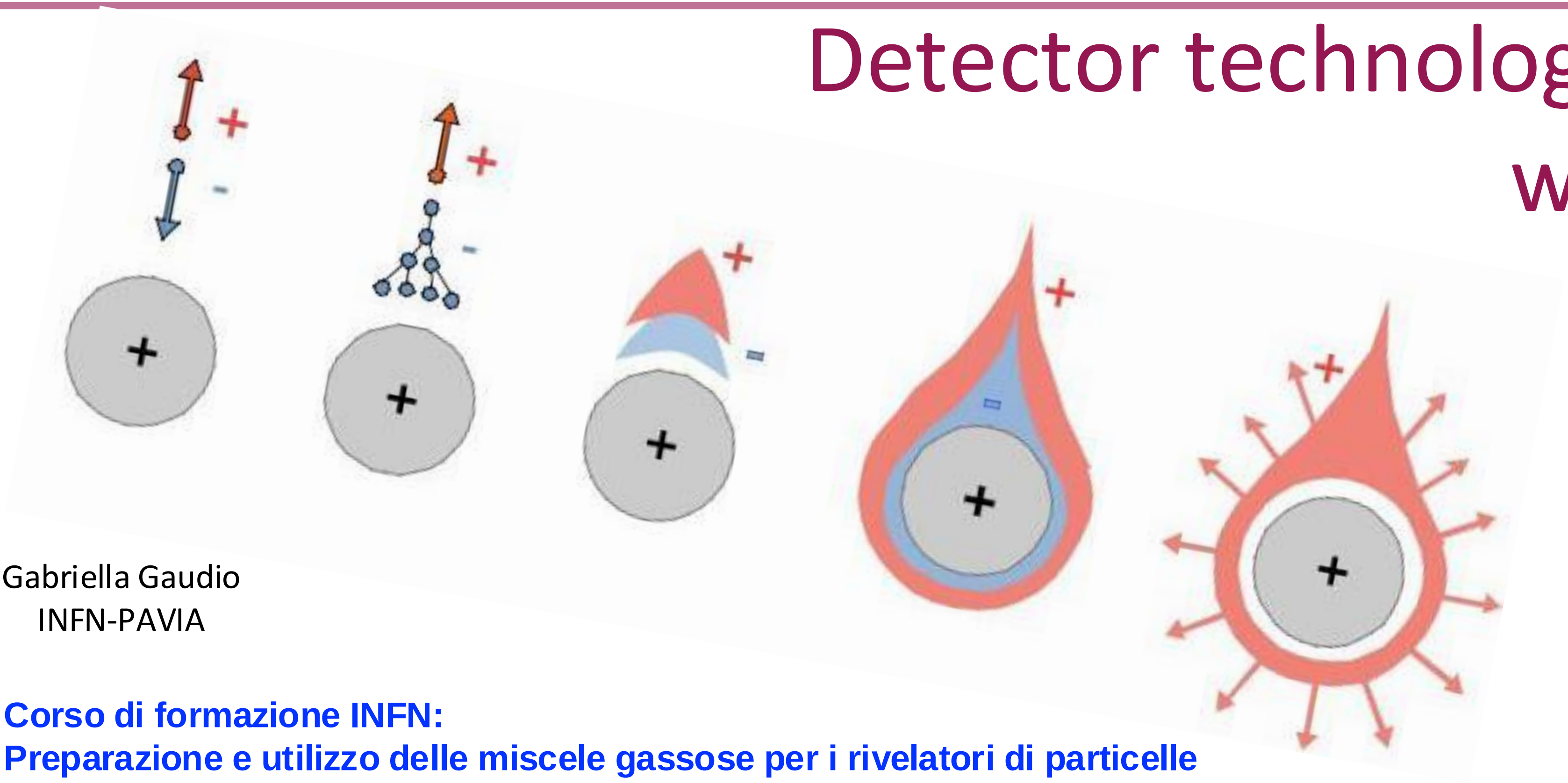
Detector technologies: wires



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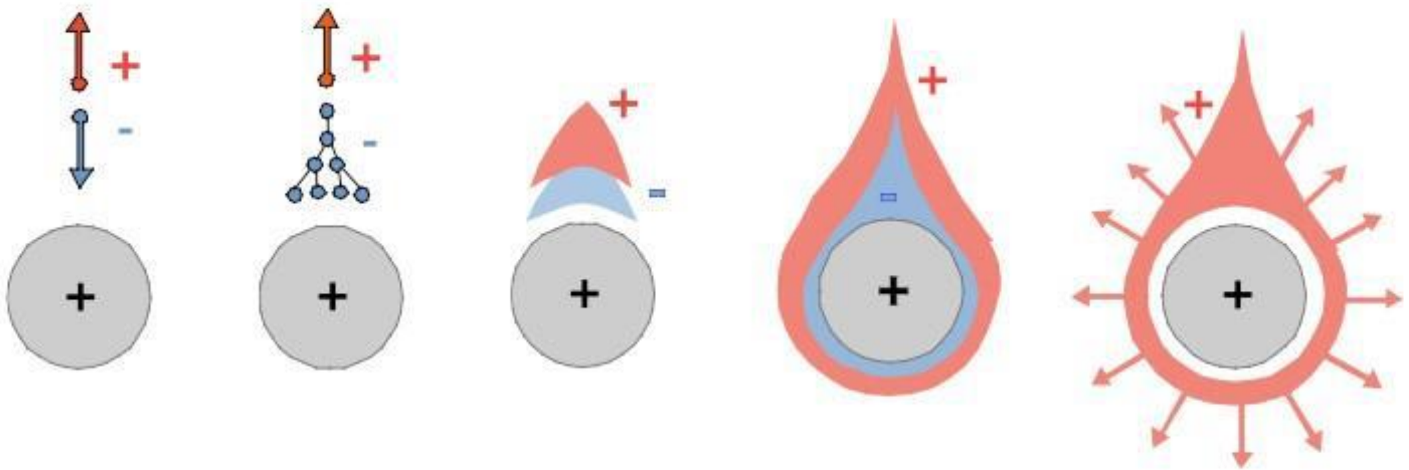
Corso di formazione INFN:
Preparazione e utilizzo delle miscele gassose per i rivelatori di particelle

Wire detectors: Avalanche development

Avalanche development around a thin wire:

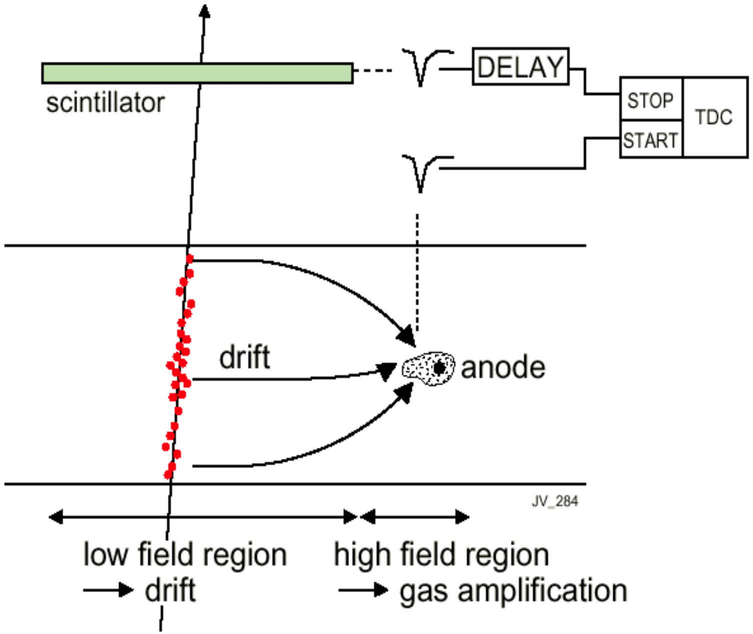


Wire-based gaseous detector

Some examples – no exhaustive overview

Drift chamber

- The drift chamber are characterised by a region (drift region) with a low |E| field, followed by a region with |E| > 10^4 V/m (proportional region)
- The spatial information is obtained by measuring the time of drift of electrons.



- The traversal of the particle is signalled by a scintillator or by the bunch crossing time in collider experiments. The stop on a TDC is given by the arrival of the electrons.

Drift chamber: space-time relation

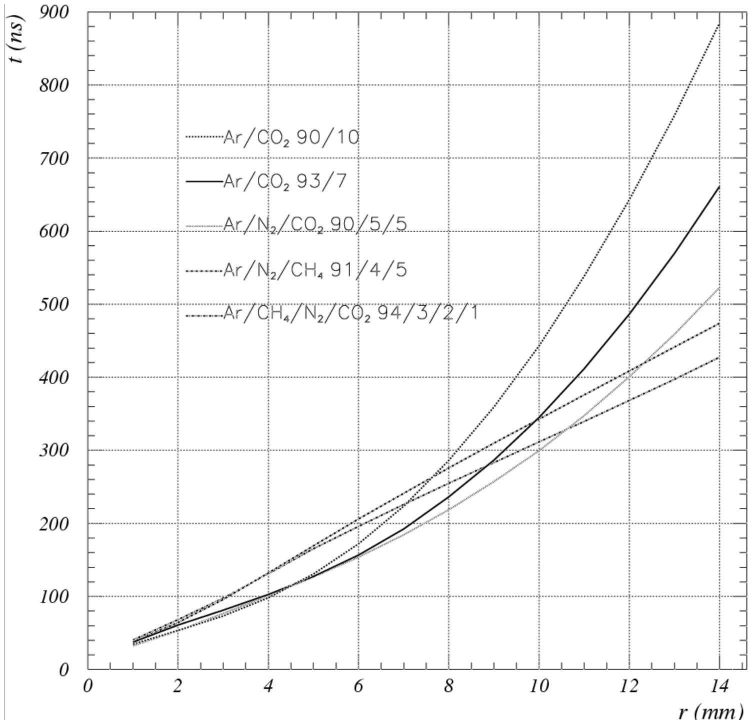
The drift distance is obtained integrating the detector specific space-time relation v(t)

Measured drift time

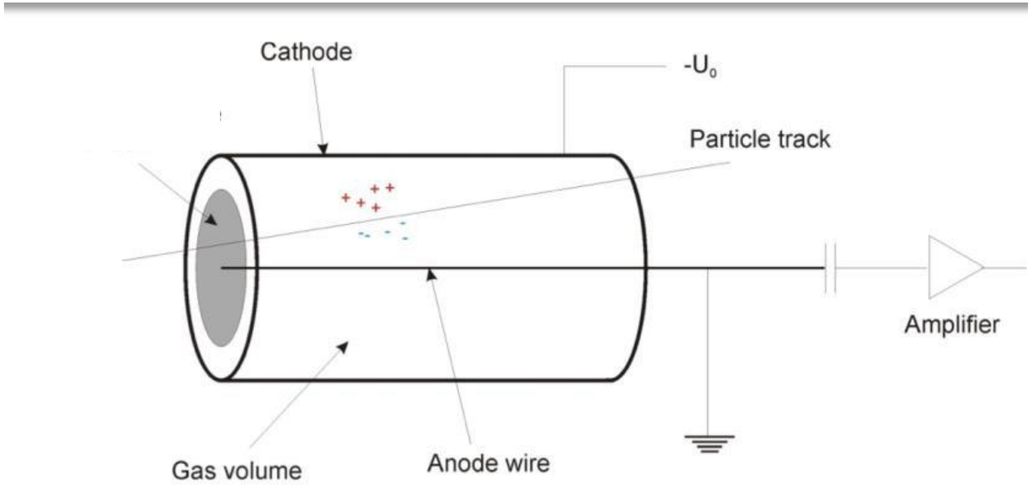
$$x = \int_{t_0}^{t_1} v(t) \cdot dt$$

Start time from external trigger

A complicate function of the detector geometry, the gas mixture, the magnetic field, etc.



Drift Tube – Working principle



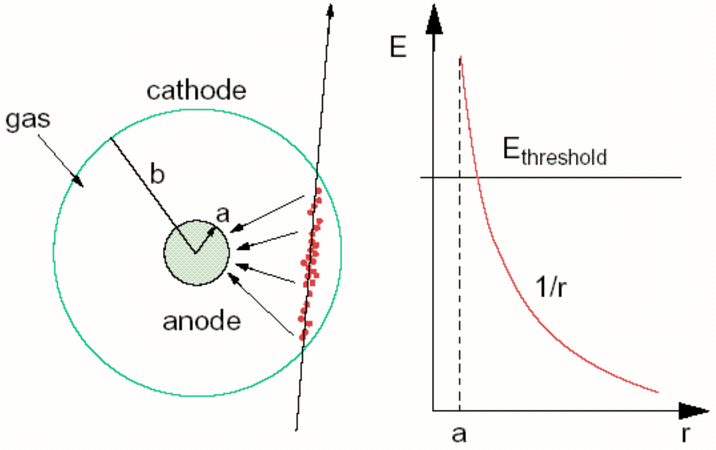
Charge gain:

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

Typical values:

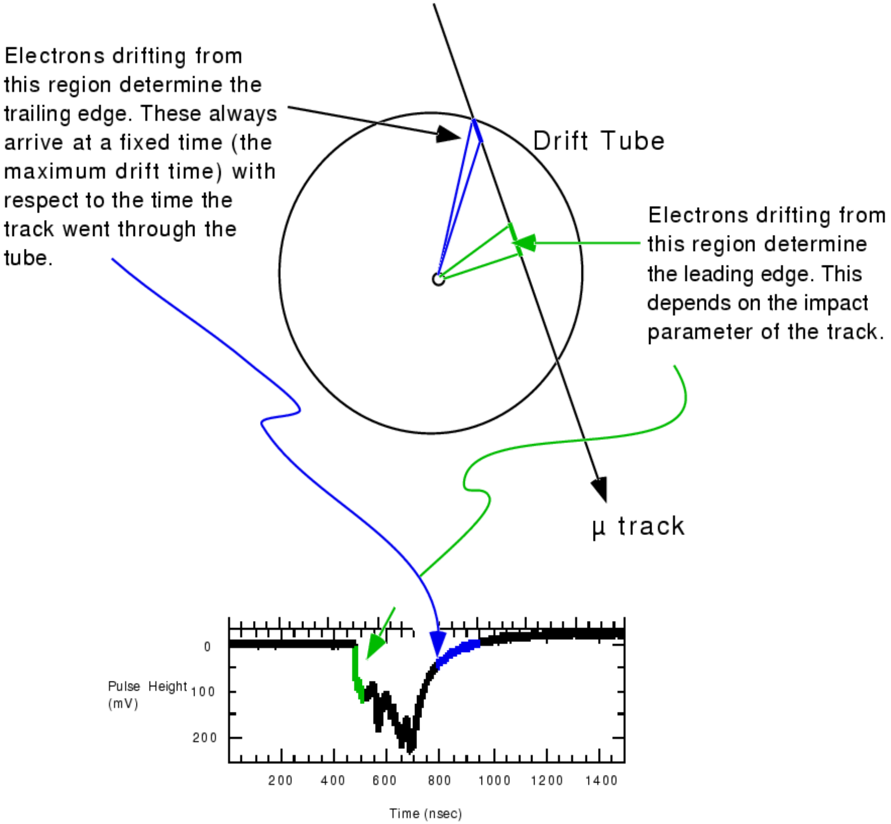
- **Proportional wire counter: G~10^4-10^6**

Avalanche starts at a distance of a few time the wire diameter => negligible position dependence of the pulse height



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

Drift Tube - Signals



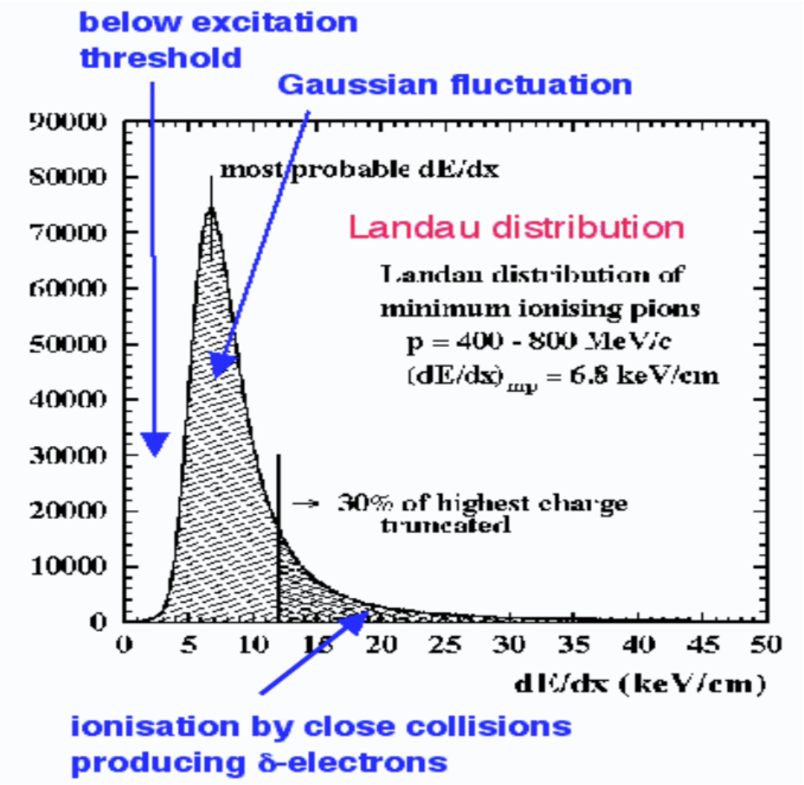
Electrons drifting from this region determine the trailing edge. These always arrive at a fixed time (the maximum drift time) with respect to the time the track went through the tube.

Electrons drifting from this region determine the leading edge. This depends on the impact parameter of the track.

Drift Tube Resolution

Tube resolution depends on drift time measurements and is therefore determined by:

- Statistical fluctuation of the gas gain for different primary electrons
- Fluctuations in the single cluster dimension due to the Landau distribution of charge deposition
- Discrete characteristic of the primary ionization process which implies a fluctuation in the relative distance of the clusters
- Diffusion of electrons during drift (grow with radial distance)
- Effect of the magnetic field
- Electronic noise



below excitation threshold

Gaussian fluctuation

ionisation by close collisions producing δ-electrons

Diffusion of ionization charge in a gas

- Charges produced in a ionization process uniformly diffuse from the interaction point (if no electric field is applied)
- Charges loose energy (by multiple collision with the gas molecules)

- Speed distribution is given by:

$$\frac{dN}{dv} = \sqrt{\frac{2}{\pi}}\left(\frac{m}{KT}\right)^{\frac{3}{2}} v^{2} \exp\left(-\frac{mv^{2}}{2KT}\right) \qquad v = \sqrt{\frac{8KT}{\pi m}}$$

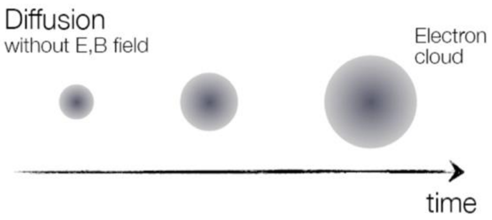
Mean square root speed

- Without external effects, a charge distribution diffuse accordingly to a gaussian law, characterized by a standard deviation (for three-dimensional diffusion)

$$\sigma_{V} = \sqrt{6Dt}$$

- Where D is the diffusion coefficient and is given by

$$D = \frac{2}{3P\sigma_{o}}\sqrt{\frac{KT}{\pi m}}$$

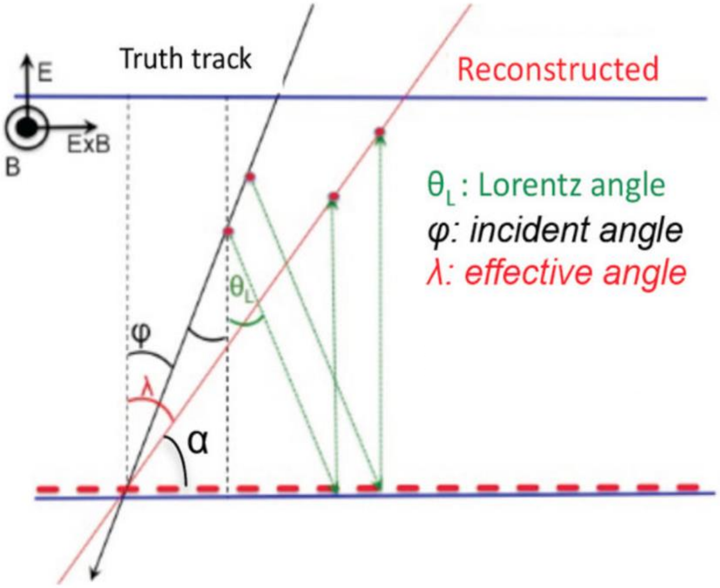


Increase gas pressure to minimize diffusion contribution on resolution

Effect of magnetic field

- The presence of a magnetic field modifies the drift properties of the charges.
- Macroscopic effect consists in
  - Reduction of drift velocity
  - Drift path different from the electric field lines
- If a constant magnetic and electric field is applied, the trajectory followed by the charges is a path bent of an angle a_L, called Lorentz angle

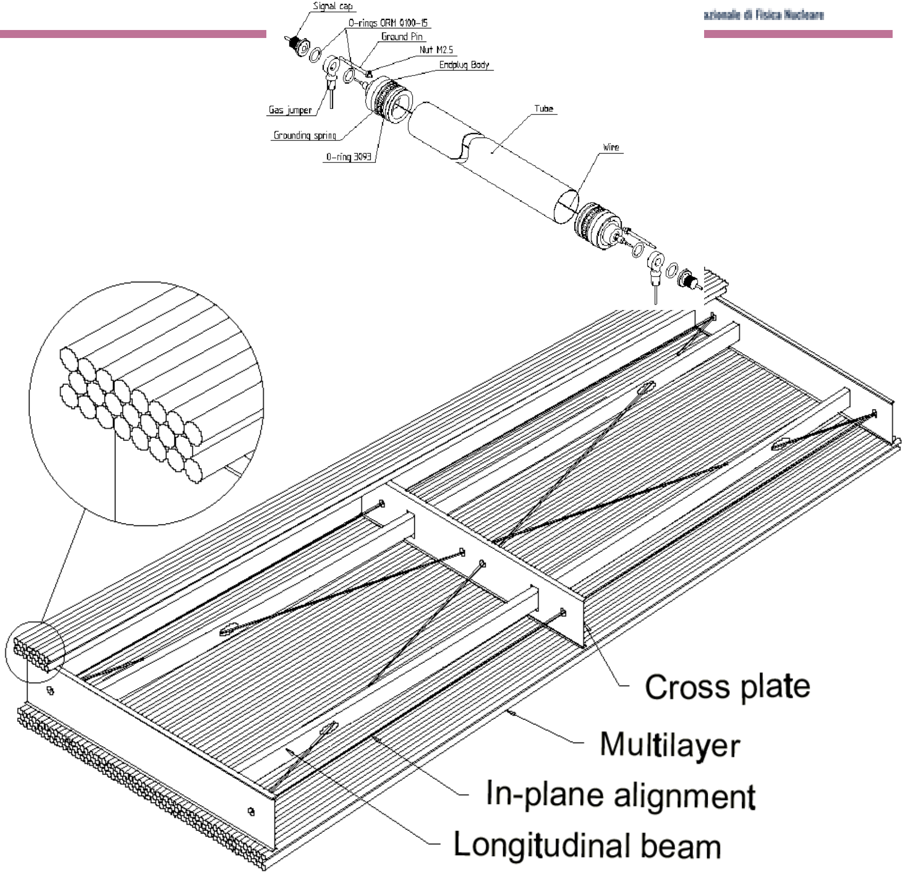
$$u_L = \frac{u}{\sqrt{1+\omega^2\tau^2}}; \quad \omega = \frac{eB}{m}; \quad tg\alpha = \omega\tau$$



The ATLAS Monitored Drift Tubes

- Two multi-layer of drift tubes separated by a spacer to increment the level arm
  - 4 layer per ML in the inner station (3 in the others)
- Tubes installed perpendicular to the beam direction
- Gas Mixture Ar-CO_2: 93/7
- Tube pressurised at 3 Atm to improve the resolution

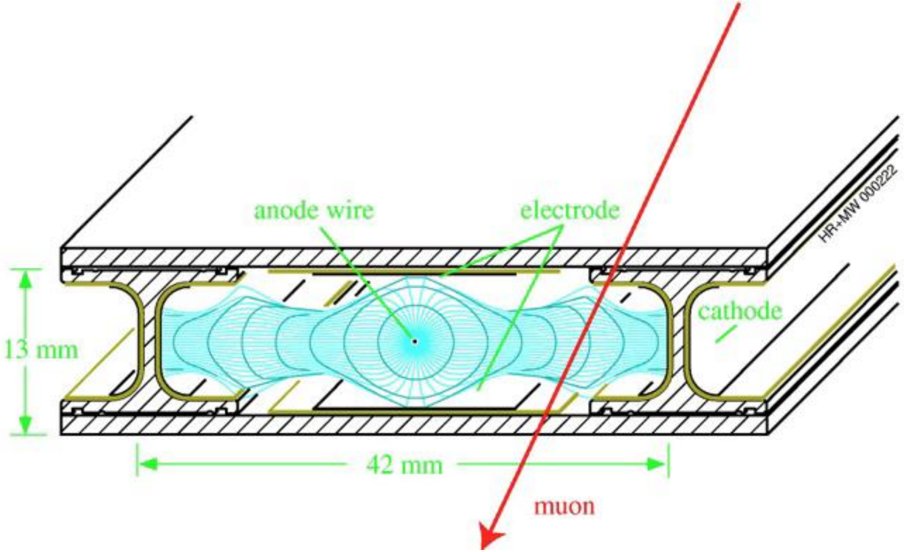
$$\boxed{\text{Diffusion} = \frac{2}{3P\sigma_0}\cdot\sqrt{\frac{kT}{\pi m}}}$$

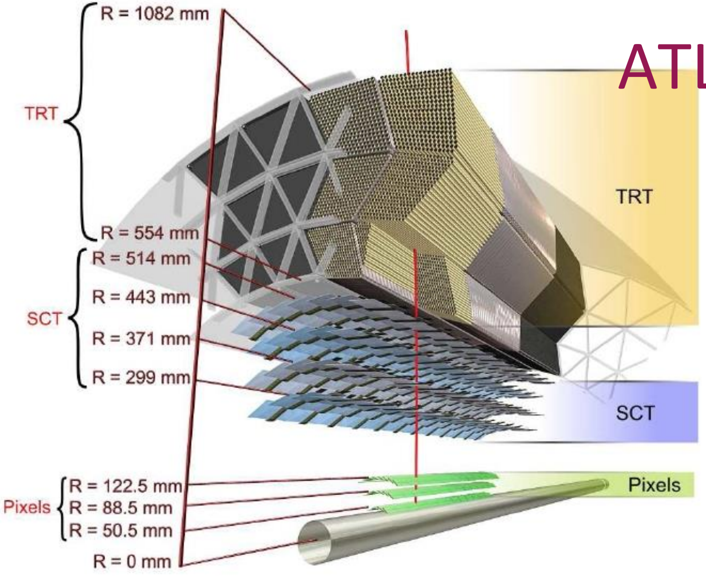


Drift Tube @CMS

Rectangular 10x40 mm^2 tubes with electric field shaping electrodes

- Rectangular shapes extends the drift distance while keeping the detectors thin
- Max drift time 400 ns
- Spatial resolution 250 !m



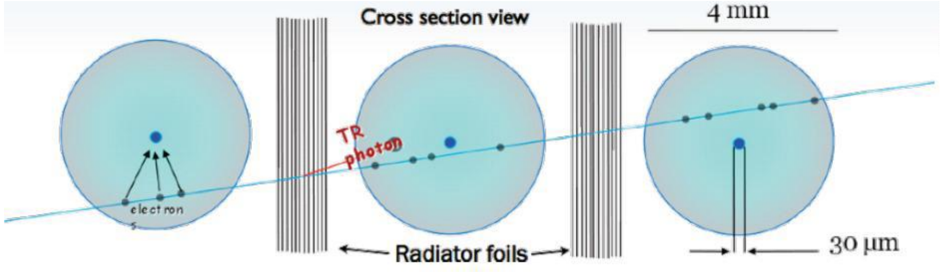


ATLAS Transition Radiation Tracker

The TRT provides both

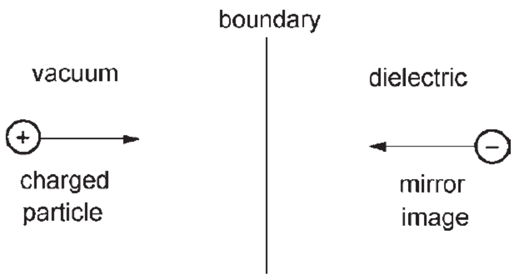
- continuous tracking in individual axial drift tubes (or straws)
- electron identification using the straws to absorb and to detect transition radiation X-ray photons originating from fibers (in the barrel) or thin foils (in the end-caps) between the straw themselves.

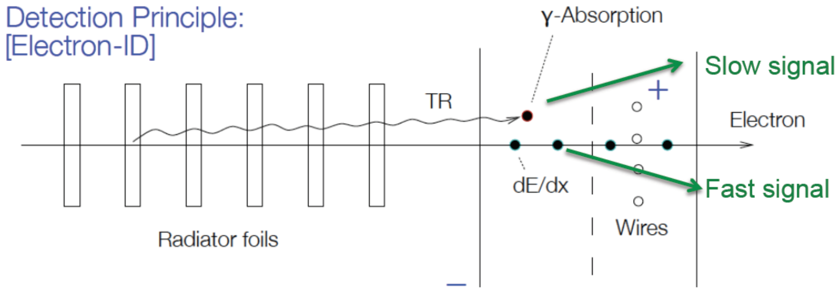
- Straw tubes with Xenon-based gas mixture
- 4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire
- Straw tube interleaved with TR material



Transition Radiation

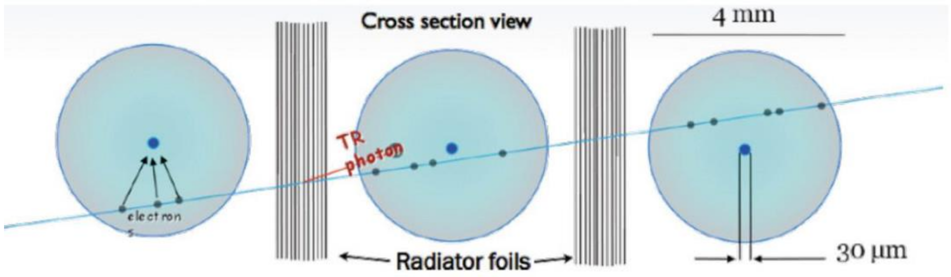
If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.





- A charged particle moving towards a boundary forms together with its mirror charge an electric dipole, whose field strength varies in time, i.e. with the movement of the particle.
- The field strength vanishes when the particle enters the medium.
- The time-dependent dipole electric field causes the emission of electromagnetic radiation.

TRT Straw tube – Particle identification

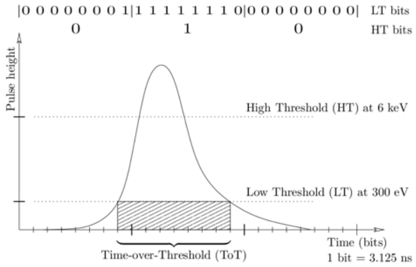


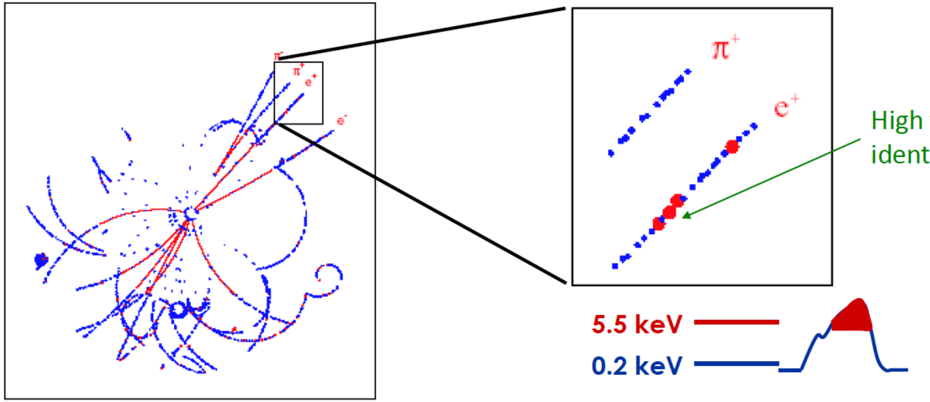
Ionized electrons drift to straw wire to create signal (~several 100 eV)

- Detect with **Low Threshold (LT)**

TR photons generate signal ~10keV

- Detect with **High Threshold (HT)**



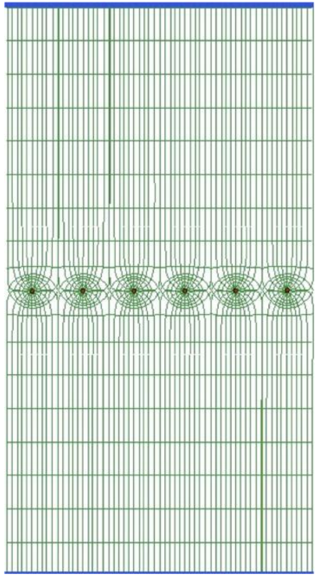


High threshold hits identify electrons

Readout pulse

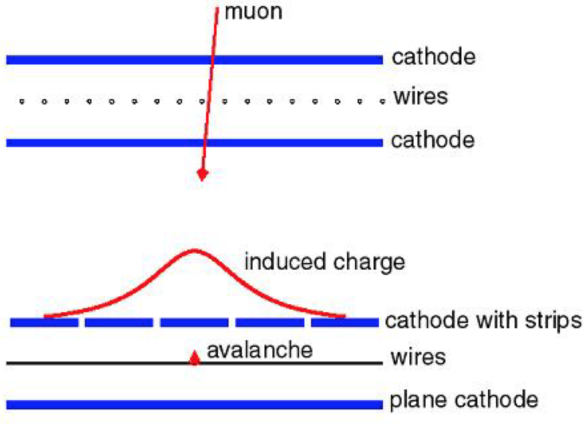
Energy deposition in the straw is the sum of ionization loss (~2 keV) and the larger deposition due to transition radiation absorption (> 5 keV) → use two thresholds in the readout electronics

Multiwire Proportional and Cathod Strip Chambers



MWPC (Charpak 1969)
chambers made of planes of wires
typical geometry:

- anode-cathode gap is 5 mm
- 20 µm anode wires, 1-2 mm pitch
- Spatial resolution: ~500 µm



- CSC = MWPC with cathode planes segmented into strips running perpendicular to wires
- The shape of induced charge on the cathode surface is defined by the plain electrostatics
- The space resolution mostly depends on a wire-cathode distance and the strip width.

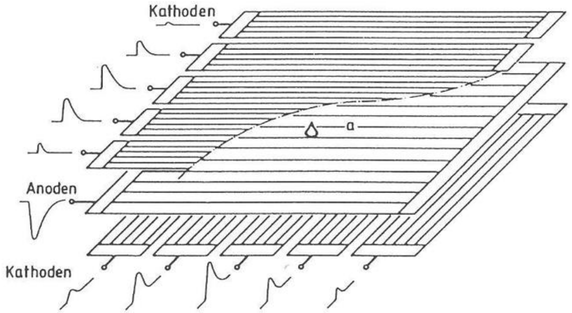
Cathod Strip Chambers

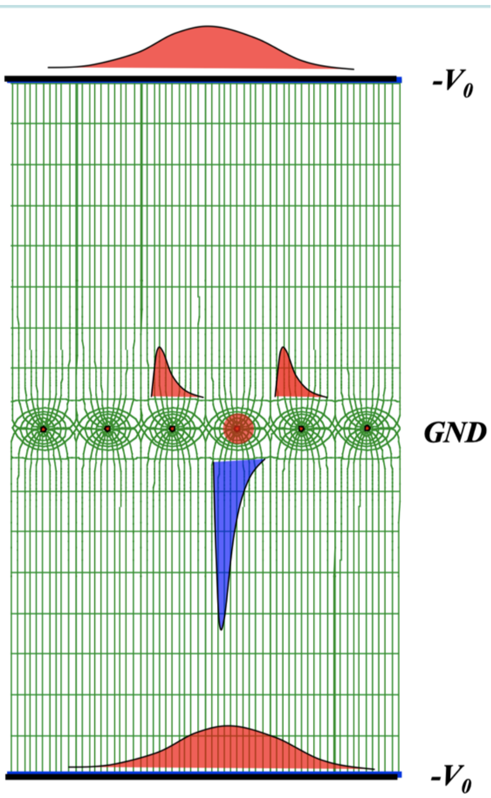
Segmented cathodes:

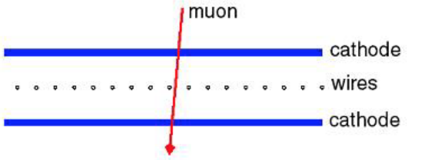
- cathode strips (often perpendicular and parallel to anode wires)
- cathode wires
- Pads/Strips

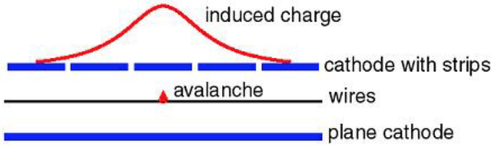
Avalanche induces signals on cathode strips/pads with amplitude varying with the distance to the avalanche

Centre of gravity method to improve resolution









Gas effects in gaseous detectors

Gas detector choice

Nobel gas:

- To obtain a large gas gain at lower HV
- Electron energy is not wasted on breaking up molecules without releasing new electrons
- The larger atomic number is, the lower the ionization potential is. However, Xe and Kr are fairly expensive => Hence, Ar is the noble gas of choice

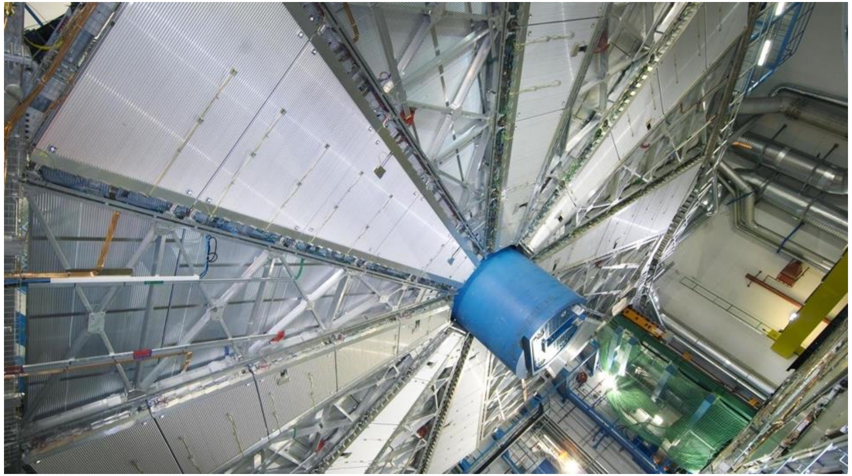
Quenching gas: to prevent discharges

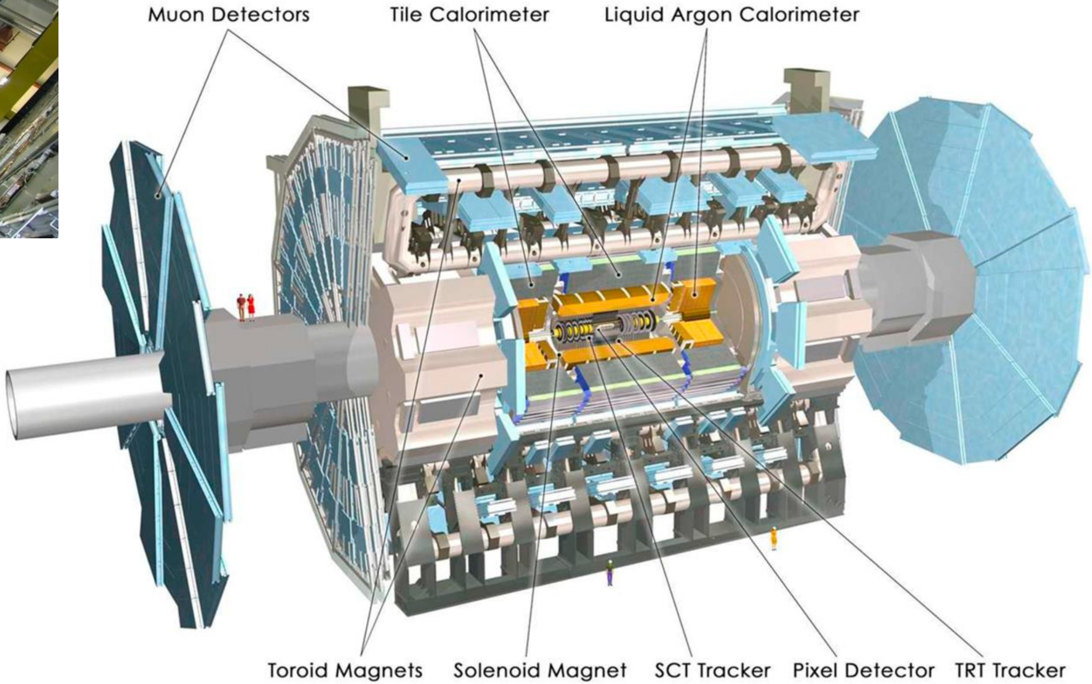
- Add gas with complex molecules that absorb easily de-excitation photons produced in avalanches before they reach cathode surface and knock out new electrons…
- CO_2 , isobutane (i-C4H10), pentane (C5H12), etc.
- Typically, the more complex the molecule is, the better its quenching properties are
- Complex organic molecules tend to polymerize under radiation leading to detector "aging"

General considerations:

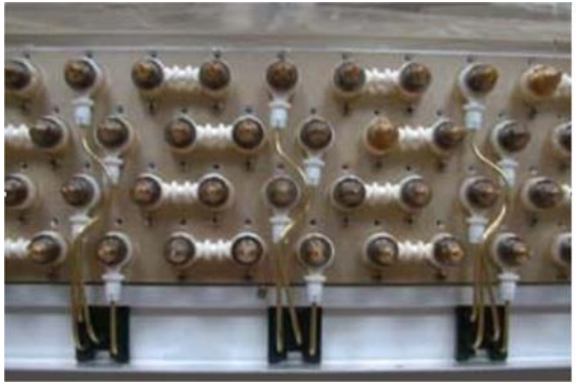
- Add H_20, O_2, CF_4 to prevent detector aging under radiation
- Drift velocity varies between gasses
- Electron diffusion varies between gasses
- Electronegative properties of gases (electron attachment), their physical and chemical activity

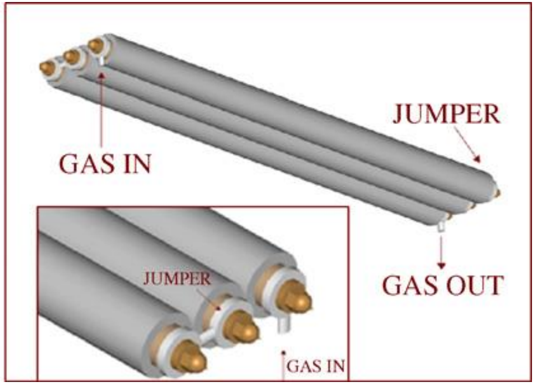
Use Case: ATLAS MDT chamber





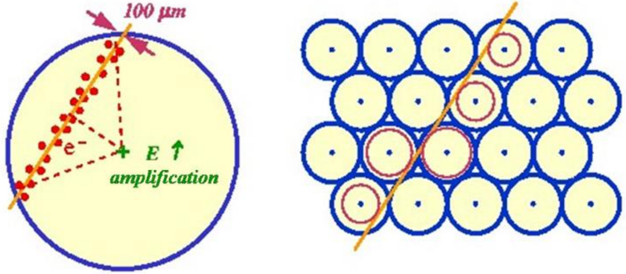
Use Case: ATLAS MDT chamber



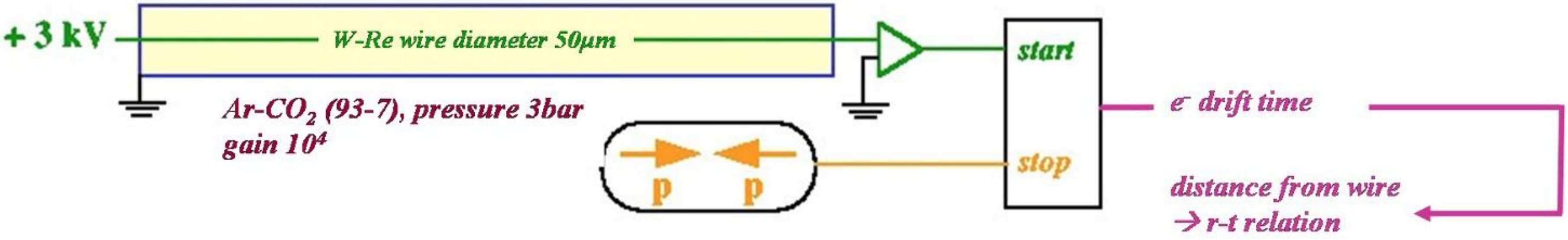


To ensure stable and uniform drift properties, the leak rate at room temperature should not exceed 2×10^{-8} bar l/s per tube

Drift time measurements

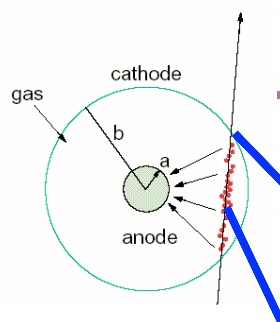


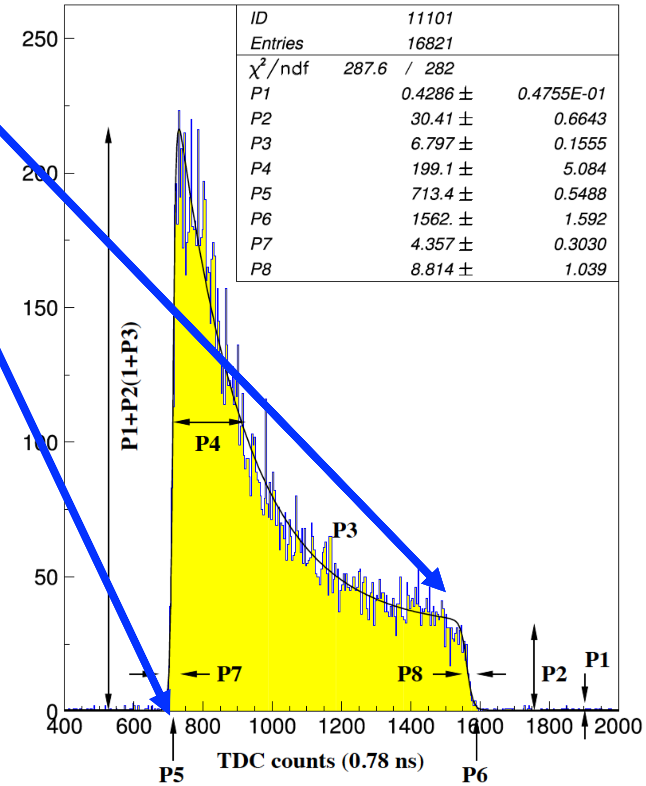
Original MDTs = diameter 3 cm (1076 chambers),
Small MDT (sMDT) = diameter 1.5cm (22 chambers)



MDT Time Spectra

$$f(t) = p_1 + \frac{p_2\left(1 + p_3 e^{-\frac{t-p_5}{p_4}}\right)}{\left(1 + e^{\frac{-t+p_5}{p_7}}\right)\left(1 + e^{\frac{t-p_6}{p_8}}\right)}$$





- two Fermi Dirac functions describing the leading and trailing edge
- an exponential function for the central part

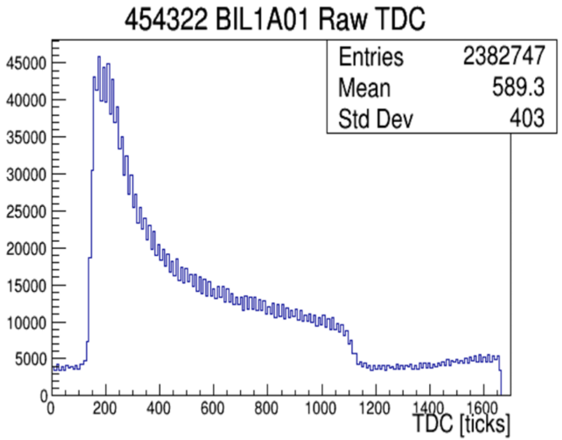
- Parameters:
  - •p1 is the uncorrelated (flat) background
  - •p2, p3 and p4 shape of the central part of the distribution
  - •p5 is the t0
  - •p6 is the maximum drift time
  - •p7 and p8 leading and trailing edges

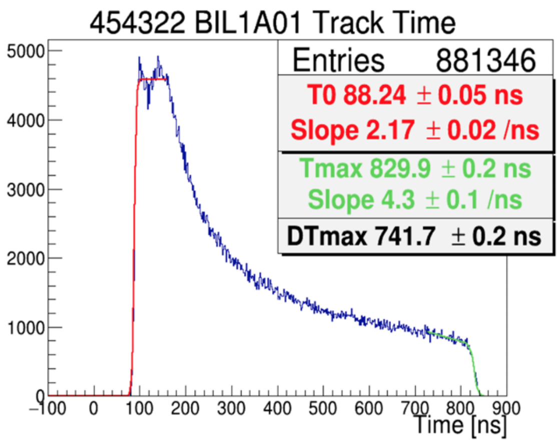
Drift time corrections

$$\text{Drift time} = \text{tdc} * 0.78125 - T_0 - T_{\text{flight}} - T_{\text{slew}} - T_{\text{Bfield}} - T_{\text{prop}} \ [\text{ns}]$$

① tdc = raw time of hit [ticks]; 0.78125 = ticksize [ns/tick];
② T_0 = timing offset of tube [ns];
③ T_{flight} = time of flight from ATLAS IP to MDT tube [ns];
④ T_{slew} = timeslew correction, to correct for jitter related to pulse height of signal [ns];
⑤ T_{Bfield} = Magnetic field correction, removes increase in drift time caused by magnetic field [ns];
⑥ T_{prop} = Propagation time of the signal relative to the center of the tube (+-) [ns].

Applying the time corrections sharpens the rising edge of the time spectrum:

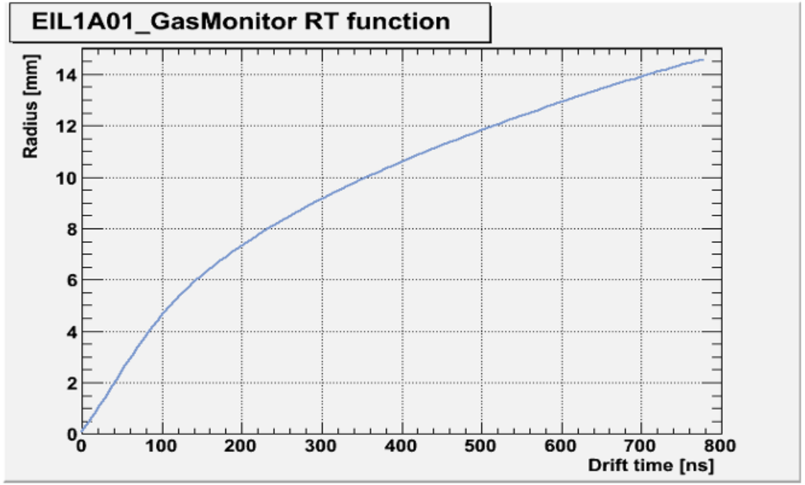




Position information

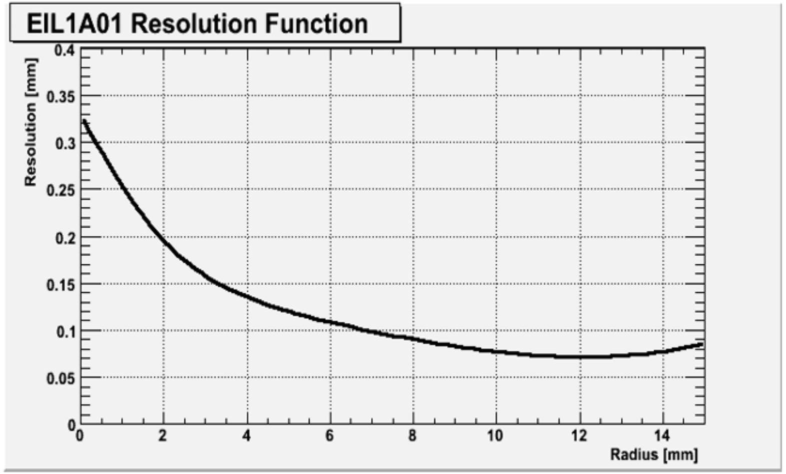
Time-to-space function

(RT function) Used to convert Drift time to drift radius



Resolution Function

Resolution as a function Of drift radius



Gas Monitoring Chamber info

Monitor simultaneously the input feed and exhaust gas to the complete MDT system

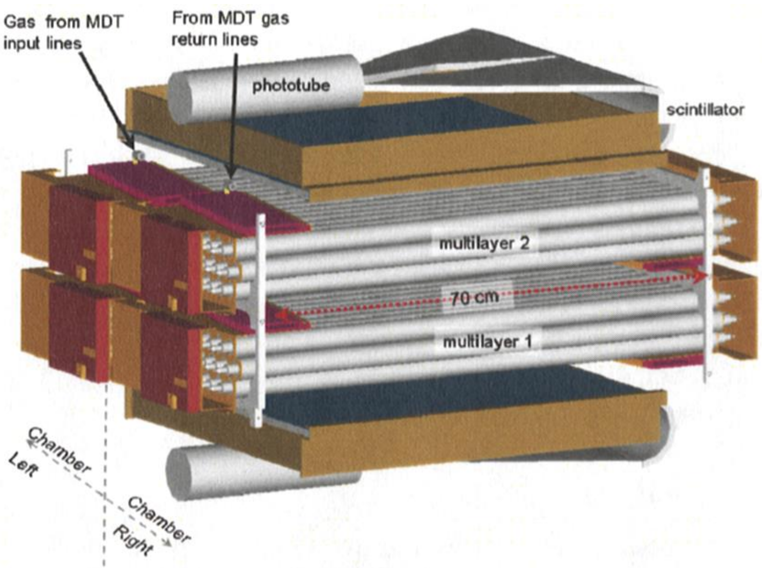
Sensitive to changes of 1 part per mil to the internal gas composition

Monitoring

- drift time
- gas flow rate
- temperature and pressure
- RT-relation per drift tube

Parameter mostly sensitive to gas composition is the T_{max}

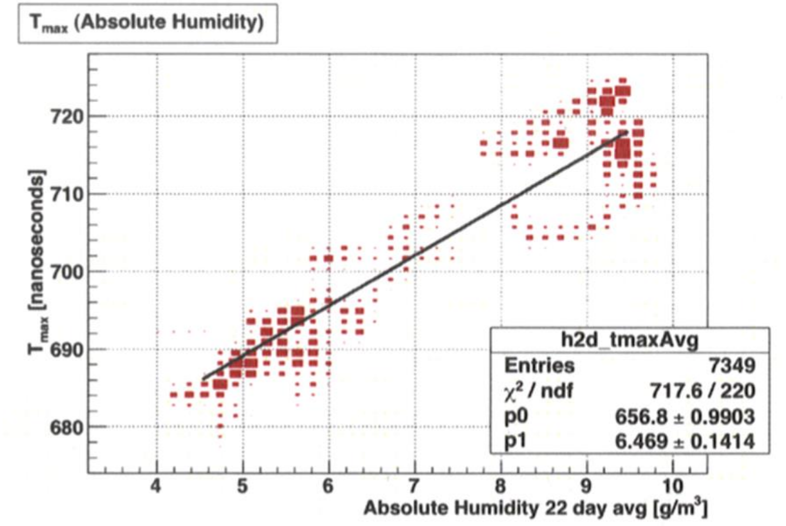
Determine the radius-time (RT) relation : correlation between drift tube time and hit radius

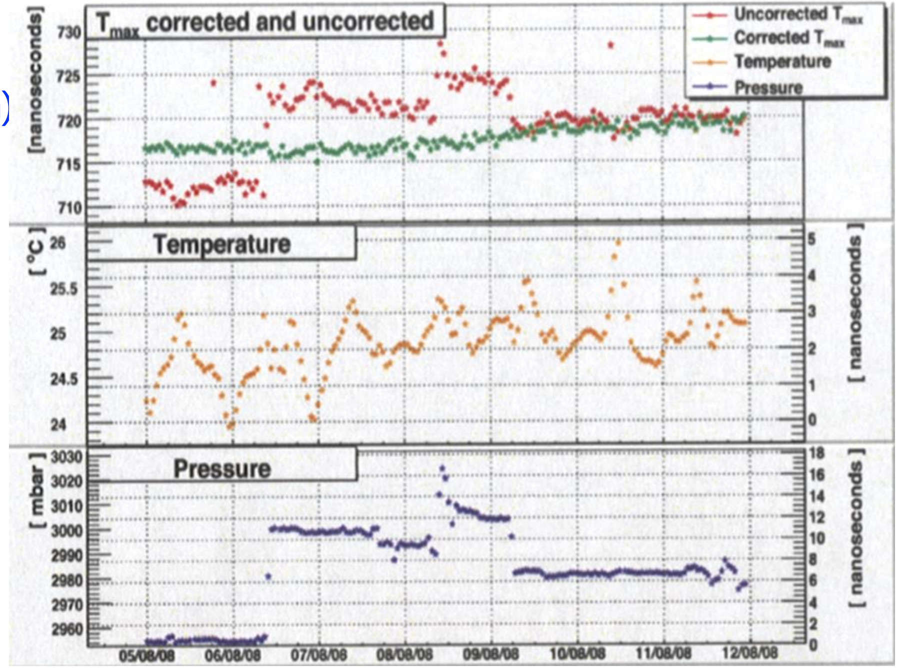


gas flow change 1 volume per day.
90 % recycled gas + 10% fresh gas
time for the gas pollution to be eliminated ~ 2 weeks

Effects on MDT performance

- dT_{Max} / dT 2.5ns/ C (T=temperature in °C);
- dT_{Max} / dP 0.2Gns/mbar (P=pressure in mbar);
- dT_{Max}/ dH 0.066ns/ppm (H=water in parts per million)
- dT_{Max} /df_{CO2} 91ns/%C02 (f_{C02} = %CO_2);





Aging effects: gaseous detector drawbacks

Problems development in gaseous detectors

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.

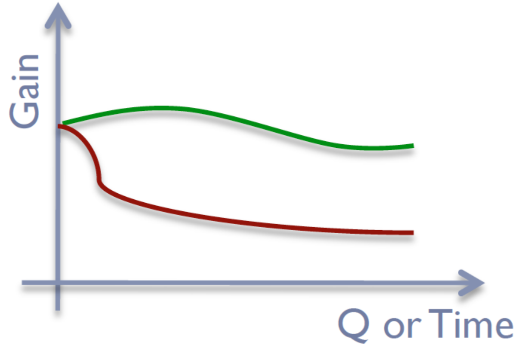
This behaviour is intimately associated with the gas mixture in the chamber and with certain contaminants.
However, the material properties of the anodes and cathodes as well as their size also play a role in this area which is far from being clearly understood.
Given the practical importance of the subject and that the new accelerators will produce extremely high levels of radiation, efforts towards better understanding are under way.

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

Gas detector Aging

Deterioration in Performance due to irradiation

- 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.

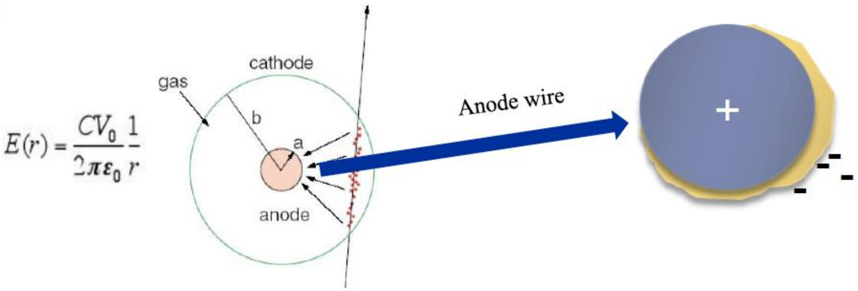
- HV
- Gas mixture
- Pressure
- Gas exchange rate
- Electrical field strength
- Detector geometry
- …

- Dose rate
- Ionization density
- Particle type
- …

Aging effects

Wire aging

- complex organic molecules tend to polymerize
- the processes is often driven by minute gas impurities and material outgassing
- as the cumulative charge released in avalanches increases, deposits start appearing on either wires or cathode
- Wire deposits ones decrease gas gain and cause operational instabilities

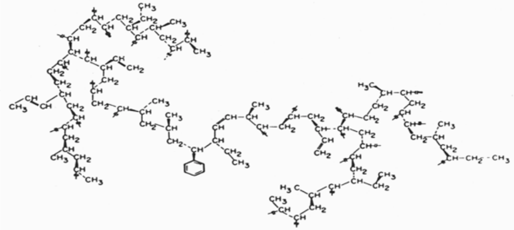


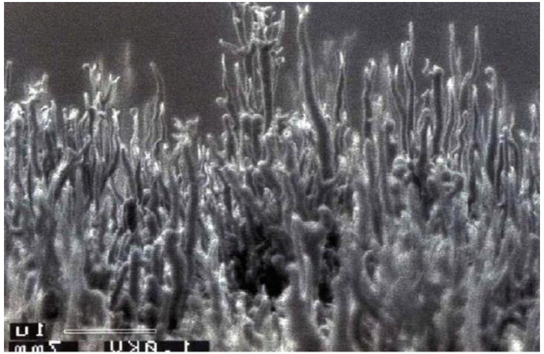
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

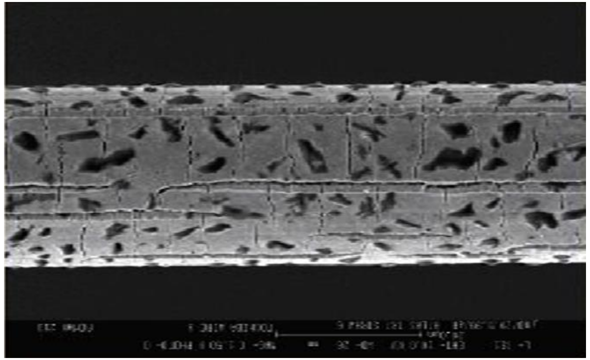
- If deposit is conductive, there is a direct effect: the electric field weakens (~thicker wire)
- If deposit is insulating, there is indirect effect due to dipole charging up: the field close to the anode will be screened as new avalanches accumulate negative charges on the layer

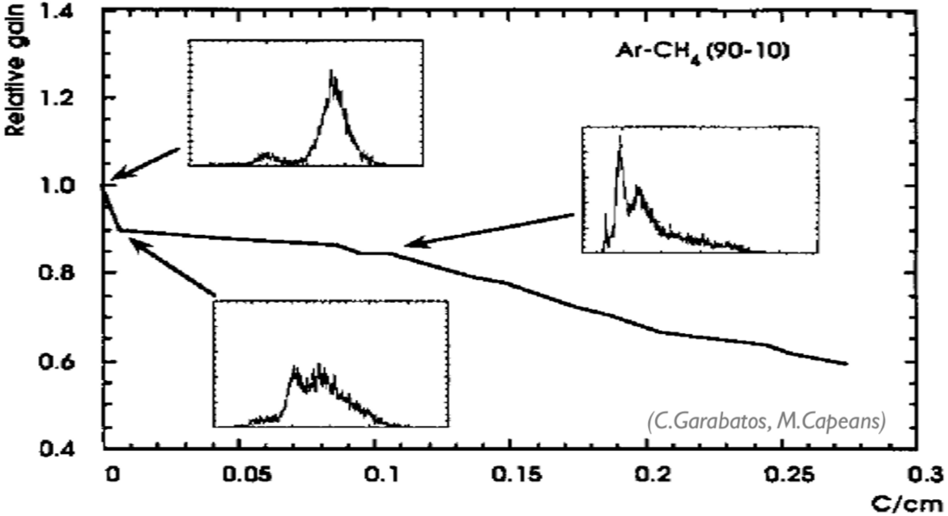
Ar-CH_4 aging effects

1. Gas mixture → Ar + CH_4
2. Initial Reaction → $e^- + CH_4 \Rightarrow CH_2{:} + H_2 + e^-$
3. Creation of radicals → $CH_2{:}$
4. Polymer Formations →
   - Solid, highly branched, cross linked
   - Excellent adhesion to surfaces
   - Resistant to most chemicals
   - Insoluble in most solvents





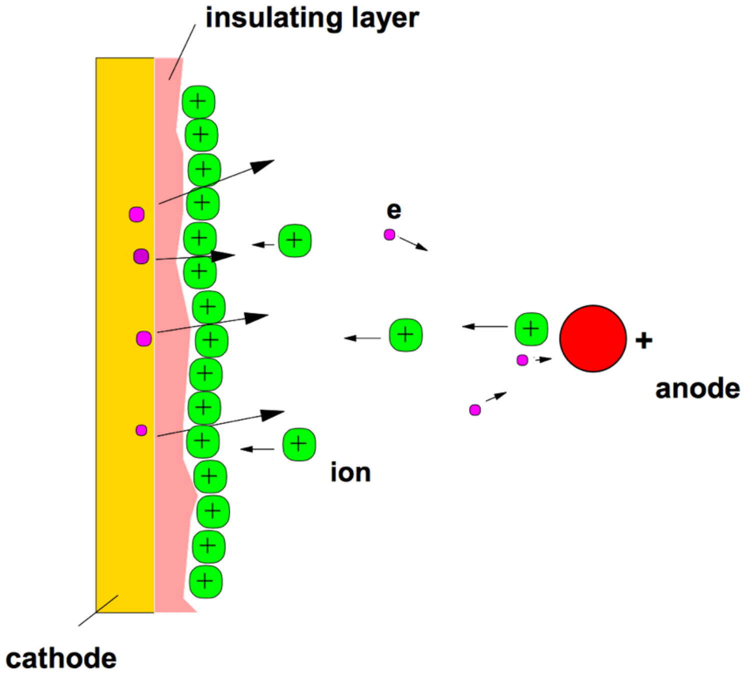




(C.Garabatos, M.Capeans)

Aging surface effect: Malter effect

- Thin film insulator deposits on cathode charge up under irradiation
- Large electric field across the thin film can cause electron emission from cathode
- This positive feedback can create a self-sustained discharge with a very large local current density, which will eventually lead to HV breakdown



“Fighting the age”

Small concentrations of some components can restore aged chambers or prevent effectively the aging process to significant accumulated charges

O_2

- Etching of HC-deposits
- Reacts with HC, and end products are stable and volatile

H_2O

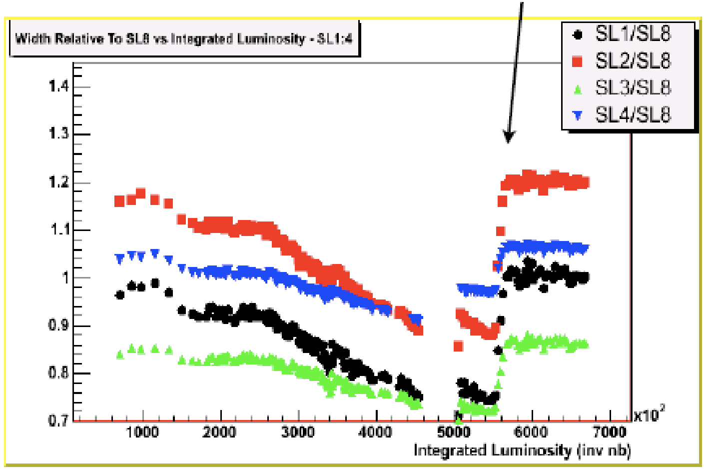
- Reduces the polymerization rate in plasma discharges
- Makes all surfaces slightly more conductive, thus preventing the accumulation of ions on thin layers responsible for the gain degradation and Malter effect
- But, modification of the electron drift parameters or change in
- rate of discharges are not always acceptable

Alcohols

- Reduction of polymerization rate
- Large cross section for absorption of UV photons

Central Outer Tracker
CDF Fermilab

Addition of O2 in the gas mixture Ar-C2H6 [50-50]

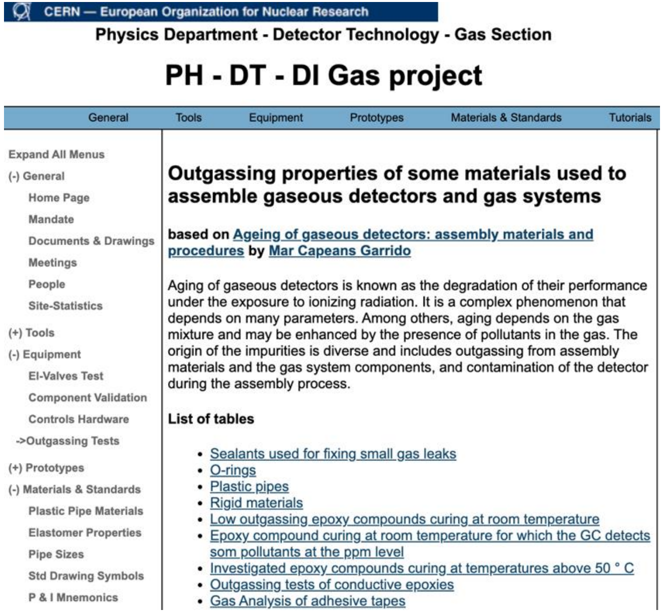


Material Choice

Minor changes, big impact

Difficult to control all parameters in large systems, at all stages

Need validation of materials (detector assembly materials and gas systems' components), with an efficient strategy



Physics Department - Detector Technology - Gas Section

PH - DT - DI Gas project

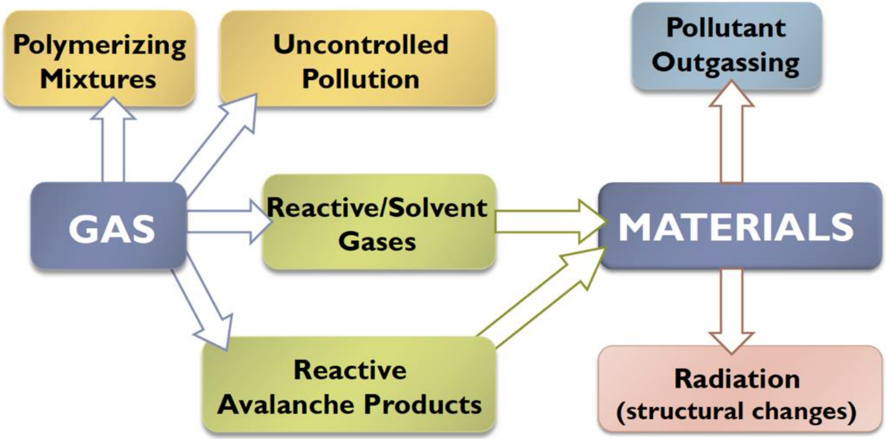
Outgassing properties of some materials used to assemble gaseous detectors and gas systems

based on Ageing of gaseous detectors: assembly materials and procedures **by** Mar Capeans Garrido

Aging of gaseous detectors is known as the degradation of their performance under the exposure to ionizing radiation. It is a complex phenomenon that depends on many parameters. Among others, aging depends on the gas mixture and may be enhanced by the presence of pollutants in the gas. The origin of the impurities is diverse and includes outgassing from assembly materials and the gas system components, and contamination of the detector during the assembly process.

List of tables

- Sealants used for fixing small gas leaks
- O-rings
- Plastic pipes
- Rigid materials
- Low outgassing epoxy compounds curing at room temperature
- Epoxy compound curing at room temperature for which the GC detects som pollutants at the ppm level
- Investigated epoxy compounds curing at temperatures above 50 ° C
- Outgassing tests of conductive epoxies
- Gas Analysis of adhesive tapes


Polymerizing Mixtures

Uncontrolled Pollution

Pollutant Outgassing

GAS

Reactive/Solvent Gases

MATERIALS

Reactive Avalanche Products

Radiation (structural changes)

https://detector-gas-systems.web.cern.ch/Equipment/outgassing.htm

Credits

M. Bianco, EURIZON Detector School | Gaseous Detectors | 17th-28th 2023 Wuppertal
M. Capeans 4th MC-PAD Network training Event