straws)

Raether limit:

$\alpha x \approx 20$
$G \sim 10^8$

Phenomenological limit:
→ discharges (sparks)

# Pressure dependence

$$\frac{dG}{G} \sim -\frac{d\rho}{\rho}$$

$$\frac{dG}{G} = -K\frac{dp}{p}$$

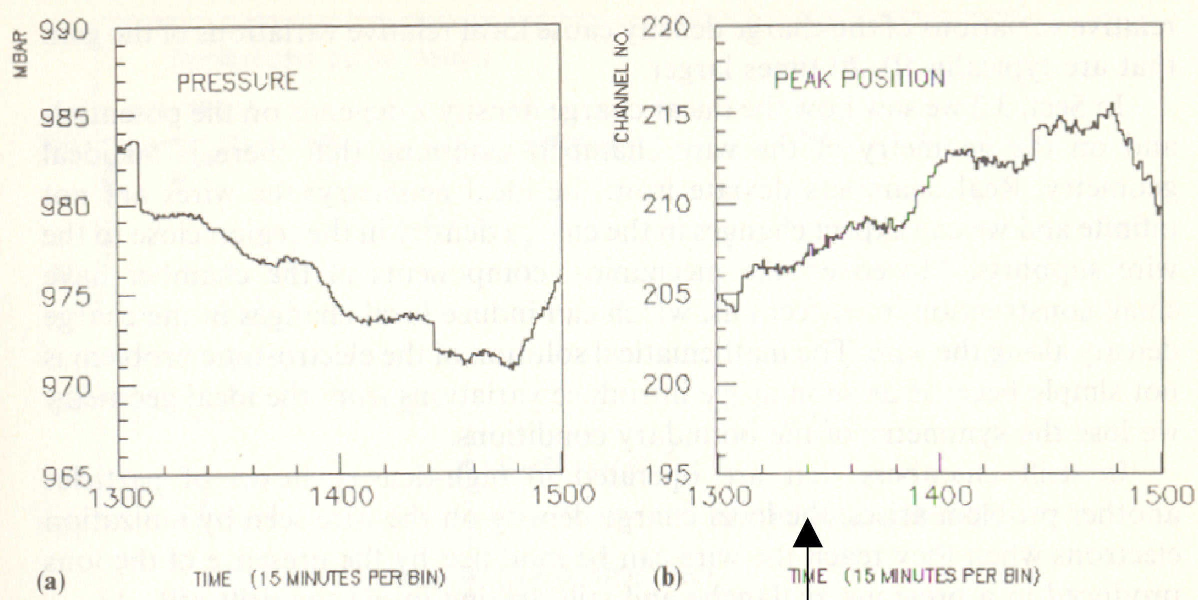



**Fig. 4.11. (a)** Atmospheric pressure $p$ as a function of the time in a time interval of two days. **(b)** Average pulse-height measured by the chamber in the same period. Measurements done with the ALEPH TPC

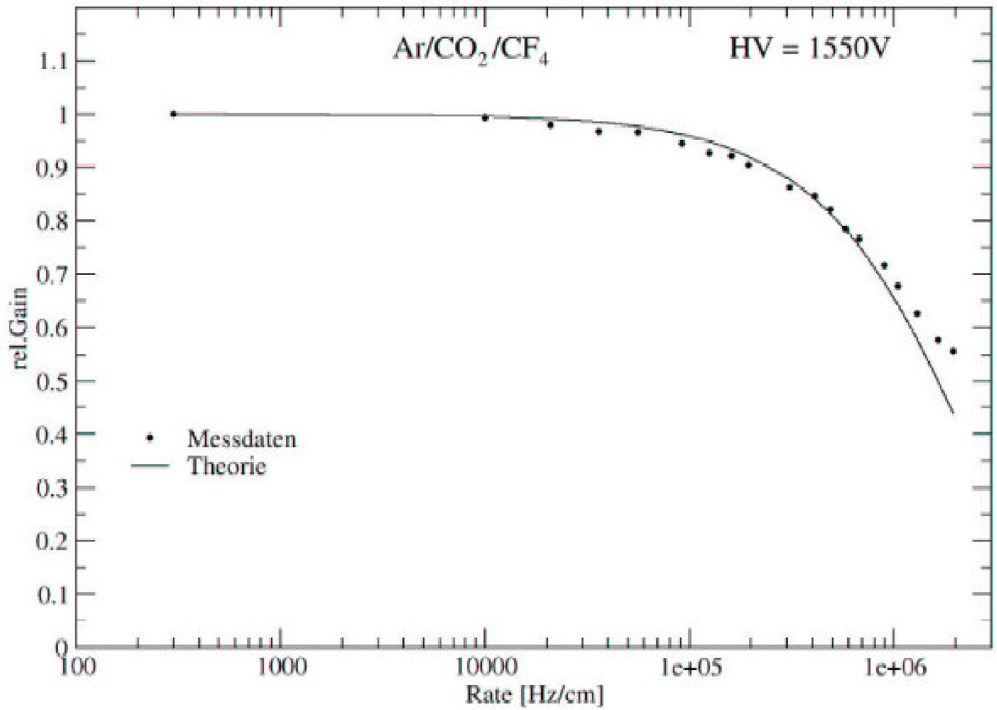
K = gas/configuration dependent constant = 5…8

Charge signal / rel. gain with mono chromatic γ source:

Fe55: 6.9 keV γs

# Space Charge Effect

Gain drop at high particle densities: space charge around the anode.




(LHCb straws)

# $2^{nd}$ Townsend Coefficient & Quencher

UV photons from avalanche so far neglected:

UV photons $\rightarrow$ photo effect (gas molecules / cathode)

Gas amplification $\mathbf{G_\gamma}$ including effect of UV photons:

$$G_\gamma = G + G(\gamma G) + G(\gamma G)^2 + .... = \frac{G}{1-\gamma G}$$

0× 1× 2× photo effect

$\gamma$ = probability for photo effect

$2^{nd}$ Townsend coefficient

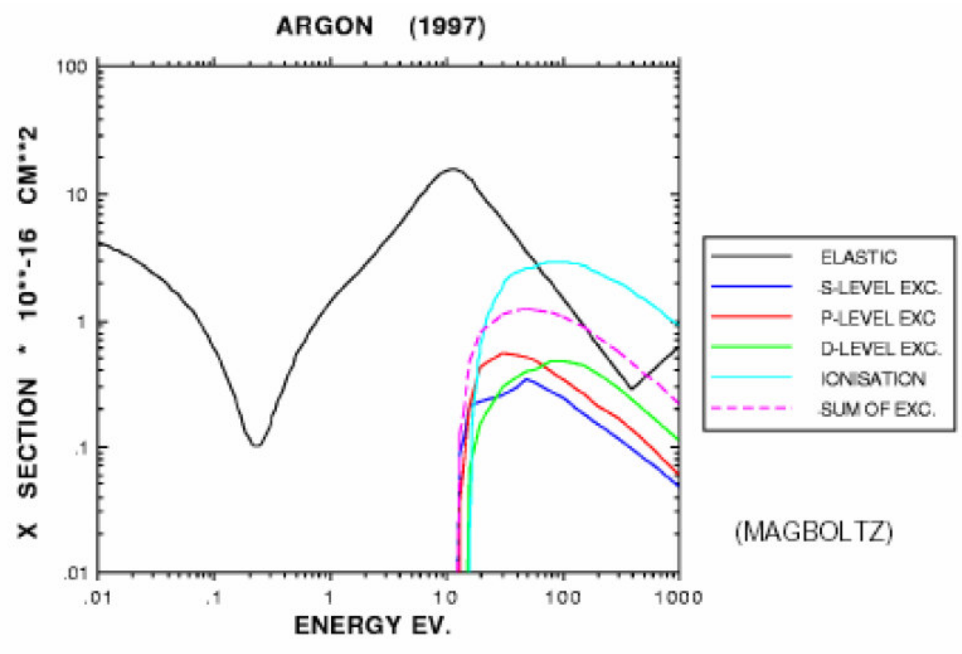
For $\gamma G \rightarrow 1$ : gas amplification becomes infinite

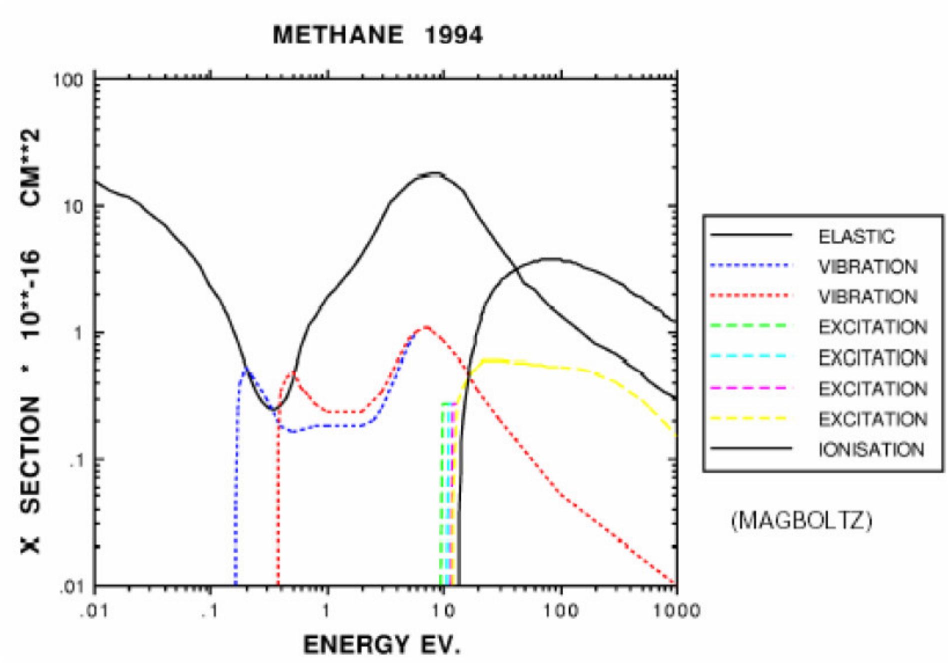
continuous discharges (sparks)

Use poly-atomic gas admixtures to absorb photons: Quencher

# Quencher

Excitation cross section for Noble gases (Ar) and poly-atomic gases ($CH_4$)

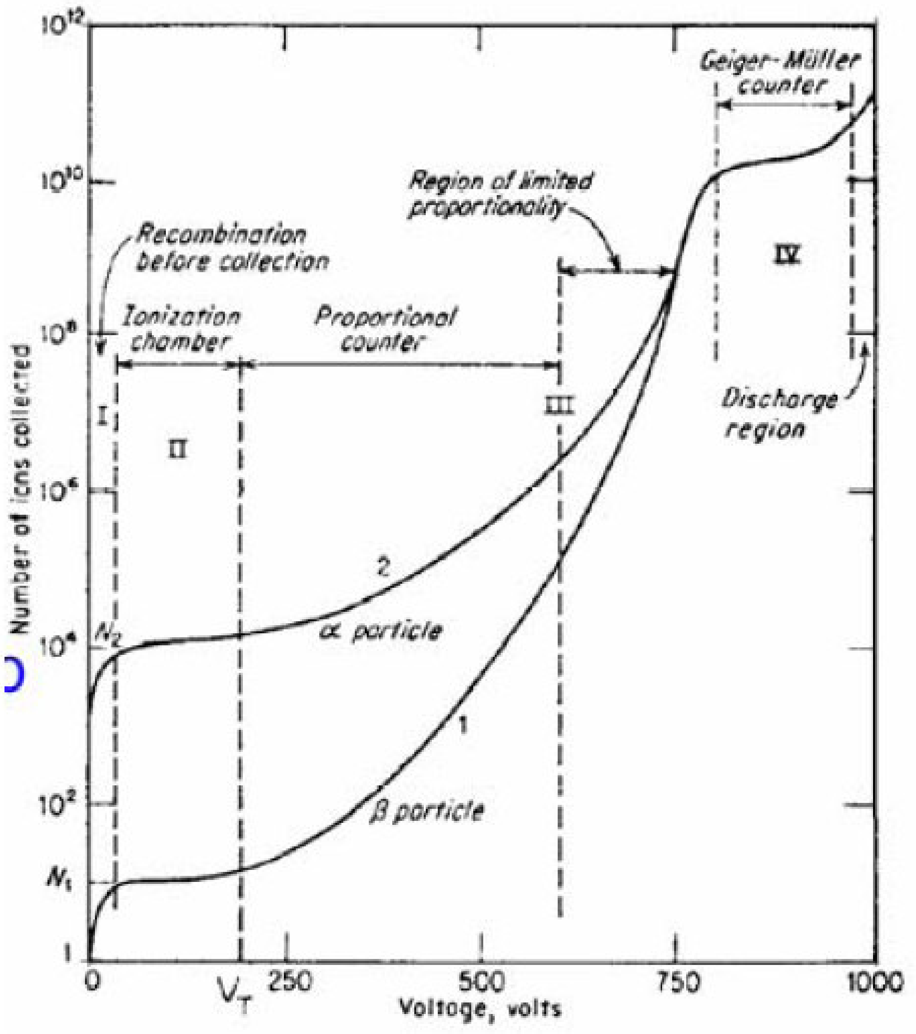



→ Energy dissipation through collisions (radiation less transitions)

Quencher: $CH_4$, $C_2H_6$, $CO_2$, $CF_4$

# Operation modes




**I) Recombination before collection**

**II) Ionization mode**
full charge collection, no charge multiplication.

**III) Proportional mode** detector signal proportional to primary ionization, gas amplifications $10^4 \ldots 10^5$, needs quencher

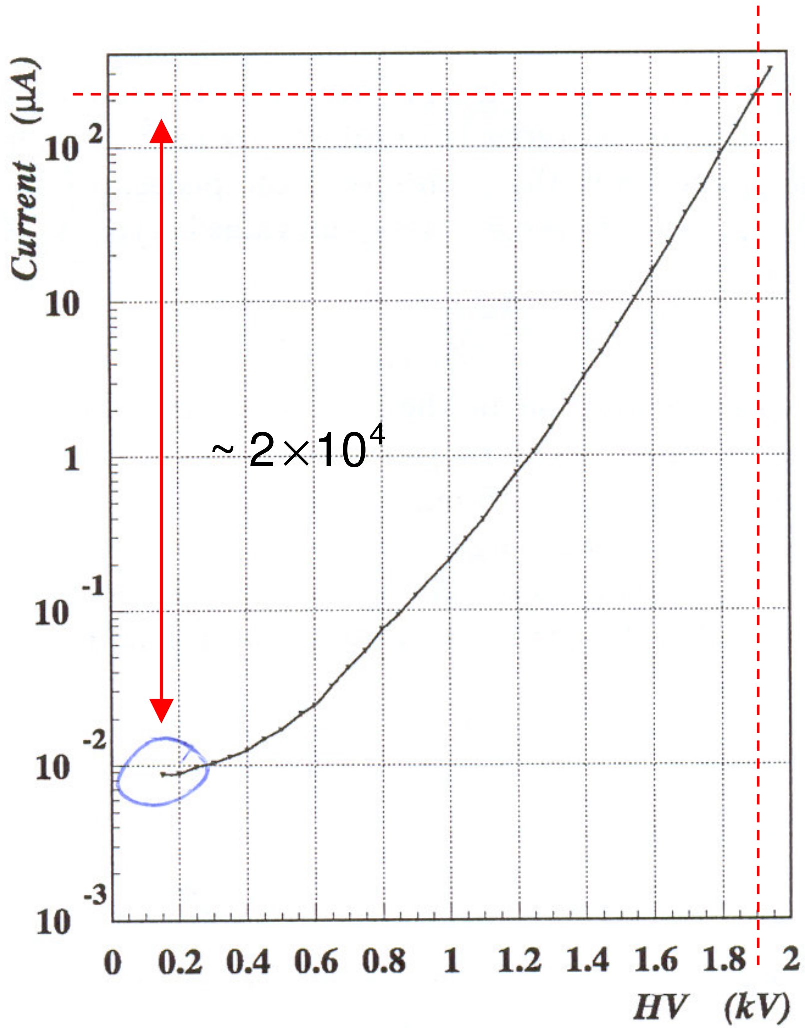
**IV) Streamer mode**
strong photon emission produced secondary avalanche, strong quencher to localize streamer, large signals

**Geiger mode**
massive photon emission, no quencher → discharge over full length, needs to be stopped by HV drop

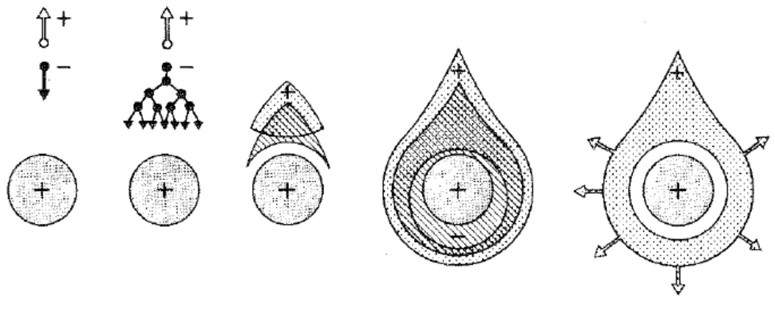
# Absolute gain measurement

HERA-B Honeycomb Tracker:

Chamber current at a constant/stable irradiation for different HV (~10000 single channels contribute)



# Signal development




- Avalanche starts at a few radii distance from wire (typ. 50µm)
- Electrons reach anode with ~1ns: Multiplication process takes less than 1ns
- Ions will slowly drift towards cathode and induce a negative signal on anode

Induced signal of charge Q moved by dr in a system with total capacity C=l·C'

$$dv = \frac{Q}{lC'V_0}\frac{dV}{dr}dr$$

➡ Electron signal $$v^- = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{a+d}{a}$$ ⟵ Assumes all charge produced at distance d

➡ Ion signal $$v^+ = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{b}{a+d}$$

➡ Total signal $$v = v^+ + v^- = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{b}{a} = -\frac{Q}{lC'}$$

$$v^-/v^+ \approx 1.4\ (1)\%$$

for LHCb straws / ATLAS MDT

# Signal timing

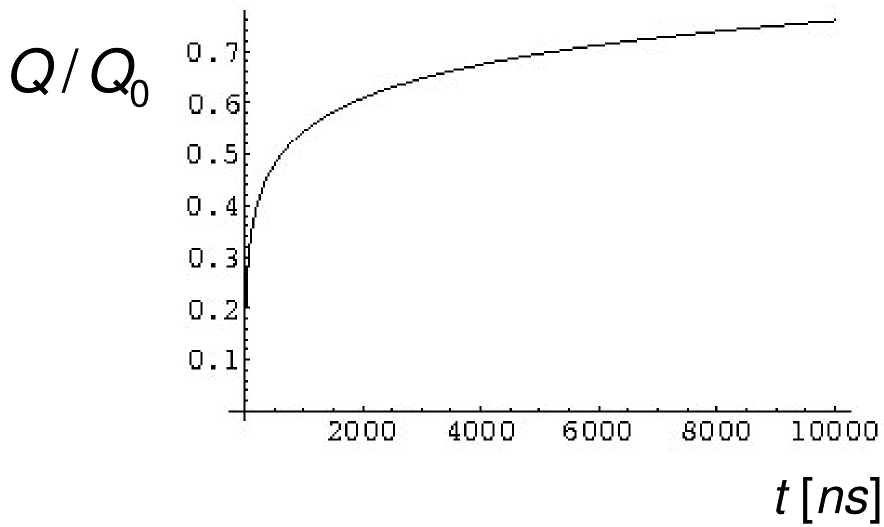
**Ion signal** $$Q(t) = Q_0 \ln(1 + t/t_0) / \ln(1 + t_{max}/t_0)$$

Signal rise time $$t_0 = \frac{pa^2}{2\mu V}\ln(b/a) \sim 5ns$$

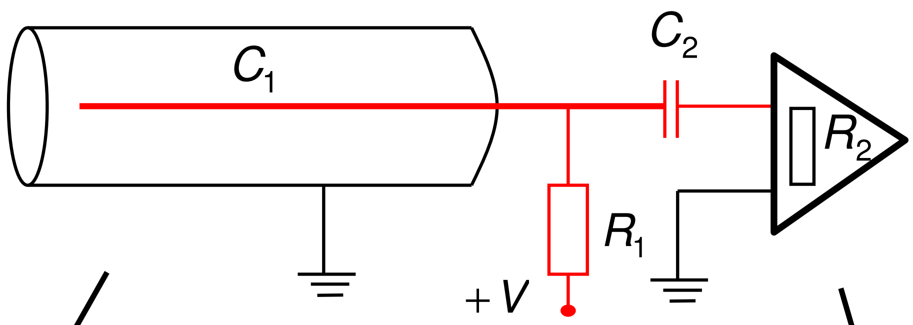
Max. ion drift time $$t_{max} = \frac{p(b^2 - a^2)}{\mu V}\ln(b/a) \sim 130\mu s$$

p = pressure
V = voltage
μ = ion mobility

LHCb straws



# Signal readout

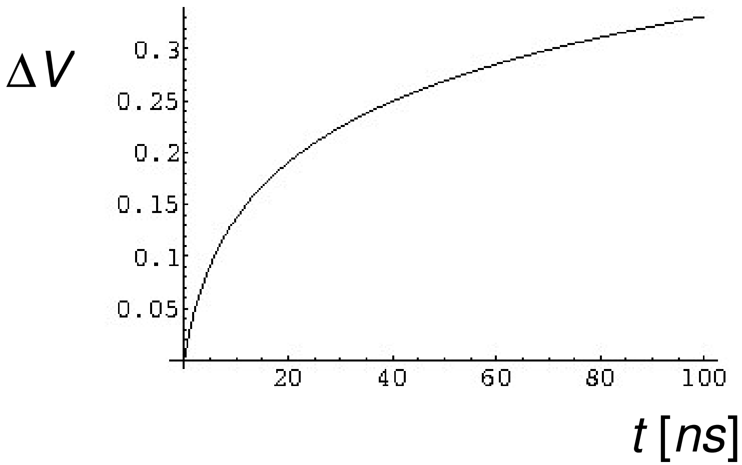


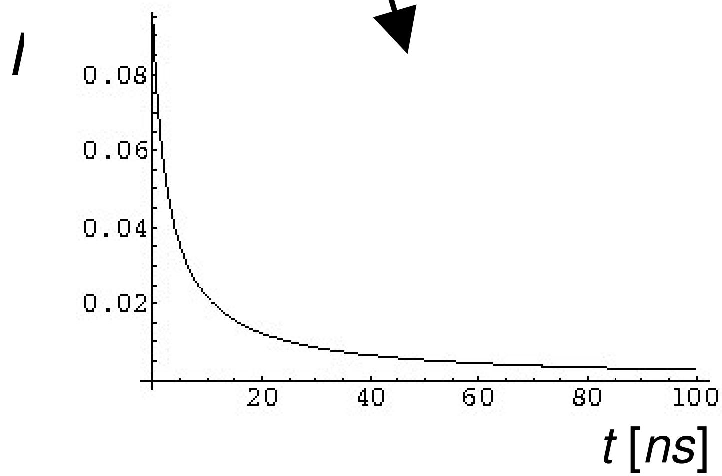

$R_2C_2, R_2C_1 >> t_0$

"Voltage source"

$R_2C_2, R_2C_1 << t_0$

"Current source"

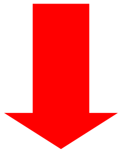


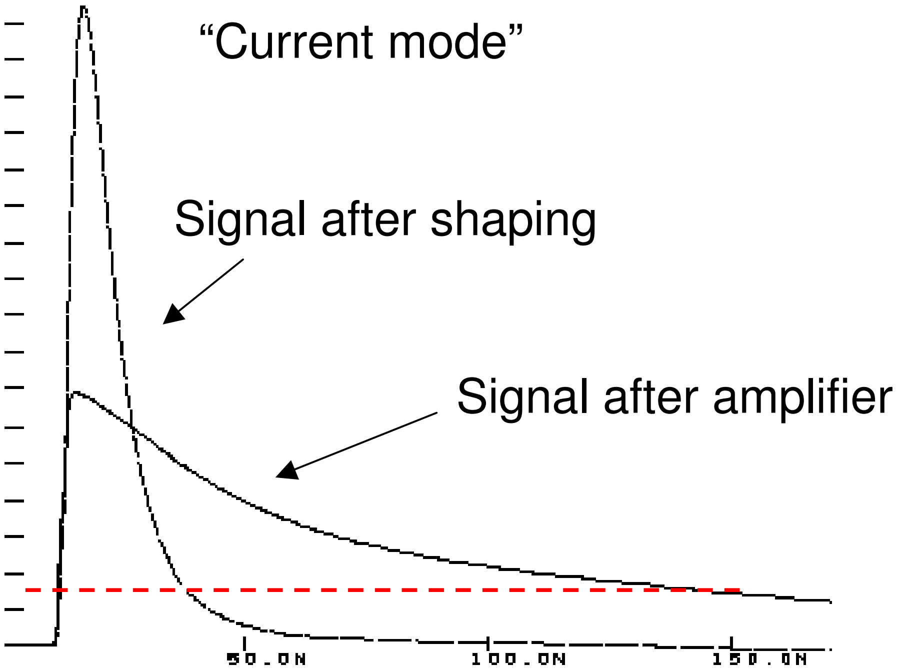
# Signal Shaping

Long ion tail will shadow subsequent ionizing particles:

If threshold for particle detection is used, signal stays long time above threshold.



RC/CR Shaping

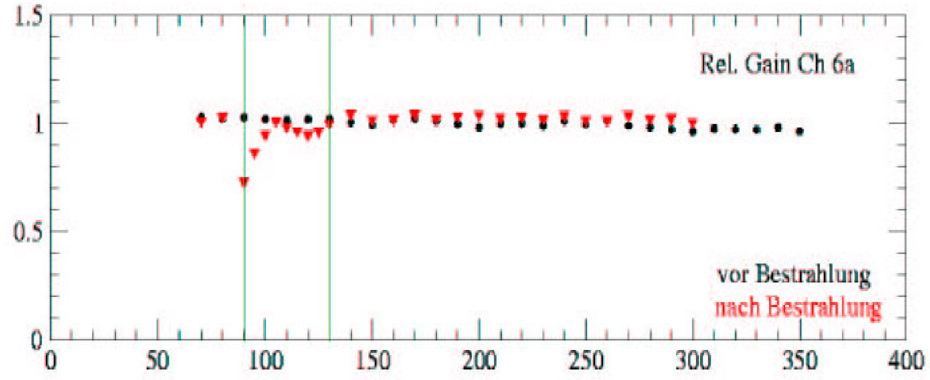


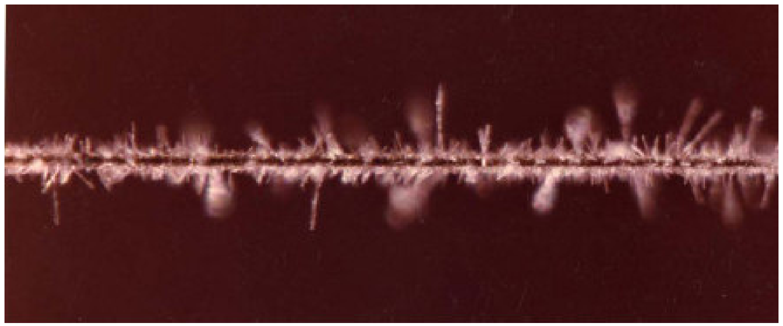
# Ageing Effects

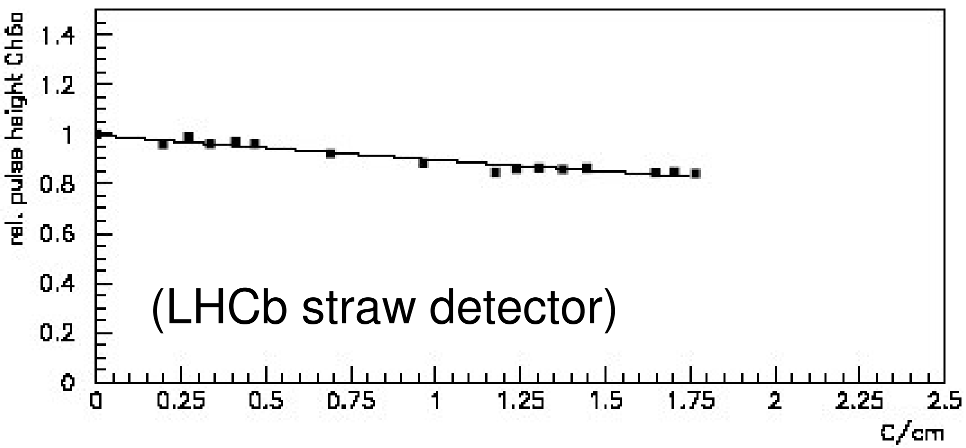
In a high rate environment (e.g. LHC) wire chambers could show several “ageing effects”, nearly all of them triggered by pollutants in the gas/chamber:

- **Deposits** on the anode wire:
  → **gain loss**

  Study gain as function of totol charge deposition per length



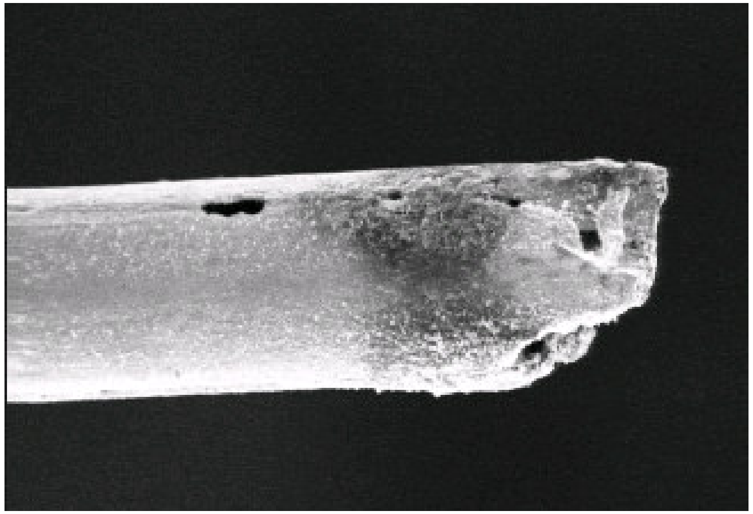





# Ageing Effects II

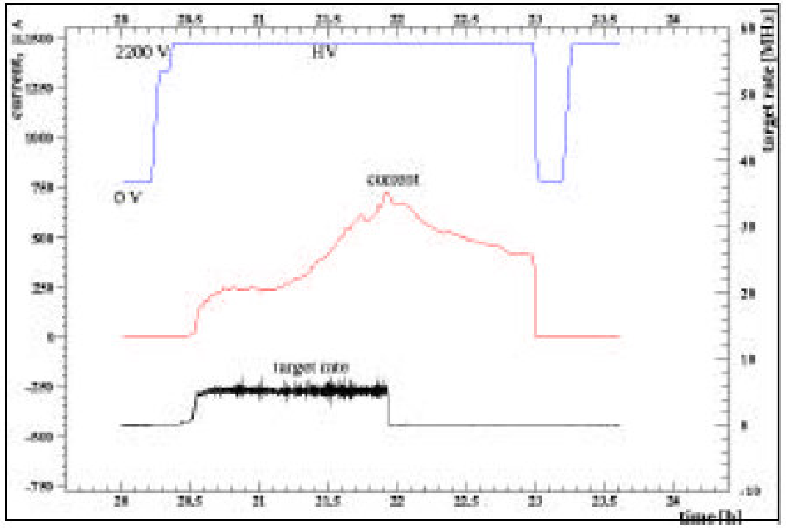
- **Etching** of anode wire in case of counting gas with $CF_4$ admixtures

  (LHCb straws)



- **Modification** of the cathode surface: Malter effect → self sustaining currents

  (HERA-B, Honeycomb tracker)



# Tools for detector development

**Garfield - simulation of gaseous detectors**

*http://consult.cern.ch/writeup/garfield/*

Garfield is a computer program for the detailed simulation of two- and three-dimensional drift chambers

**Magboltz - Transport of electrons in gas mixtures**

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

Magboltz solves the Boltzmann transport equations for electrons in gas mixtures under the influence of electric and magnetic fields.

**Heed - Interactions of particles with gases**

*http://consult.cern.ch/writeup/heed/*

HEED is a program that computes in detail the energy loss of fast charged particles in gases, taking delta electrons and optionally multiple scattering of the incoming particle into account. The program can also simulate the absorption of photons through photo-ionization in gaseous detectors.

# Multi Wire Proportional Chamber

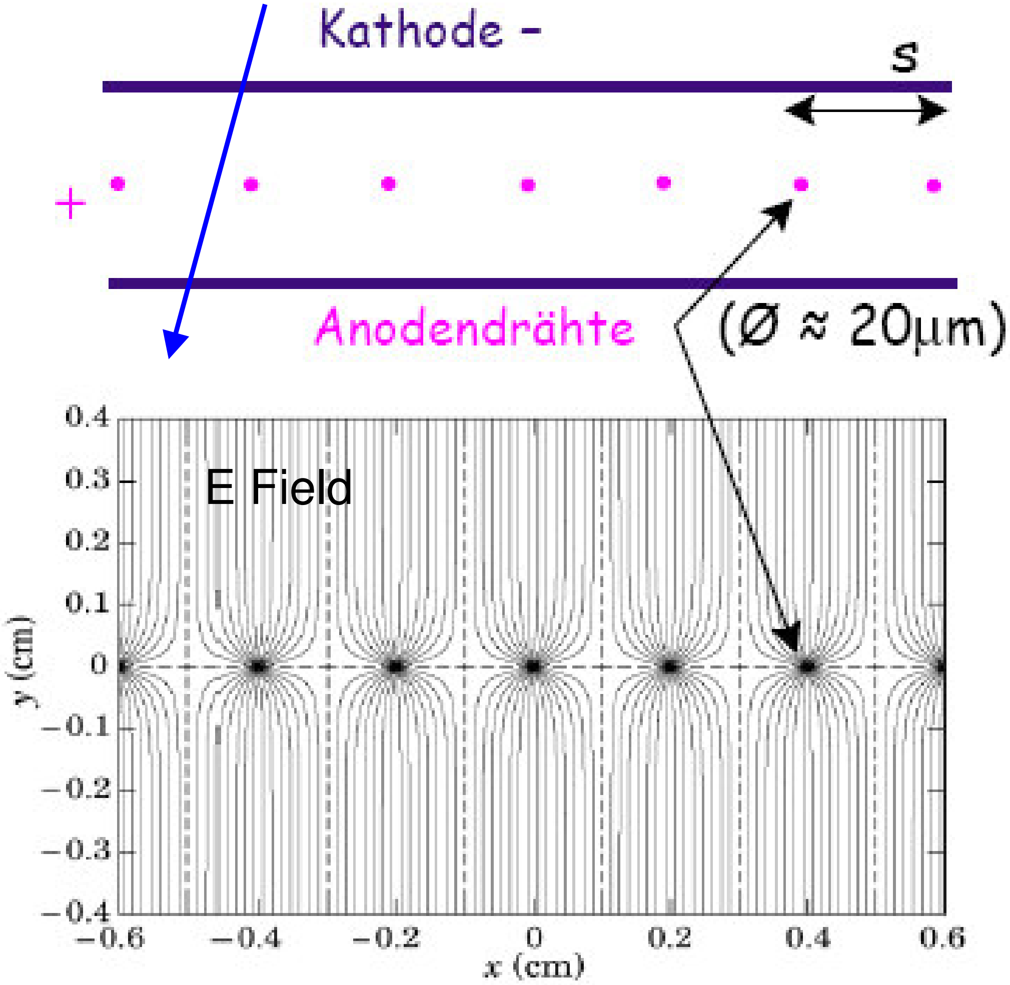
Charpak, 1967/68
Nobel prize 1992

spatial resolution

$\sim s/\sqrt{12}$

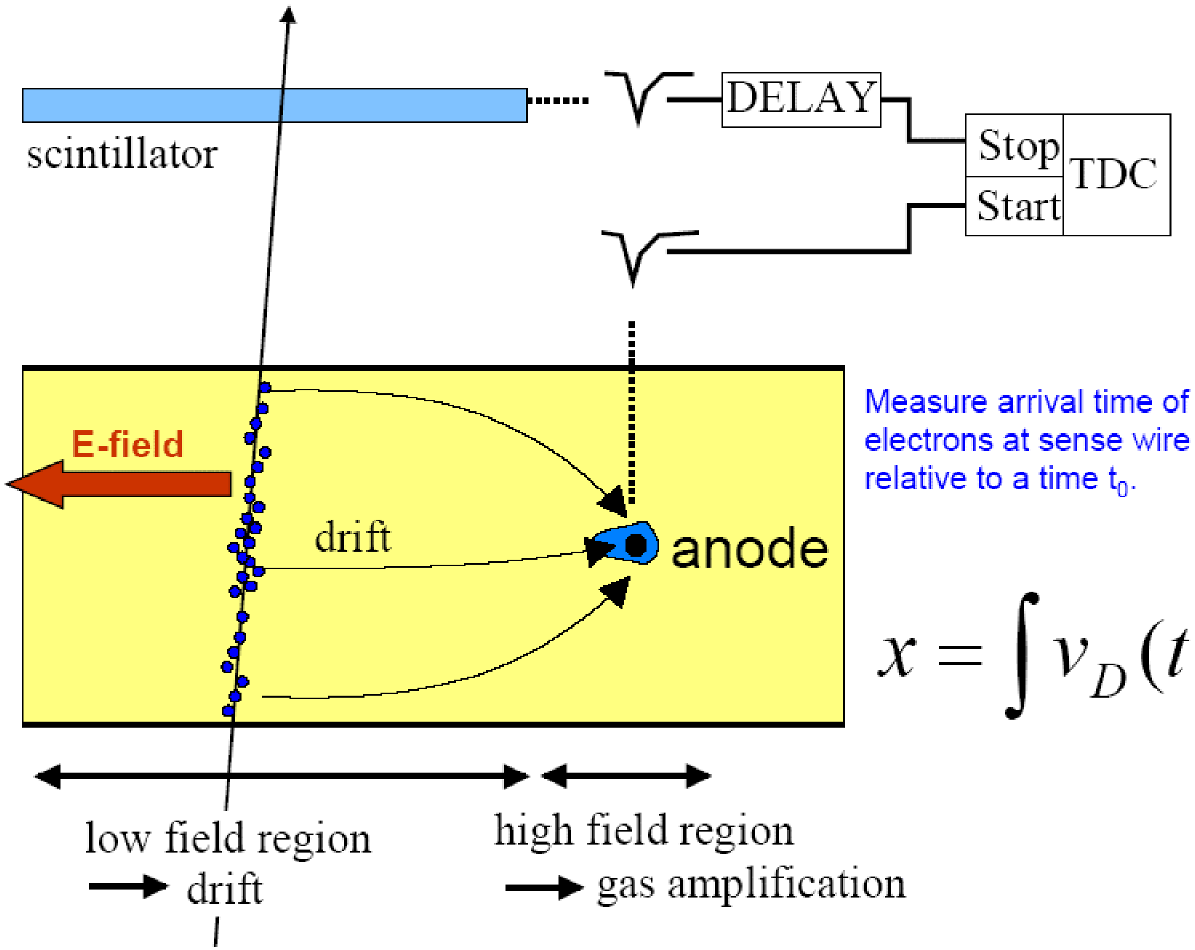
With typ. wire distance
s≈2mm ⇒ δs ≈ 0.6 mm

Significantly better spatial resolution in not achievable with MWPCs




MPWC = Multiwire proportional chambers

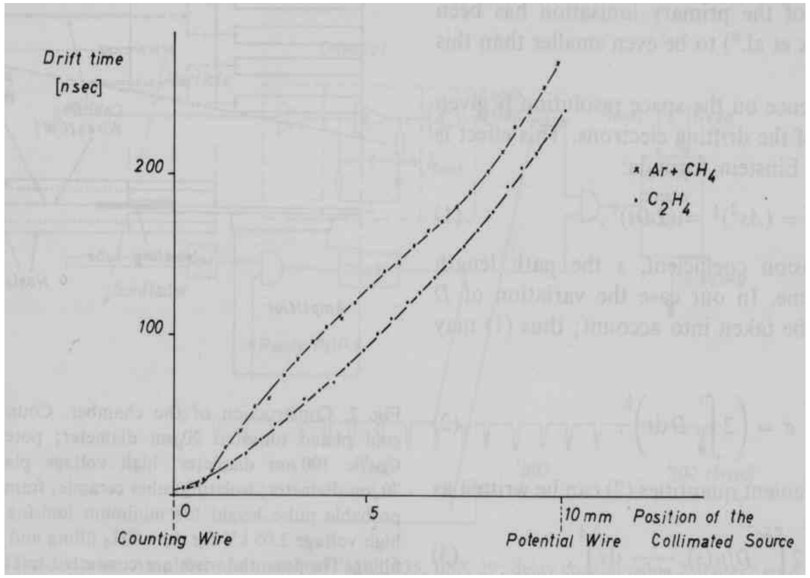
# Drift Chamber

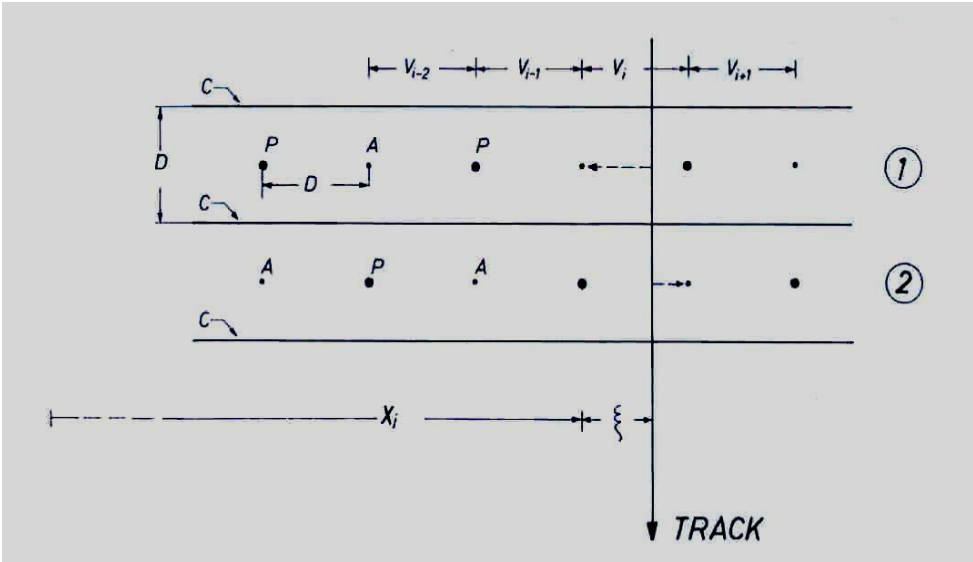



Measure arrival time of electrons at sense wire relative to a time $t_0$.

$$x = \int v_D(t)dt$$

- Drift time ⇒ drift distance and intersection point of particle
- Spatial resolution of ~100 μm achievable




# THE MULTIWIRE DRIFT CHAMBER A NEW TYPE OF PROPORTIONAL WIRE CHAMBER*


A. H. WALENTA, J. HEINTZE and B. SCHÜRLEIN

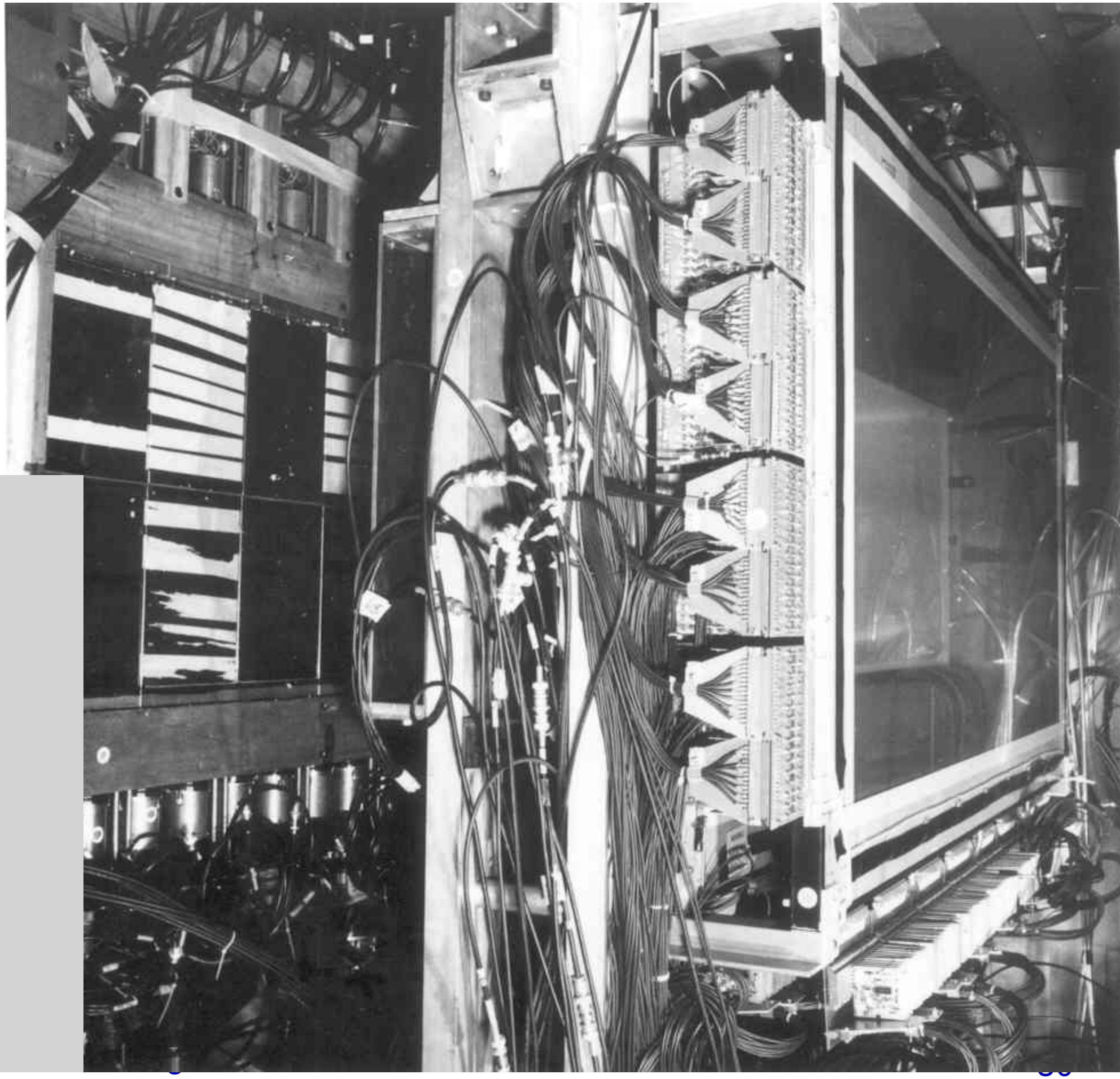
*I. Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany*

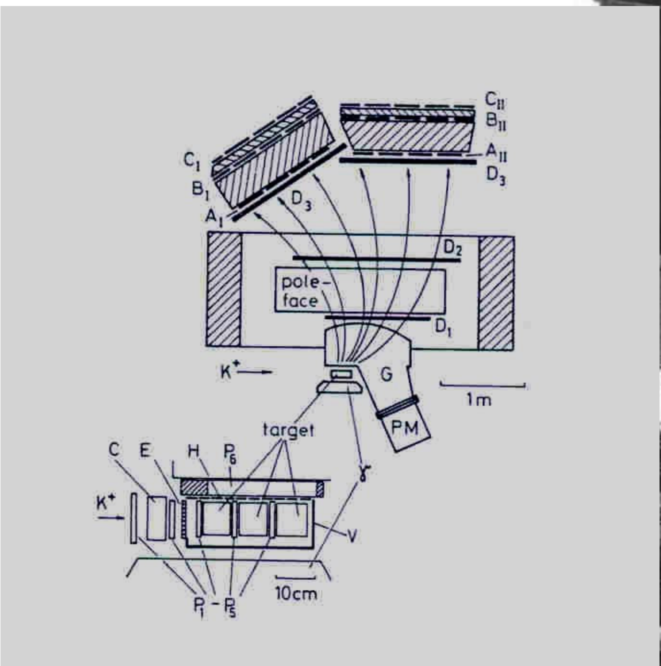


Received 27 November 1970

# First Drift Chamber

***Physikalisches Institut, Heidelberg, 1971***





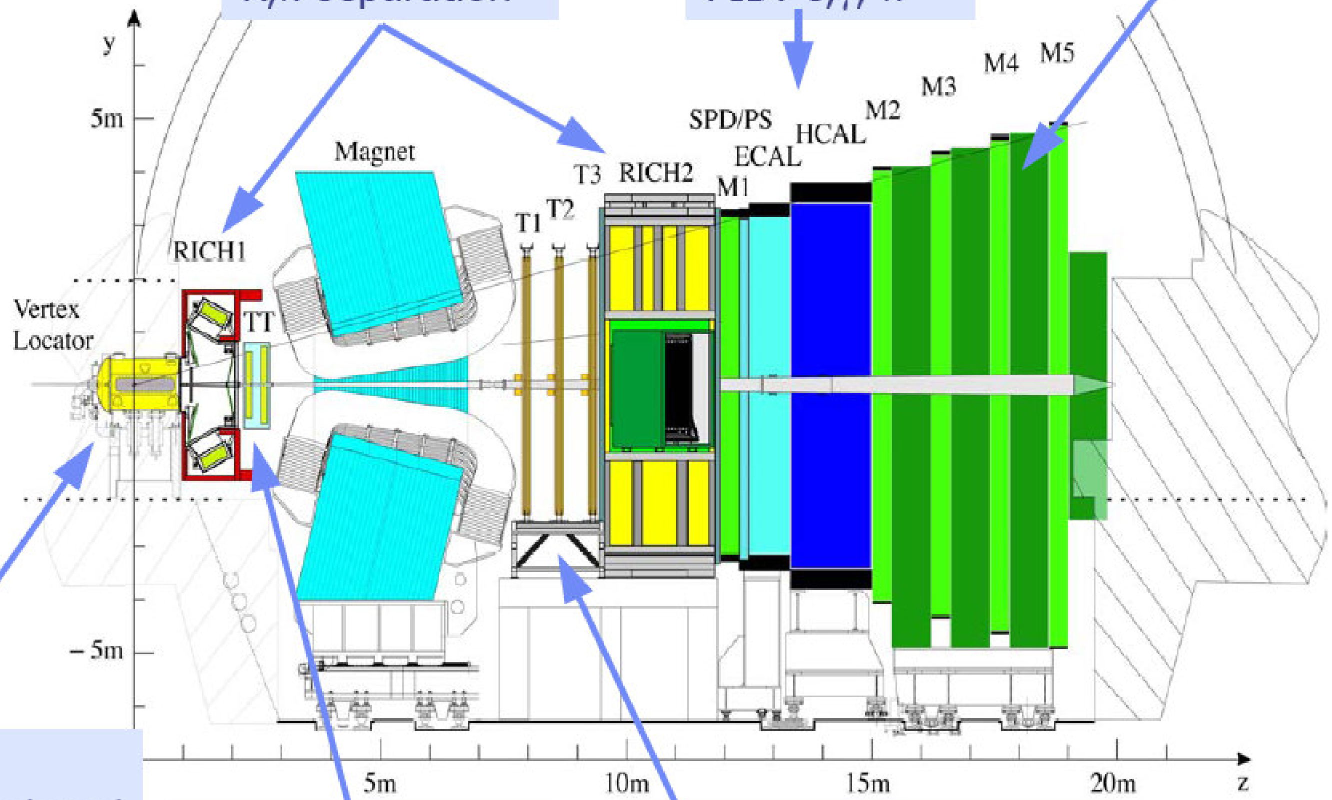
# LHCb Outer Tracker

Particle ID:

RICHES: PID
K,π separation

Calorimeters:
PID: e,γ, $\pi^0$

Muon System




Tracking system:

VELO:
- primary +displaced vertex
- impact parameter

Trigger Tracker:
p for trigger

Tracking Stations:
p of charged particles

# Outer Tracker - Demands

1. Measurement of momentum

   ($\delta p/p$ = 0.4% @ 20GeV)

   ➔ $\sigma_x$ < 200µm

2. LHC bunch structure

   ➔ fast charge collection

3. LHC environment

   ➔ rate capability (~400kHz/cm²)

   ageing resistance up to 2C/cm

   (~10 years at LHCb)

4. Pattern recognition

   ➔ Occupancy < 7%

# Planar Tracking Stations

3 stations (6m x 5m)

4 planes per station (X/U/V/X)

2 layers of straw tubes per plane

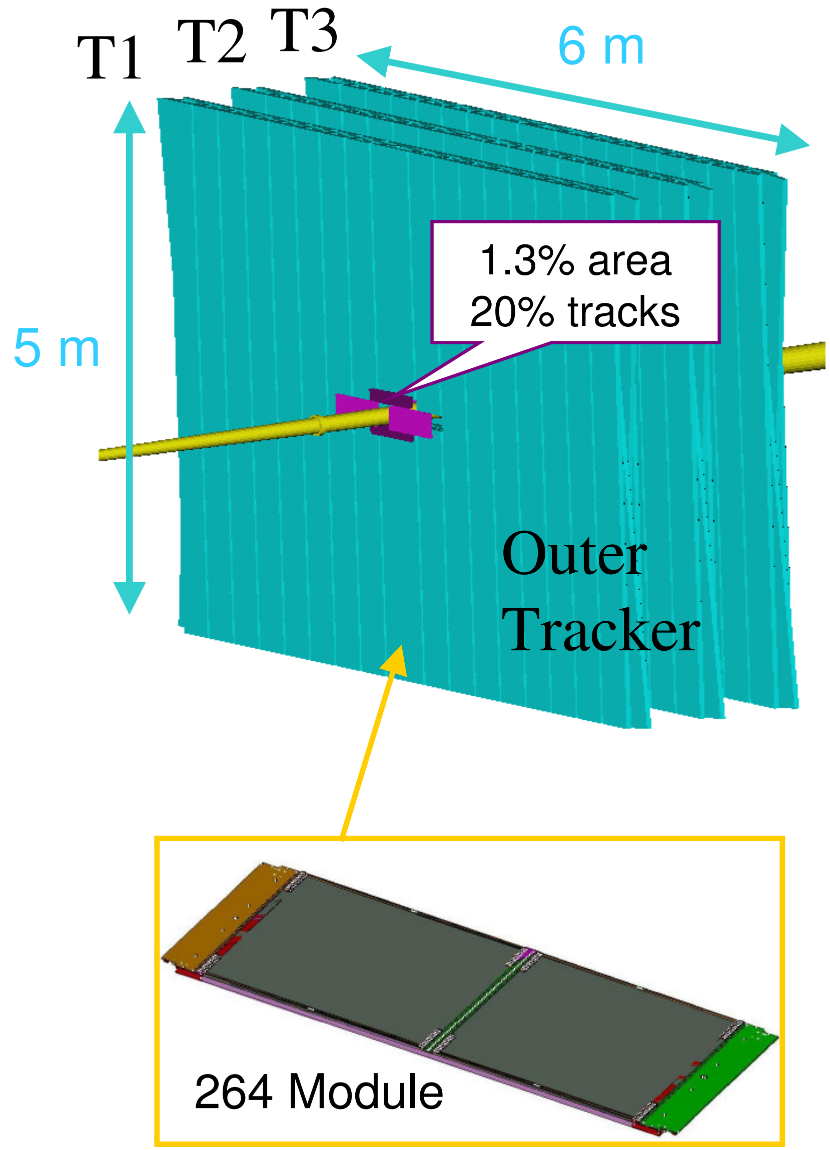
➔ 55.000 straw tubes

137.5 km of straw tubes

➔ modular design

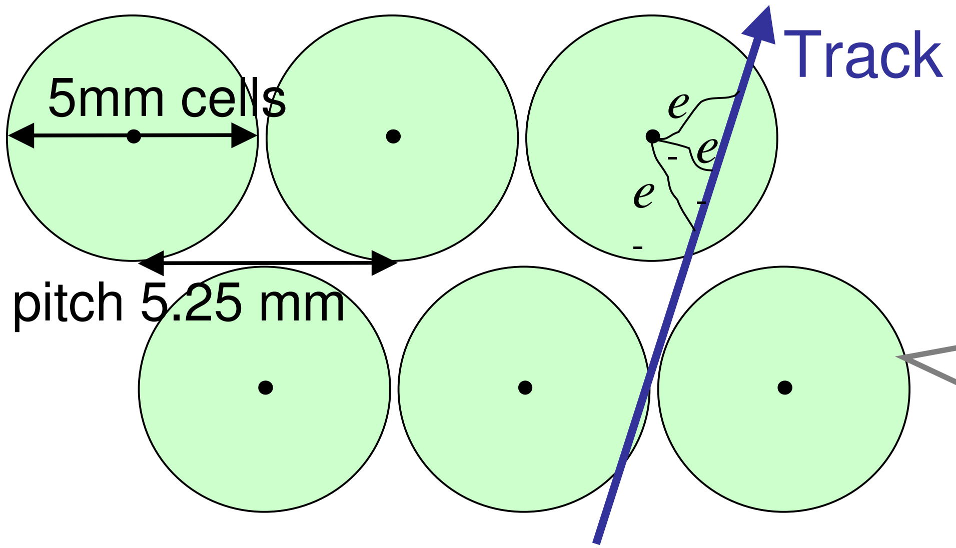
264 modules of 5 m x 0.34 m

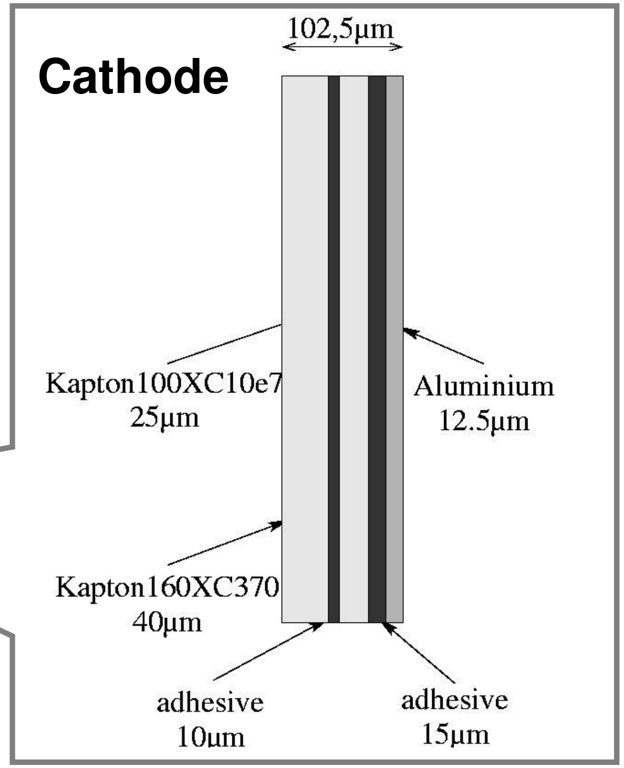
256 straws of 2.5 m

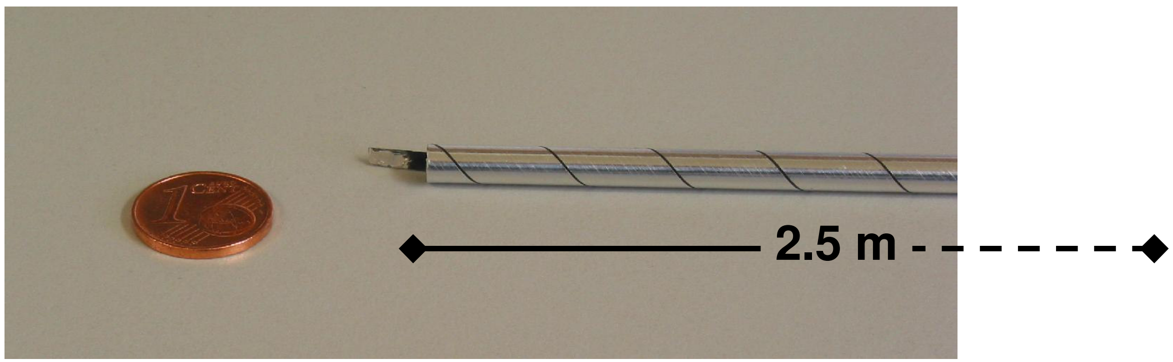


# Straw Tubes

## Straw tube drift chamber modules



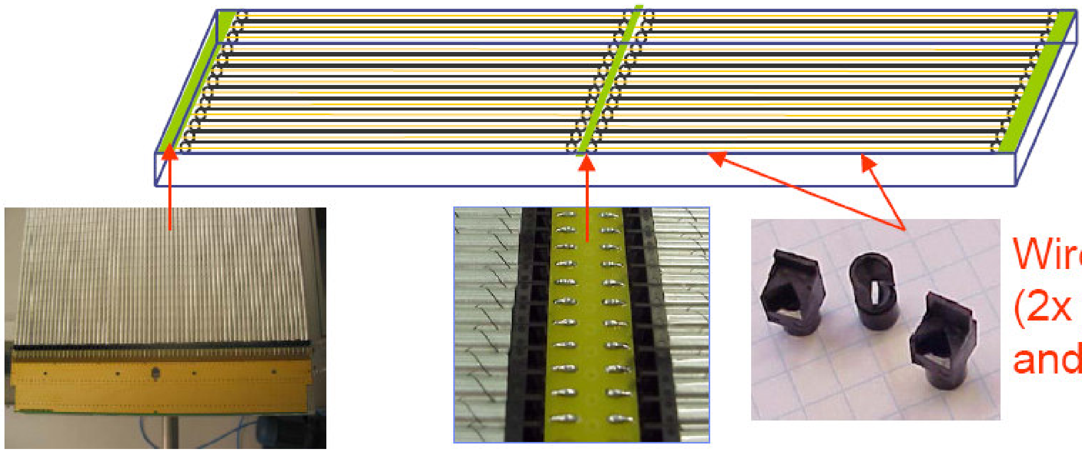




Straw tube winding:

Lamina Dielectrics Ltd.

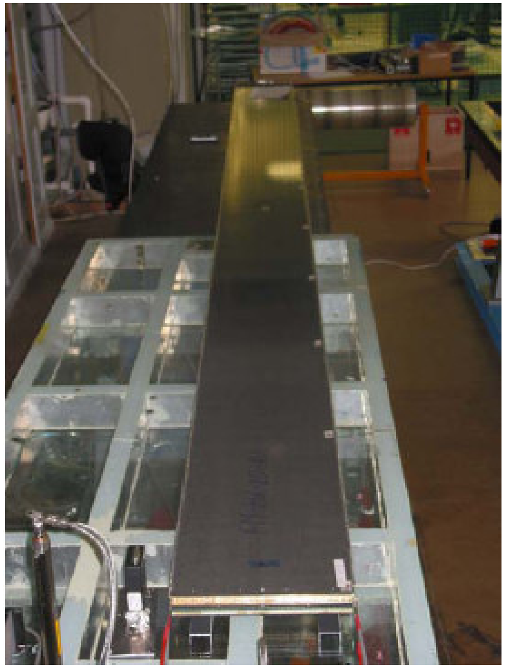
# Module Construction



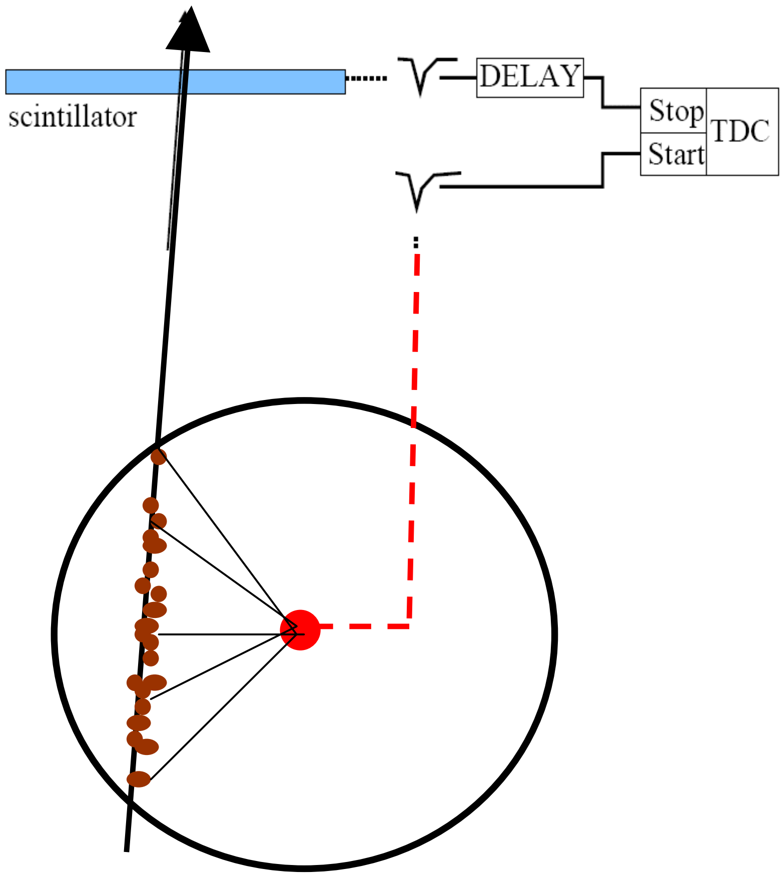
Wire locator
(2x per straw)
and endpieces

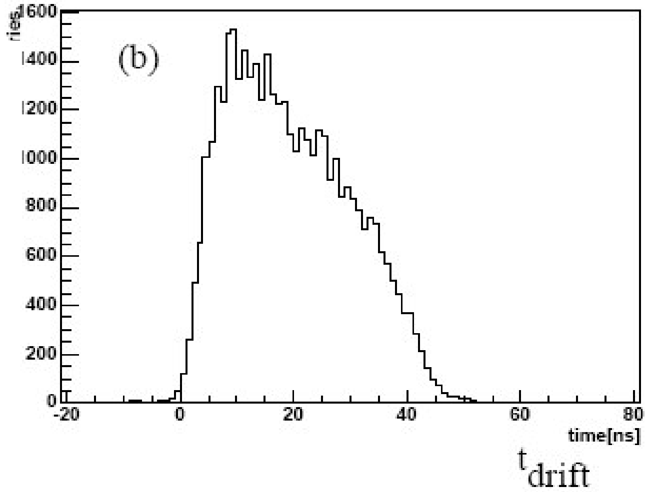
2 ×

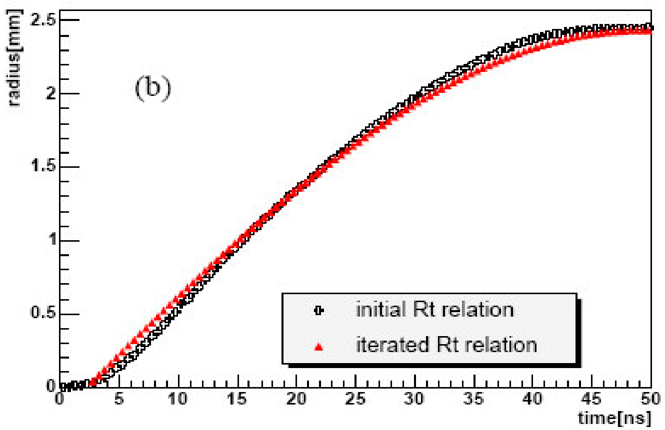
=



# Drift time spectrum



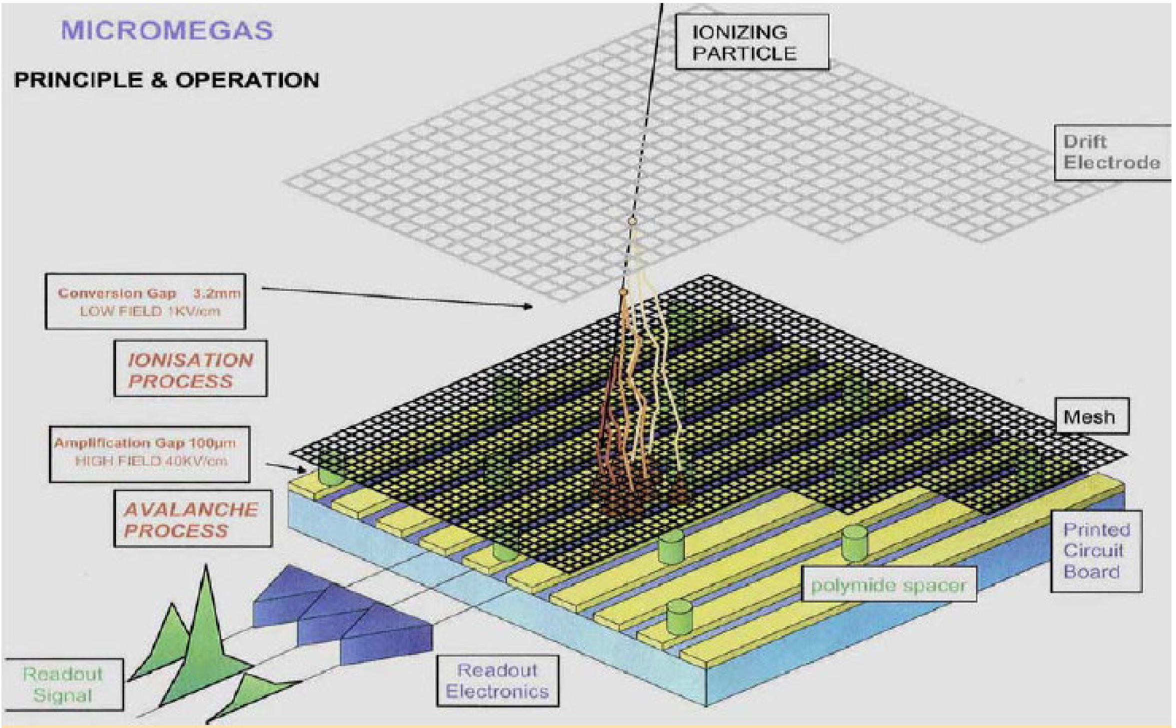
# Wire Chambers -Summary

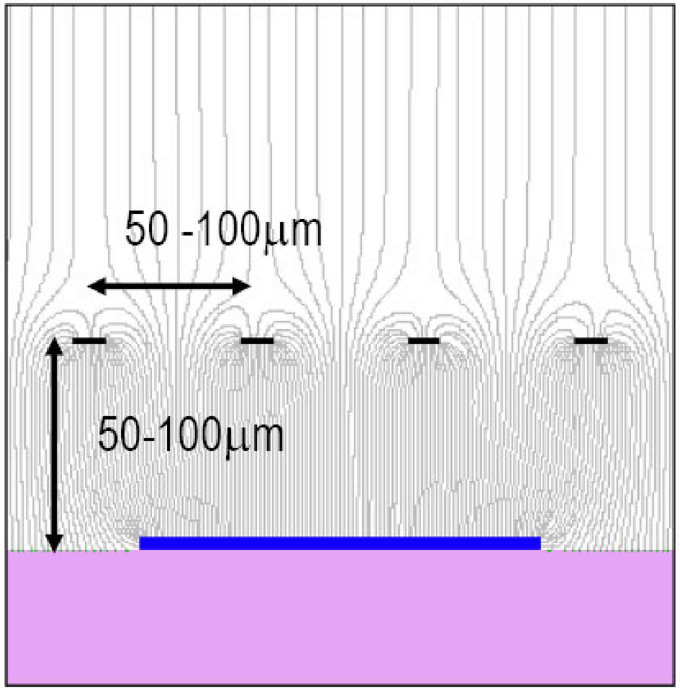
- Technology widely used in HEP experiments
- Proven to be robust, precise and reliable devices
- Detector geometry and counting gas can be tuned and optimized to fulfill requirements of the given application
- Play an important role in all LHC detectors
- Will continue to used in future particle detector:
  ILC detector PANDA, CBM

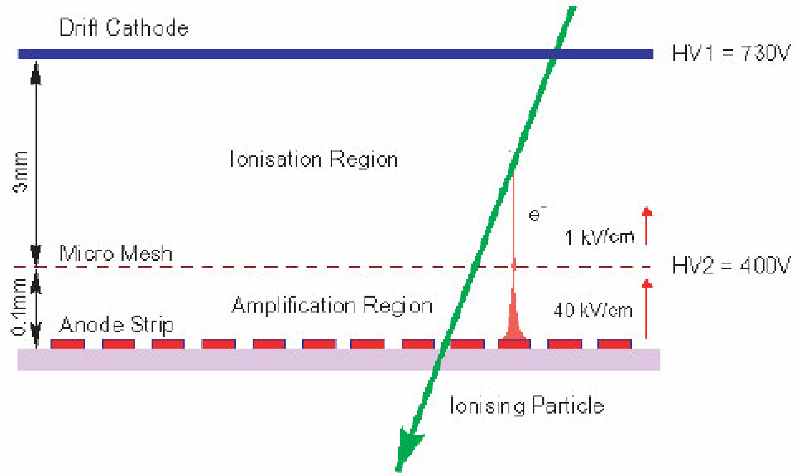
# Micro pattern detectors

- Micromegas
- GEM detectors

# Micromegas

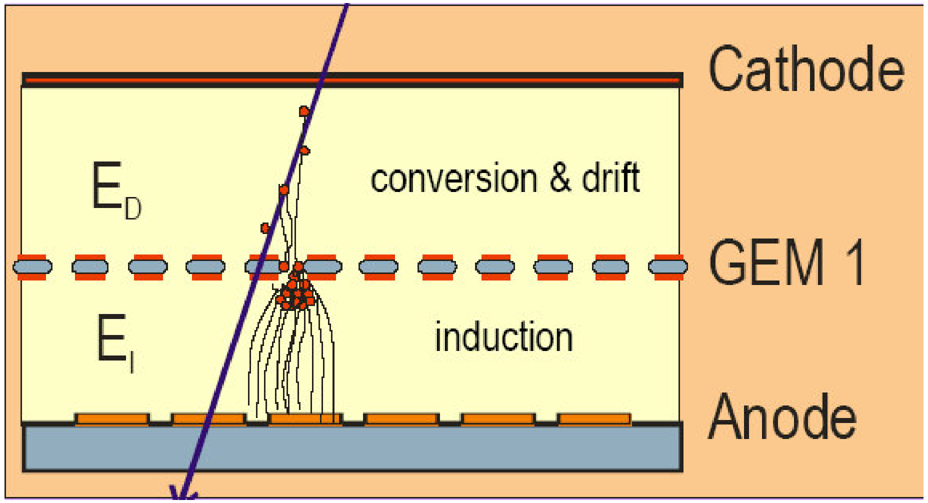


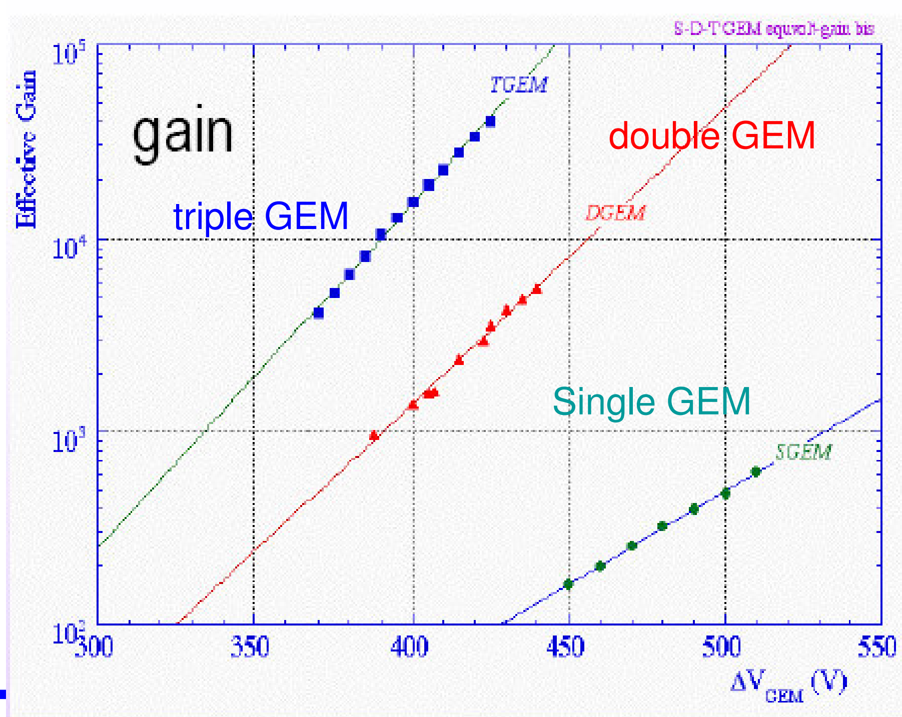



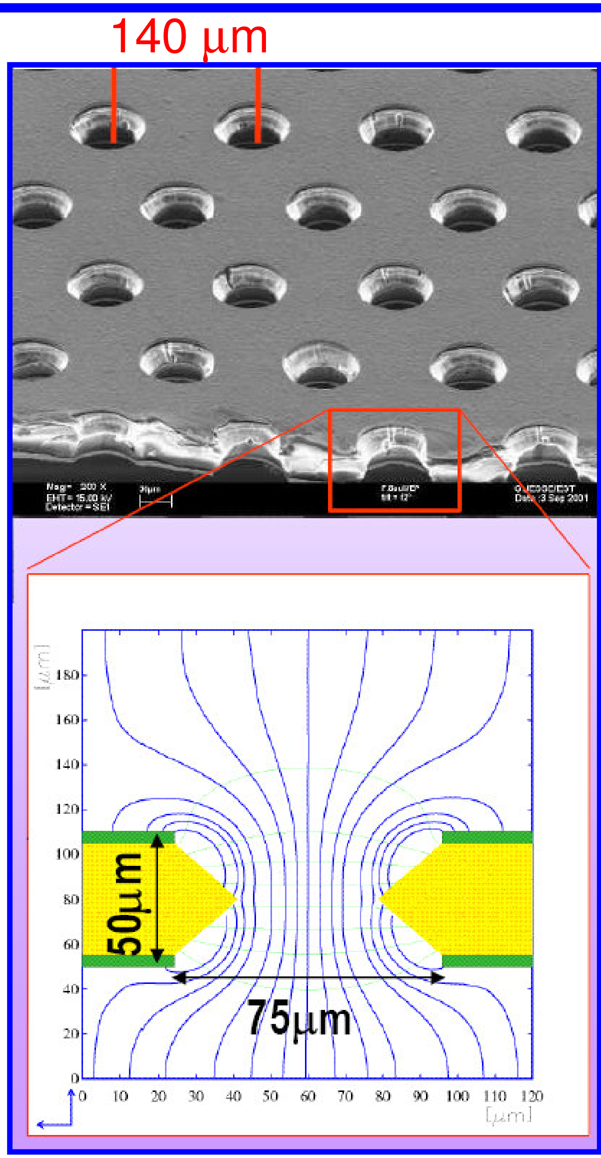




Large efficiency plateau > 40 V
Time resolution : 9 ns
Spatial resolution < 70 μm

# Gas Electron Multiplier (GEM)

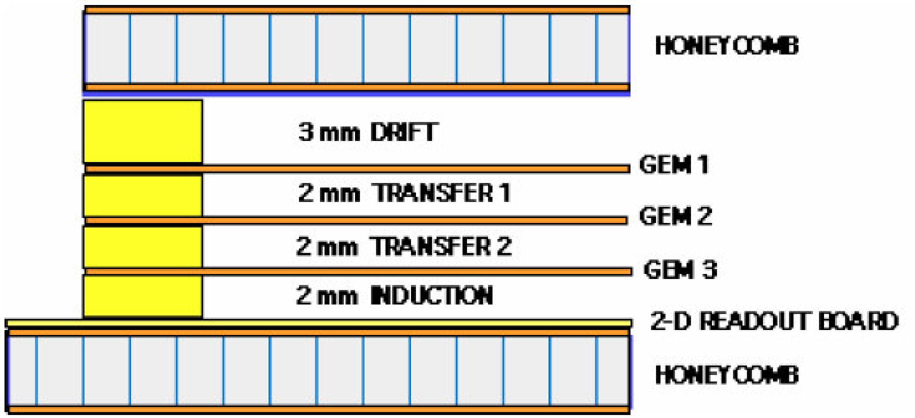


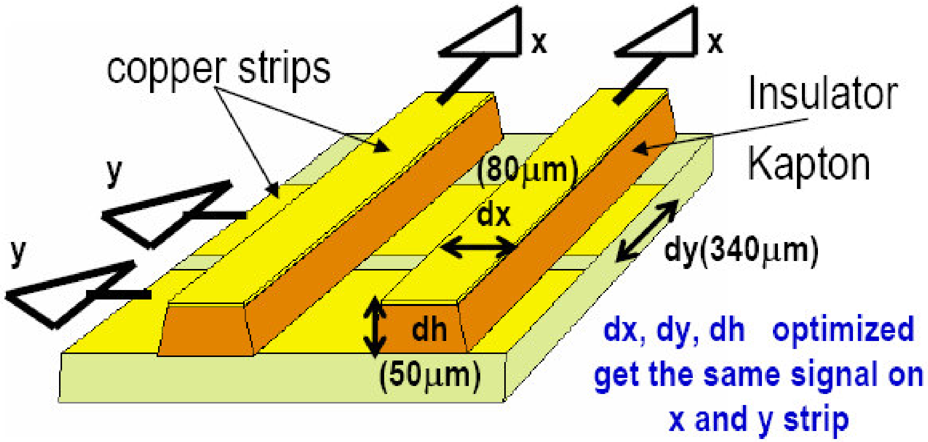



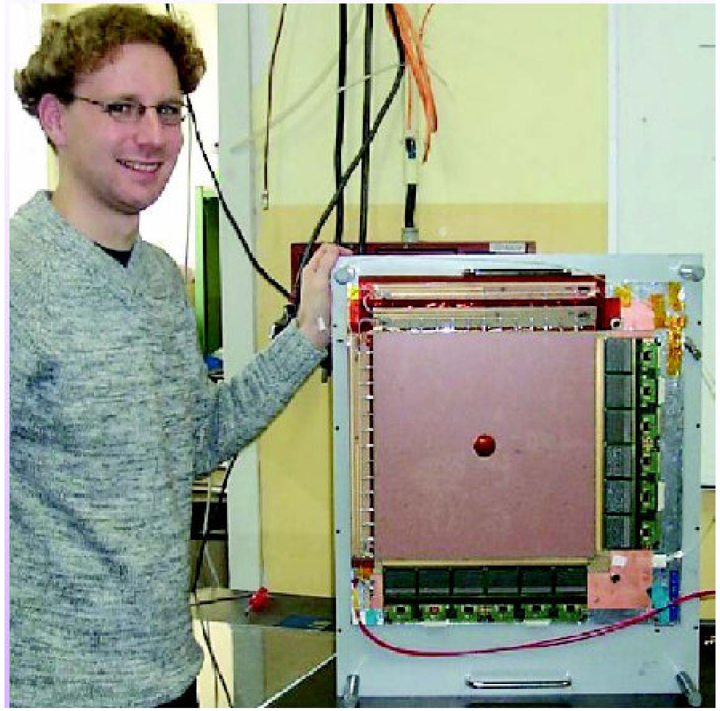



# Compass Triple-GEM

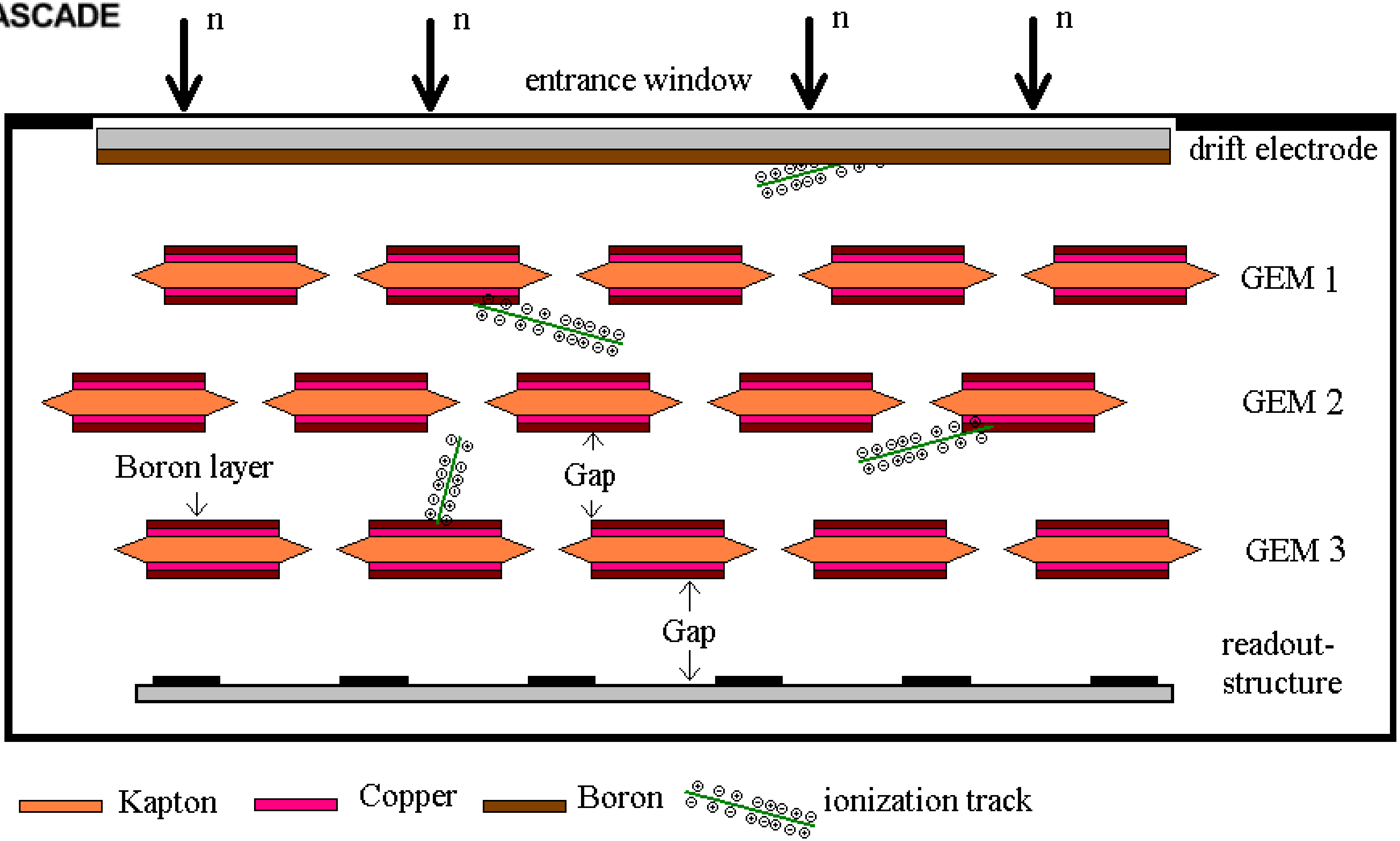
- 3GEM foils, active area: 30.7 x 30.7 $cm^2$
- 2D readout, 400 μm pitch
- Radiation length 0.7% $X_0$



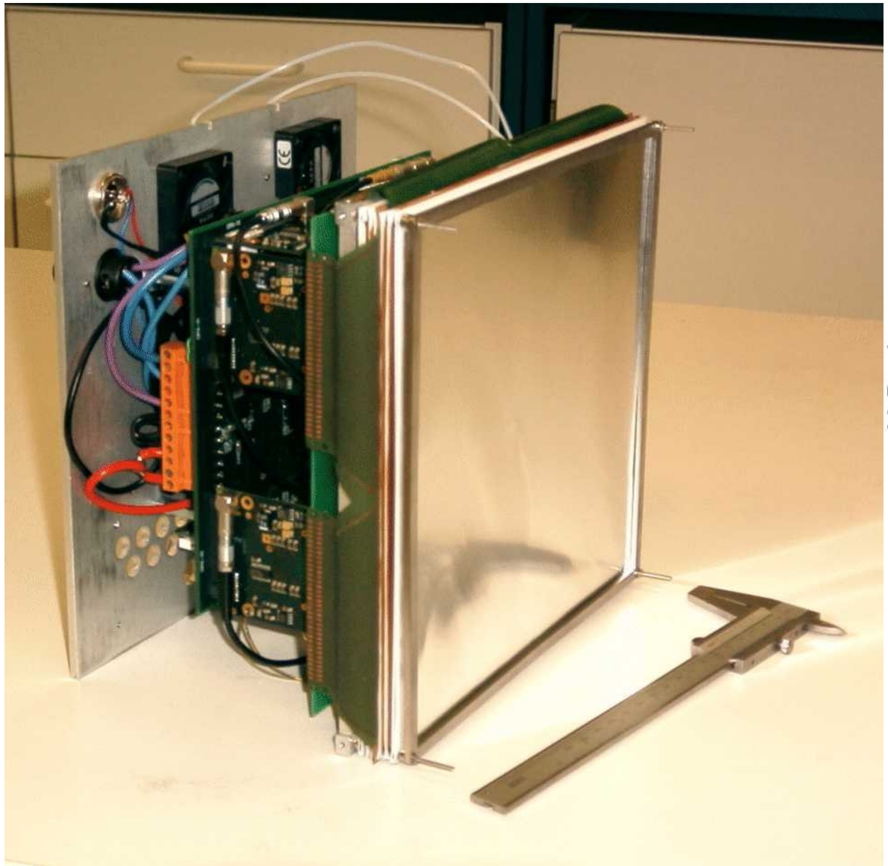



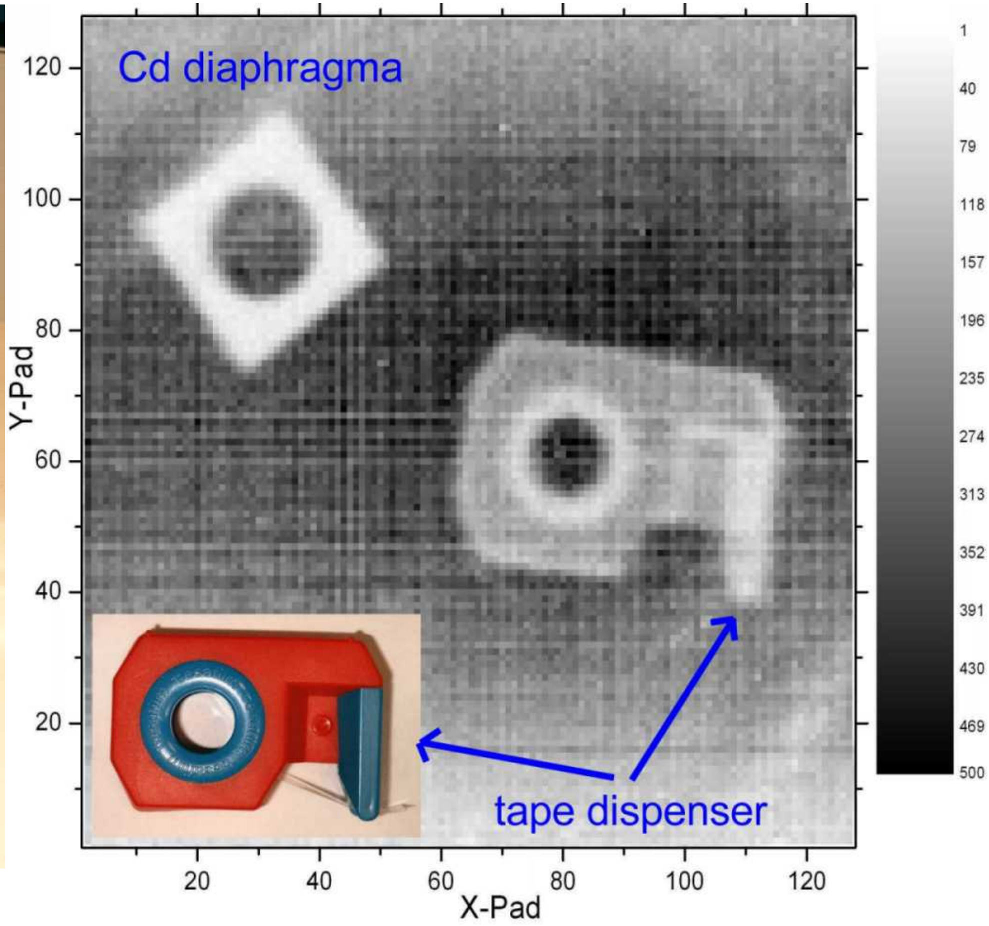



# Novel Neutron Detector



# CASCADE Neutron Detector





# Detector development tools