The "ZOO" of Gaseous Devices

Michele Bianco, CERN EP-CMX-SCI

EURIZON Detector School, Wuppertal, 17th-28th July 2023

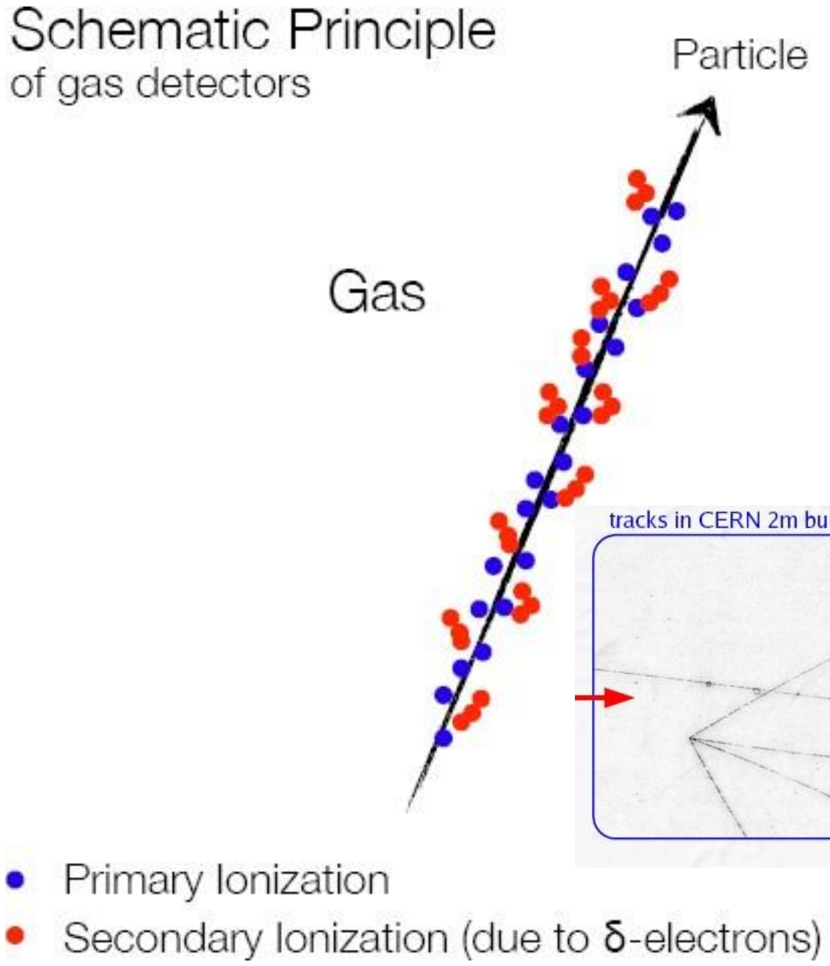
Gaseous Detector lecture #3

- Ionization and proportional gaseous detectors
- Multiwire Proportional Chamber (reminder)
    - (Recap from lecture 1)

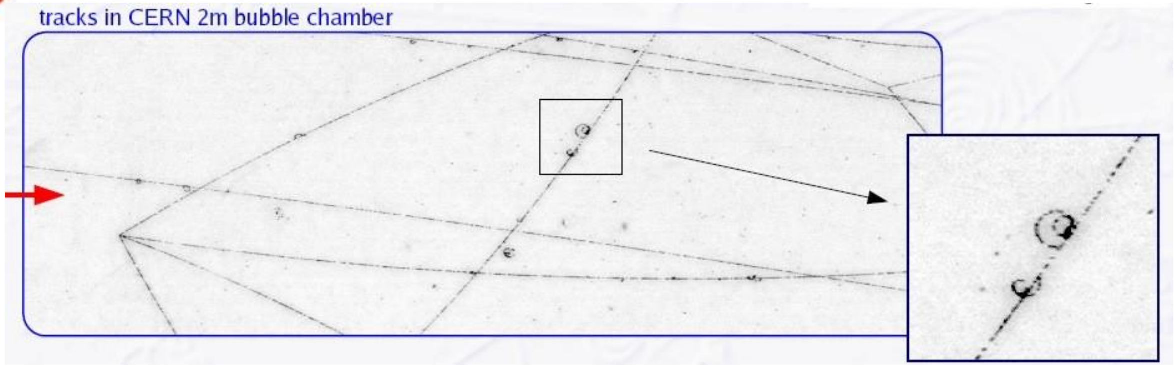
- Cathode Readout
    - CMS Cathodic Strip Chamber (CSC) and ATLAS Thin Gap Chambers (TGC)
- Very precision tracking with gaseous detectors
    - Straw tube; Cluster counting technique
- Limitations of Wire-based Detectors
    - Rate limitation vs gas mixtures, Aging/discharge

- MSGC: operation, long term operation and discharge

Ionization



δ-electron



Ionization

Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

Primary ionization

$$X + p \rightarrow X^{+} + p + e^{-}$$

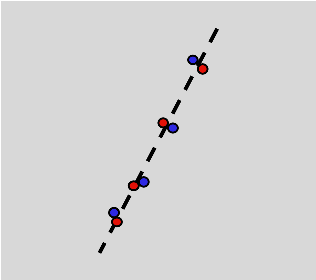
p = charge particle traversing the gas X = gas atom
e$^-$ = delta-electron (δ)

Secondary ionization

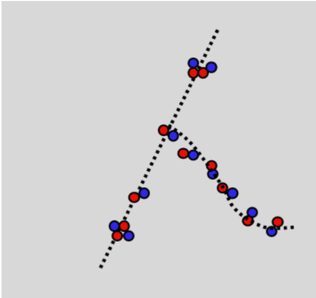
if E_δ is high enough ($E_\delta > E_i$)

$$X + e^{-} \rightarrow X^{+} + e^{-} + e^{-}$$

PRIMARY IONIZATION:



TOTAL IONIZATION:



Relevant Parameters
for gas detectors

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

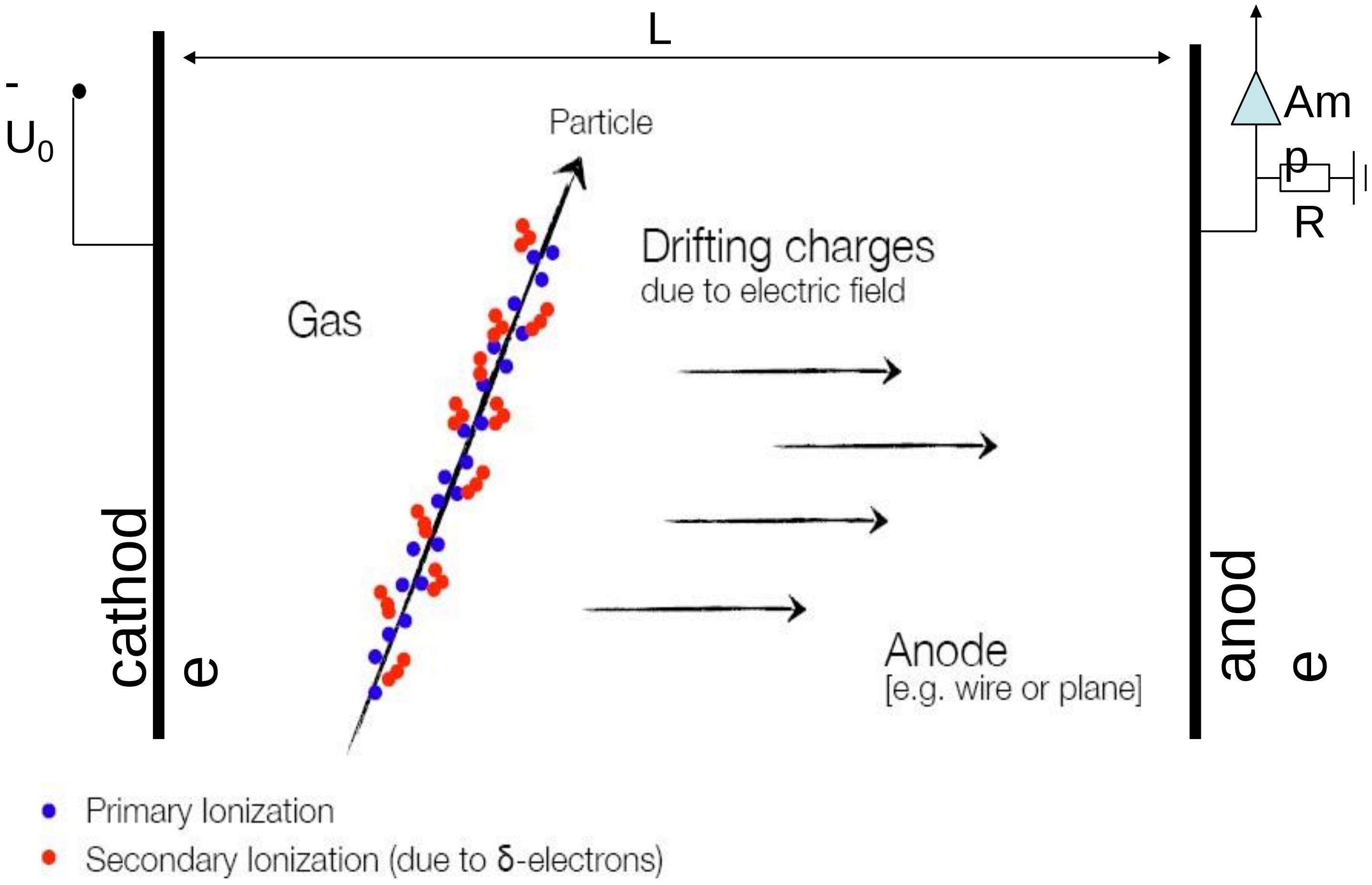
Differences due to δ-electrons

$$\langle n_T \rangle = \frac{L \cdot \langle \frac{dE}{dx} \rangle_i}{W_i}$$

[about 2-6 times n_p]
[L: layer thickness]

Typical values: E_i ~ 20 eV, Wi ~ 25 eV
n_T ~ 100 pairs/cm / 3 keV incident particle

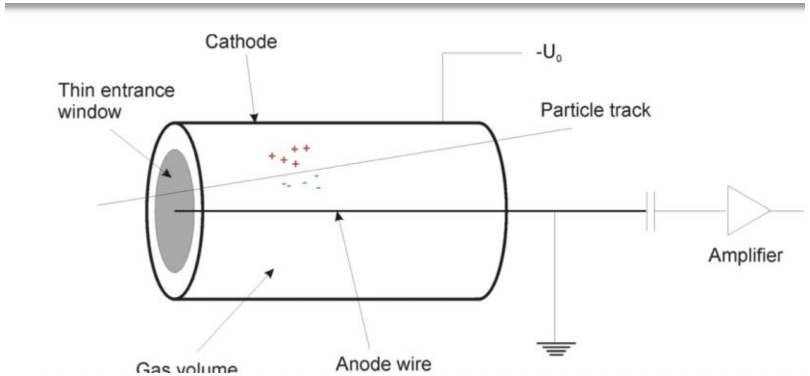
HIGH FIELD-INELASTIC COLLISIONS

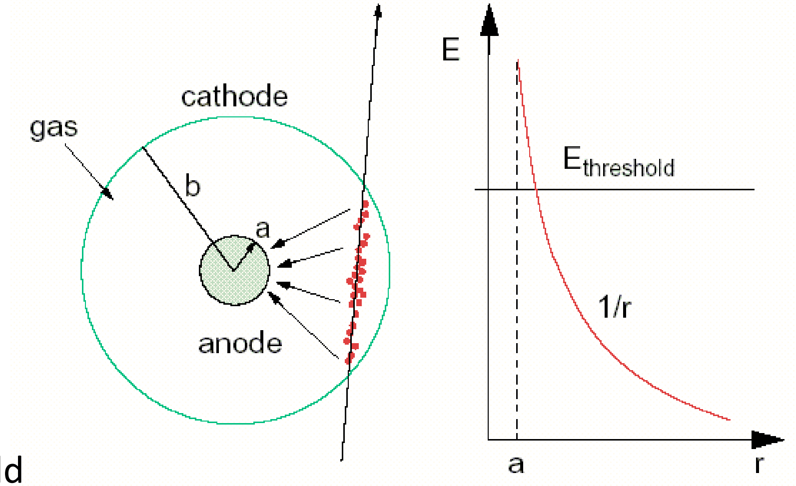


1)	A+e	⇒	A^++e+e	Ionisation by electronic impact.
2)	A+e	⇒	A^*+e	Excitation by electronic impact.
3)	A^*+e	⇒	A+e	Deexcitation by electronic collision.
4)	A+hν	⇒	A^*	Photo-excitation (absorption of light).
5)	A^*	⇒	A+hν	Photo-emission (radiative deexcitation).
6)	A+hν	⇒	A^++e	Photoionisation.
7)	A^++e	⇒	A+hν	Radiative recombination.
8)	A^++B+e	⇒	A+B	Three body recombination.
9)	A^*+B	⇒	A+B^*	Collisional deexcitation.
10)	A^*+B	⇒	A+B^++e	Penning effect.
11)	A^++B	⇒	A+B^+	Charge exchange.
12)	A^++B	⇒	A^++B^++e	Ionisation by ionic impact.
13)	A+B	⇒	A^*+B	Excitation by atomic impact.
14)	A+B	⇒	A^++B+e	Ionisation by atomic impact.
15)	A+e	⇒	A^-	Formation of negative ions.
16)	A^-	⇒	A+e	Electrons release by negative ions.
17)	A^{**}+A	⇒	A_2^++e	Associative ionisation.
18)	A^++2A	⇒	A_2^++A	Molecular ion formation.
19)	A^*+A+A	⇒	A_2^*+A	Excimer formation.
20)	A_2^*	⇒	A+A+hν	Radiative excimer dissociation.
21)	$(XY)^*$	⇒	X+Y^*	Dissociation.
22)	$(XY)^+$+e	⇒	X+Y^*	Recombinational dissociation

J.Meek and J. D. Cragg, Electrical Breakdown of Gases (Clarendon Press, Oxford 1953)

Drift Tube





Electric field

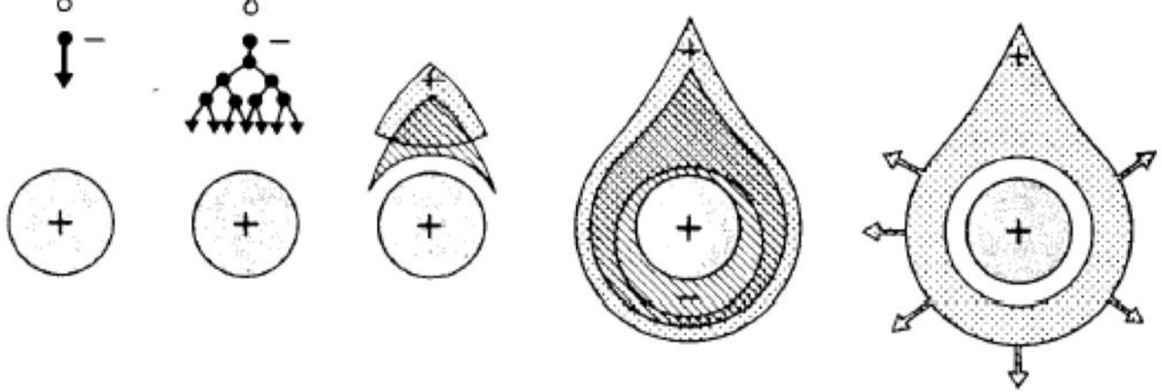
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r} \quad and \quad V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

Charge gain:

$$G = \frac{N}{N_0} \approx e^{\mathrm{const}\cdot U}$$

Typical values:

- Proportional wire counter: $G \sim 10^4 - 10^6$



(F. Sauli, CERN 77-09)

Avalanche multiplication starts at r~5a

⇨ negligible position dependence of pulse height

Multiwire proportional chambers

MWPC [G. Charpak et al., NIM 62, 262 (1968)]

NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 262–268; © NORTH-HOLLAND PUBLISHING CO.

Up to now (today and past lectures on Gas Detectors):

- we have defined the ionization and avalanche multiplication process
- we presented a single wire proportional counter
- with it we can measure the pulse signal from ionization

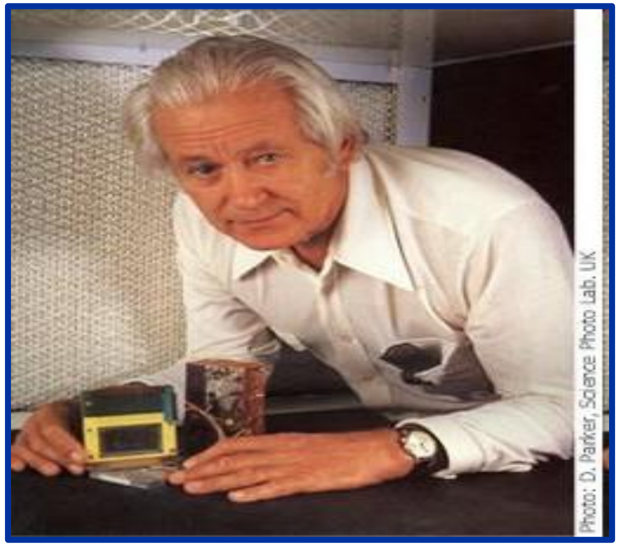
THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

G. CHARPAK, R. BOUCLIER, T. BRESSANI, J. FAVIER and Č. ZUPANČIČ

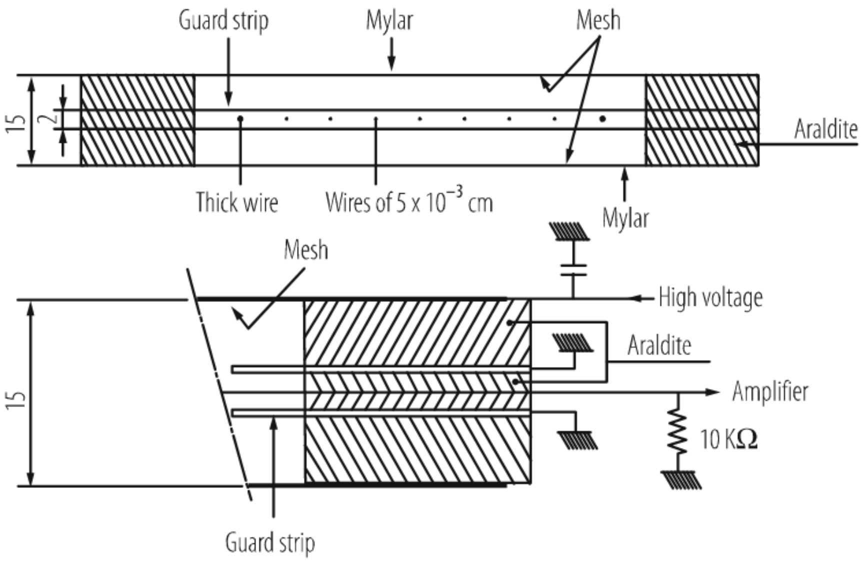
CERN, Geneva, Switzerland

Received 27 February 1968

G. Charpak Nobel price (1992)

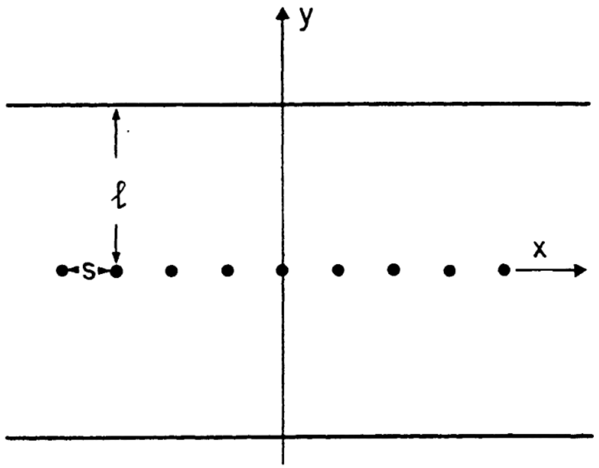


Multi-wire proportional chamber



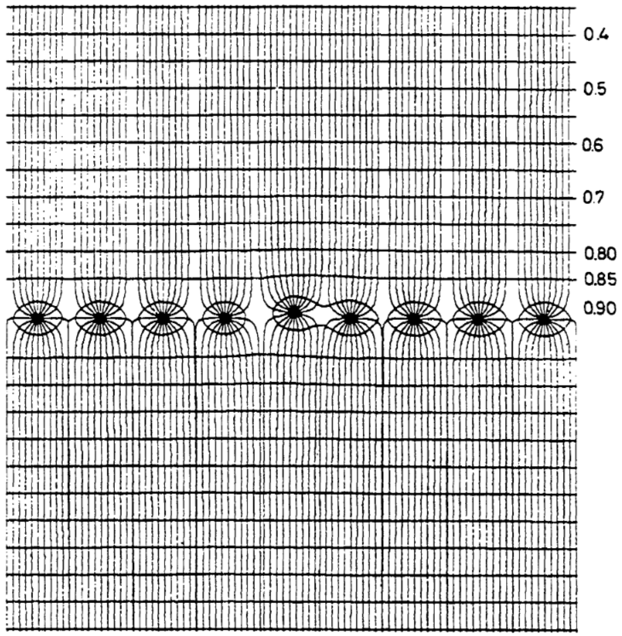
Multiwire proportional chambers

A MWPC consists of a set of thin, parallel and equally spaced anode wires, symmetrically sandwiched between two cathode planes.



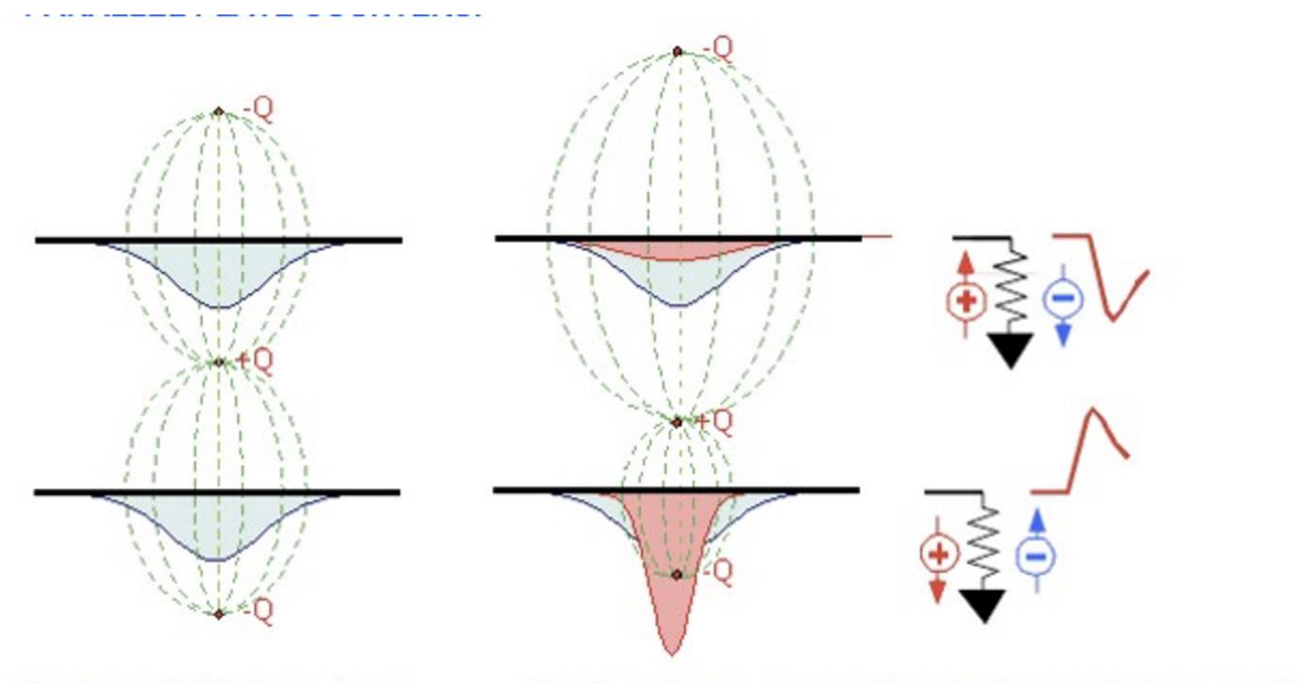
For proper operation, the gap “l” is normally three/four times larger than the wire spacing “s”
Typical parameters are an anode spacing s, of 1 mm, anode to cathode distance of 3-5 mm, and diameter of anode wires ~ 20 μm.
With a digital read-out the spatial resolution is limited to:

$$\sigma_x \approx \frac{s}{\sqrt{12}} \, (s = 1mm, \sigma_x = 300\,\mu m)$$



Electrical field within a MWPC, around the wire and defect due to the misplacement of wires

Cathodic Readout: Basic Principle



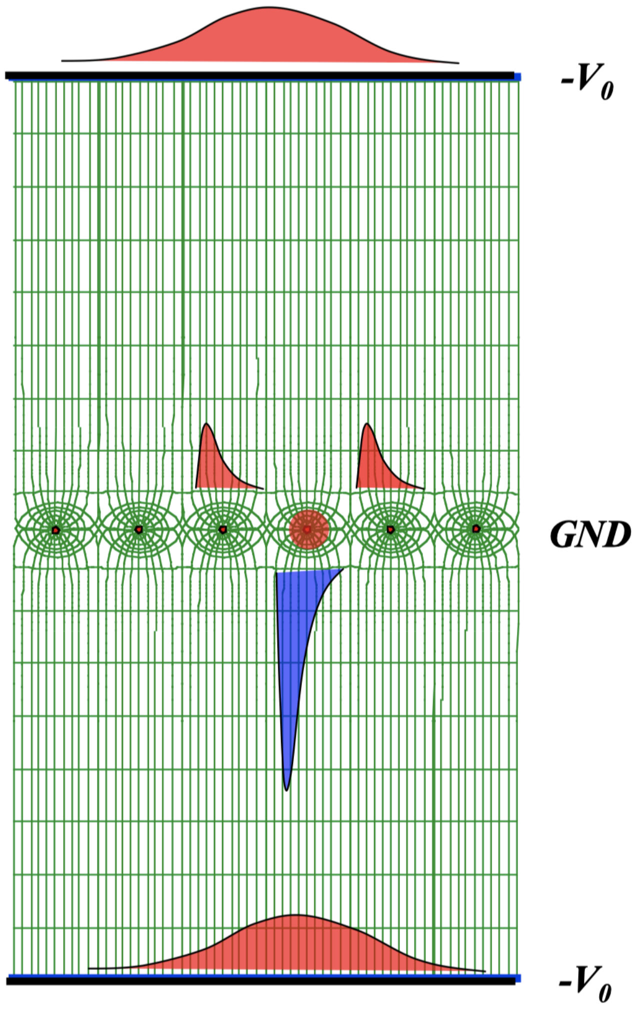
A charge +Q between two conductors induced two negative charge profiles (image charge)

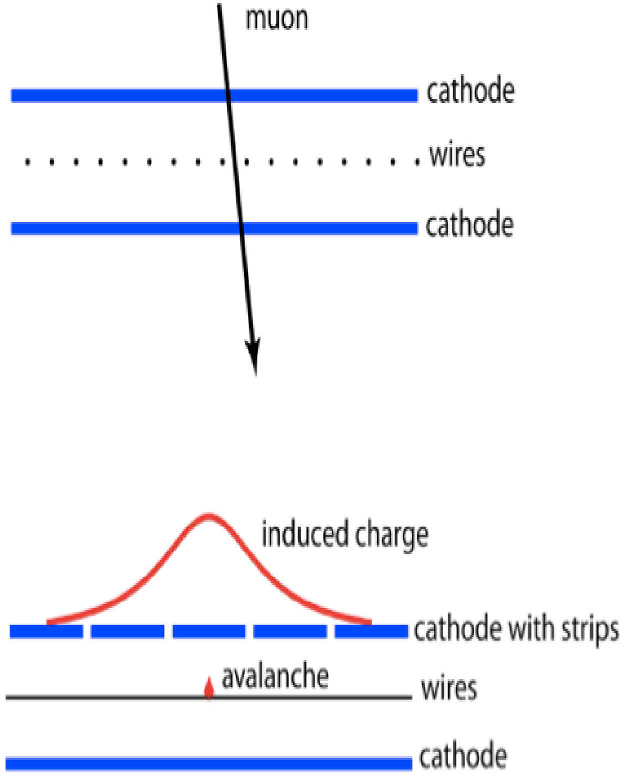
A charge moving between the electrodes modify the induced charge profile on the conductors generating a detectable signals

Cathode Strip Chambers

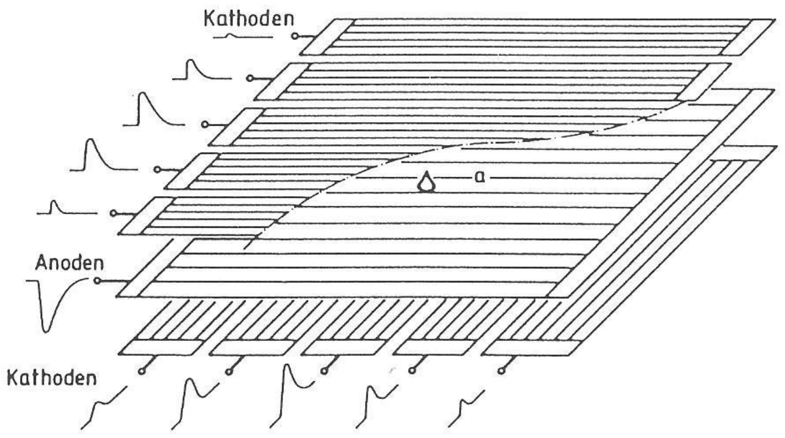
- In 1968 Charpak with co-‐authors investigated a possibility of detection coordinates by detecting the positive signals from segmented cathodes (strips).
- It was found that the center of gravity of charge distribution gives very high space resolution along the wire(~50 µm).
- The space resolution mostly depends on a wire-‐cathode distance and the strip width.

  The method needs measurements of strip signals with precision of ~1%. That was the main reason of sometime delay in developing CSC technique.





Cathode Strip Chambers



Segmented cathodes:

- cathode strips (often perpendicular and parallel to anode wires)
- cathode wires
- Pads/Strips

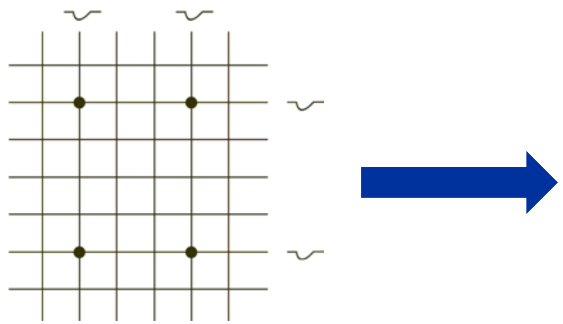
Avalanche induces signals on cathode strips/pads with amplitude varying with the distance to the avalanche

$\sigma \sim 50 - 100\ \mu m$

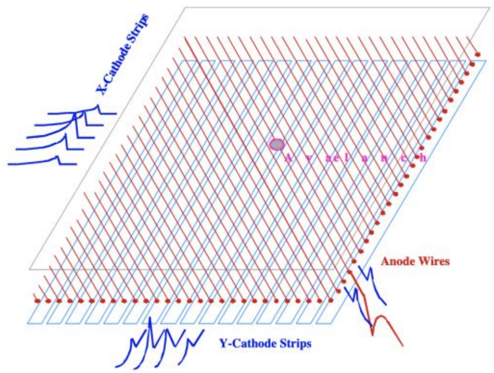
with clusterization

Analog readout (ADC), allow for center-of-gravity method

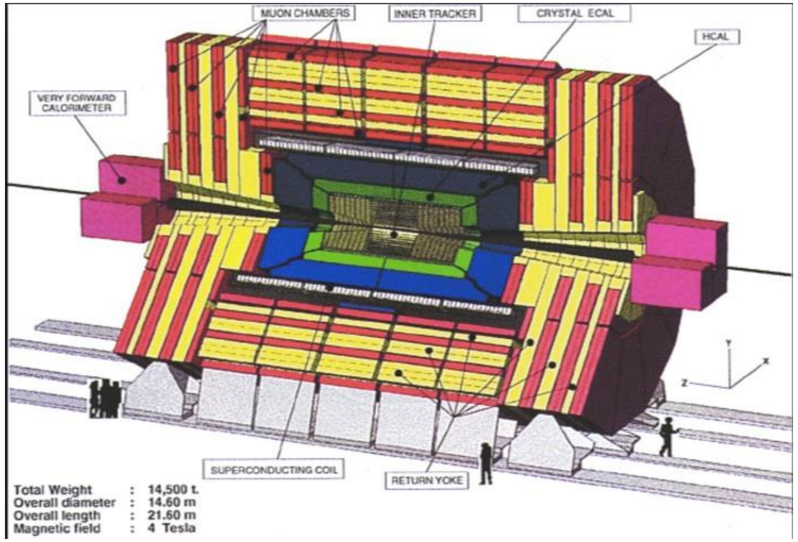
Problem at higher particle rates: ambiguities (if >1 particle at the same time)

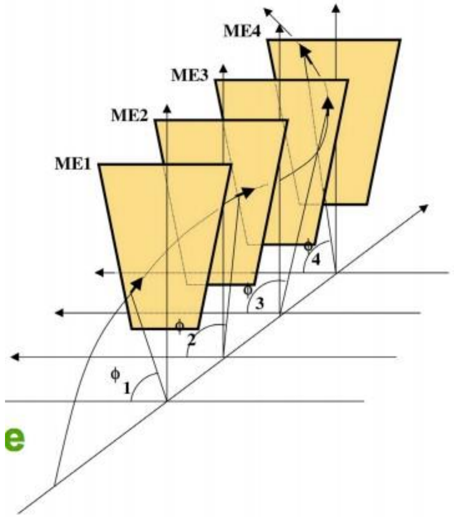


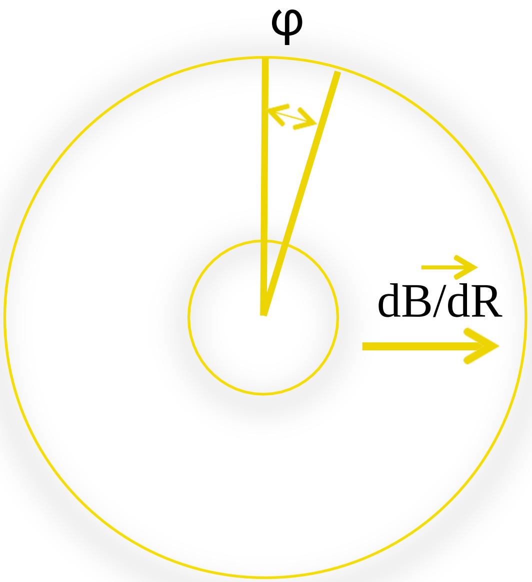
multiple projections, pads, pixels



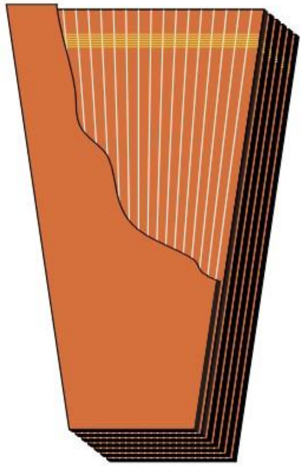
CMS Cathode Strip Chambers

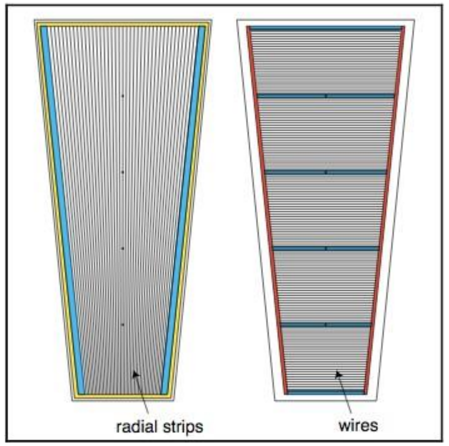






- Main goal of endcap muon detectors is to define the bending angle of muon in the magnetic field of steel disks.
- It means that a detector need a good space resolution in direction perpendicular to the radius of a disk (strip segmentation). Second coordinate is not very critical.
- 3 CSC rings in the station 1, and 2 rings in the stations 2-4.
- Trapezoid in shape with 6 sensitive gas gaps each.
- Strips radially and wires stretched across strips and joint in wire groups.

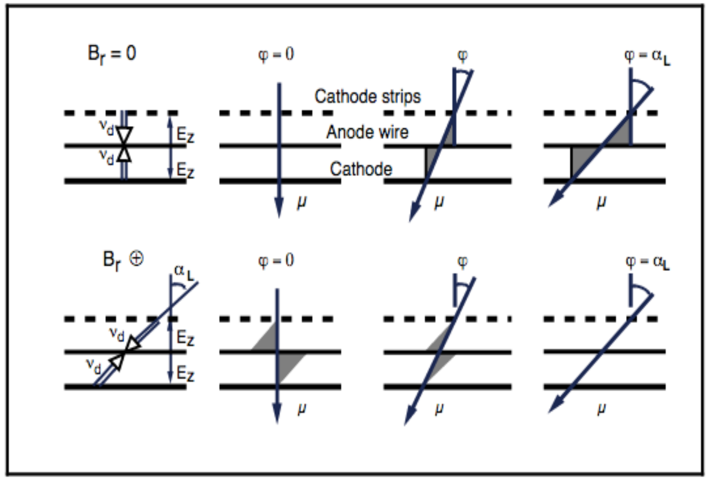




CMS CSC in Magnetic field

- Primary electrons arrive on a wire not in a single spot but distributed along the wire

- The charge distribution on the strips gets wider reducing the space resolution.

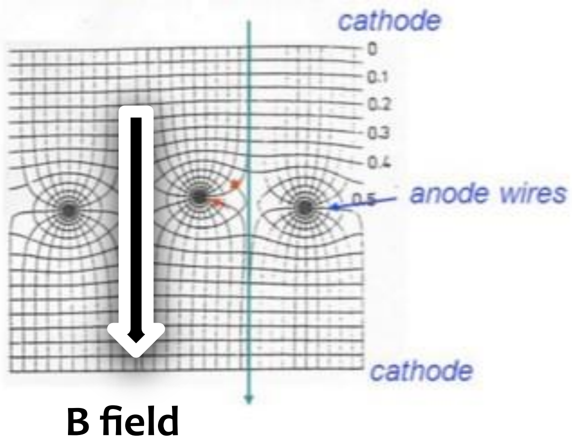


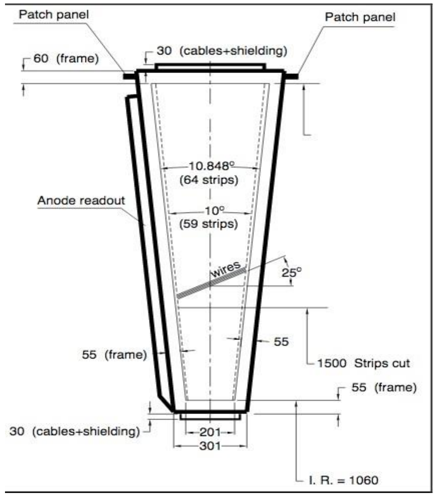
CSC in CMS axial magnetic field:

- Once primary electrons drift along magnetic field lines nothing bad happens

- But near the wire plane they start moving almost perpendicular to the B field

- Then the Lorenz force makes them drift to a different place (Δx) along a wire.

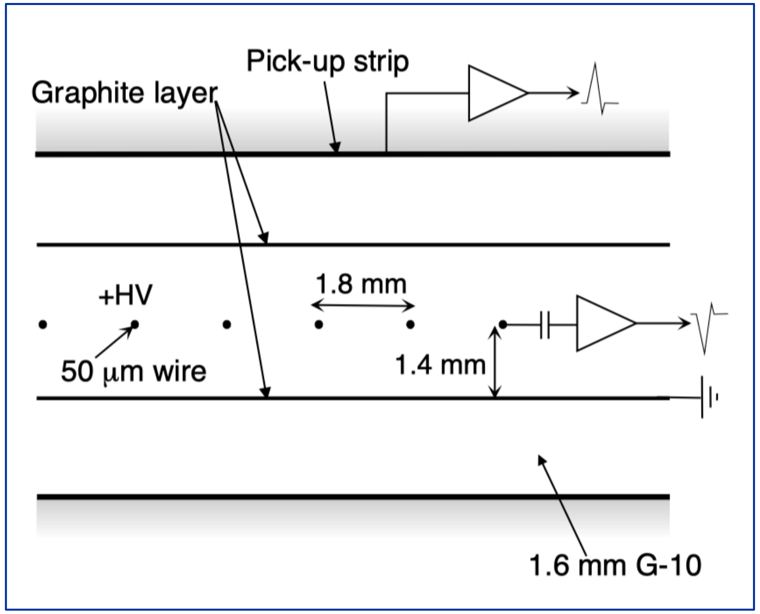




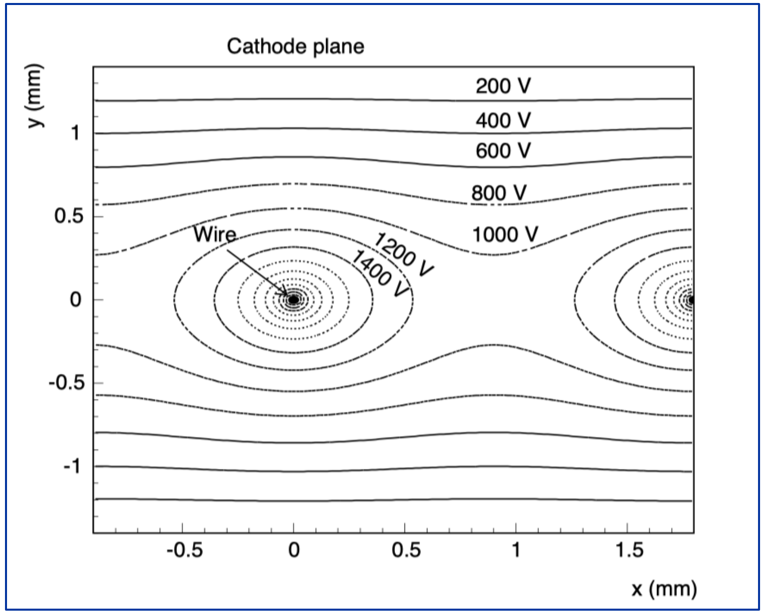
ME11 have wires tilted at 29º.

ATLAS TGC / sTGC

The ATLAS Thin Gap Chambers (**TGC**) operating in a saturated mode have a structure similar to Multi-Wire Proportional Chambers (MWPCs), except that the anode-to-anode, i.e. wire-to-wire, distance is larger than the cathode-to-anode distance



TGC structure showing anode wires, graphite cathodes, G-10 layers, and a read-out strip orthogonal to the wires

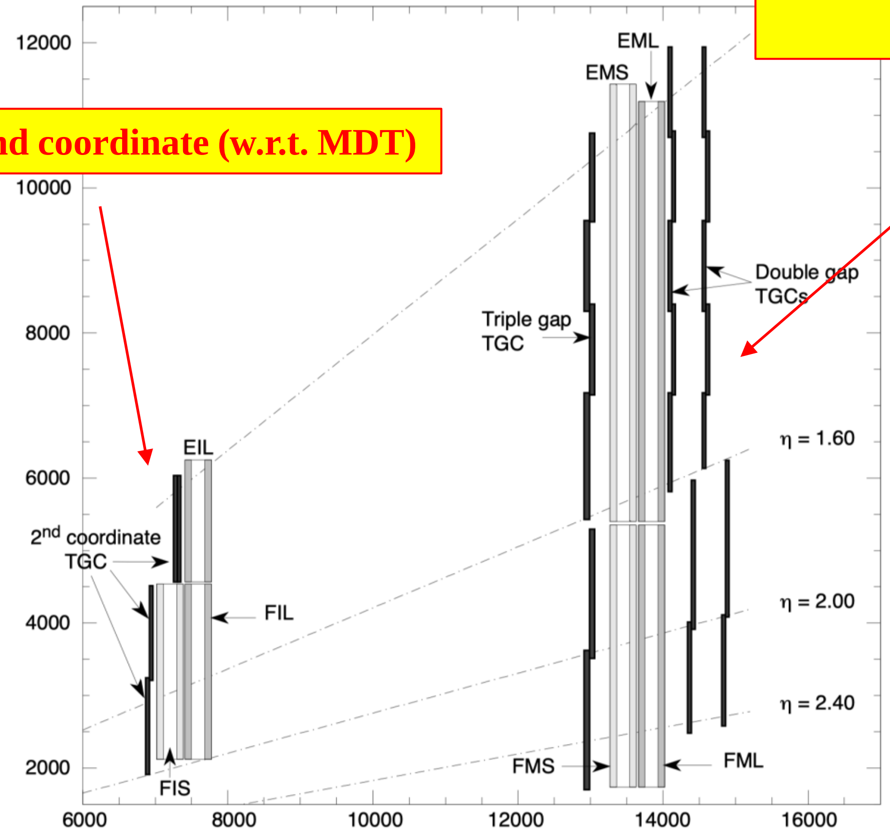


Equipotential lines in the ATLAS thin gap chamber. The applied voltage is 3200 V, wire spacing is 1.8 mm, and wire-to-cathode gap is 1.4 mm.

ATLAS TGC / sTGC

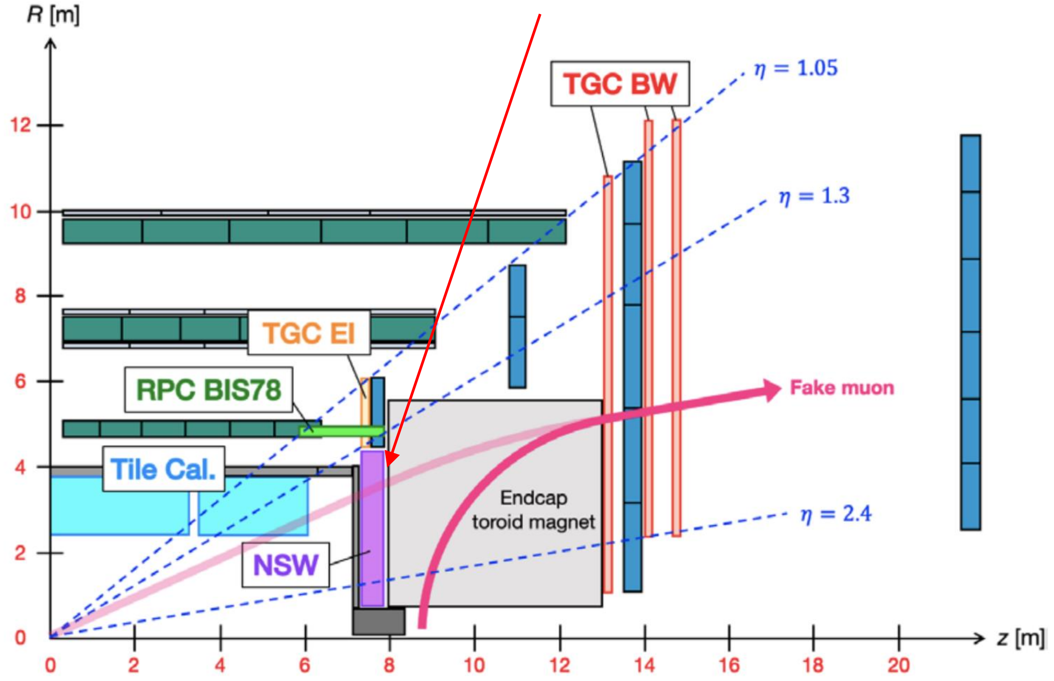
Second coordinate (w.r.t. MDT) and Trigger

Second coordinate (w.r.t. MDT)



Longitudinal view of the TGC system. The TGCs in the FI station at 7000 mm from the interaction point are used for the second coordinate measurement only. The trigger function is provided by the triplet at 13 000 mm and the two doublets at 14 000–14 500 mm and 14 500–15 000 mm, respectively.

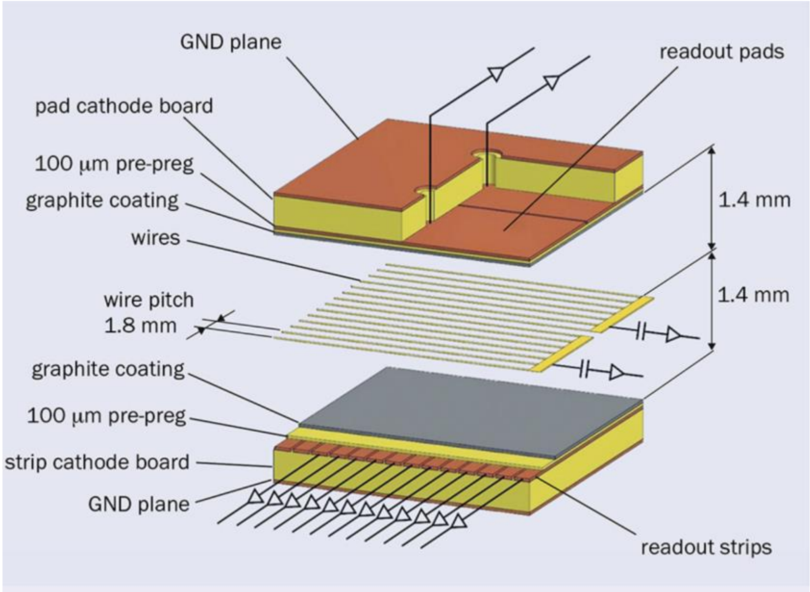
sTGC in the ATLAS Muon Trigger



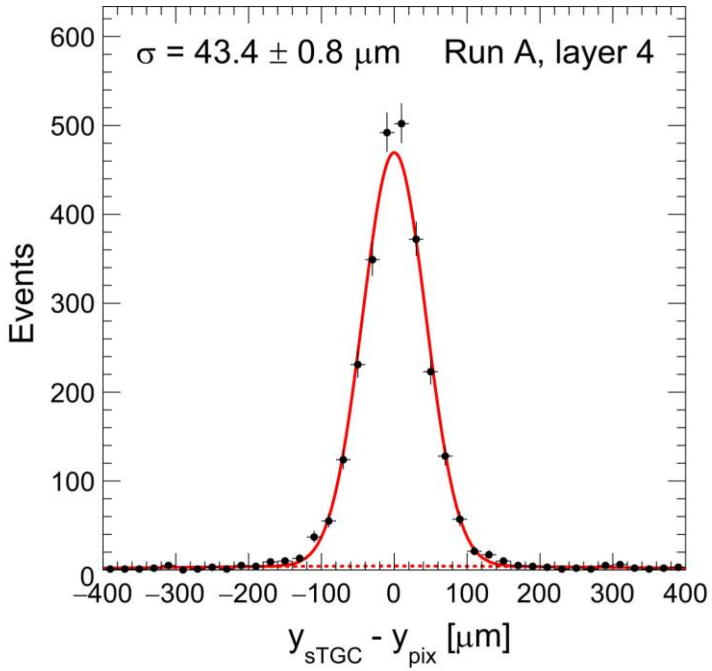
ATLAS NSW and sTGC system in the Muon selection logic, sTGC together with Micromegas chambers enhance the capability to select prompt muons.

ATLAS TGC / sTGC

- The basic **sTGC:** grid of 50 μm gold-plated tungsten wires with a 1.8 mm pitch, sandwiched between two cathode planes at a distance of 1.4 mm from the wire plane.
- The cathode planes are made of a graphite-epoxy mixture with surface resistivity of 100 kΩ/❑ sprayed on a 100 μm thick G-10 plane.
- The strips have a 3.2 mm pitch, much smaller than the strip pitch of the ATLAS TGC, hence the name 'Small TGC' for this technology.



Gap structure of the small-strip thin-gap chambers (sTGC) showing the wires, readout pads and strips



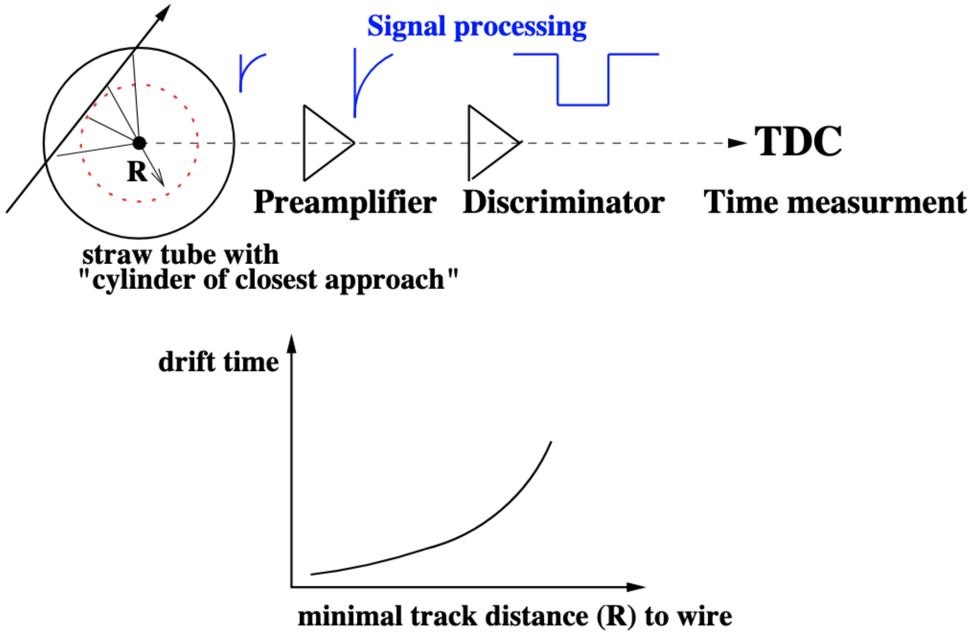
Residual distribution of sTGC vs Pixel Tracking system with the result for the intrinsic resolution parameter σ

Straw Tubes

Despite the revolution started with the multiwire proportional chambers (MWPC), single wire tubes are still widely used, mostly as drift tubes

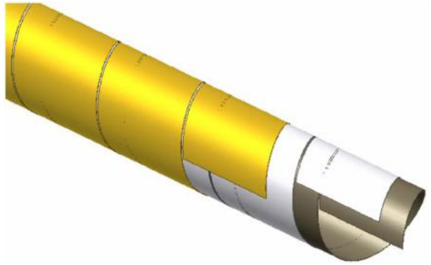
Straw tubes, has become very popular since several years. Straw tubes offer high-rate capability due to small diameters and relatively little material in the particle path

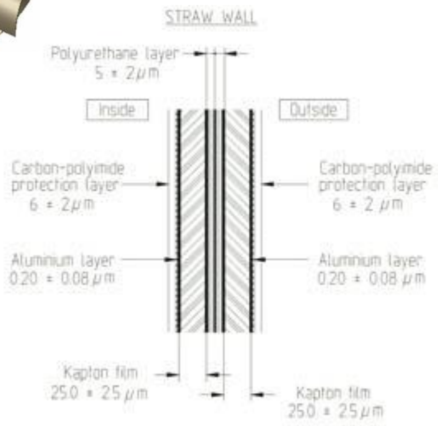
- Sort of proportional drift tube
  - Tracking detector
- Difference
  - Low material budget
  - Smaller in diameter (2-10 mm)
  - Large number of detector elements crossed by particle
  - Can be used also for particle identification (TRT)
    - (tuned to sustain high particle rate)
- How to recognize
  - Fancy detector which looks like a stock of hay
  - Distributor of straws for drinking your favorite potion



Straw Tubes

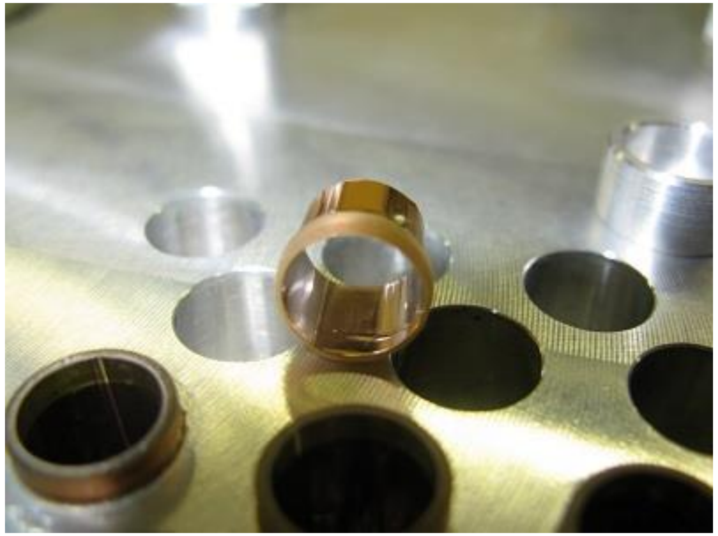
Gluing 2 overlapping strips (COMPASS)

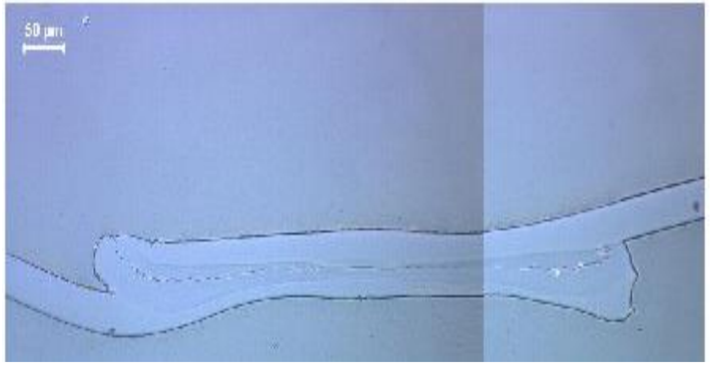




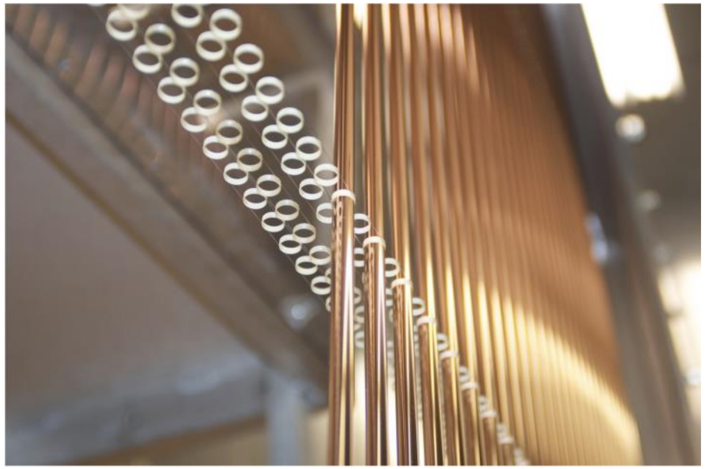
Glued and reinforced by carbon fibres (also improving cathode resistivity)

1 strip ultrasonically or thermally welded (NA62)

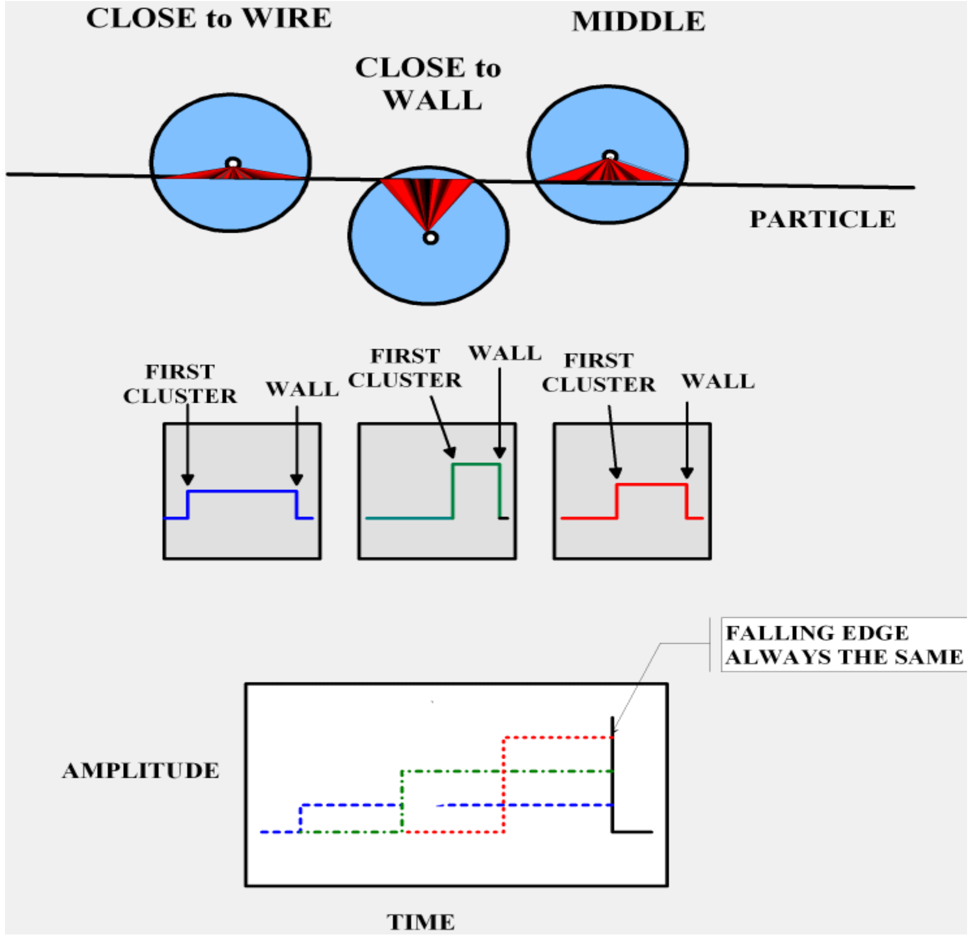




NA62 straws manufactured from 36 μm thin PET foils coated with two thin layers of Cu and Au.



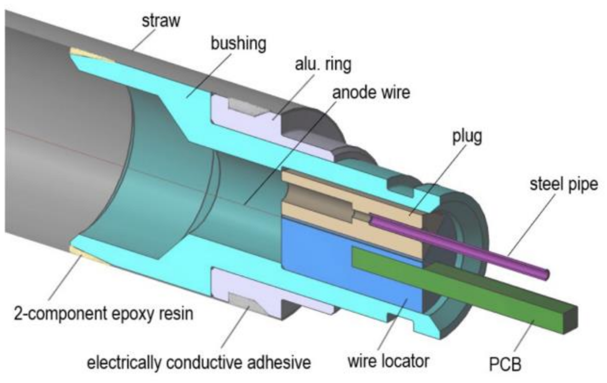
How does it work?



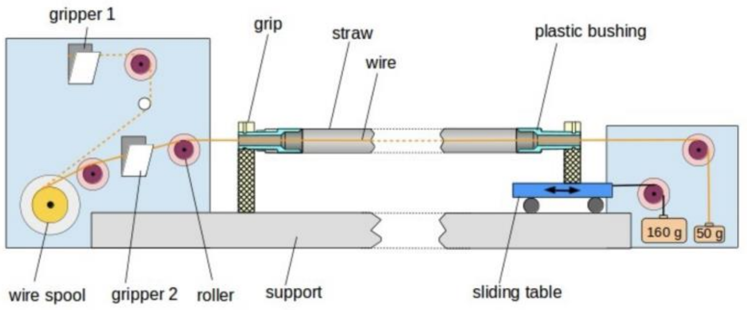
- Falling edge has the same time for all straws on track.
- Rising edge gives the arrival time of the first cluster
- The closer is the track to the wall, the bigger is the signal (clusters closer)
- Don’t want to see clusters => shaping must be chosen in relation to gas properties
- Tracks from drift time measurements

CERN EP-ESE Electronics Seminars **Peter Lichard** *Straw detectors and their electronics*

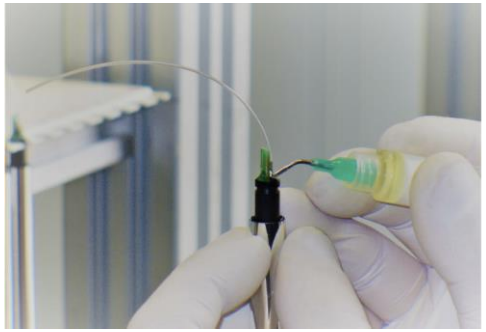
Straw Tubes PANDA



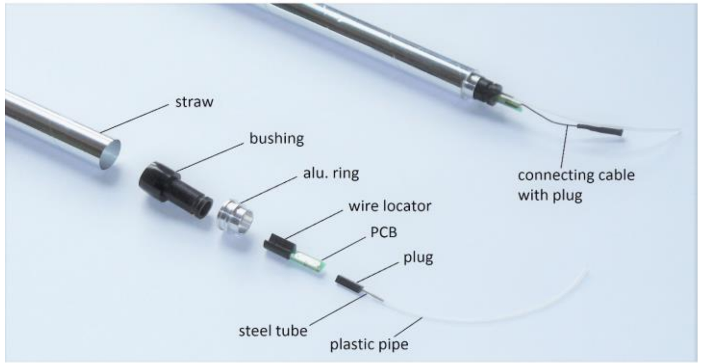
- Straw tubes of 10.0 mm inner diameter and a total wall thickness of 27 μm
- Two layers of 12 μm thick aluminized Mylar by wrapping two long strips around a rotating mandrel and gluing the two half-overlapping strips together
- Aluminization at the inner tube wall used as a cathode whereas the aluminization of the second, outer strip layer used to screen light incidence
- 20 μm diameter gold-plated tungsten-rhenium wire used as anode



Scheme of the stand for tensioning an anode wire in a straw



Sealing of a plug with adhesive



Components of an end-plug and the assembled end-plug

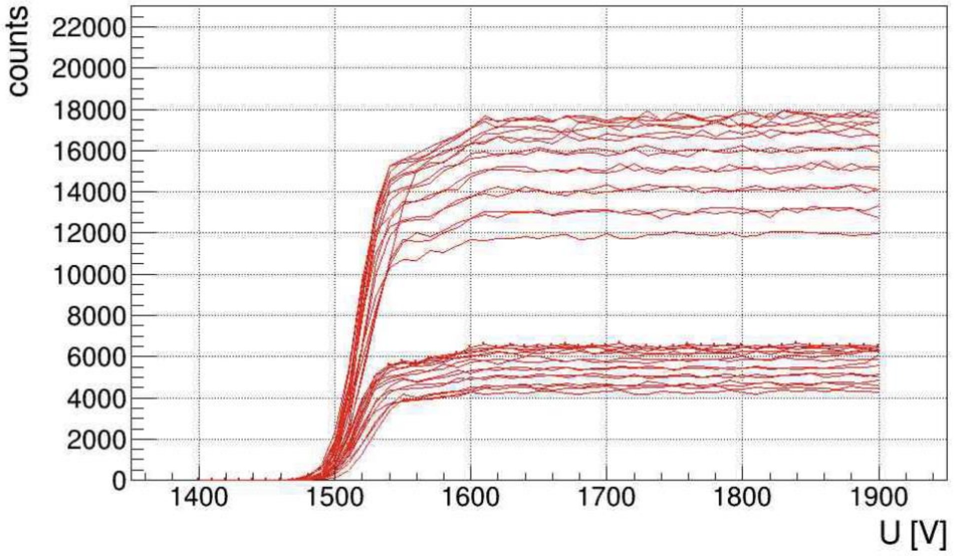
- Very low material budget.
- Straws filled with Ar-CO2 (90:10) at 2 bar absolute pressure,
- Radiation length X_0 of the straw is of 4.4 × 10−4
- PANDA Forward Tracker: six tracking stations, and each made by four double layers of straw tubes, total material budget only 2.1% X_0

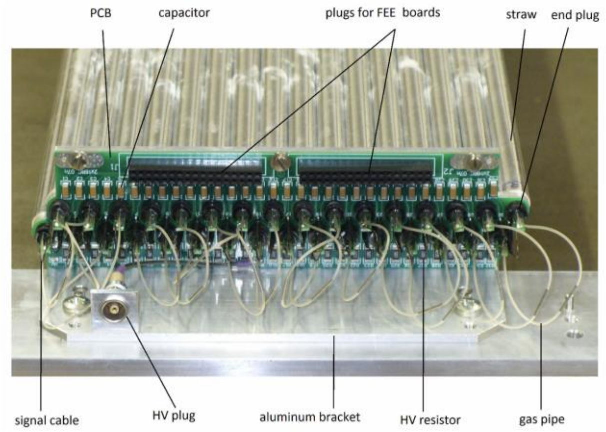
Straw Tubes PANDA

Straw tube detectors are grouped into modules constituting independent mechanical and electrical units. A single module consists of 32 straw tube detectors arranged in a planar double layer

Straw tube performance validation (as proportional counters), with X-rays from ^{55}Fe source

- Plateau curves for 32 straws in one module; two groups of curves, respectively, the first and second straw tube layer in the module looking from the source side
- Main step, above 1500 V, correspond to the total absorption of the 5.9 keV X-rays from ^{55}Fe, the smaller step, around 1600 V, from the argon escape peak (energy deposit of 2.9 keV)
- Low number of counts at low voltages → low level of pick-up noise
- Same position of the main step for various straws → equal gas





Double layer (32 straw tubes) with FE electronics

Transition Radiation

Local speed of light in a medium with refractive index *n* is $c_p = c/n$

If its relative velocity v/c_p changes, a particle will radiate photons:

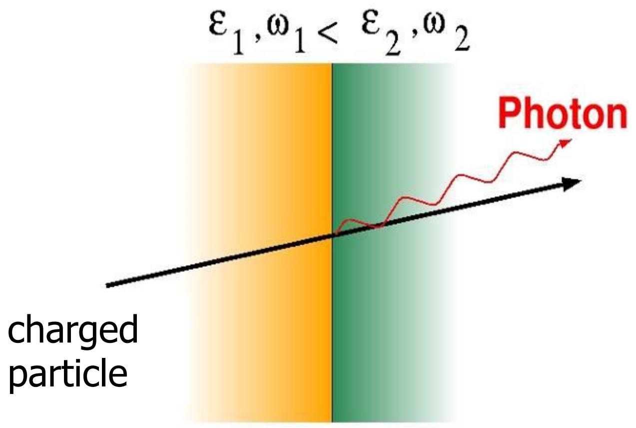
1. Change of direction ***v*** (in magnetic field) → **Synchrotron**
2. Change of |*v*| (passing through matter) → **Bremsstrahlung**
3. Change of refractive index *n* of medium → **Transition Radiation**

Transition radiation is emitted whenever

a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)

The energy emitted is proportional to the boost γ of the particle

→ Particularly useful for electron ID



Transition Radiation

Local speed of light in a medium with refractive index *n* is $c_p = c/n$

If its relative velocity v/c_p changes, a particle will radiate photons:

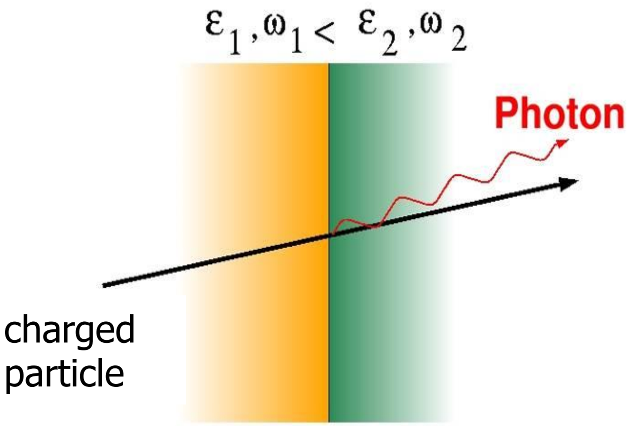
1. Change of direction ***v*** (in magnetic field) → **Synchrotron**
2. Change of |*v*| (passing through matter) → **Bremsstrahlung**
3. Change of refractive index *n* of medium → **Transition Radiation**

Transition radiation is emitted whenever

a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)

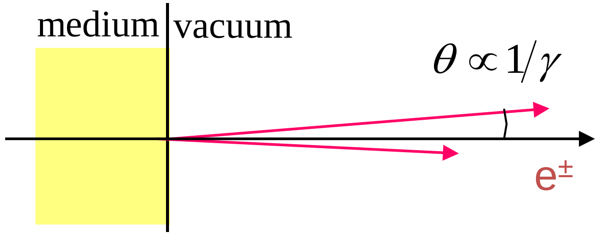
The energy emitted is proportional to the boost γ of the particle

→ Particularly useful for electron ID



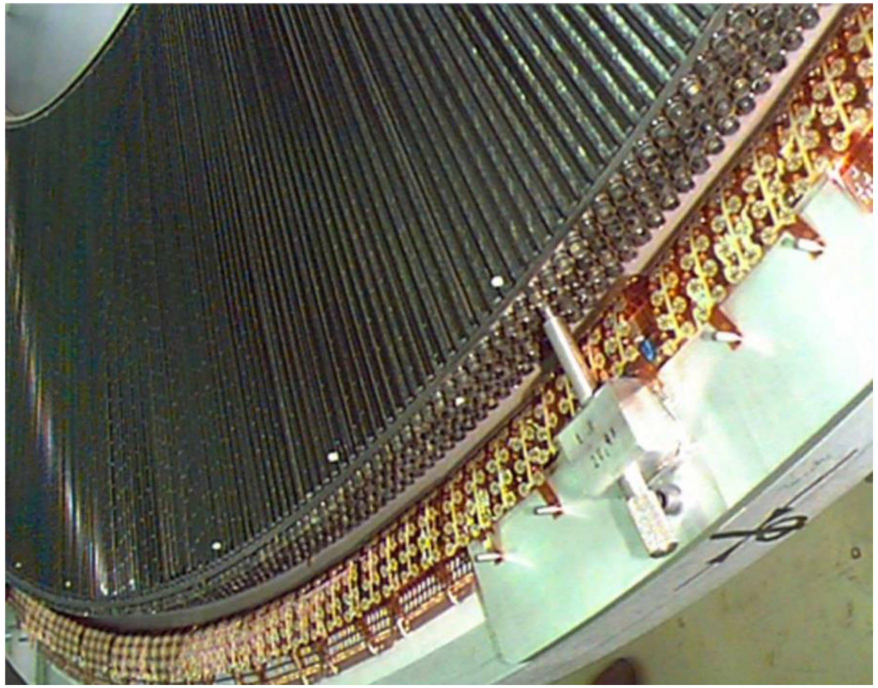
Radiation emitted in the very forward direction, in cone of angle 1/γ around the particle direction

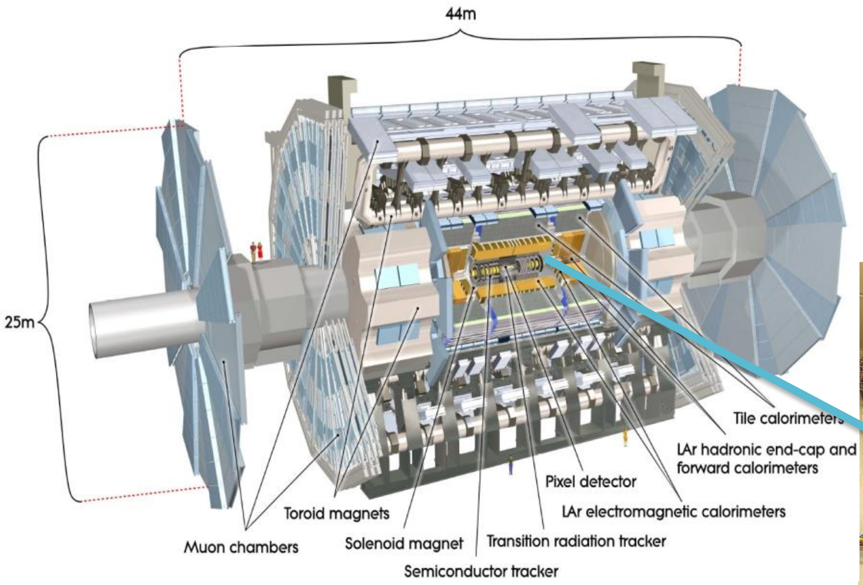
→ photons will be seen in same detector as the ionization from the track

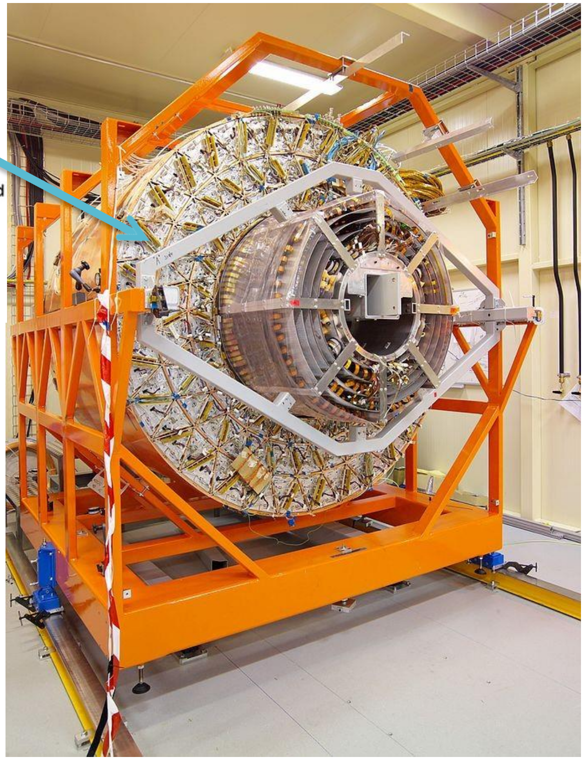


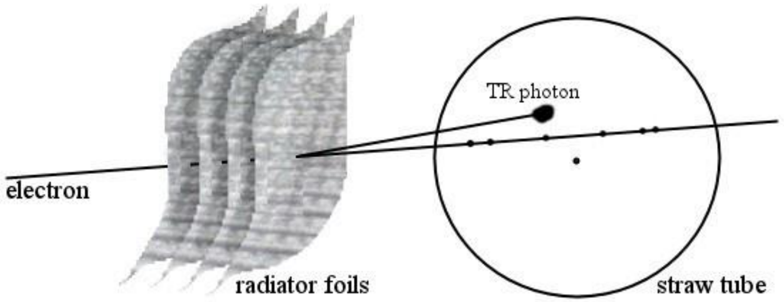
ATLAS Transition Radiation Tracker (TRT)

Transition Radiation Tracker: also acts as a central tracker using ~ 400 000 straw tubes
15 μm-thin polypropylene foils (radiator) interleaved with straws → transition radiation
Xe as active gas for high X-ray absorption

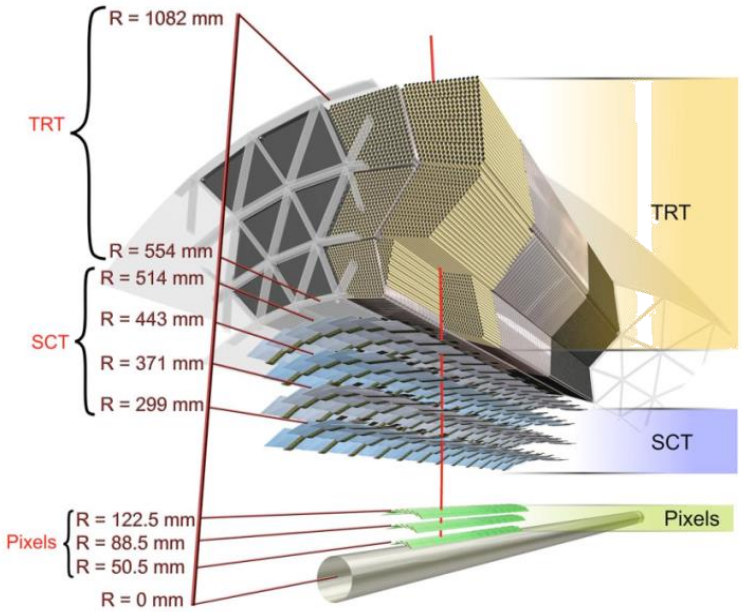


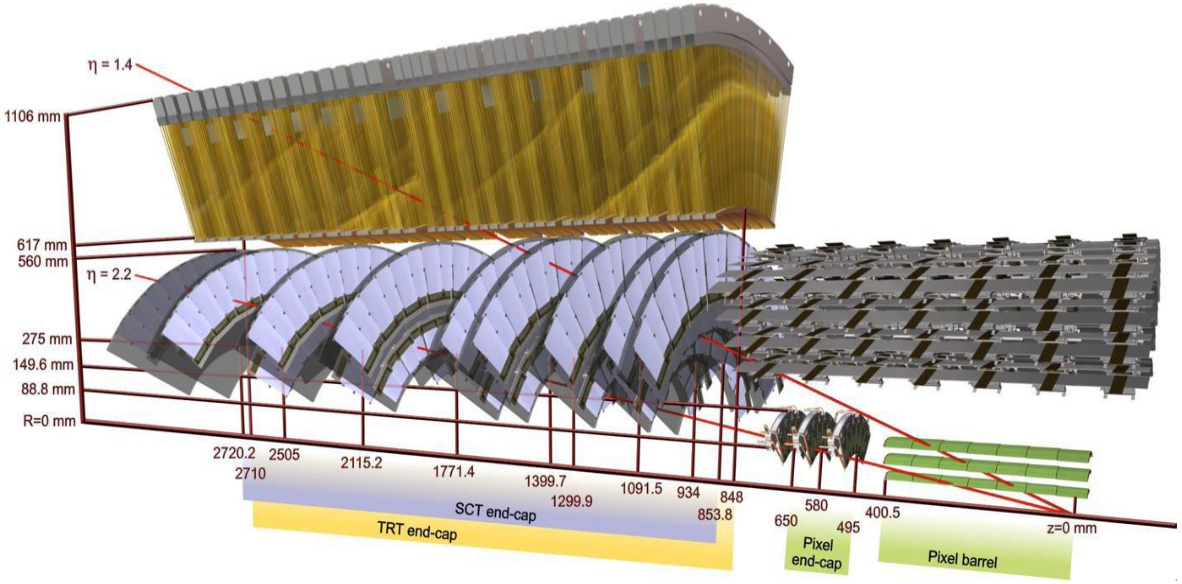




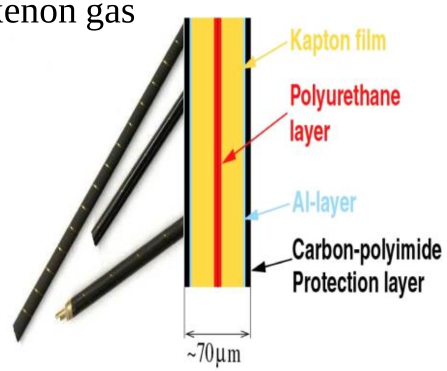


ATLAS Transition Radiation Tracker (TRT)





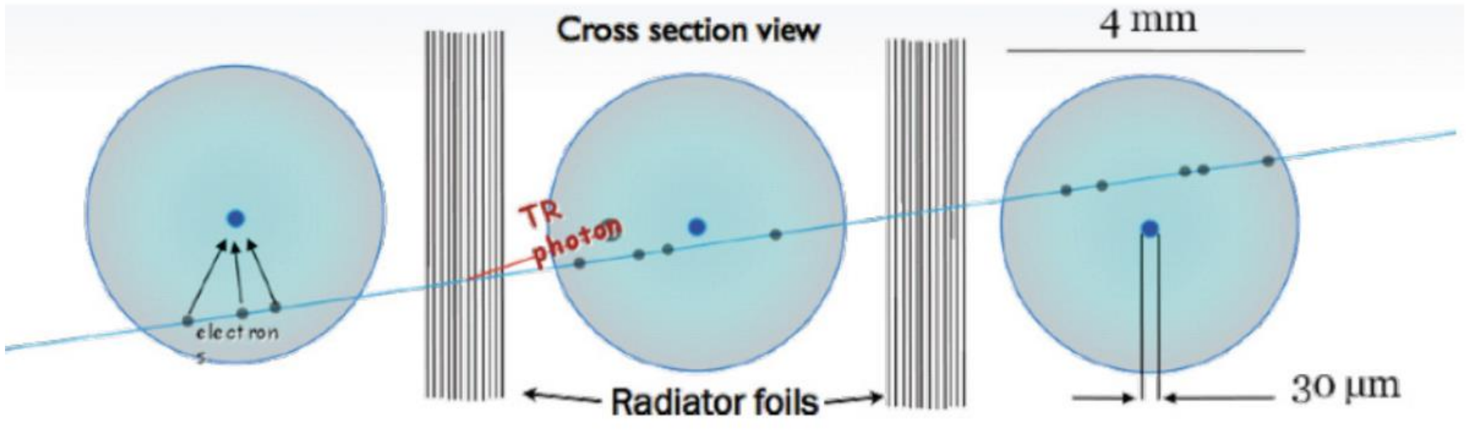
Straw filled with xenon gas mixture

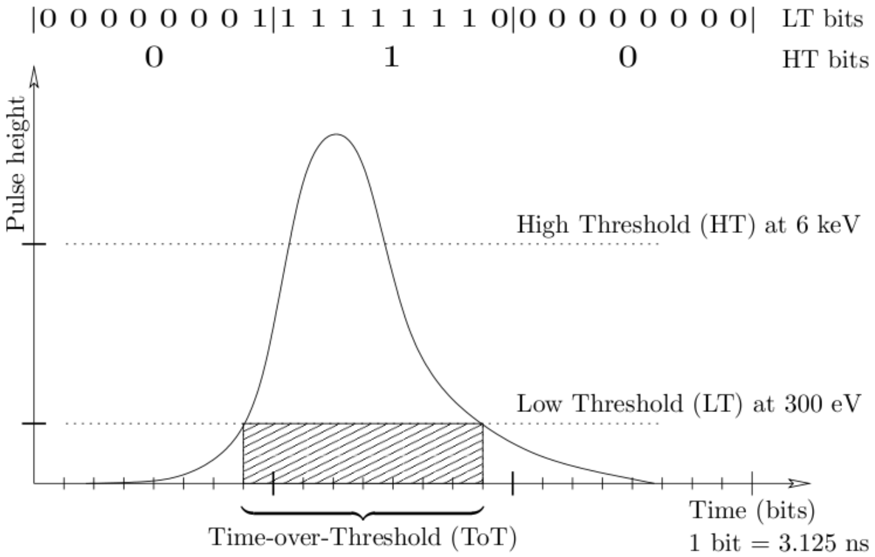


Straw wall (d=70µm) = cathode @ -1530V
Wire (d=30µm) gold-plated tungsten = anode @ 0V

- ✓ ≈ 0.4 M channels give ≈ 30 two--dimensional space--points for charged particles with $|\eta|<2$ and $p_T > 0.5$ GeV
- ✓ Single hit resolution: ≈120 µm
- ✓ Particle identification (electron--pion separation) by detection of transition radiation
- ✓ Provides accurate p_T measurements
- ✓ Works at high occupancy conditions
- ✓ Stable performance in hard radiation environment

ATLAS Transition Radiation Tracker (TRT)





Ionized electrons drift to straw wire to create signal (~several 100 eV)

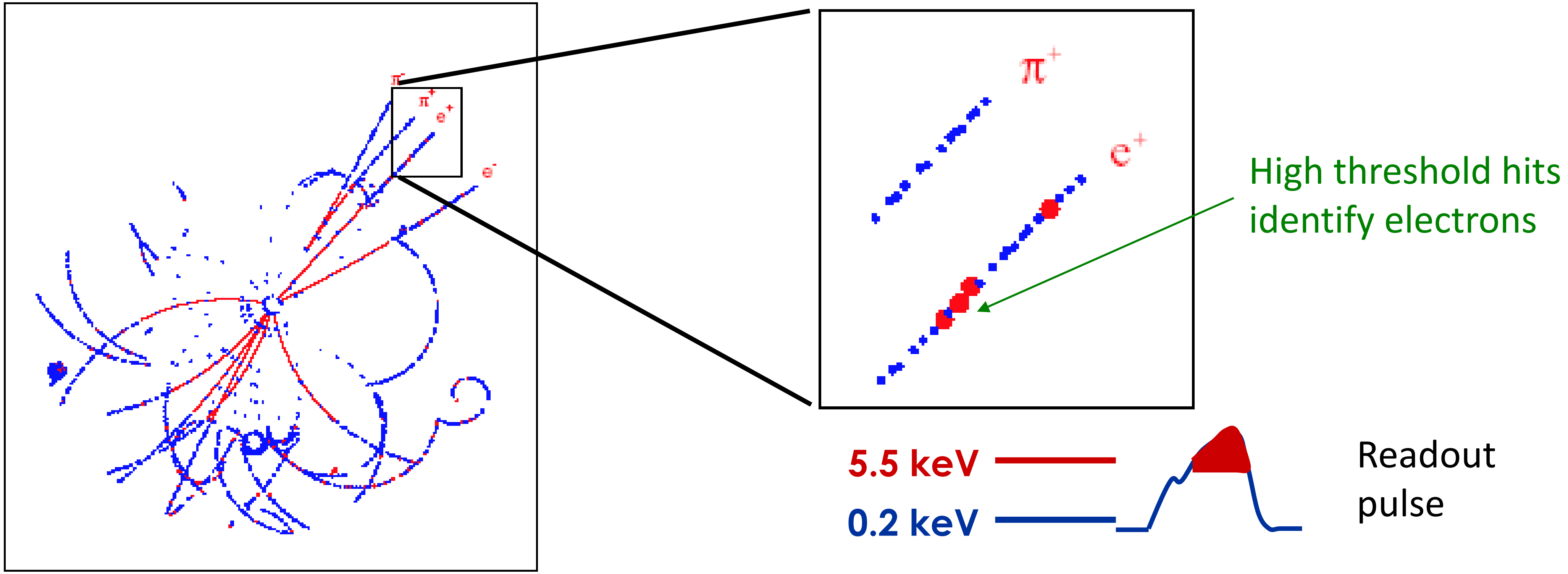
— Detect with **Low Threshold (LT)**

- TR photons generate signal ~10keV
  - — Detect with **High Threshold (HT)**
  - — Also with **Time over Threshold (ToT)**
- Readout granularity: **3.12ns**
  - — 1/8 of 25ns LHC bunch crossing (BC)
  - — Readout 3 BCs / trigger

ATLAS Transition Radiation Tracker (TRT)

Energy deposition in the straw is the sum of ionization loss (~2 keV) and the larger deposition due to transition radiation absorption (> 5 keV)

→ use two thresholds in the readout electronics

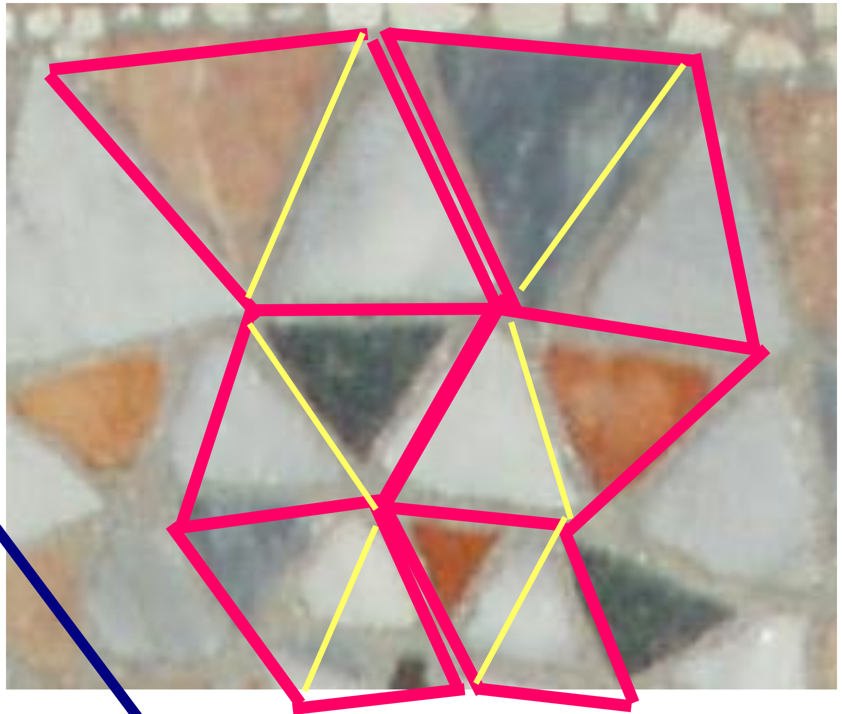


ATLAS *TRT* – *classical &modern design*

ATLAS

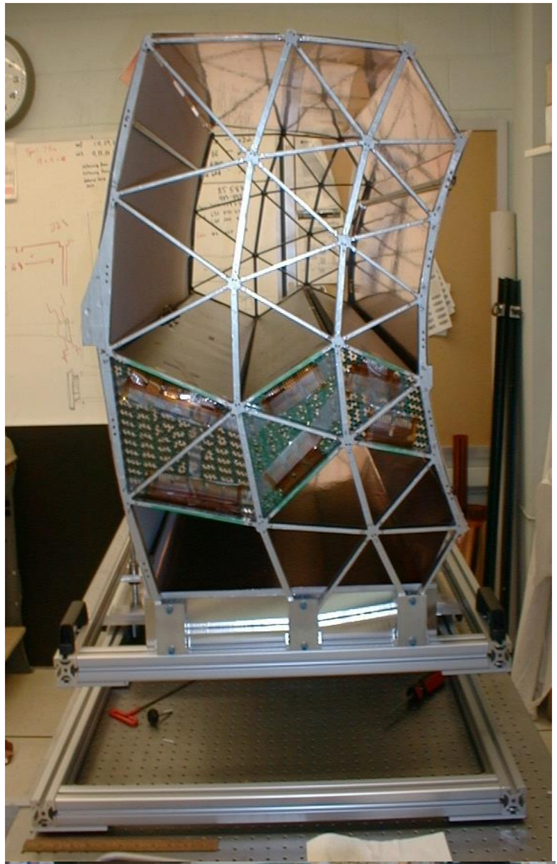
12th century mosaic.

Otranto cathedral, Italy



“Original” classical design: 4 layers

Simulation particles + Missing Energy?



Cluster counting technique (excursus dE/dx)

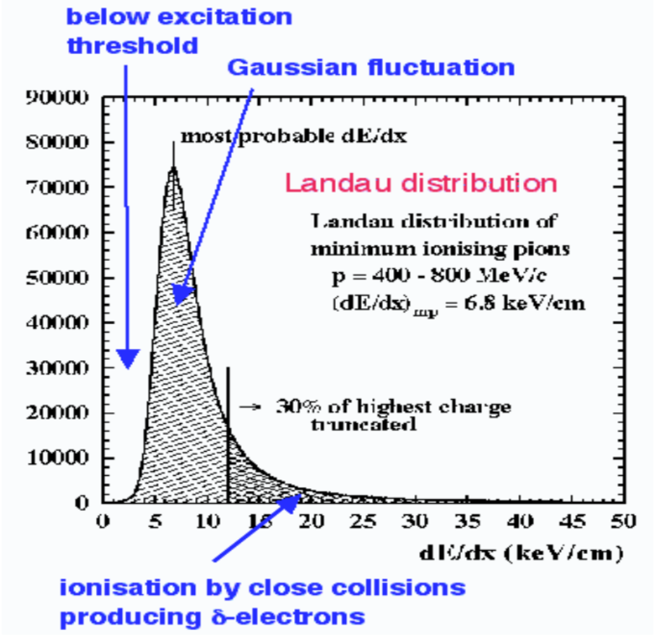
Ionization is used in ~ all tracking detectors

Tracking measures, the *position* of ionization for particle ID measure the *amount of ionization* (dE/dx)

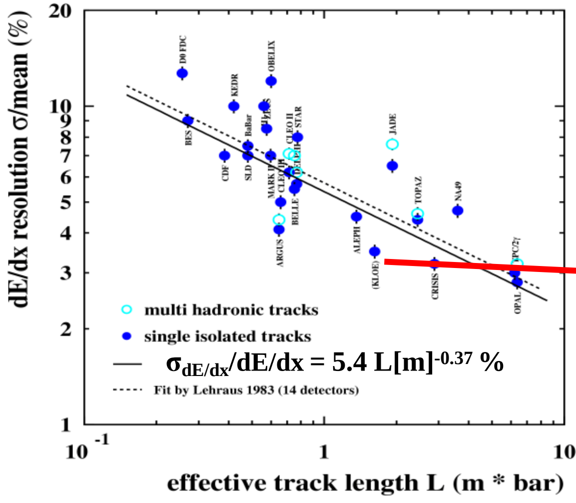
This is subject to large fluctuations due to ejection of d-electrons (Landau distribution)

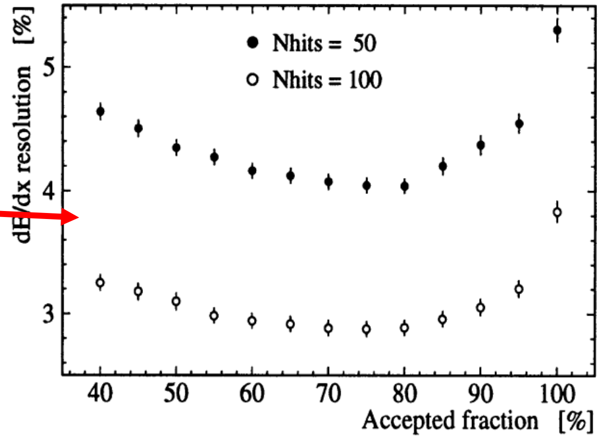
To avoid bias from the long tail, best to have many independent samples of the ionization, and perform a truncated mean

To get an excellent *dE/dx* measurements many samples and good energy resolution are needed (e.g., TPCs silicon detectors)



Lehraus' plot

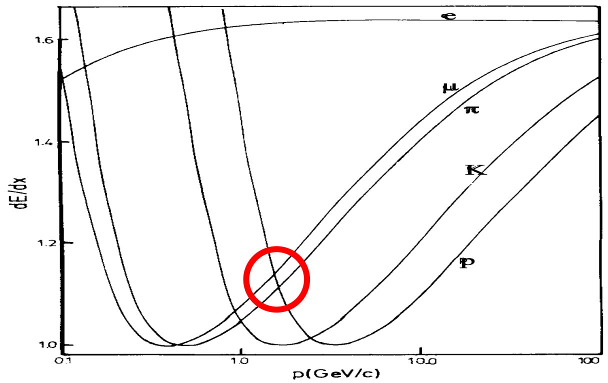




Dependence of dE/dx resolution vs. truncated mean fraction and number of samples (KLOE: He mix.)

Cluster counting technique

Note that the *dE/dx* plot as a function of momentum has a lot of *overlap* regions between the different mass hypotheses → limits usefulness for those momenta



Walenta

"It has been experimentally confirmed that the relativistic rise is mainly due to the increased number of the primary clusters, rather than due to the energy of clusters."

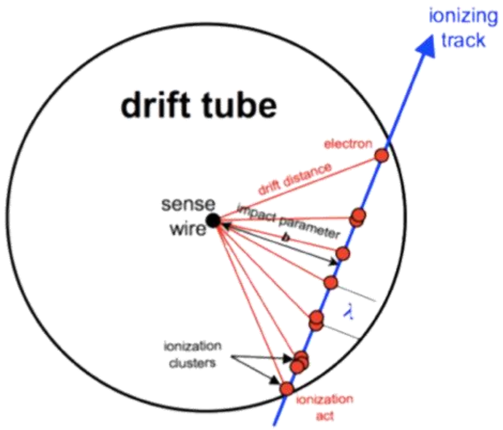
P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

Cluster timing in drift chambers consists in recording the drift times of all individual ionization cluster

Cluster Counting/Timing techniques may be beneficial to a variety of particle physics experiments, from rare decays search, where high resolution at low momentum (50-300 MeV) is of paramount importance

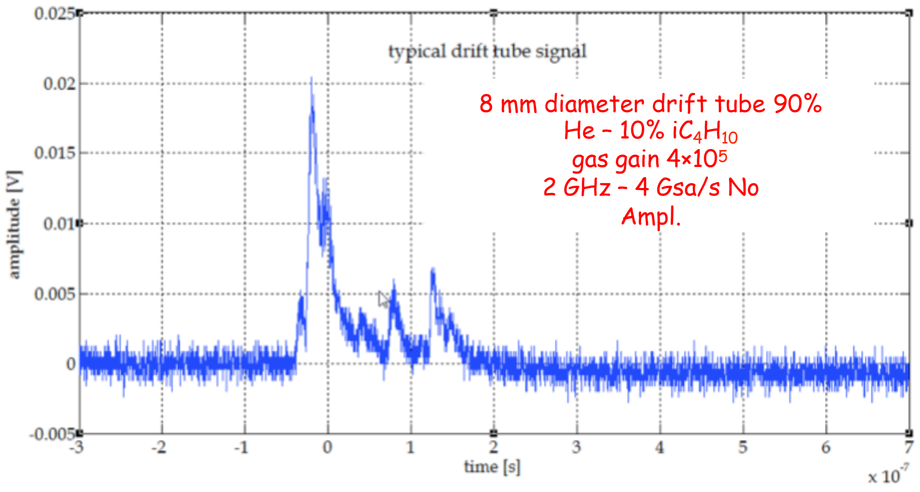
Cluster counting technique

G. Cataldi, F. Grancagnolo and S. Spagnolo, *Nucl.Instrum.Meth. A 386 (1997) 458-469*



In every recorded detector signal, the **isolated structures** related to the arrival on the anode wire of the **electrons belonging to a single ionization act.**

Pulses from **electrons belonging to different clusters must have a little chance of overlapping in time** and, at the same time, the time distance between pulses generated by **electrons coming from the same cluster must be small enough to prevent over--counting**.



- Use of He as drift chamber gas promoted by the need of limiting the **multiple scattering** contribution:

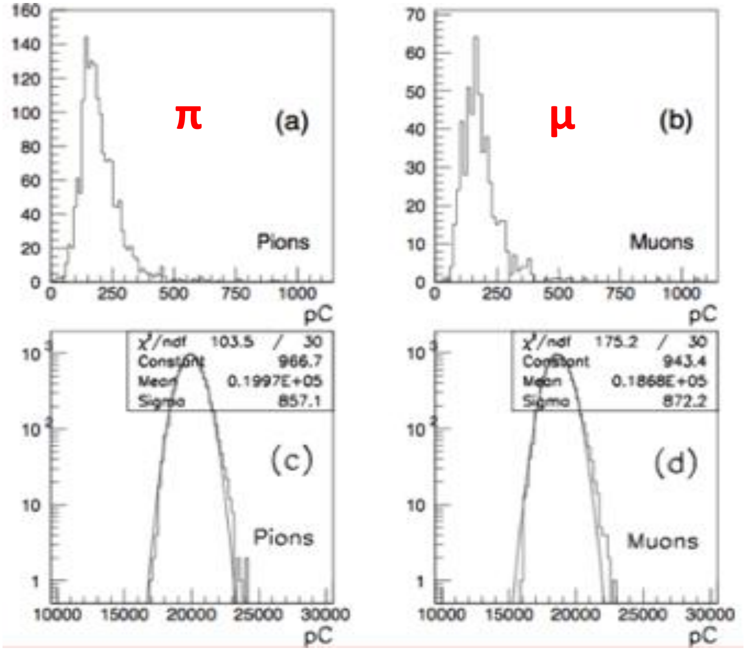
  X_0(He) = 5600 m as opposed to **X_0(Ar) = 110 m**

- The **Cluster counting** concept could, profit of to the opportunities given by the lower primary ionization, **N_{cl} ≈ 6/cm**, a factor 5 *vs* Ar, and by the slower drift velocity, **v_{drift} ≈ 2 cm/µs**, a factor 2. 5 *vs* Ar (cluster time expansion)

Cluster counting technique

μ/π separation at 200 MeV/c in He/iC_4H_{10} – 95/5 100 samples 3.7 cm

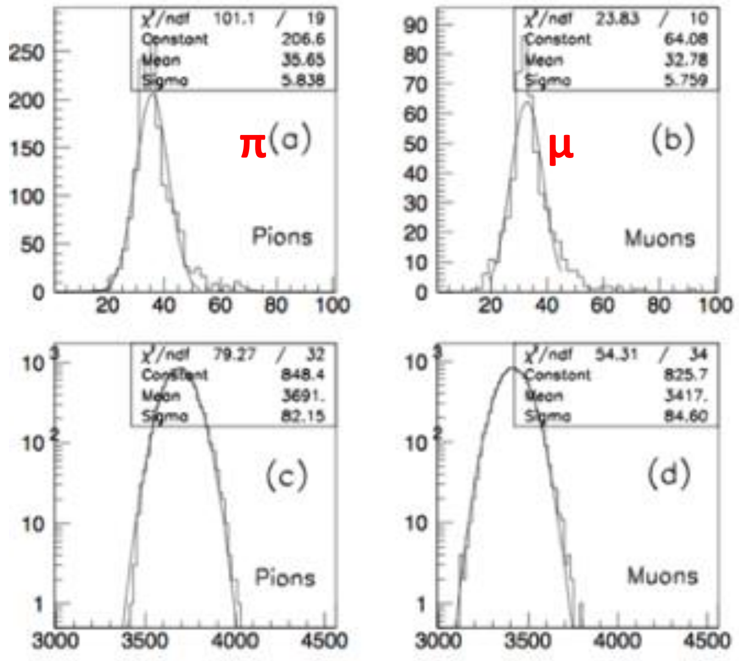
gas gain $2×10^5$, 1.7 GHz – gain 10 amplifier, 2GSa/s – 1.1 GHz – 8 bit digitizer



single sample
20% truncated
mean

sum over
100 samples

test beam data



single sample

π: $σ/\sqrt{N_{cl}}$=0.978
μ: $σ/\sqrt{N_{cl}}$=1.006

sum over
100 samples

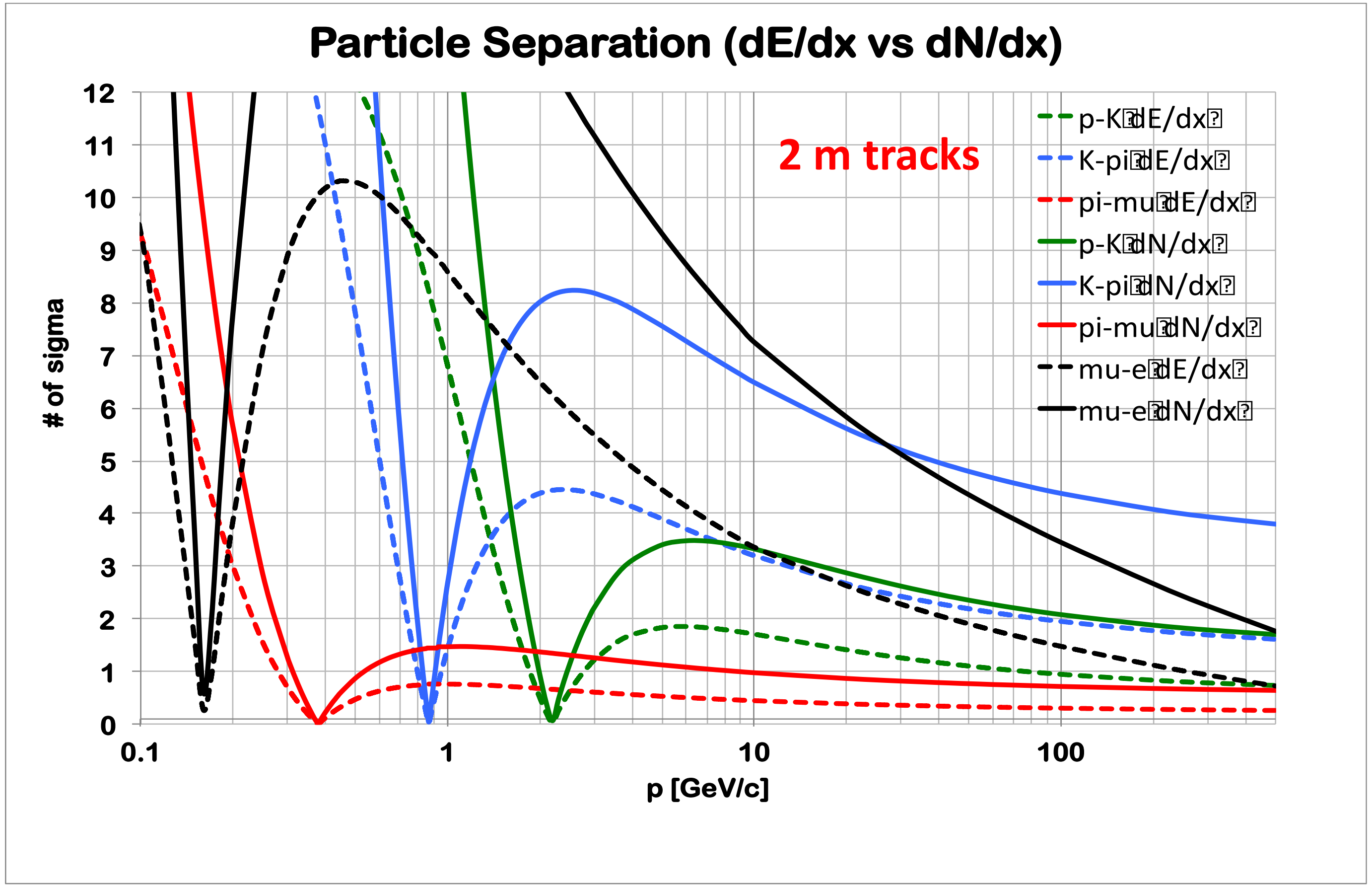
π: $σ/\sqrt{N_{cl}}$=1.35
μ: $σ/\sqrt{N_{cl}}$=1.45

integrated charge
expected 2.0 σ separation
measured 1.4 σ separation

cluster counting
expected 5.0 σ separation
measured 3.2 σ separation

Cluster counting technique

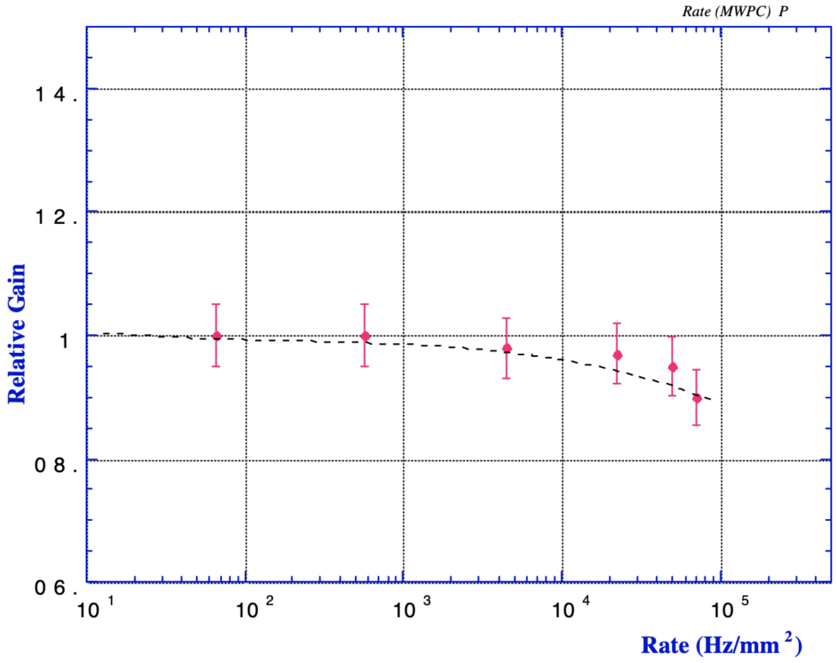
Expected from analytical calculation for IDEA (FCCee) Drift Chamber



https://indico.cern.ch/event/996326/contributions/4200962/attachments/2191650/3704305/dEdx.pdf

Limitations of Wire-based Detectors

- Spacing of wires
  - The maximum permissible length of the wire is also dominated by electrostatic and mechanical constraints such that the maximum stable length l_c is given by: $l_c = s\,(4\pi\varepsilon_0\,T) / CV_0$
    - s : wire spacing
    - V_0 : cathode voltage
    - T : wire tension
- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm^3 (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode
- Gas Mixture (and GWP)
- Ageing



Limitations of Wire-based Detectors: Gas Mixture

A whole lesson dedicated to gas mixtures would not be even remotely sufficient to adequately introduce the topic

Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

Quelle: K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

What to consider:
-) Primary ionization
-) Drift Velocity
-) Ion mobility
-) Diffusion
-) Magnet field
-) Recombination – attaching –electron capture
-) Penning effects
-) Safety (flammable/toxic gas)
-) Environment (GWP)
-) ….

Limitations of Wire-based Detectors : Ageing

Blum, W. Riegler and L. Rolandi, "*Gas Ionization by Charged Particles and by Laser Rays, in Particle Detection with Drift Chambers*"

Drift and proportional chambers that have been in use for some time have a tendency to malfunction sooner or later – an increase in the dark current, a lowering of the gain, and a loss of pulse-height resolution are the typical symptoms. Once it has started, the problem seems to become worse and to spread from a few wires to many, until finally the chamber may no longer hold the operating voltage.

This behavior is intimately associated with the gas mixture in the chamber and with certain contaminants. However, the material properties of the anodes and cathodes as well as their size also play a role in this area which is far from being clearly understood. Given the practical importance of the subject and that the new accelerators will produce extremely high levels of radiation, efforts towards better understanding are under way. Workshops held at Berkeley [WOR 86] and Hamburg [WOR 01] summarized the experience. A comparison of the reports at the two proceedings shows that during the 15 years between them there was much progress towards mastering the high particle fluxes of modern times. On the other hand, there is still no fundamental understanding of ageing. Nobody can calculate the lifetime of a chamber to be built, and in most cases, one cannot even calculate what the result will be when some parameter is changed in a given chamber and its gas supply system

Limitations of Wire-based Detectors : Ageing

Blum, W. Riegler and L. Rolandi, "*Gas Ionization by Charged Particles and by Laser Rays, in Particle Detection with Drift Chambers*"

Drift and proportional chambers that have been in use for some time have a tendency to malfunction sooner or later – an increase in the dark current, a lowering of the gain, and a loss of pulse-height resolution are the typical symptoms. Once it has started, the problem seems to become worse and to spread from a few wires to many, until finally the chamber may no longer hold the operating voltage.

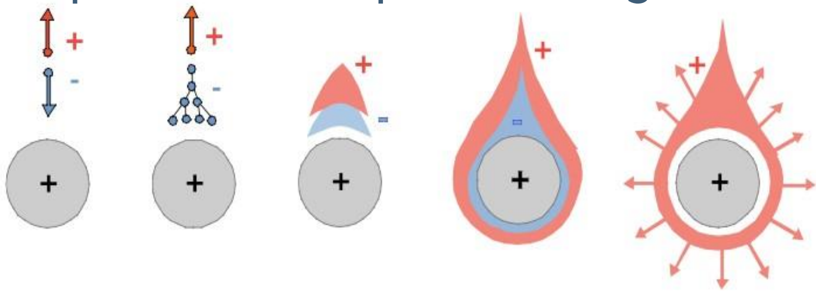
This behavior is intimately associated with the gas mixture in the chamber and with certain contaminants. However, the material properties of the anodes and cathodes as well as their size also play a role in this area which is far from being clearly understood. Given the practical importance of the subject and that the new accelerators will produce extremely high levels of radiation, efforts towards better understanding are under way. Workshops held at Berkeley [WOR 86] and Hamburg [WOR 01] summarized the experience. A comparison of the reports at the two proceedings shows that during the 15 years between them there was much progress towards mastering the high particle fluxes of modern times. On the other hand, there is still no fundamental understanding of ageing. Nobody can calculate the lifetime of a chamber to be built, and in most cases, one cannot even calculate what the result will be when some parameter is changed in a given chamber and its gas supply system

Classical Ageing

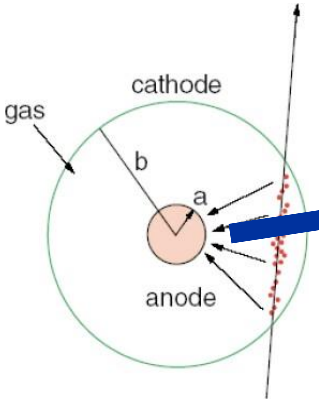
Limitations of Wire-based Detectors : Ageing

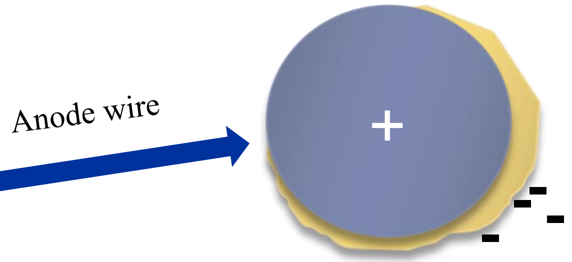
Gaseous Detectors – Principle (once again!!!)

Principle of Gas Multiplication ~ Signal development



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$



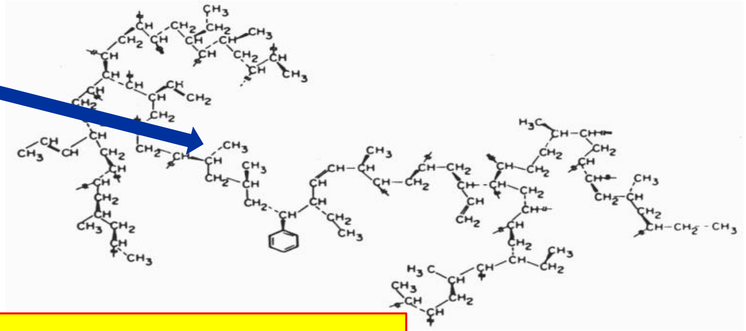


Let's consider standard gas mixture: → Ar / CH_4

In a reaction with primary electron: → $e^- + CH4 \rightarrow CH2: + H2 + e^-$

With free radicals: → CH2:

And formation of polymer:



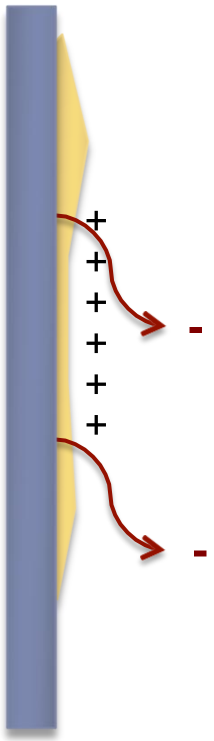
- **Solid, highly branched, cross linked**
- **Excellent adhesion to surfaces**
- **Resistant to most chemicals**
- **Insoluble in most solvents**

https://indico.cern.ch/event/122157/attachments/69728/99910/M_Capeans.pdf

- If the deposit is conductive, there is a direct effect on the electric field, which become weak (thick wire)
- If the deposit is insulating, there is indirect effect, dipole charging up, the field close to the wire will be screened, as the new avalanche will accumulate on insulating layer

Limitations of Wire-based Detectors : Ageing

Malter Effect

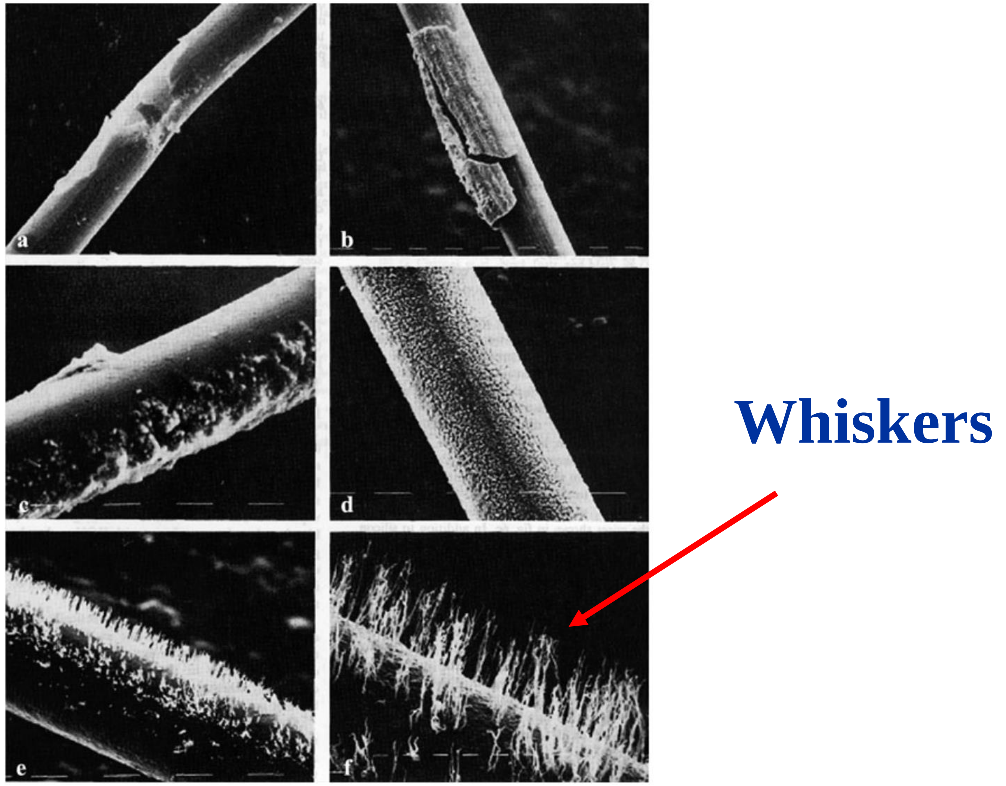


- ✓ A positive surface charge deposited on a thin insulating film that covers a cathode can provoke the emission of electrons from the cathode through the film
- ✓ A very high electric field may be created in the film between the deposited charge and the countercharges accumulated on the metallic cathode
- ✓ Electrons are extracted from the metal through field emission
- ✓ In a wire chamber, some thin insulating coating on the cathodes is charged up by the positive ions that are produced in the avalanches and drift to the cathodes
- ✓ If second emission become self-sustaining process the dark current remains, even if the source of the primary radiation is removed from the chamber
- ✓ To prevent the development of cathode deposits, better to keep low electrical field on the cathodes surface, plane cathodes and wires with larger diameters show smaller deposits

Limitations of Wire-based Detectors : Ageing

Whiskers

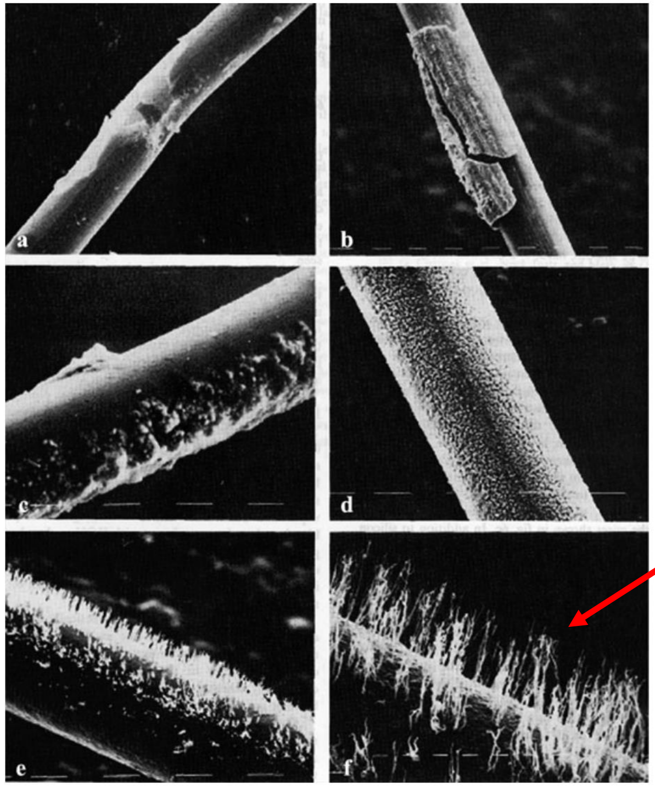
- ✓ Whiskers as primarily consequence of gas composition
- ✓ According to a test by the JADE group, moving from [1] Ar(89%) + CO 2 (10%) + CH4 (1%) to [2] Ar(90%) + CO 2 (5%) + CH4 (5%) produced whiskers which grew from the cathode wires in the field direction, Going back to mixture [1], the whiskers shrank and then disappeared
- ✓ Other tests shown that whisker growth on cathode wires is supported by gas mixtures containing the lower alkanes, (CH 2)n-type polymers
- ✓ On the other hand, no mixtures of carbon dioxide and argon support whisker growth; rather they make existing whiskers retreat and disappear



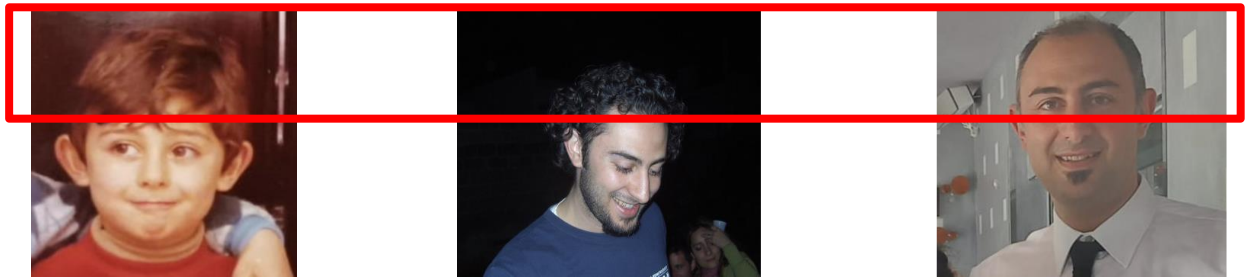
Limitations of Wire-based Detectors : Ageing

Whiskers

- ✓ Whiskers as primarily consequence of gas composition
- ✓ According to a test by the JADE group, moving from [1] Ar(89%) + CO 2 (10%) + CH4 (1%) to [2] Ar(90%) + CO 2 (5%) + CH4 (5%) produced whiskers which grew from the cathode wires in the field direction, Going back to mixture [1], the whiskers shrank and then disappeared
- ✓ Other tests shown that whisker growth on cathode wires is supported by gas mixtures containing the lower alkanes, (CH 2)n-type polymers
- ✓ On the other hand, no mixtures of carbon dioxide and argon support whisker growth; rather they make existing whiskers retreat and disappear



Whiskers

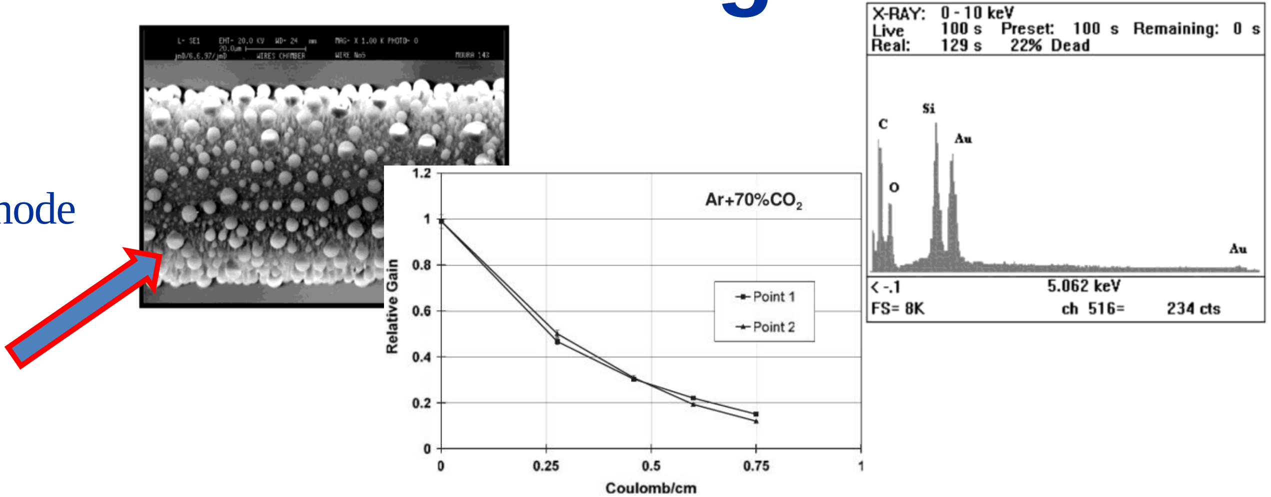


Whiskers ???

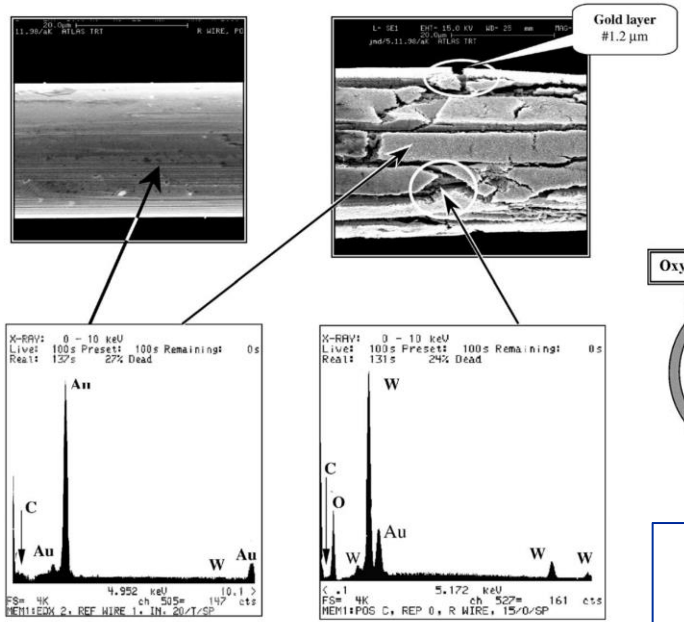
Limitations of Wire-based Detectors : Ageing

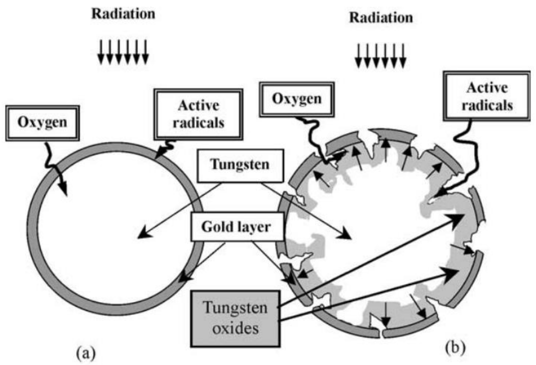
CMS CSC Gas Mixture: 40% Ar + 50% CO_2 + 10% CF_4

The main purpose of CF4 in the gas mixture – protection against anode wire aging : $Si + F_4 \rightarrow SiF_4$
also breaking C-chains in polymer formation
Till now far, we said F to be avoided due to Radical formation, but Si is even worst !!!



- Ageing may occur for non-gold plated wires, which contain chemically active elements in the wire surface
- Mechanism involves dissociation reactions in the avalanches and resulting in the oxidation of tungsten under the gold coating of the anode wire
  - **Stage #1**: Production of oxygen and other active chemical radicals in the gas avalanche
  - **Stage #2**: Oxygen penetration through the gold layer of the anode wire
  - **Stage #3**: Anode wire swelling





The mechanism for the anode swelling effect

https://agenda.infn.it/event/30846/contributions/185024/attachments/99583/138277/Kuznetsova_Erice2022.pdf

Limitations of Wire-based Detectors : Ageing

Drift and proportional chambers that have been in use for some time have a tendency to malfunction sooner or later – an increase in the dark current, a lowering of the gain, and a loss of pulse-height resolution are the typical symptoms. Once it has started, the problem seems to become worse and to spread from a few wires to many, until finally the chamber may no longer hold the operating voltage.
This behavior is intimately associated with the gas mixture in the chamber and with certain contaminants. However, the material properties of the anodes and cathodes as well as their size also play a role in this area which is far from being clearly understood. ***Given the practical importance of the subject and that the new accelerators will produce extremely high levels of radiation, efforts towards better understanding are under way. Workshops held at Berkeley [WOR 86] and Hamburg [WOR 01] summarized the experience. A comparison of the reports at the two proceedings shows that during the 15 years between them there was much progress towards mastering the high particle fluxes of modern times.*** *On the other hand, there is still no fundamental understanding of ageing. Nobody can calculate the lifetime of a chamber to be built, and in most cases, one cannot even calculate what the result will be when some parameter is changed in a given chamber and its gas supply system*

Stay tuned 3rd Workshop "International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors" will take place at CERN, November 6th to 10th, 2023.

The Indico conference site is: https://indico.cern.ch/event/1237829

Why MPGD???

Let’s try to summarize the previous slides:

- Complexity in mechanical construction
- Resolution
- Relative low rate capability
- Ageing

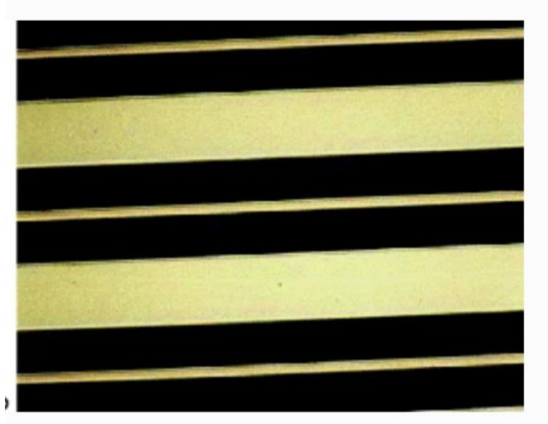
A new family of detector (without wires) is needed!!!

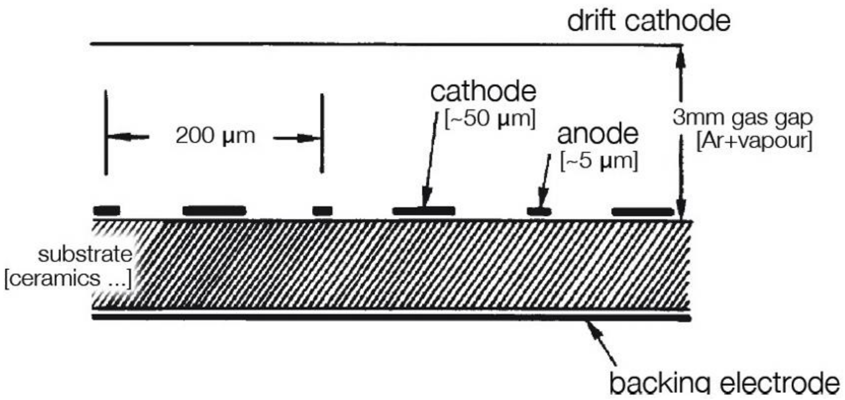
Micro-Strip Gas Chamber (MSGC)

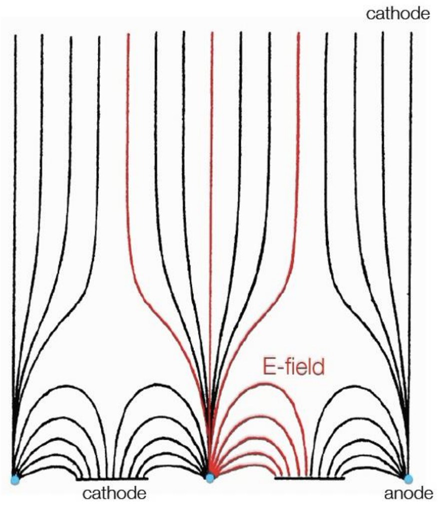
In 1988, **Anton Oed**, at the Institute Laue-Langevin (ILL) in Grenoble, introduced a novel concept in detection:

Micro-Strip Gas Chamber (MSGC)

- Consisting of a set of tiny metal strips engraved on a thin insulating support, and alternatively connected as anodes and cathodes
- Relies for its operation on the same processes of avalanche multiplication as the multi-wire devices
- Photolithography technology used for manufacturing, permits to reduce the electrode spacing by at least an order of magnitude, improving the multi-hit capability.
- Fast collection of most positive ions by the nearby cathode strips reduces space charge build-up and provides a largely increased rate capability



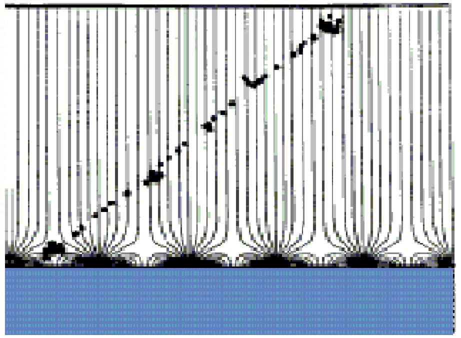


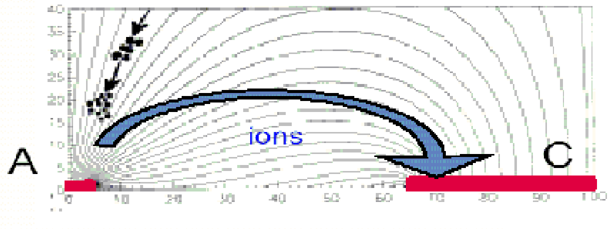


Introduced coincidentally with the first projects of high luminosity colliders, MSGCs filled a gap in the available detector technologies, between solid state strip detectors, having excellent performances but high costs, and the cheap but rate-limited traditional gas devices

MSGC

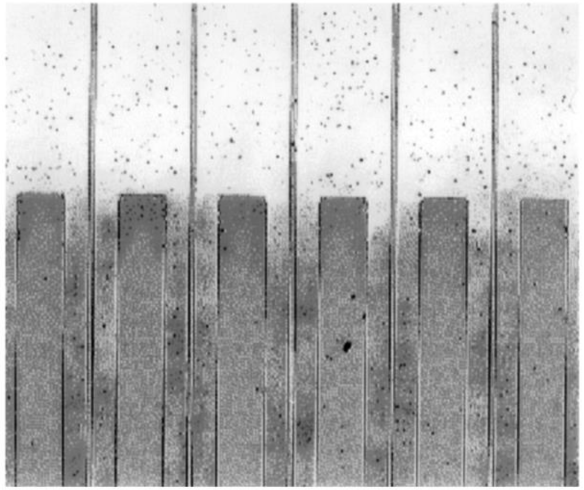
- Cathode strips are arranged between the anode strips for an improved field quality and to improve the rate by **fast removal of positive ions**
  - Reduced dead time between signals



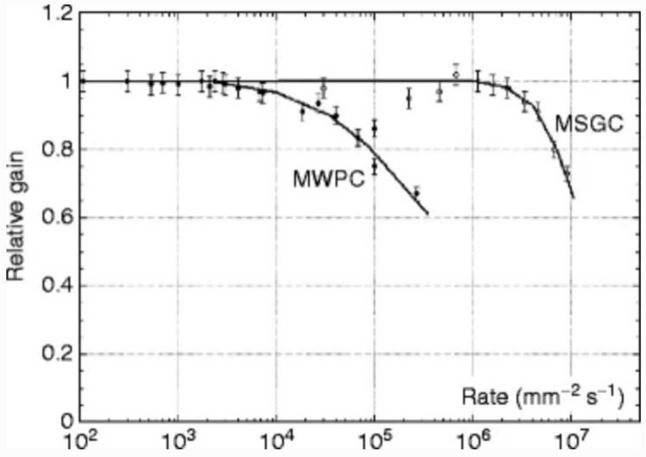


- Rate and spatial resolution improved w.r.t. MWPCs by more than an order of magnitude

  Spatial resolution can be a few tens of microns
- Segmentation of the cathodes also possible to allow 2-dimensional readout

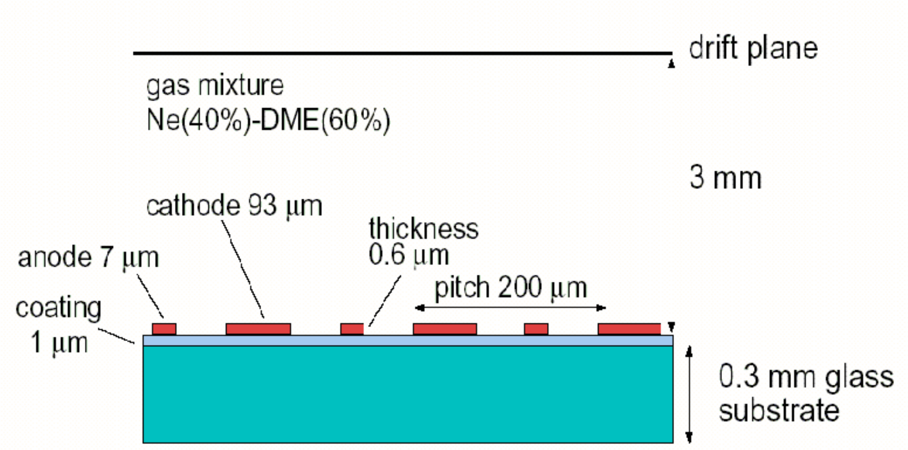


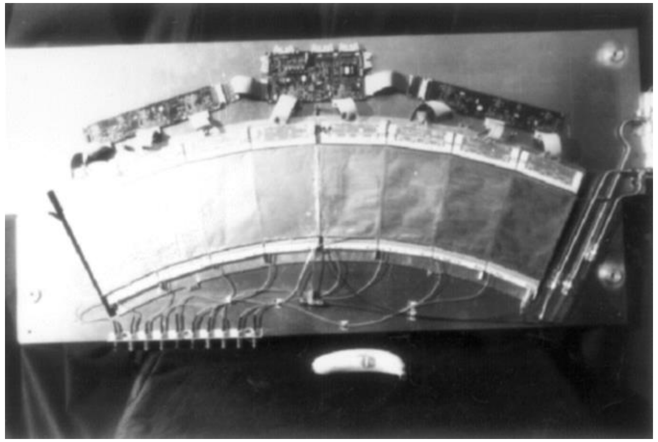
Close view of one of the first microstrip plates developed by Oed at the Institute Laue-Langevin. On an insulating substrate, thin metallic anode strips alternate with wider cathodes; the pitch is 200 μm.



Rate Capability comparison for MWPC and MSGC

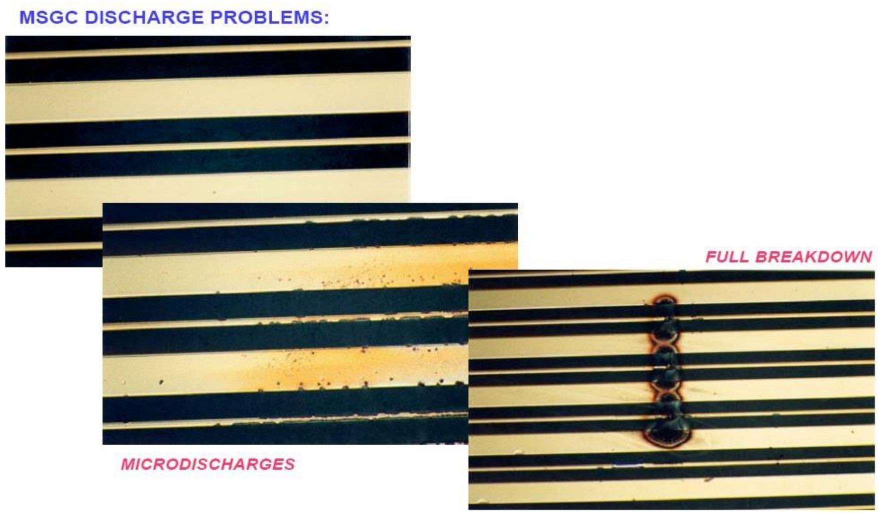
Micro-Strip Gas Chamber (MSGC)

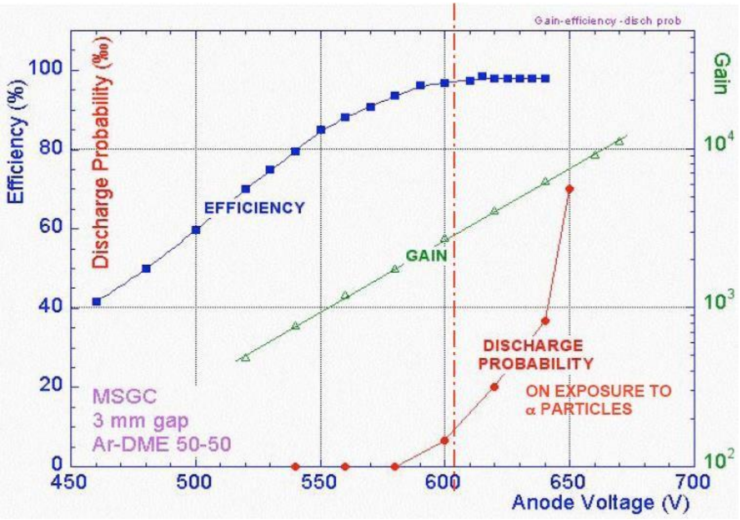




Considered by CMS experiment,
but ageing problems…(replaced by Si)

- Ar:DME 50:50
- Resolution ~30 to 40µm
- Gain <10000
- Anode: 0V
- Cathodes: -520 V
- Drift Cathodes: -3500V
- Rate up to 10^6 particles/mm^2/s





… one second back to wire detectors

- The successful development of multiwire chambers has somewhat sidestepped the research on gas detectors that exploit the multiplication in uniform fields

- Parallel-plate multipliers not only are mechanically sturdier but also have better energy resolution and higher rate capability

  However, experimental data and theoretical considerations indicate that the maximum proportional gain in parallel-plate chambers is limited by the total amount of charge in the avalanche, around 10^7–10^8 , above this value, (Raether limit), transition to a streamer occurs, followed by breakdown

- The exponential dependence of gain on the gap has also discouraged the construction of large-area devices.

Micro-Strip Gas Chamber: A door toward a new era of gas detectors

- Operating properties of MSGCs manufactured with different metals and a range of geometrical parameters, as well as the resistance of the devices to local discharges have been widely studied

- Several variants of the basic microgap structures have been tested to improve their performance and reliability, with particular attention to the onset of discharges, which so far is still the major limitation for reliable application in HEP

- Nevertheless, the detailed studies on their properties, and, on the radiation-induced processes leading to discharge breakdown, led to the development of more powerful devices with improved reliability and radiation hardness.

- On the basis of the MSGC Photolithography technology have been further developed and used for manufacturing particle detectors and in particular gaseous based particle detectors

- Modern MPGD structures can be grouped into two large families: hole-type structures and micromesh-based detectors
  The hole-type structures are GEMs, THGEM, RETGEM, Micro-Hole, …..
  The micromesh-based structures include: Micromegas, "Bulk" Micromegas, "Microbulk" Micromegas, ….

…see you tomorrow!!!

References:

-) Blum, W. Riegler and L. Rolandi, "*Particle Detection with Drift Chambers*", Springer (2008)

-) Hilke, H.J., Riegler, W. (2020), "*Gaseous Detectors*", In: Fabjan, C., Schopper, H. (eds) Particle Physics Reference Library. Springer, Cham. https://doi.org/10.1007/978-3-030-35318-6_4

-) G. Charpak et al., *"The use of multiwire proportional counter to select and localize charged particle",* NIM 62, 262 (1968)

-) The ATLAS Muon Collaboration, "*ATLAS Muon Spectrometer Technical Design Report*" , CERN/LHCC 97–22

-) S. Majewski et al., "*A thin multiwire chamber operating in the high multiplication mode*", NIM. 217 (1983) 265.

-) G. Mikenberg, "*Thin-gap gas chambers for hadronic calorimetry*", NIM A 265 (1988) 223.

-) C. Beard et al., "*Thin, high gain wire chambers for electromagnetic presampling in OPAL*", NIM A 286 (1990) 117.

-) Y. Arai et al., "*Timing optimization of thin gap chambers for the use in the ATLAS muon end-cap trigger*", NIM A 367 (1995) 398.

-) G. Cataldi, F. Grancagnolo and S. Spagnolo, "*Cluster counting in helium based gas mixtures*" NIM A 386 (1997) 458-469

-) T. Akesson et al., "*Study of straw proportional tubes detector/tracker for a transition radiation at LHC*" NIM. A 361 (1995) 440-456

References:

-) A. Andronic, J.P. Wessels “*Transition radiation detectors*” NIM. A 666 (2012) 130-147

-) V.I. Razin, “*The choice of the optimum gas mixture for high rate wire chambers*” NIM A 367 (1995) 295-297

-) T. Ferguson, et al.,“*Anode wire swelling--a possible phenomenon in anode wire aging under high-accumulated dose*”, NIMA 483 (2002) 698–712

-) L. Benussi, S. Bianco, et al.,“*Candidate eco-friendly gas mixtures for MPGDs*” EPJ Web of Conferences 174, 05004 (2018)

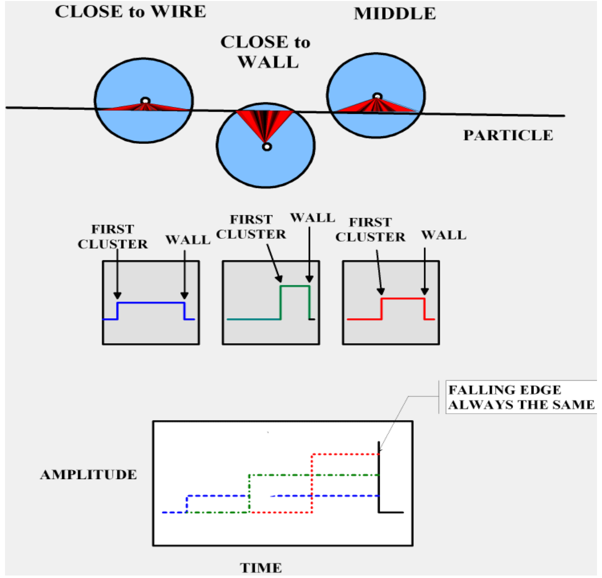
-) J.H. Dieperink, et al, “*Construction problems with large proportional wire chambers*” CERN Internal Report 69-28

-) A. Oed, “*Position-sensitive detector with microstrip anode for electron multiplication with gases*”, NIM A 263 (1988) 351-359

-) F. Sauli, A. Sharma, “Micropattern Gaseous Detectors”, Annu. Rev. Nucl. Part. Sci. 1999. 49:341–88

Backup

How does it work?



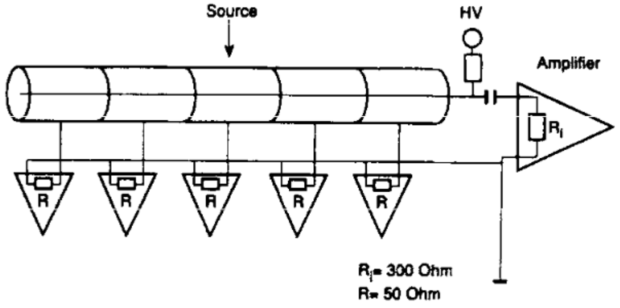
- Falling edge has the same time for all straws on track.
- Rising edge gives the arrival time of the first cluster
- The closer is the track to the wall, the bigger is the signal (clusters closer)
- Don’t want to see clusters => shaping must be chosen in relation to gas properties
- Tracks from drift time measurements

Readout concept

- **Precise tracks from drift time measurement**
  - Arrival of the first cluster
- **Track selection, identification and validation from the trailing edge**
  - Arrival of the last cluster
  - ID attached to trailing edge should be used for matching with trigger ID
  - All straws with matched IDs within time window (for straw propagation time) are on the track
  - Straw propagation time should be subtracted from leading edge before calculating particle position
- **Trailing edge can be used for crude z-by-time measurement to help track reconstruction**
- **Trailing edge can be used in fast trigger or as an anti-coincidence (VETO) on multiple tracks**

Improving rate capability

- **Smaller diameter**
  - Less particles
  - Less charge in gas volume
  - Shorter collection time
- **Segmented straw**
  - Cathode segmentation
  - Highly resistive inner coating
  - External metallic rings on which signal is induced
  - Anode segmentation
  - ATLAS/TRT barrel 2 sections
- **Faster gas**



CERN EP-ESE Electronics Seminars **Peter Lichard** *Straw detectors and their electronics*

Transition Radiation

Local speed of light in a medium with refractive index *n* is $c_p = c/n$

If its relative velocity v/c_p changes, a particle will radiate photons:

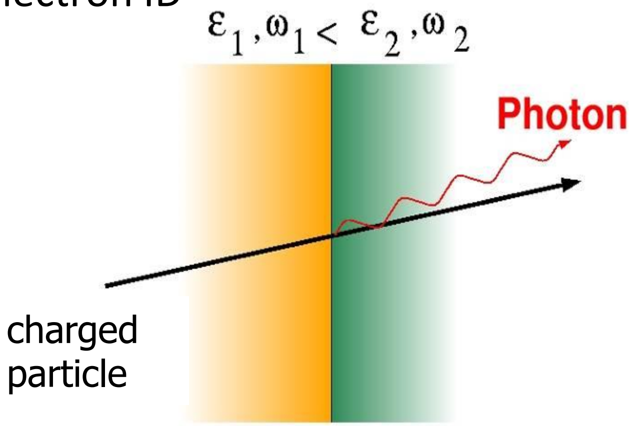
1. Change of direction **v** (in magnetic field) → **Synchrotron**
2. Change of $|v|$ (passing through matter) → **Bremsstrahlung**
3. Change of refractive index *n* of medium → **Transition Radiation**

Transition radiation is emitted whenever

a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)

The energy emitted is proportional to the boost γ of the particle

→ Particularly useful for electron ID



The Transition Radiation energy emitted when charged particle crosses a boundary between vacuum and a medium with plasma frequency ω_p

$$\Delta E = \alpha\, h\omega_p \gamma / 3$$

- α = fine structure constant ≈ 1/137
- $h\omega_p$ depends on the electron density in the material ~ 20 eV for a low-*Z* material such as plastic (e.g. polypropylene)
- For a 10 GeV electron, $\gamma \sim 2 \times 10^4$, so

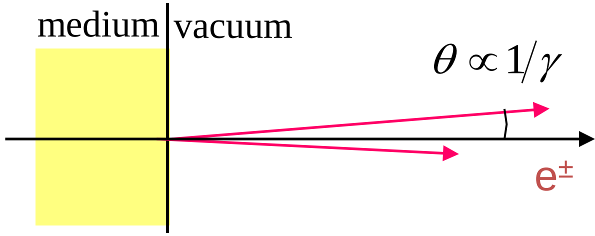
$\Delta E \sim$ keV (i.e. X-ray energy)

Low probability of photon emission at one interface (~ 1%) so many layers of thin foils are used for the radiator

Low *Z* is important to limit re-absorbtion of the radiation

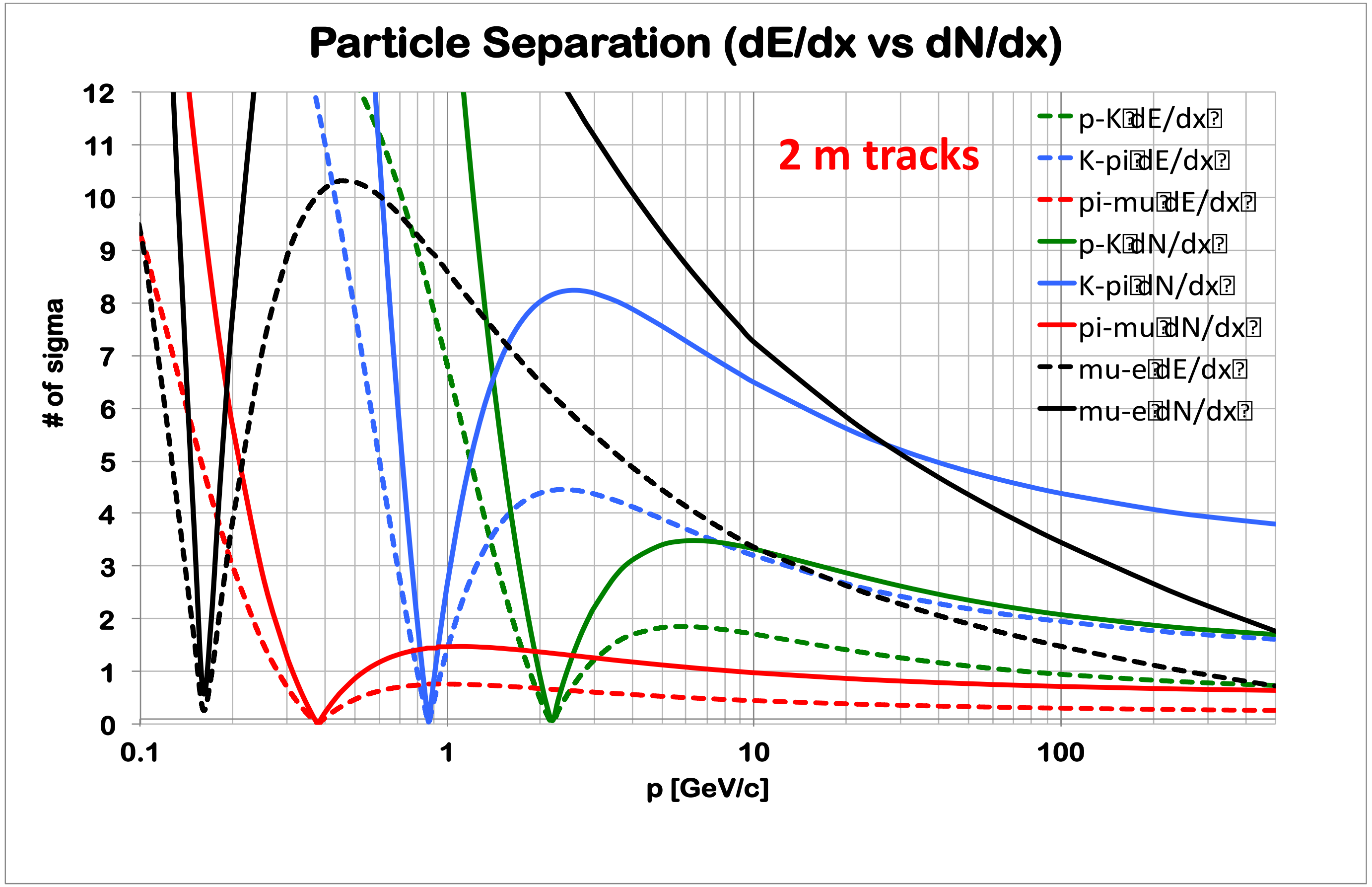
Radiation emitted in the very forward direction, in cone of angle $1/\gamma$ around the particle direction

→ photons will be seen in same detector as the ionization from the track



Cluster counting technique

Expected from analytical calculation for IDEA (FCCee) Drift Chamber



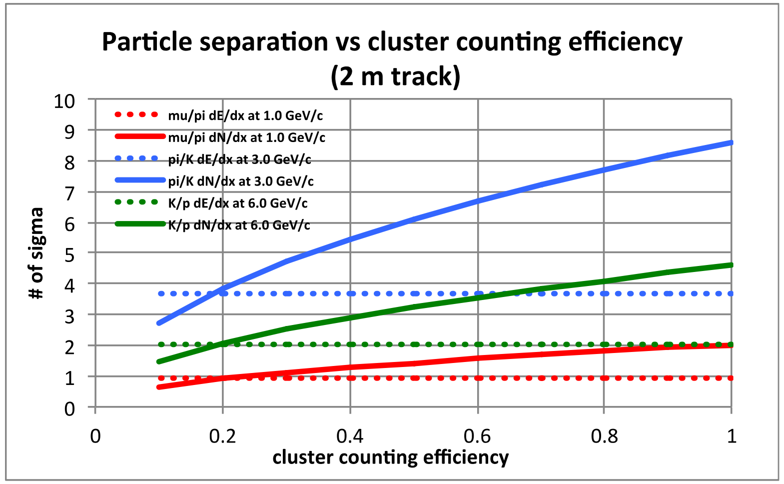
He/iC4H10 90/10

δ_{cl}=12 cm^{-1}

σ(dE/dx)/(dE/dx) =4.3%

σ(dN_{cl}/dx)/(dN_{cl}/dx) =2.2%

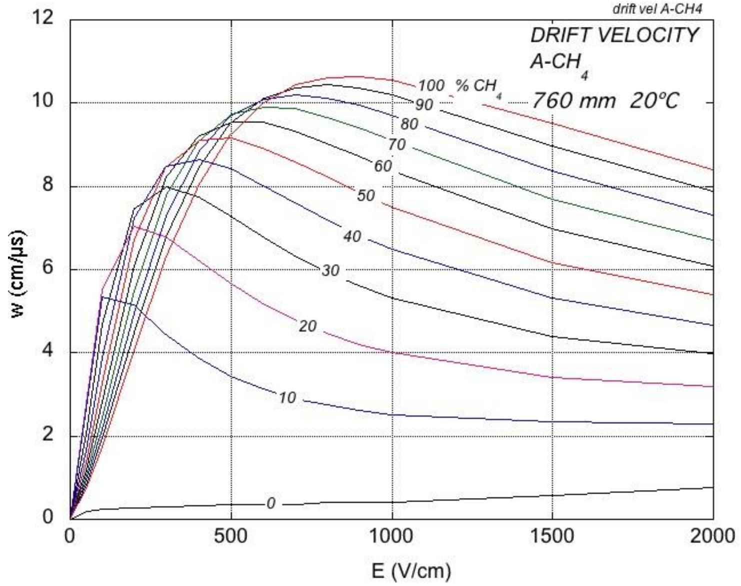
80% cluster counting efficiency

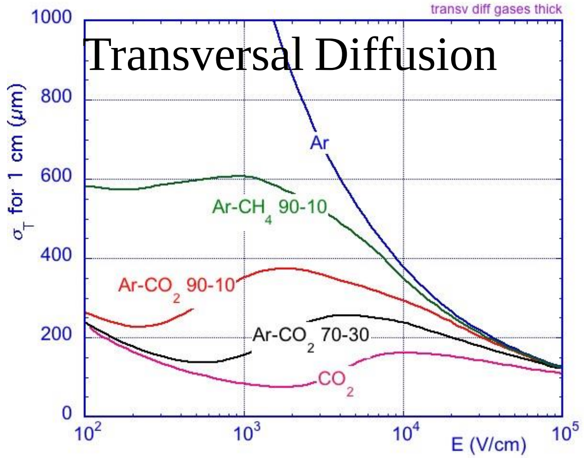


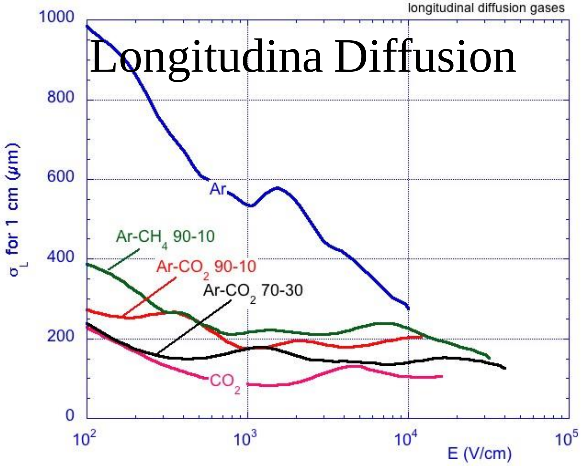
https://indico.cern.ch/event/996326/contributions/4200962/attachments/2191650/3704305/dEdx.pdf

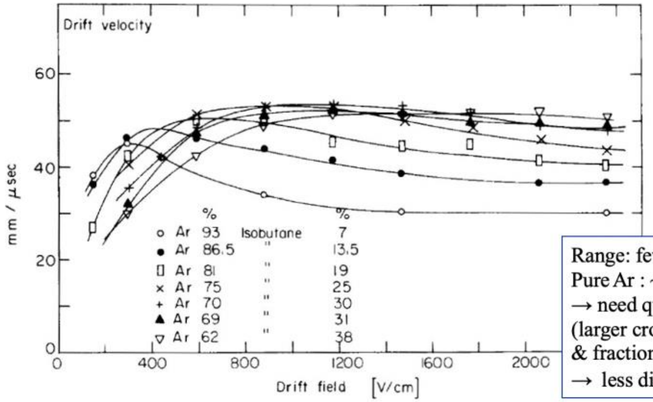
Limitations of Wire-based Detectors: Gas Mixture

DRIFT VELOCITY IN ARGON-METHANE MIXTURES



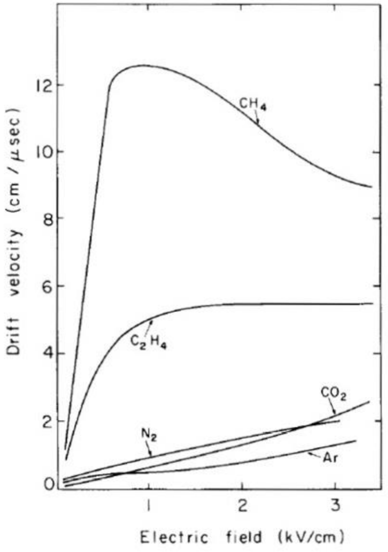






Range: few 10 mm/µs
Pure Ar : ~10 mm/µs
→ need quenching gas
(larger cross-sections
& fractional energy loss)
→ less diffusion

Drift velocity in several argon-isobutane (C_4H_{10}) mixtures



Limitations of Wire-based Detectors: Ageing

Deterioration of performance under irradiation has been observed since development of Geiger and proportional counters (~100 years) and yet it remains one of the main limitations to use Gas Detectors in high rate experiments.

Deterioration in Performance:

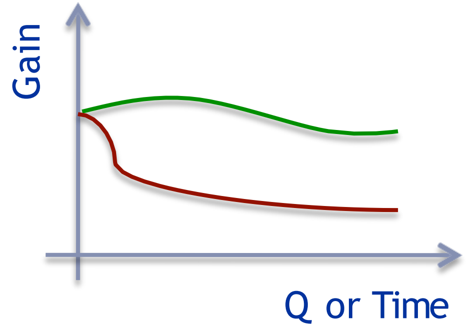
- loss of gas gain
- loss of efficiency
- worsening of energy resolution
- excessive currents
- self-sustained discharges
- sparks
- loss of wires
- changes of surface quality…

Ageing depends on the total collected charge Q:

Q [C] = Gain x Rate x Time x Primaries

Rate of Aging: R(%) ~ slope of **Gain vs. Q**

where Q is expressed in [C/cm] for wire detectors and [C/cm^2] for strips or continuous electrodes.



https://indico.cern.ch/event/122157/attachments/69728/99910/M_Capeans.pdf home.cern