Detection Techniques & Detectors

- When particles interact with matter, the results of those interactions can be used as basis for the detectors.

- The main interactions of charged particles with matter produce ionization and excitation.. For relativistic particles, bremsstrahlung becomes significant and should be considered.

- Neutral particles must produce charged particles in an interaction, to be detected.
  - Photons produce electrons (positrons) through photoelectric effect, Compton scattering, pair-production.
  - Neutrons produce other charged particles through strong interactions.

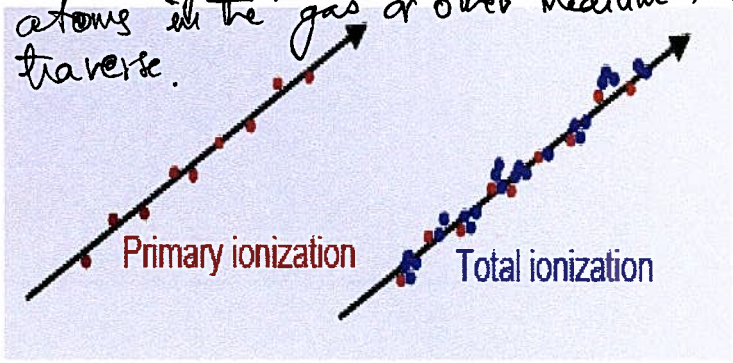
- Physics goals define what detectors to build, measure what particles and quantities and with what precision

Ionization Loss and Particle Detection

We have learnt that Ionization of the atoms in the medium is one of the ways charged particle lose energy in matter.

If we can detect the ionization along the path of the particle, we can detect it, even track it

Fast charged particles can ionize atoms in the gas or other medium they traverse.



The electrons produced in the primary collisions may have enough energy to ionize other atoms.

→ Secondary Ionization

Thickness traversed

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

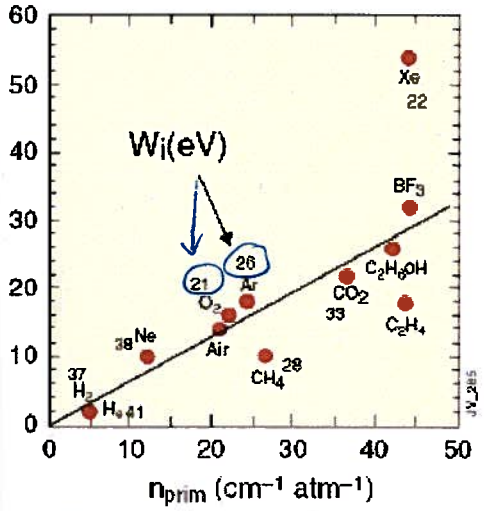
n_{total} - number of created electron-ion pairs

Δ_E = total energy loss

W_i = effective <energy loss>/pair

Work Function

Lohse and Witzeling, Instrumentation in High Energy Physics, World Scientific, 1992



n_p = No. of Primary ion pairs

n_t = Total number of ion pairs

Gas	$\bar{Z}$	A	I_0 (eV)	W_i (eV)	$\frac{dE}{dx}$ [keV/cm]	n_p [/cm]	n_t [/cm]
He	2	4	24.6	41	0.32	5.9	7.8
Ar	18	39.9	15.8	26	2.44	29.4	94
Xe	54	131.3	12.1	22	6.76	44	307
CO_2	22	44	13.7	33	3.01	34	91
CH_4	10	16	13.1	28	1.48	16	53
CF_4	42	88		54	5.40	51	100

For a mixture of gases:

$$n_t = \sum_i \frac{1}{W_i} \cdot \frac{dE}{dx} \cdot f_i$$

f_i = Component fraction

Example:

For Run I Muon System (PDTs) at DØ

we used Ar (90%) / CF_4 (5%) / CO_2 (5%)

$n_p \simeq 31/cm$ $\quad n_t = 94/cm$

Average distance between primary interactions

$= \frac{10{,}000\,\mu m}{31} \simeq 323\,\mu m$

Each primary interaction produces ~3 secondary interactions

Run II gas mixture:

Ar (80%) CF_4 (10%) CH_4 (10%)

$n_p \simeq 29/cm$ $\quad n_t = 91/cm$

The medium can be gas, liquid or solid.

Note that in gases, $W \sim 30\,eV$

On the other hand,

in Silicon $W \sim 3.6\,eV$; in Germanium $W \sim 2.85\,eV$

Solid state detectors

More compact, higher precision

Drift and Diffusion in Gases

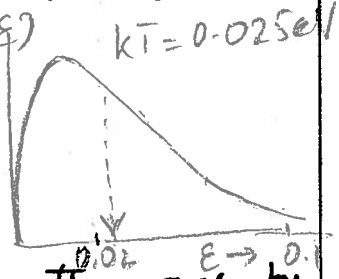
Electrons and ions produced in an ionization process will lose their energy by multiple collisions with atoms and molecules in the gas. They approach the thermal energy distribution with average energy,

$$\mathcal{E} = \frac{3}{2} kT \qquad (k = \text{Boltzmann constant}, \; T = \text{temperature in } ^\circ K)$$
$$\simeq 0.040\,eV$$
$$\simeq 40\,meV \quad \text{at RT.}$$

(Equipartition law)

The distribution of kinetic energies will follow Maxwell-Boltzmann distribution,

$$F(\mathcal{E}) = c \cdot \sqrt{\mathcal{E}}\; e^{-\mathcal{E}/kT}$$



The charges/ions diffuse through the gas by multiple collisions with a Gaussian differential density distribution.

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi D t}} \cdot e^{-x^2/4Dt} \cdot dx$$

→ fraction of the charge found in elemental length dx at a distance x from the origin and after time t.

D = Diffusion coefficient.

The standard deviation

$$\sigma_x = \sqrt{2Dt}$$

The Diffusion coefficient, D depends on the thermal velocity 'u' of the charged particles

$D \uparrow$ if $u \uparrow$

$$u = \sqrt{3kT/m}$$

$$\frac{mu^2}{2} = \frac{3}{2}kT$$

$$u = \sqrt{3kT/m}$$

$\therefore$ D decreases with increasing mass of the particles, as expected.

The average mean free path in the diffusion process

$$\lambda = \frac{1}{N \cdot \sigma(\epsilon)}$$

where $N = \frac{N_A}{A} \cdot \rho$ (N_A = Avogadro Number
A = Molar mass
ρ = density of the gas)

$\sigma(\epsilon)$ is the collision cross-section.

$$\lambda_e >> \lambda_{ion}$$

If the charge carriers are subject to an electric field, then an orderly drift along the field is superposed over the statistically disordered diffusion.

In an electric field of strength E, the drift velocity v_D:

$$v_D \propto E \; ; \text{ also } v_D \propto \frac{1}{p} \quad (p = \text{gas pressure})$$

$$v_D = \mu \cdot E \cdot \frac{p_0}{p} \quad (p_0 = 760 \text{ Torr i.e., Standard Pressure})$$

μ = mobility of the ions
→ drift velocity per unit reduced / effective electric field

For a mixture of gases, for a given type of ion,

$$\frac{1}{\mu} = \sum_{k=1}^{n} \frac{C_k}{\mu_k} \quad (C_k = \text{concentration of gas } k, \; \mu_k = \text{mobility of ion in gas } k)$$

gas	λ_{ion} (cm)	D_{ion} (cm^2/s)	μ_{ion} ($\frac{cm/s}{V/cm}$ or $\frac{cm^2/s}{V}$)
H_2	1.8×10^{-5}	0.34	13.0
He	2.8×10^{-5}	0.26	10.2
Ar	1.0×10^{-5}	0.04	1.7
O_2	1.0×10^{-5}	0.06	2.2

Electrons, because of their small mass, can gain substantial amounts of energy in an electric field between collisions (their mean free paths are large). The mobilities of electrons in gases are about three orders of magnitude larger than that for ions. Electron mobility is not a constant, but depends on electron energy, electric field and the gas composition.

Mean electron energy ϵ_k is much larger in Ar than in e.g., CH_4 or CO_2.

Because 1st excitation level of Ar is at 11.6 eV,

1st excitation level in CH_4 is at 0.03 eV (molecular rotational and vibrational levels).

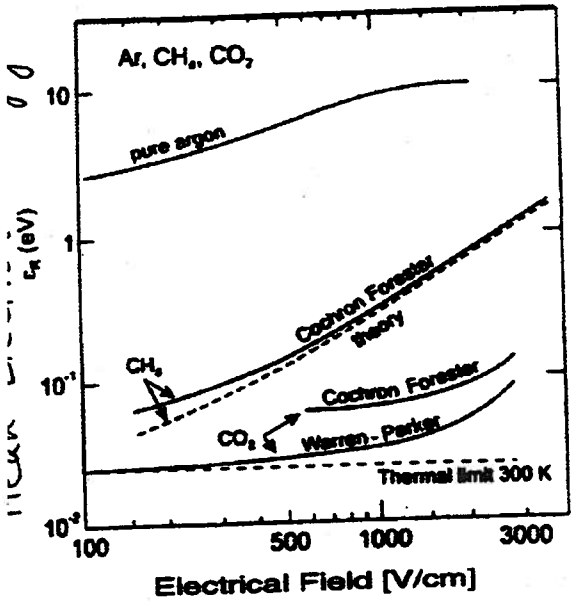
∴ Much more energy is needed to ionize/excite Ar gas than CH_4 or CO_2

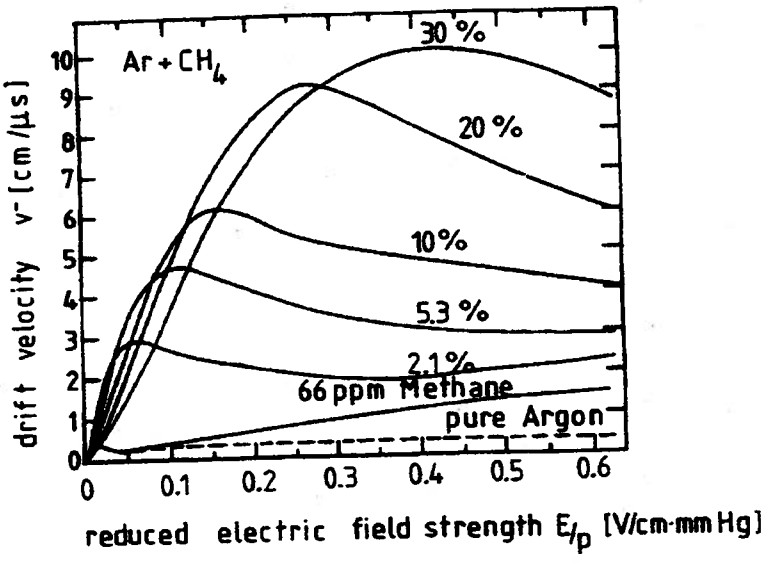
∴ Ar is called a 'hot' gas

CH_4 and CO_2 are 'cold' gases

∴ Addition of small amounts of cold gas to a hot gas can alter the drift properties of a gas mixture drastically.

Heavy organic molecules (called quenchers) have many degrees of freedom to absorb energy efficiently from the gas.

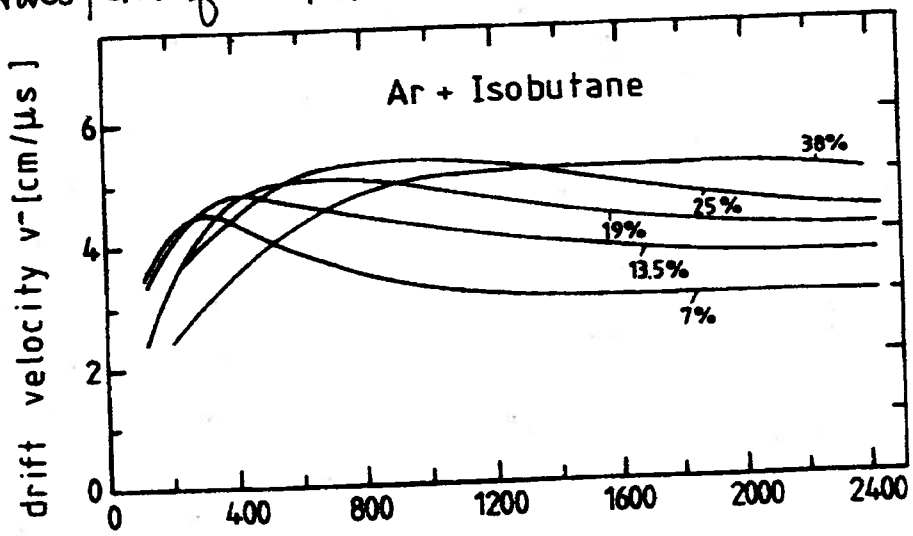




Adding small amounts of 'cold' gas to a 'hot' gas like Ar increases the drift velocity.

There are also <u>unwanted</u> effects of admixtures.

1% of air admixture in Ar will remove 33% of migrating electrons/cm of drift! (This is because of molecules that have electron affinity).



So gas tightness of the chambers needed.

(e affinity large for H_2O and O_2, negligible in N_2)

Diffusion of electrons result in longitudinal and tranverse brodening ← accuracy of position determination is reduced.

We had

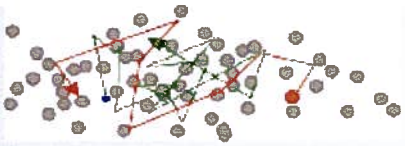
$$\sigma_x = \sqrt{2Dt} = \sqrt{\frac{2Dx}{v_d}}$$

$$= \sqrt{\frac{2\varepsilon_k}{eE}} \cdot \sqrt{x}$$

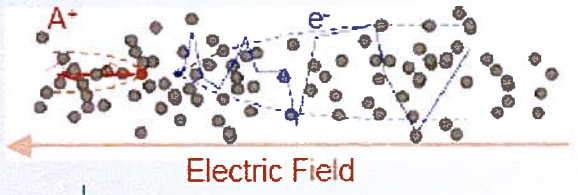
σ_x is much larger for hot gases than for cold gases which are therefore preferred at high values of electric field.

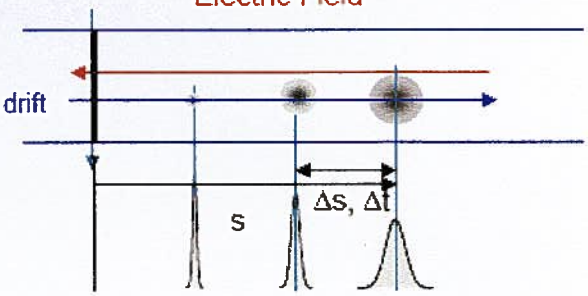
Drift and Diffusion in the presence of Electric field

E=0 thermal diffusion $\langle v \rangle_x = 0$



E>0 charge transport and diffusion $\langle v \rangle_x = v_D$



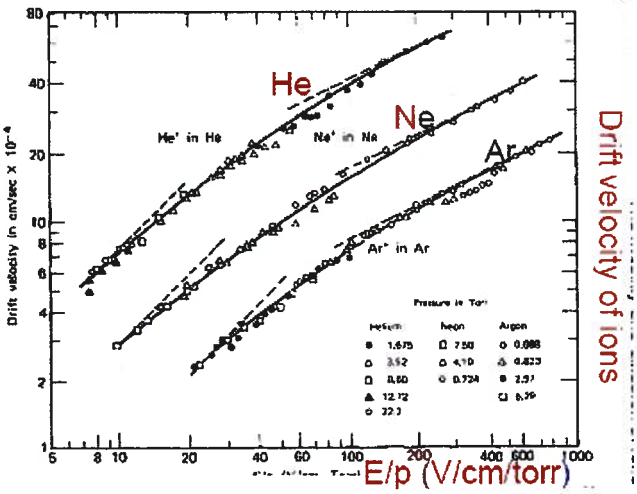


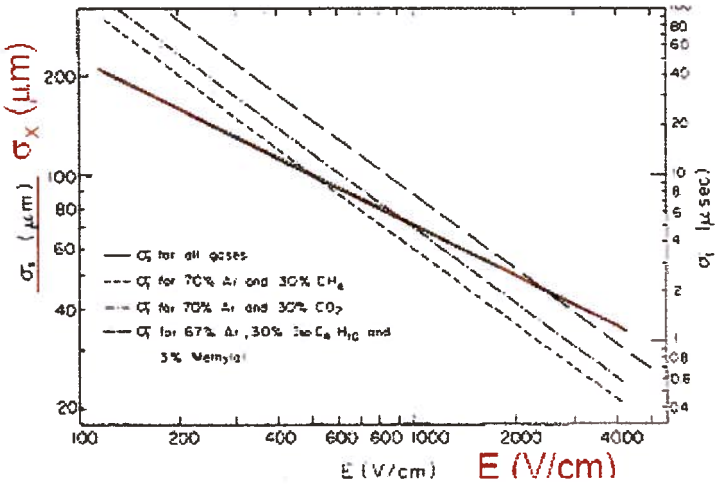
$v_D = \frac{\Delta s}{\Delta t}$ Drift velocity

$\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$ Diffusion

$v_D^{ion} = \mu^{ion} E \; ; \mu = \frac{e\tau}{m}$

$\sigma_x = \sqrt{\frac{2kT}{e} \cdot \frac{x}{E}}$





In the presence of both electric and magnetic fields, the equation of motion becomes, (for the free charge carriers)

$$m\ddot{\vec{x}} = q\vec{E} + q.\vec{v}\times\vec{B} + m\vec{A}(t)$$

$\vec{A}(t)$: stochastic time-dependent force due to multiple collisions with gas molecules

$$m\vec{A}(t) = -m\frac{\vec{v}}{\tau} \quad ; \quad \tau = \text{mean time between collisions}$$

$$\vec{v}_D = \frac{\mu}{1+\omega^2\tau^2}\left(\vec{E} + \frac{\vec{E}\times\vec{B}}{B}.\omega\tau + \frac{(\vec{E}\cdot\vec{B})\cdot\vec{B}}{B^2}\omega^2\tau^2\right)$$

where $\mu = \frac{e.\tau}{m}$; $\omega = \frac{e.B}{m}$ (cyclotron frequency)

$\therefore$ Drift velocity has components in the direction of $\vec{E}$, of $\vec{B}$ and perpendicular to $\vec{E}$ and $\vec{B}$

If $\vec{E} \perp \vec{B}$, then electrons drift at an angle ψ w.r.t. $\vec{E}$, and

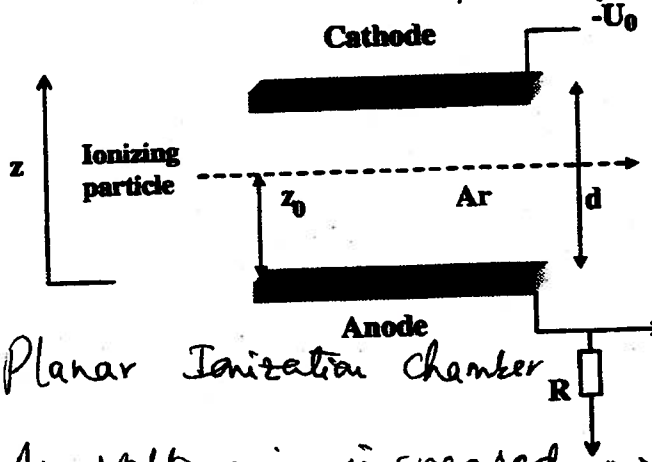
$$\tan\psi = \omega\tau$$

GAS AMPLIFICATION

The signal from ionization may not be big enough. So, need amplification

The simplest gaseous tracking detector is a parallel plate chamber

If one chooses $E = U_0/d$ such that no secondary ionization occurs, and all primary ionization is collected on the electrodes, the device is called an "Ionization Chamber."



Planar Ionization Chamber

Signal collected:

$$V = \frac{Ne}{C}$$

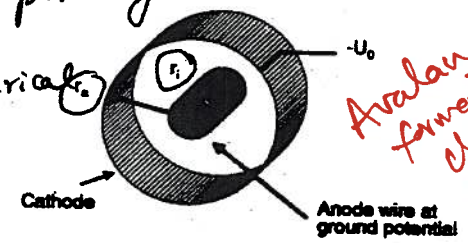
with $N \simeq 100$, $C = 10\,pF$,

$V \simeq 2\,\mu V$

As voltage is increased, more and more electrons become energetic enough to produce secondary ionization. (avalanche)

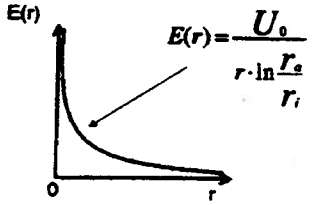
But, the detected signal becomes dependent on the avalanche length and hence the position of the primary ionization.

This is avoided by using a cylindrical chamber.



Avalanche formation very close to the anode

Here $E(r) = \dfrac{U_0}{r \ln\left(\frac{r_a}{r_i}\right)}$



From Laplace equation in cylindrical coordinates and azimuthal symmetry

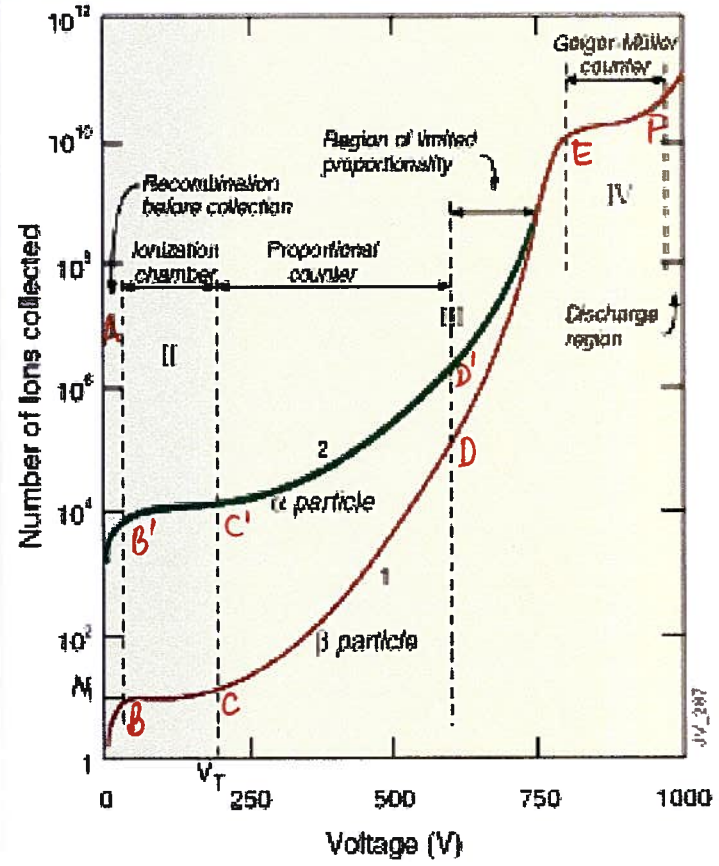
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) = 0$$

Cylindrical chamber

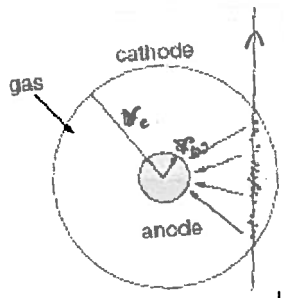
Integrate with constraints $V = 0$ @ $r = r_a$; $V = U_0$ @ $r = r_i$

Gain-Voltage characteristic for Ionization Chambers

- At very low voltages, charges begin to get collected but recombination is dominant. (Region A)
- Region B-C: Full collection of primary ionization. No amplification ← "Ionization Chamber"
- C-D: Avalanche multiplication occurs.
  Detected charge: $Q_{det} = G \cdot Q_{deposited}$ where G = Gain
  ← "Proportional Counter" Region
  G depends on applied voltage (exponentially growing), on gas composition, temperature and pressure.
  1% change in voltage ⇒ 15% change in G.
  signal ∝ ionization ∝ $\frac{dE}{dx}$
- Beyond D: Proportionality lost due to space-charge build-up around the anode wire, screening the field for electrons
  ← Region of limited proportionality.



- E-f: Gain saturates. Generated signal is independent of the original ionizing event.
  ← Geiger Muller Counter
- Beyond f, the counter discharges.



Proportional Counter

- Secondary ionization occurs due to higher electric fields.
  charge collected ∝ primary ionization
- In a cylindrical electric field, kinetic energy gained by an electron between collisions at r_1 and r_2 is:

$$\Delta T_{kin} = e\int_{r_1}^{r_2} E(r)\,dr = e\,V_0\,\frac{\ln(r_2/r_1)}{\ln(r_c/r_w)}$$

($r_c = r_{cathode}$; $r_w = r_{wire}$)

If $\Delta T_{kin} > W$ (↓ ionization potential) for the gas, secondary ionization takes place.

- But, high field strengths are present only very close to the anode wire.

  So, in most of the region, the electric field just makes the e^- and ions to simply drift towards the electrodes.

  And, multiplication and avalanche formation occurs very close to the anode (within a few wire radii)

- The primary ionization Ne is amplified by a "gas amplification factor" A

The voltage pulse at the electrodes:

$$\Delta U = -A \cdot \frac{Ne}{C} \qquad (C = \text{Capacitance})$$

- # of electron-ion pairs/cm produced by an electron is called First "Townsend Coefficient" 'α'.

$$\alpha = \sigma_i \cdot N_A/V$$

(σ_i = Collision cross section producing ionization; N_A = Avogadro No.; V = Molar volume)

and $$dN(x) = \alpha \cdot N(x)\, dx$$

$$\therefore \quad N(x) = N_0 e^{\alpha x} \qquad (N_0 = \text{Number of primary electrons})$$

More generally, since α depends on $\vec{E}$ and hence x,

$$N(x) = N_0 e^{\int \alpha(x) dx}$$

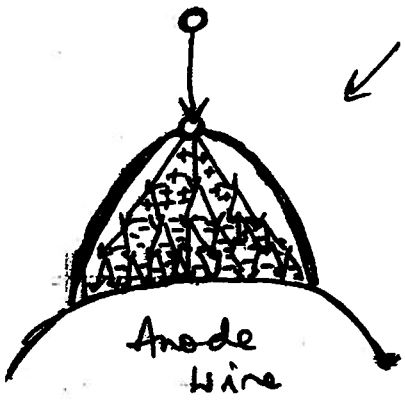
Gas amplification,

$$A = \exp\left(\int_{r_k}^{r_i} \alpha(x)\, dx \right)$$

Typically, $A \simeq 10^4 - 10^5$

r_k = radius where $\vec{E}$ is above critical value for charge multiplication

Avalanche formation near the Anode wire



↙ Lateral diffusion of electrons & ions cause a drop-shaped avalanche. The electron & ion clouds drift apart.

Pulses/signals generated by e^- at the anode

$$\Delta U^- = -\frac{Nq}{C}\int_{r_0}^{r_w} E(r)\,dr = -\frac{Nq}{C}\cdot\frac{V_0}{\ln(r_c/r_w)}\cdot\int_{r_0}^{r_w}\frac{dr}{r}$$

$$= -\frac{Nq}{C}\cdot V_0\cdot\frac{\ln(r_w/r_0)}{\ln(r_c/r_w)}$$

Ditto for ions;

$$\Delta U^+ = -\frac{Nq}{C}\cdot V_0\cdot\frac{\ln(r_c/r_0)}{\ln(r_c/r_w)}$$

$$\therefore R = \frac{\Delta U^+}{\Delta U^-} = \frac{\ln(r_c/r_w)}{\ln(r_0/r_w)} = \frac{\ln(r_c/r_w)}{\ln\left(\frac{r_w + k\lambda}{r_w}\right)}$$

$$= \frac{\ln(r_c/r_w)}{k\lambda/r_w}$$

For $r_c = 20\text{mm}$; $r_w = 0.1\text{mm}$, $k\lambda = 0.02\text{ mm}$; $R = 25$

Photon production due to de-excitation of atoms can add to further ionization or amplification of the signal.

$$N_0 A_\gamma = N_0 A + N_0 A^2\gamma + N_0 A^3\gamma^2 + \dots$$

$$= N_0 A \sum_{k=0}^{\infty} (A\gamma)^k = \frac{N_0 A}{1-\gamma A} ; \quad \boxed{A_\gamma = \frac{A}{1-\gamma A}}$$

A_γ = Second Townsend coefficient

(γ = probability to produce one photoelectron / electron)

Photon feedback: Photons reaching cathode can release electrons, which in turn can get accelerated and generate avalanches.

So, "quenching" gases which have large photo-absorption cross-sections (in the visible and UV) are added. Examples: CO_2 and CH_4.

Ion feedback:

Ions reaching cathode can produce similar effect by releasing photons and electrons.

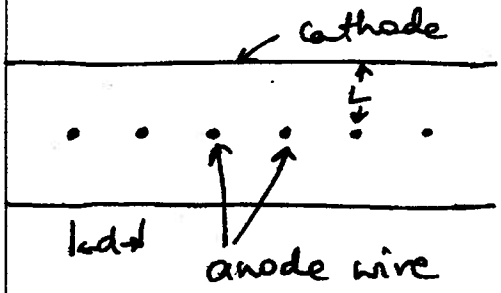
Quenchers help here as well.

$$Ar^+ + \text{Quencher} \longrightarrow Ar + \text{Quencher}^+$$

∴ Ions of the quencher gas reach the cathode. They have lower ionization and excitation potential. So, they do not stimulate a secondary emission.

Multi-Wire Proportional chambers: (MWPC)

- A planar layer of proportional counters without separating walls



Used mostly to determine spatial coordinates of particles passing through.

Typically,

anodes: 10–30 μm gold-plated tungsten wire

d = distance between wires ~ a few mm

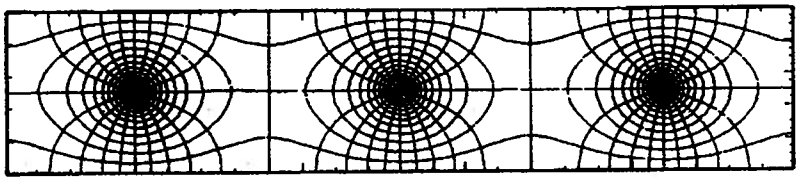
L = distance between anode & cathode ~ 1 cm

Cathodes: metal foils or stretched wires

Gas mixtures: Noble gas + quencher

Gas amplification ~ 10^5

Electric fields are modified as below:

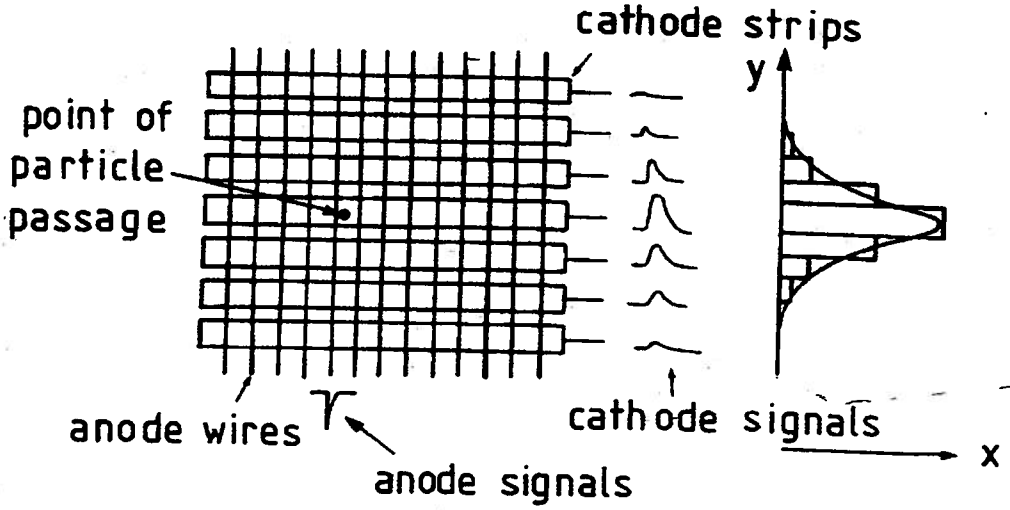


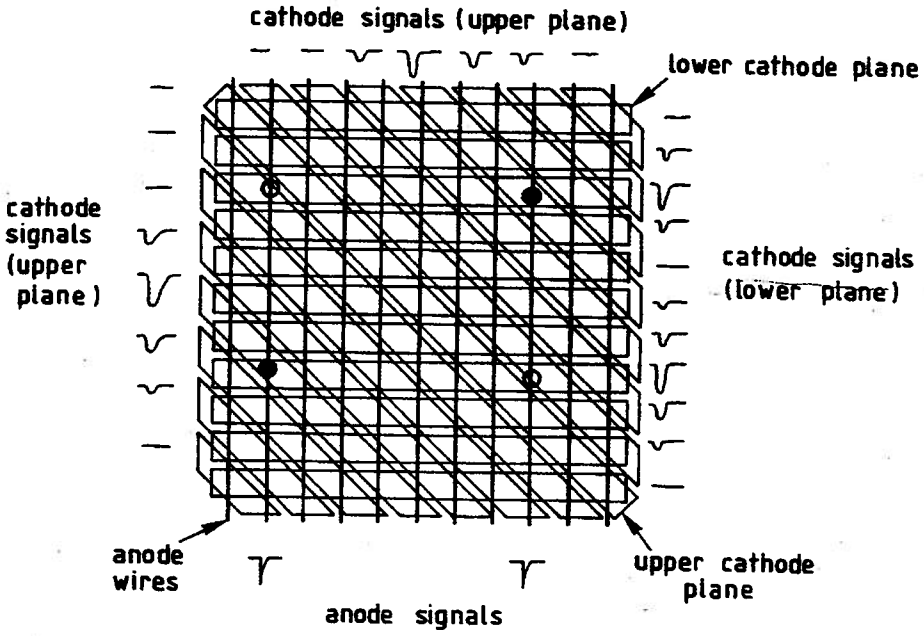
MWPC spatial resolution

$$\sigma_z = \frac{d}{\sqrt{12}} \simeq 600\,\mu m$$ ($\perp^r$ to the anode wires)

no information along wire

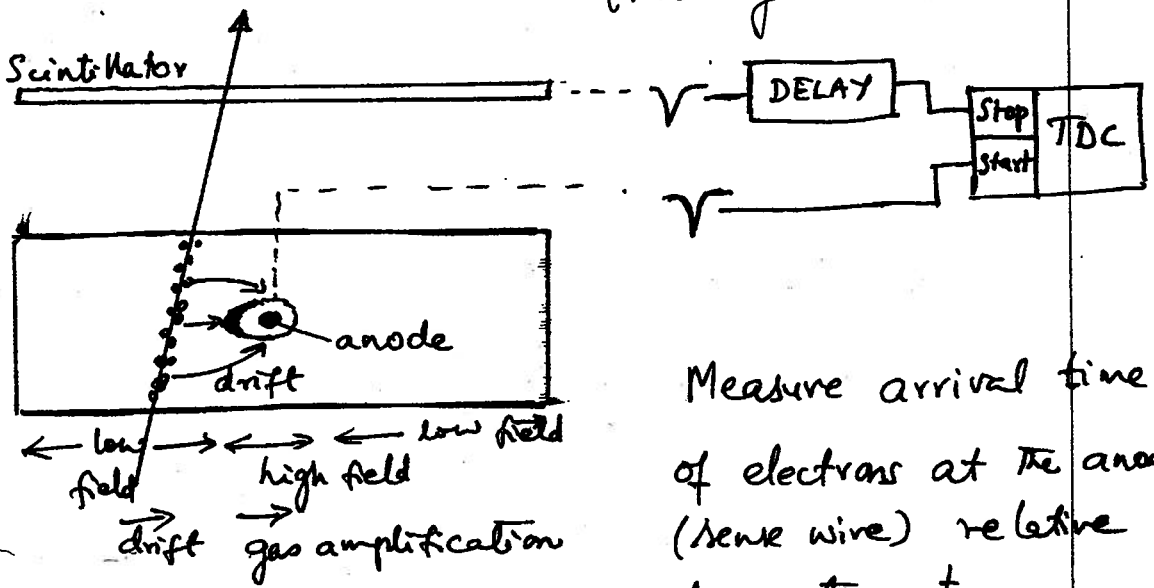
So, improvements are made using Cathode strips, pads or a layer of wires





DRIFT CHAMBERS

Drift chambers allow more cost-effective tracking than MWPCs



Measure arrival time of electrons at the anode (sense wire) relative to a time to.

A Time "t" is required for the drift of primary electrons to reach the anode (near which gas amplification occurs).

← Depends on where the particle passed through.

Time to distance conversion

$$X = \int v_D(t)\, dt$$

If v_D is constant, then $x = v_D \cdot t$

Compared to MWPC:

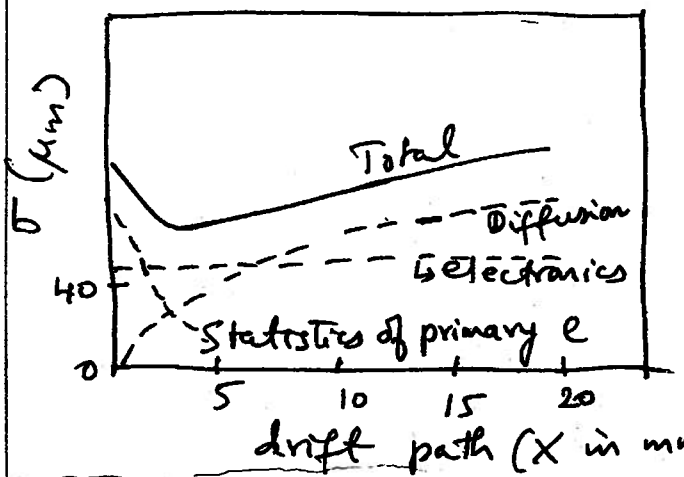
→ less number of wires, less electronics

→ better spatial resolution

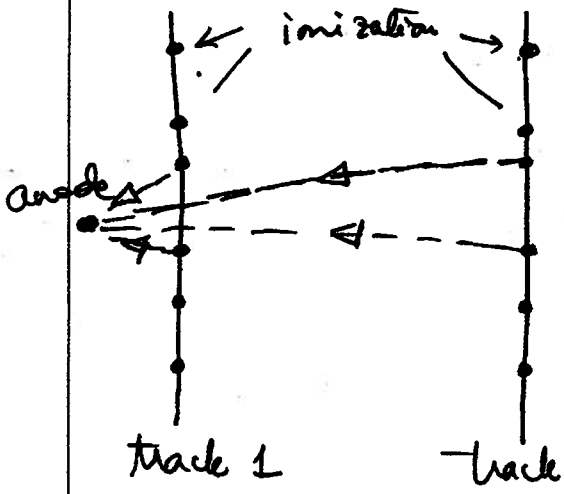
Eg., $v_0 = 5\ cm/\mu s$ (typical velocity)

with time resolution $\sim 1ns = \sigma_t$

$$\sigma_z = v \cdot \sigma_t = 50\ \mu m$$



Spatial resolution has contributions from Diffusion and statistics of primary electrons (close to the anode)



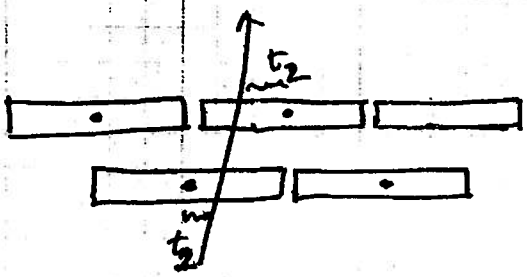
← different drift paths for 'near' and 'distant' particle tracks

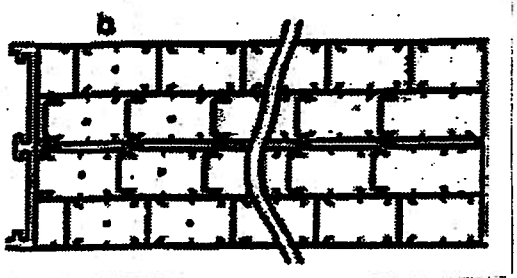
The spatial resolution therefore depends on primary ionization statistics for near tracks.

Left - right ambiguity

The drift time measurement cannot tell us if the particle passed the anode wire on the left or the right.

So, layers are staggered.





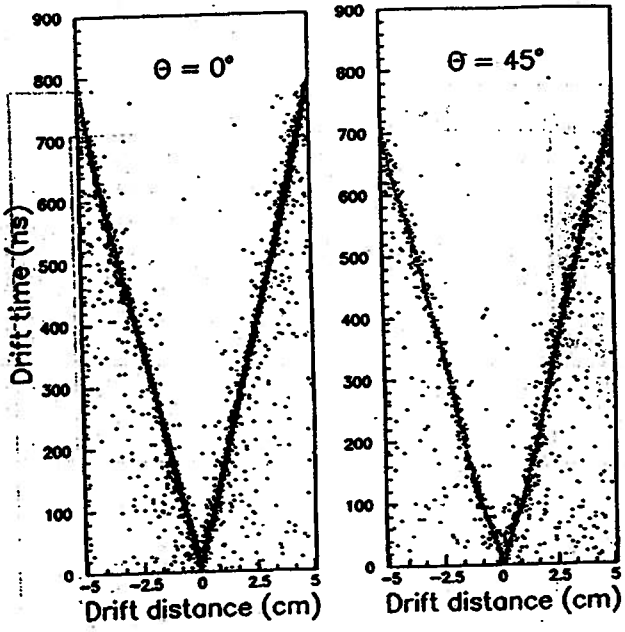
DØ Muon PDT

Anode: 50μ Gold-plated Tungsten @ +4.5 kV; Cathode @ +2.3 kV

Drift-Time-to-distance relation almost linear.

Using proper non-linear fit

$\Rightarrow \sigma \sim 0.3$ mm

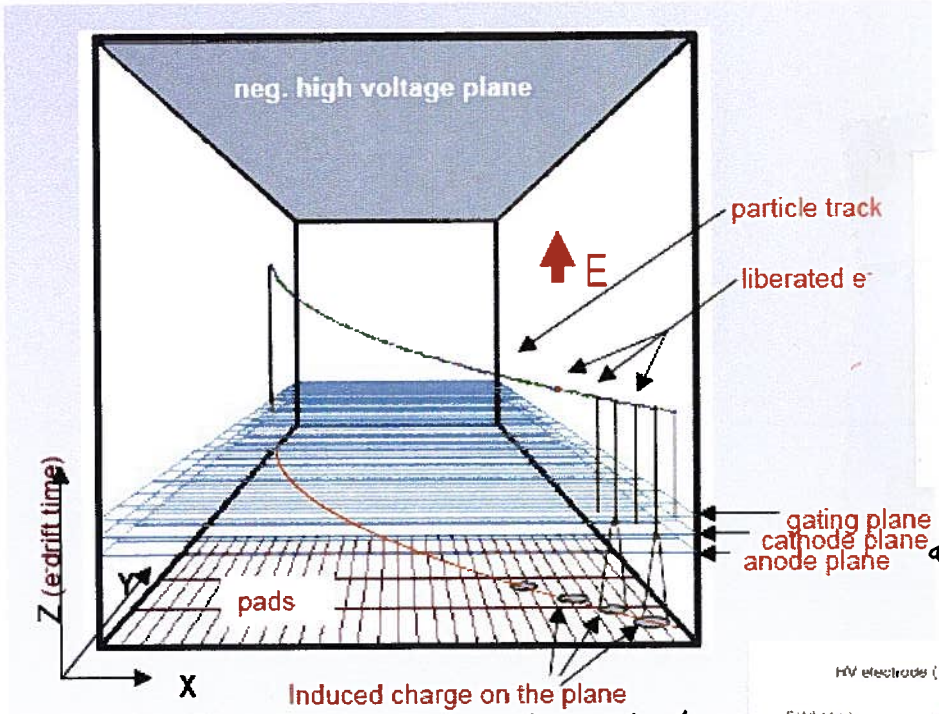


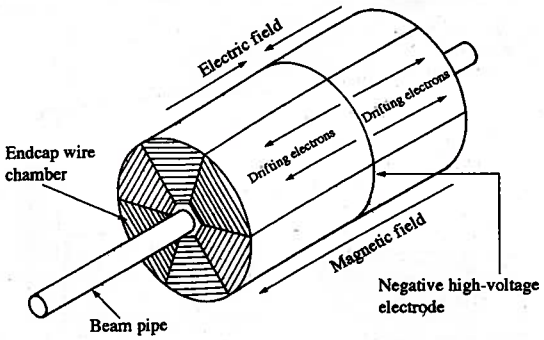
Gas used: Ar (90%) / CF_4 (5%) / CO_2 (5%)

Time Projection Chamber (for full 3D-reconstruction)

Very Versatile Drift Chamber

- x-y from wires and segmented cathode of MWPC
- z from Drift time
- dE/dx information





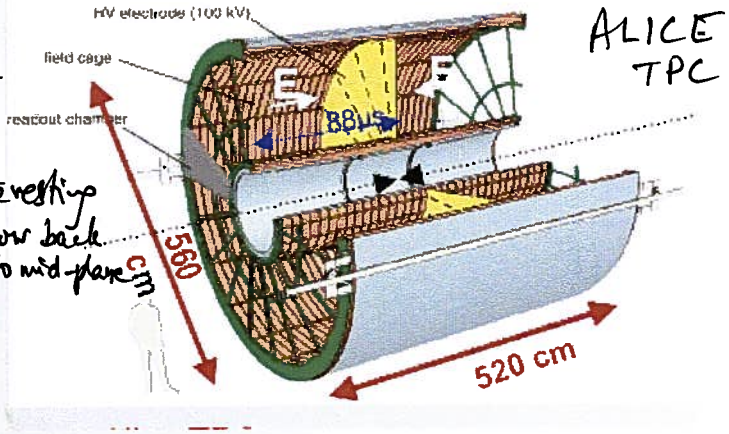
- Diffusion significantly reduced by B-field

Problem: Positive ion back-flow to mid-plane

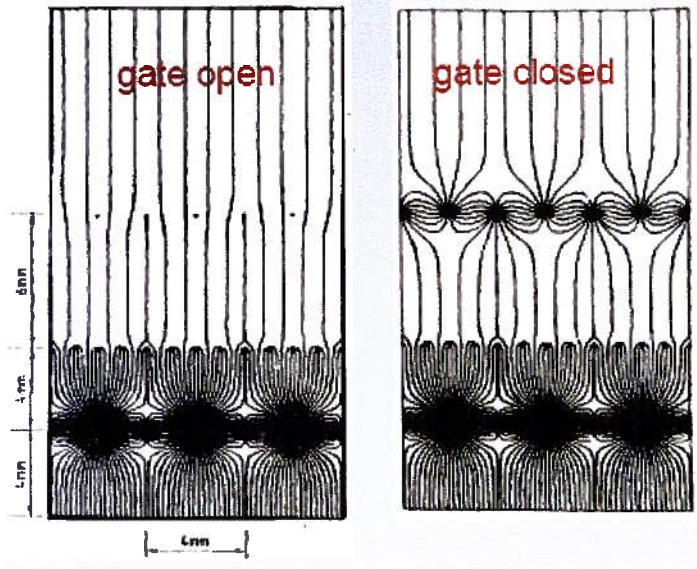
Solution: gating

→ Prevents electrons to enter amplification region when event is uninteresting

→ Prevents ions created in avalanches to flow back to mid-plane



ALICE TPC



gating plane

cathode plane

anode wires

readout pads

DETECTOR AGING

- Crucial & complex issues

Several types of effects:

- Loss of chamber gain (or increase)
- Reduction of operational region
- Loss of energy resolution
- Generation of excessive or self-sustained currents, sparking etc
- Dark currents

Chamber aging can be defined as "deterioration in the performance of the device as a function of the irradiation time/dose."

Radiation hardness of a detector can be quantitatively calibrated using "charge accumulated/cm of anode wire"

$$\frac{Q}{\Delta l} = \frac{1}{\Delta l}\int i\,dt$$

Causes / Mechanisms of aging

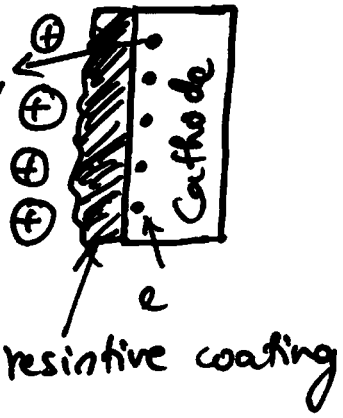
- Decomposition of chamber gas
  - quenching gases that dissociate at the cathode get used up; change gas composition
  - molecules (such as CF_4) break-up can produce highly aggressive radicals
  - dissociation of the quencher gas at the cathode can result in polymerization and deposition of non-conducting material on the cathode
- Gas Contamination
  - Very small contaminations can have very large effects
  - Probable sources: Outgassing of various materials used in the chamber and in the gas system
- Resistive deposits on anode wires (and cathodes)

Anode deposits:

reduced and inhomogeneous field
Variation in gain (rate-dependent)

Cathode deposits:

Formation of strong electric dipoles due to ions that cannot neutralize quickly and mirror charge



→ Malter effect

→ field emission of electrons

→ dark current
(discharge even when the original source is removed)

DØ Muon PDTs

Wires got coated with crud in Run I
Chamber performances deteriorated, some dead
Source identified as the Glassteel polyester-epoxy resin from the cathode pad

Soln: Heating the wire in <2ms to near MP of gold!

Aging can be minimized by

- Careful material selection
- Cleanliness during construction and operation (clean gas systems)
- Aging-resistant gases
- Minimize impurities
- Lots of monitoring