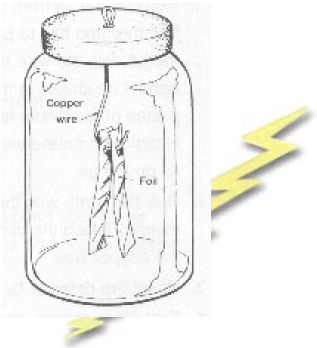
Chap. 5 Ion Chambers – the electroscope

Electroscope: an early device used to study static electricity continues to be used for personal dosimeters. Put a (known) charge on the central electrode, leaves separate, watch the leaves move back together as the charge is lost.



Create ionization in gas-filled volume: $t_{creation} \sim$ dimension/c ~ 3cm / 3×10^{10} cm/s ~10 ps

Amount of ionization: $Q \sim (\Delta E / 34\text{ eV})\, 2q_e$

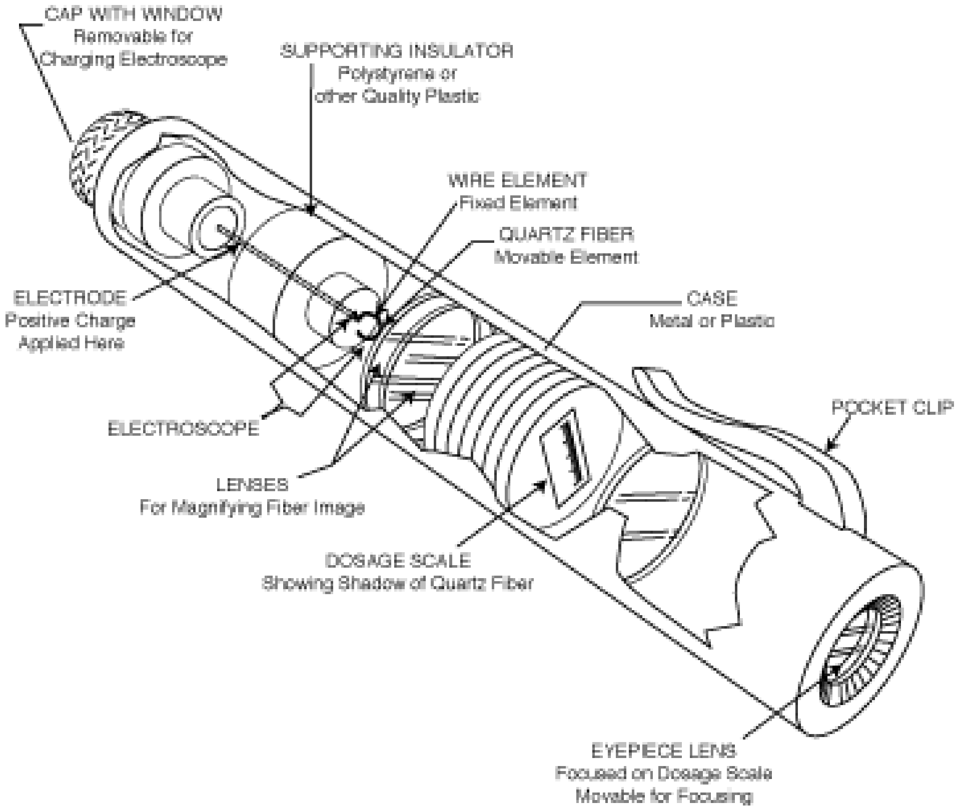
Some properties of oxygen at 25°C, 1 bar

$v_{RMS} = 480$ m/s , $\lambda_{MFP} = 70$ nm
Collision rate: $Z = v_{RMS} / \lambda_{MFP} = 7 \times 10^9$ /s

No electric field – ions diffuse $\sigma^2_x = 2Dt$
Diffusion coefficient: $D = \lambda_{MFP}\, v_{avg}/3$

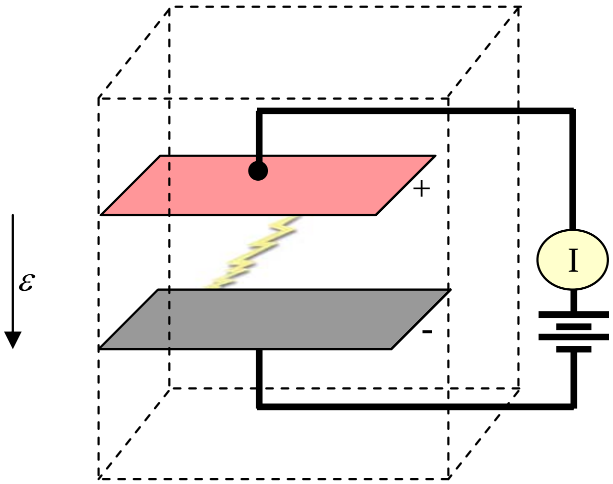
$\sigma^2_x = 2\,(\lambda_{MFP}\, v_{avg}/3) * t \rightarrow \sigma_x \sim 0.005\ (\text{m/s}) * t$

Ok for dose measurement, not so good for pulses!



http://www.nbc-med.org/SiteContent/MedRef/OnlineRef/FieldManuals/amedp6/PART_I/annexa.htm

Ion Chambers – Drift ions



Two parallel plates, ions will drift towards plates between collisions with the fill-gas that randomize the velocity and restart drift.

$v_{drift} = K\,\varepsilon$; $K = eD / k_B T = \mu/p$, μ is *ion mobility*

e.g., O_2^- $(\mu/p) = 2.5 \times 10^{-4}$ $m^2/s\,V$ at 1 atm

Typical (large) value: 1kV across a 1.0 cm gap gives:
$v_{drift} = (2.5 \times 10^{-4}\ m^2/s\,V)^* (10^3\ V / 0.01m) \sim 25\ m/s < v_{thermal}$

$t_{collection} \sim 0.005\ m / 25\ m/s = 2 \times 10^{-4}\ s = 0.2\ ms$

N.B. (μ/p) for an electron is about $10^2 - 10^3$ x larger due to its smaller mass

Ion Chambers – Ion reactions/Recombination

Drifting ions react chemically:

$X^+ + M \rightarrow X + M^+$	Charge exchange, 'M' with lowest ionization potential collects charge [$\sigma \sim 10^{-16}$ cm^2]
$e^- + O_2 \rightarrow O_2^-$	Electronegative molecules collect electrons (lose high speed of free electrons)
$X^+ + O_2^- \rightarrow X + O_2$	Neutralization – lose charge on two molecules
$M^+ + e^- \rightarrow M^*$	two-body recombination (only molecular ions)
$A^+ + e^- + A \rightarrow A^* + A$	three-body recombination (atomic ions)

Chemical kinetics:

$$\frac{dn^+}{dt} = -\alpha\, n^+\, n^- \qquad \frac{d[M^+]}{dt} = -\alpha\,[M^+][e^-]$$

If density is uniform:

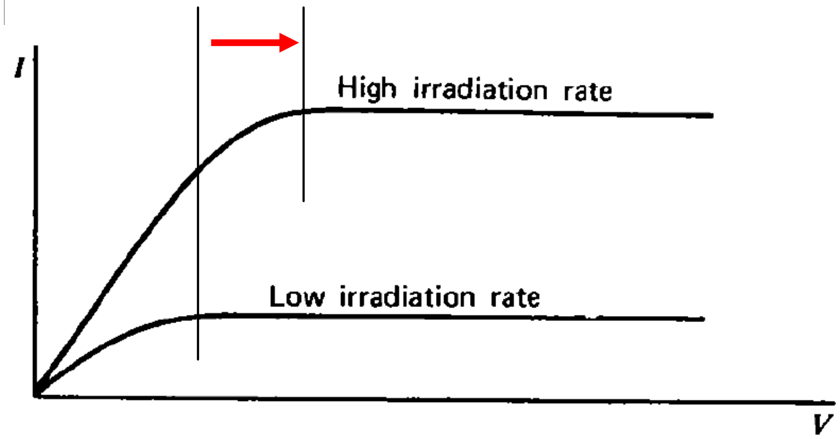
$$if\ [M^+] \approx [e^-] \quad \rightarrow \quad \frac{d[M^+]}{dt} = -\alpha\,[M^+]^2$$

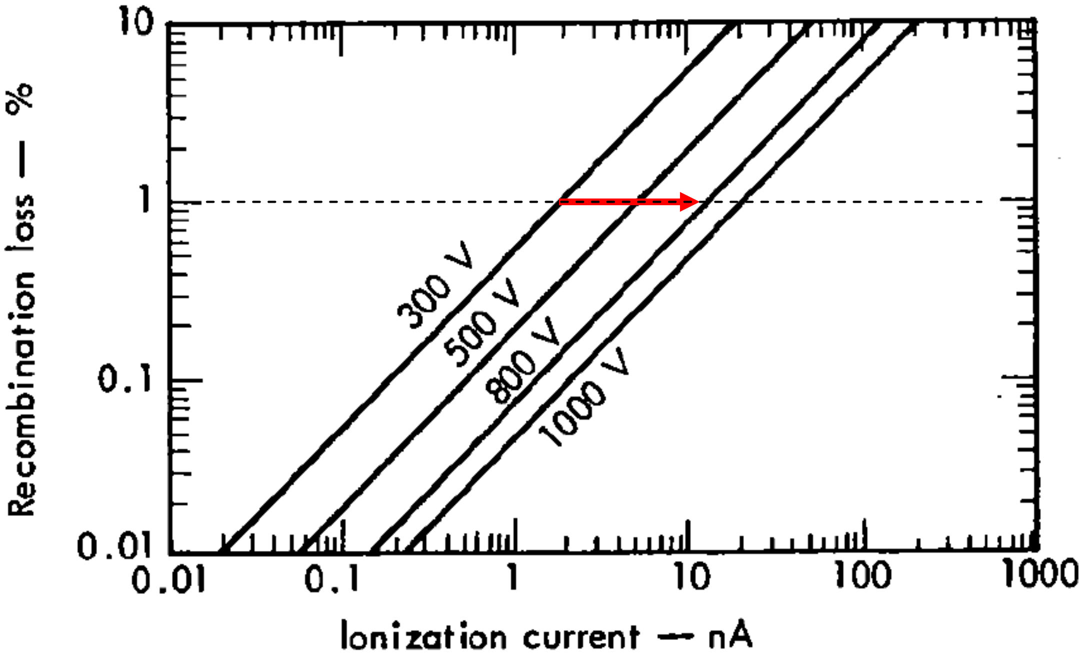
$$[M^+] = {[M^+{}_{t=0}]} \big/ {1+\alpha\, t}$$

Ion Chambers – Recombination/Saturation

The recombination is more complicated:

- All reactions are taking place simultaneously
- Ions are not distributed uniformly – column of charge, delta electrons
- Large fraction of electrons rapidly removed by electric field
- Space charge in the detector blocks the applied field … stops drift and allows recombination.





Argon-filled ion chamber, 1 atm

Fig. 5.4 Knoll, 3rd Ed.

Ion Chambers – Current Example

An ion chamber to measure biologically relevant doses:
Maximum permissible dose – 2mR/hr
1 Rad = 10^2 ergs/g = 0.01 Gray = 0.01 J/kg = 6.2×10^{13} eV/g

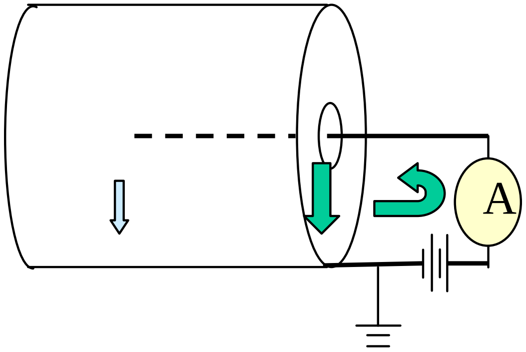
$$dE/dt = (2\text{x}10^{-3}\ \text{R/hr})\ (6.2\text{x}10^{13}\ \text{eV/g R})\ (1\ \text{hr} / 3600\ \text{s}) = 3.5\ \text{x}10^{7}\ \text{eV/g s}$$

Air filled volume – $m \sim \rho V$ $=(28.8\ \text{g/mol} / 24\ l\text{/mol})\ [\pi\ (2\text{cm})^2\ 4\text{cm}]\ \text{x}10^{-3}\ l/\text{cm}^3$
$= 1.2\ \text{g}/l\ [\ 0.050\ l\ ] = 0.060\ \text{g}$

Current –

$$I = dE/dt\ (q_e / w) = (3.5\ \text{x}10^{7}\ \text{eV/g s})\ (\ 0.060\ \text{g})\ (1.602\text{x}10^{-19}\ \text{coul} / 34\ \text{eV})$$

$$I = 9.9\text{x}10^{-15}\ \text{A}$$



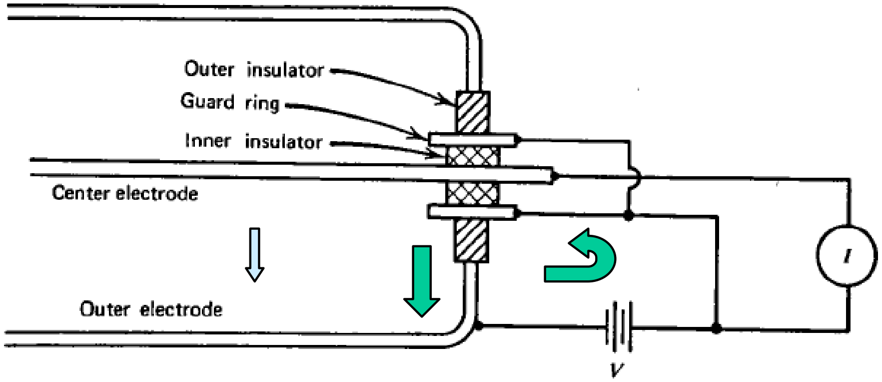


Fig. 5.5 Knoll, 3rd Ed.

Ion Chambers – Pulse mode – 1

Observe a single pulse in Ion Chamber:

- Ion chamber has an external circuit with RC > τ_{drift} for cations (~ ms)
- Parallel plates are large, ignore edge effects and ε is parallel and linear
- ε is large enough to separate charges without recombination but no avalanches
- Assume that electrons remain free and move ~ 10^3 faster than cations
- Ions are created in a line parallel to plates
- $V_{max} \sim Q/C = N_{IP}\, q_e /C$ (since RC is slow)

[General solution uses the concept of *Induced image charges* in Appendix.
Solve Poisson Equation – see Jackson's book …]

Initially two charge carriers:

$V_R(t) = (N_{IP}\, q_e /C) (v^+ + v^-) t/d$

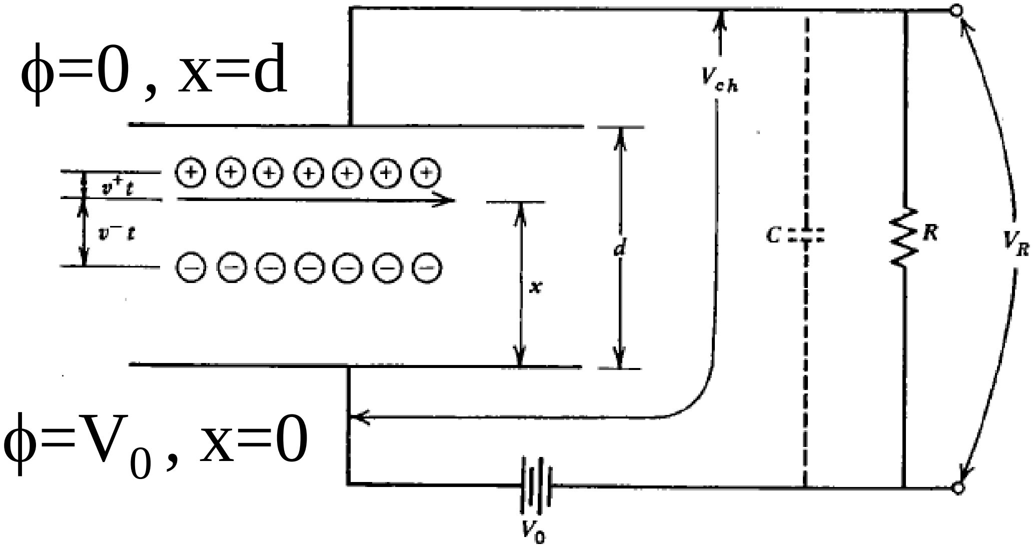
Electrons are collected:

$V_R(t) = (N_{IP}\, q_e /C) (v^+ t + x) /d$

Both are collected:

$V_R(t) = (N_{IP}\, q_e /C) (d-x + x) t/d$

Fig. 5.15 Knoll, 3rd Ed.



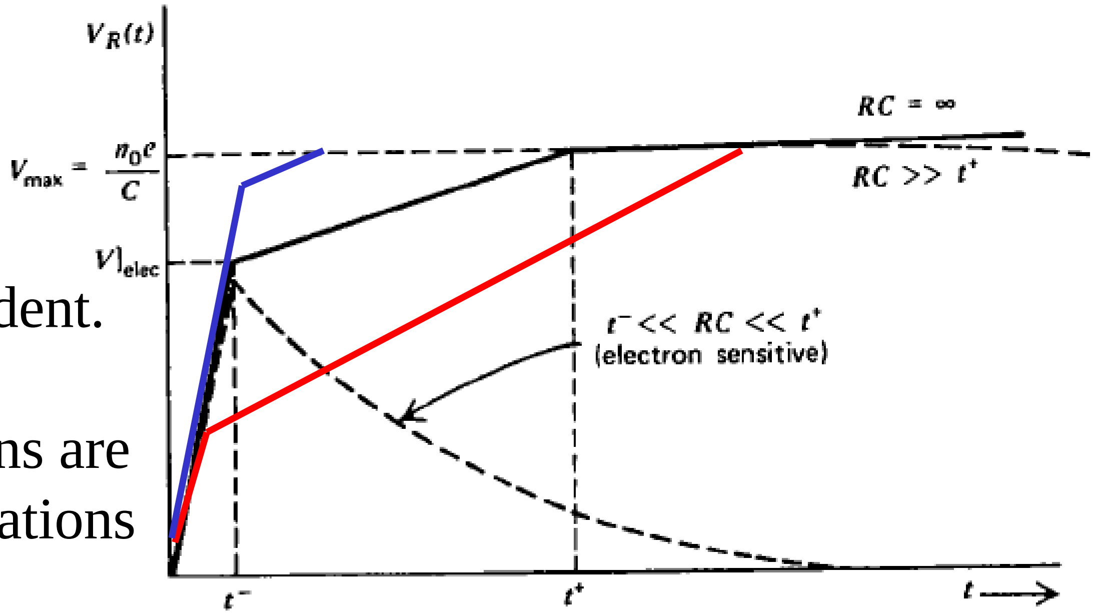
$\phi=0$, $x=d$

$\phi=V_0$, $x=0$

Ion Chambers – Pulse mode – 2

Initially two charge carriers:
$V_R(t) = (N_{IP}\, q_e /C)\ (\, v^+ + v^-\,)\ t/d$

N.B. the pulse shape is position dependent.

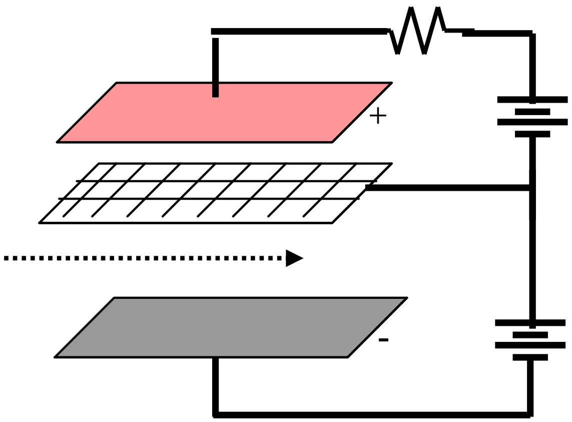


Radiation track close to anode, electrons are collected rapidly, motion of the slow cations makes bulk of the signal.

Radiation track closer to cathode, electrons move larger distance rapidly and make the bulk of the signal.

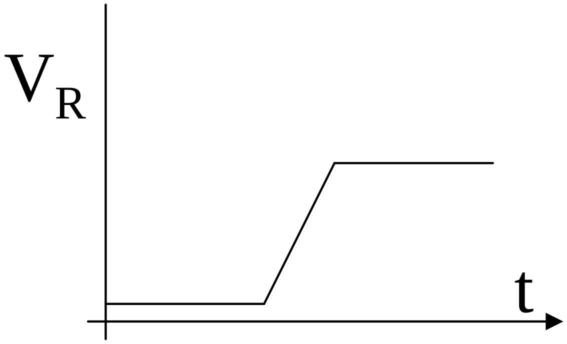
Fig. 5.16 Knoll, 3rd Ed.

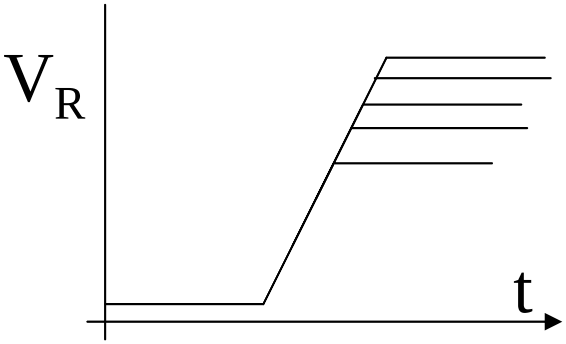
Ion Chambers – Frisch Grid



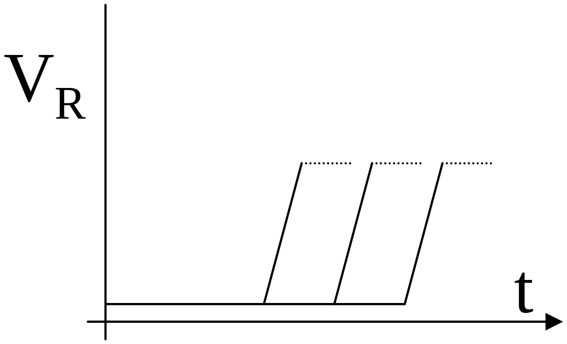
Give up the cations …

Add a grid at position between the anode and cathode but closer to the anode. The grid has a high transmission but it shields the anode electrically from the primary ionization.



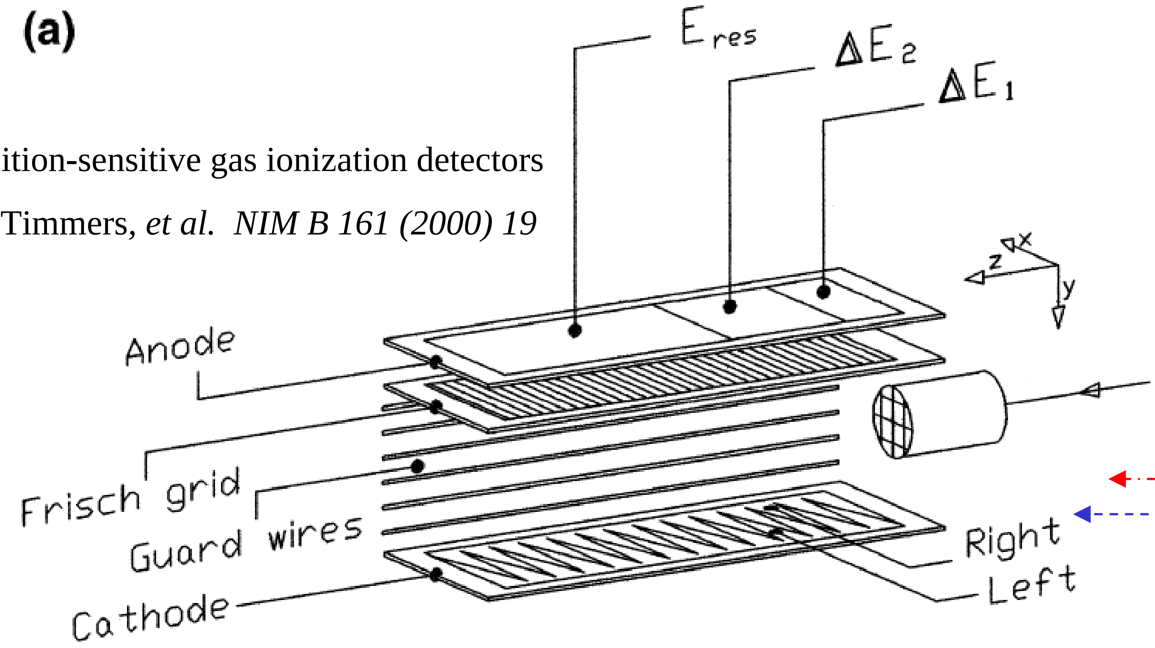


} various pulse heights on central axis – spectroscopy



} uniform pulse height at various positions from grid – drift time differences.

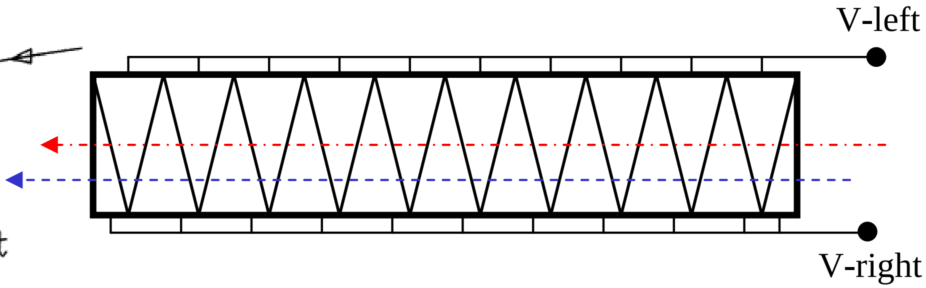
Ion Chambers – Electrode Construction

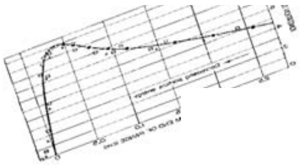


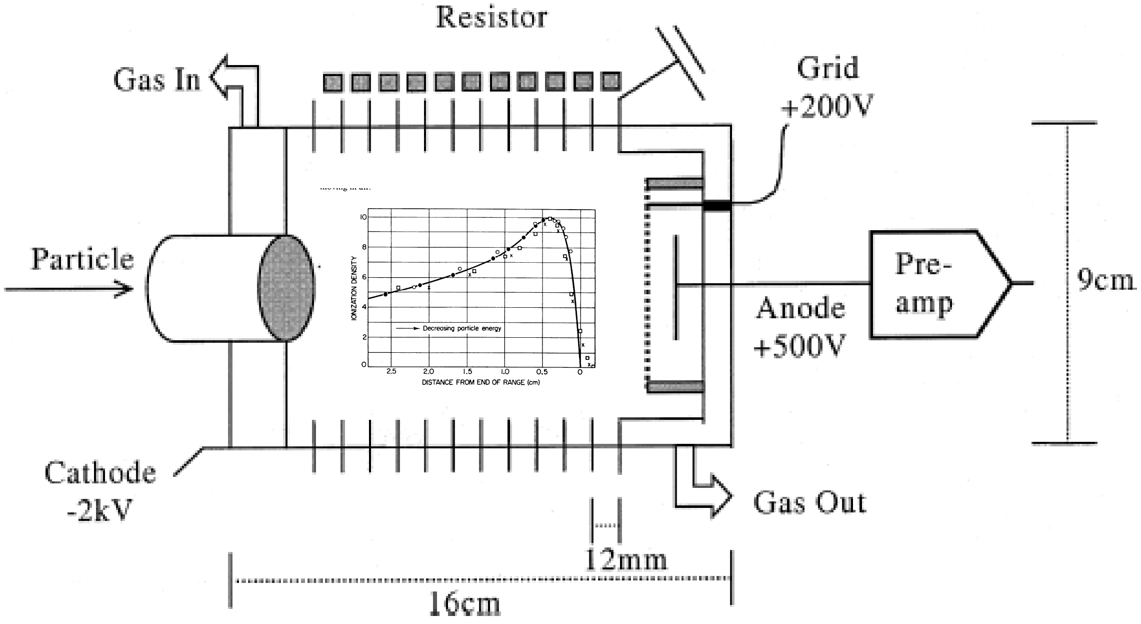
Position-sensitive gas ionization detectors

By Timmers, *et al.* *NIM B 161 (2000) 19*

- Field shaping wires
- Segmented anode – obvious
- Wedged cathode?







Bragg Curve Detector for AMS

by *Santos, et al.* *NIM B 172 (2000) 310*