Week 5: Chap. 5 Ion Chambers

Basic Detector Principles

Ion Chambers
-- Current Mode
-- Pulse Mode
--- signal shape
-- Grids
-- Examples

Proportional Counters

Chap. 5 Ion Chambers – the electroscope

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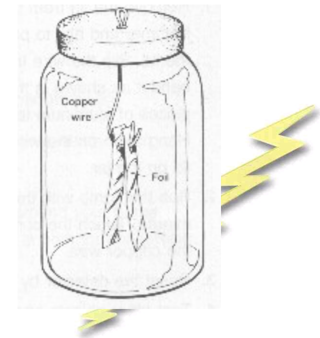
Electroscope: an early device used to study static electricity continues to be used for personal dosimeters. Put a (known) charge on the central electrode, leaves separate, watch the leaves move back together as the charge is neutralized (lost) by collecting gaseous ions.



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

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

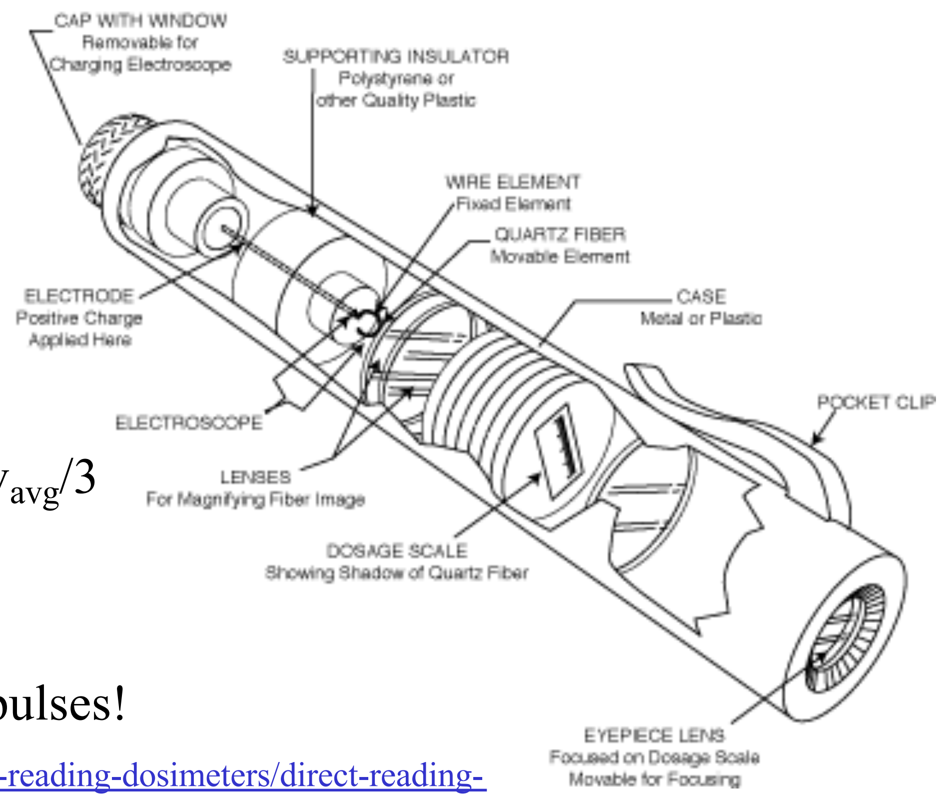
Some properties of oxygen at 25°C, 1 bar

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

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

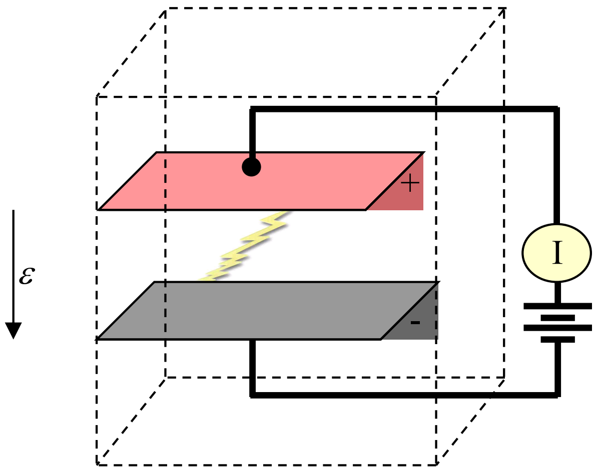
$\sigma^2_x = 2\ (\lambda_{MFP}\, v_{avg}/3) * t \rightarrow \sigma_x \sim 0.005\ (\mathrm{m}) * \sqrt{t}$ in s

Maybe Ok for dose measurement, not so good for pulses!



http://www.dosimeter.com/direct-reading-dosimeters/direct-reading-dosimeter-w138-0-200mr-with-sapphire-window/

Ion Chambers – Drift ions



Two parallel plates, ions will drift towards plates between collisions with the fill-gas. These collisions 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^- $(\mu/p) = 2.5 \times 10^{-4}\ m^2/s\text{-}V$ at 1 atm

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

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

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 (need pure fill-gases but 10^9 collisions/sec):

$X^+ + M \rightarrow X + M^+$ — Charge exchange, impurity 'M' with lowest ionization potential (most massive?) collects charge

$[\ \sigma \sim 10^{-16}\ \mathrm{cm}^2\ ]$

$e^- + O_2 \rightarrow O_2^-$ — Electronegative molecules collect electrons (lose free, high speed 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)

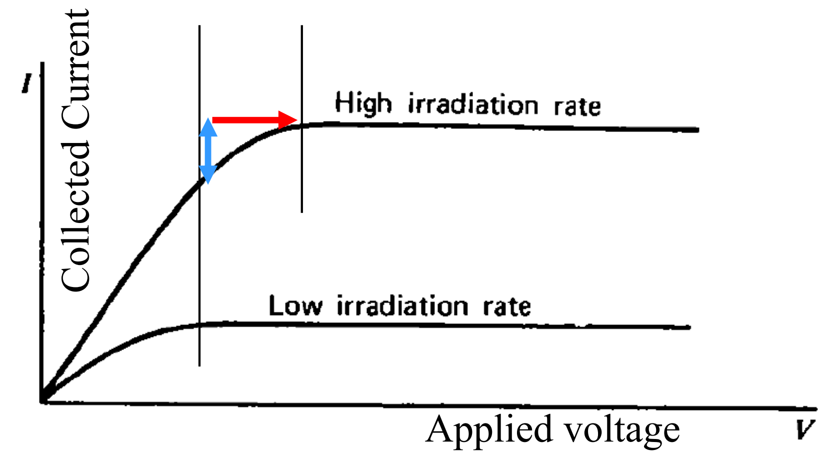
Chemical kinetics: $\frac{dn^+}{dt} = -\alpha\, n^+\, n^-$ $\qquad \frac{d[M^+]}{dt} = -\alpha\,[M^+][e^-]$

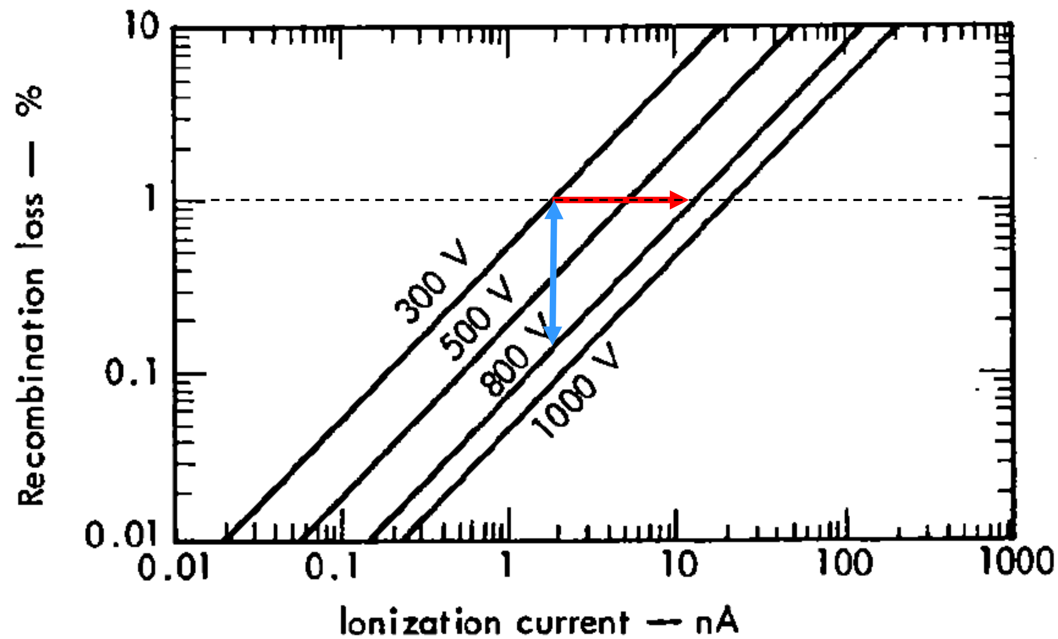
If density is uniform: $if\ [M^+] \approx [e^-] \quad \rightarrow \quad \frac{d[M^+]}{dt} = -\alpha\,[M^+]^2$

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

Ion Chambers – Recombination/Saturation

The actual 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 due to high mobility
•Space charge at high ionization rates in the detector can block the applied field … stops drift and allows recombination.





Argon-filled ion chamber, 1 atm

Fig. 5.4 Knoll, 3rd,4th Eds.

Ion Chambers – 'Current mode' Example

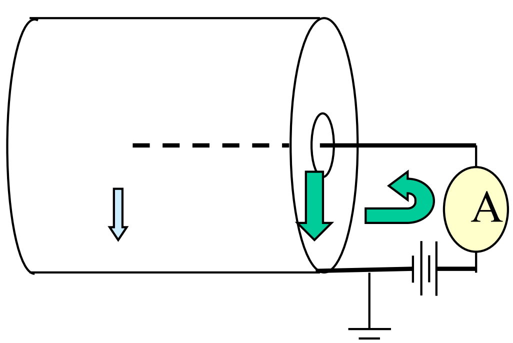
An ion chamber to measure biologically relevant doses:
Maximum permissible dose to "general public" – 2mR in any 1 hour
1 Rad = 10^2 ergs/g = 0.01 Gray = 0.01 J/kg = 6.2 $\times 10^{13}$ eV/g

$dE/dt = (2\times10^{-3}\ R/hr)\ (6.2\times10^{13}\ eV/g\ R)\ (1\ hr\ /\ 3600\ s) = 3.5\times10^{7}\ eV/g\text{-}s$

Air filled volume – $m \sim \rho V = (28.8\ g/mol\ /\ 24\ l/mol)\ [\pi\ (2cm)^2\ 4cm \times10^{-3}\ l/cm^3]$
$= 1.2\ g/l\ [\ 0.050\ l\ ] = 0.060\ g$

Current –
$I = dE/dt\ (q_e\ /\ w) = (3.5\times10^{7}\ eV/g\text{-}s)\ (\ 0.060\ g)\ (2\times1.602\times10^{-19}\ coul/IP\ /\ 34\ eV/IP)$

$I = 2\times10^{-14}\ A$



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
- $V_{max} \sim Q/C = N_{IP}\, q_e\, 2/C$ (since RC is slow)

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

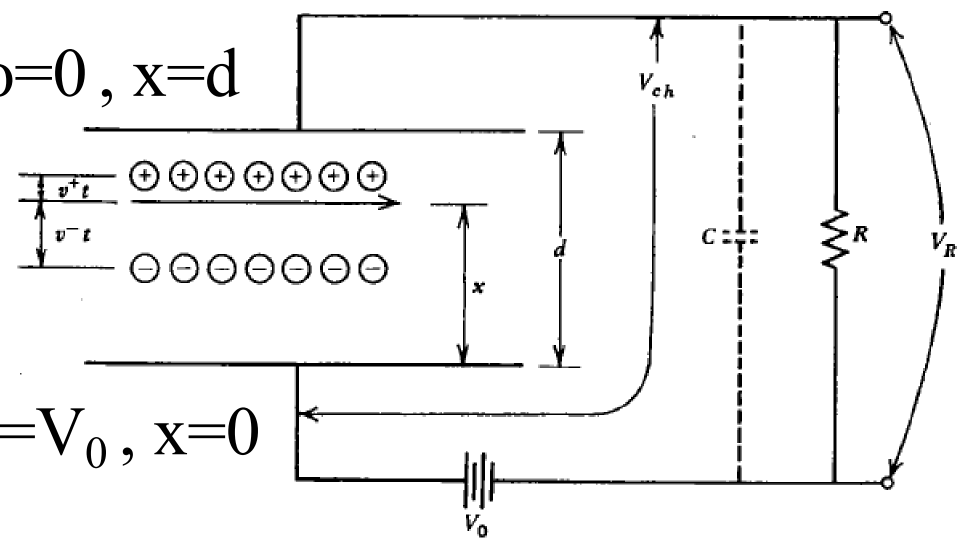
Initially two charge carriers:
$V_R(t) = (N_{IP}\, q_e\, 2/C)\, (\, v^+ + v^- \,)\, t/d$

Electrons are collected:
$V_R(t) = (N_{IP}\, q_e\, 2/C)\, (\, v^+ t + x \,)\, /d$

Both are collected:
$V_R(t) = (N_{IP}\, q_e\, 2/C)\, (\, d\text{-}x + x \,)\, /d$

Fig. 5.15 Knoll, 3rd Ed.

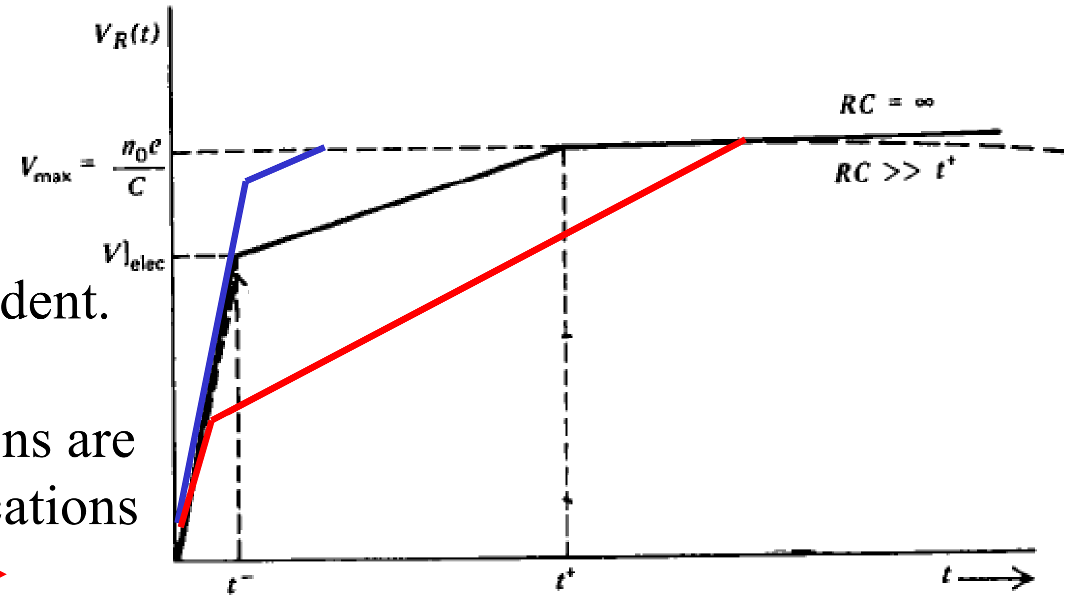
$\phi=0$, x=d



$\phi=V_0$, x=0

Ion Chambers – Pulse mode – 2

Initially two charge carriers:
$V_R(t) = (N_{IP}\, q_e\, 2/C)\,(\, v^+ + v^-\,)\; t/d$



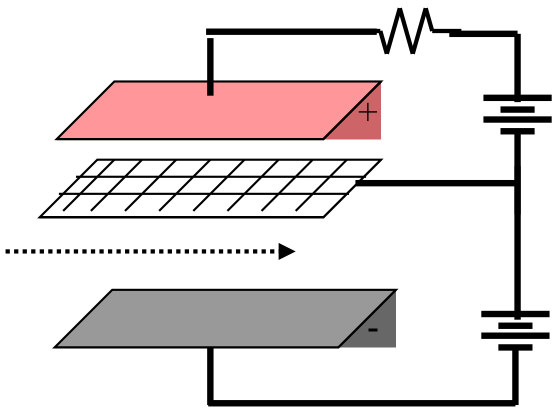
N.B. the pulse shape is position dependent.

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.

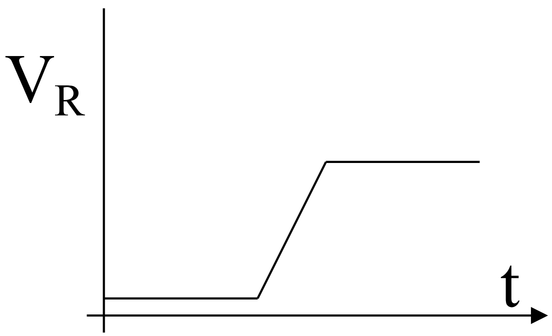
Fig. 5.16 Knoll, 3rd Ed.

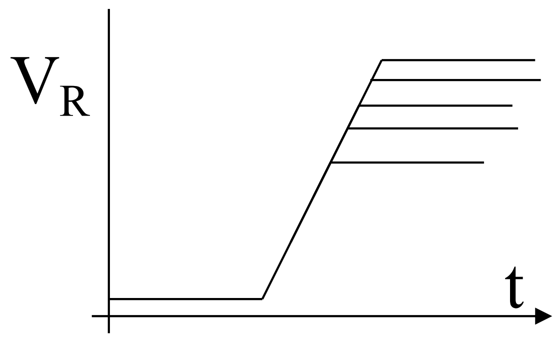
Ion Chambers – (Otto A.) Frisch Grid



Give up measuring the cations …

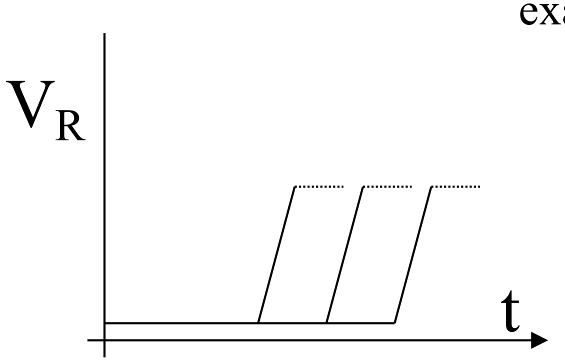
Add a grid at position between the anode and cathode but closer to the anode. The grid needs a high transmission but it will shield the anode electrically from the primary ionization.





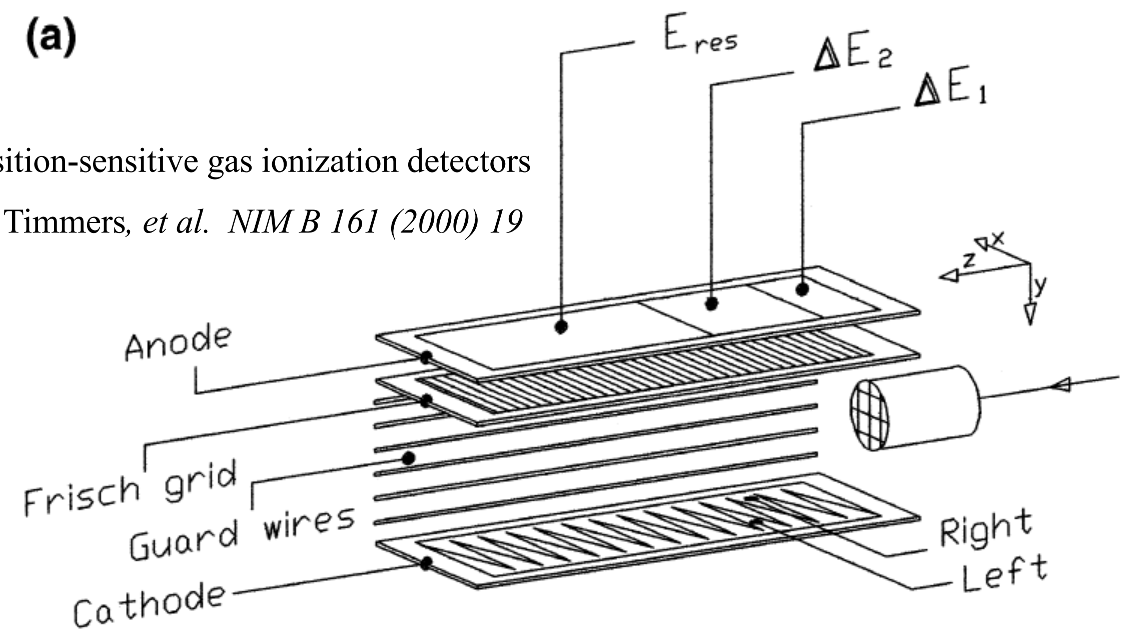
} various pulse heights on central axis give energy dependence – spectroscopy

example: *Fowler & Jared, NIM 124 (1974) 341*



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

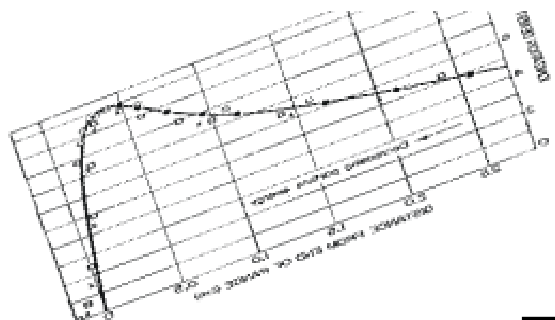
Ion Chambers – Electrode Construction

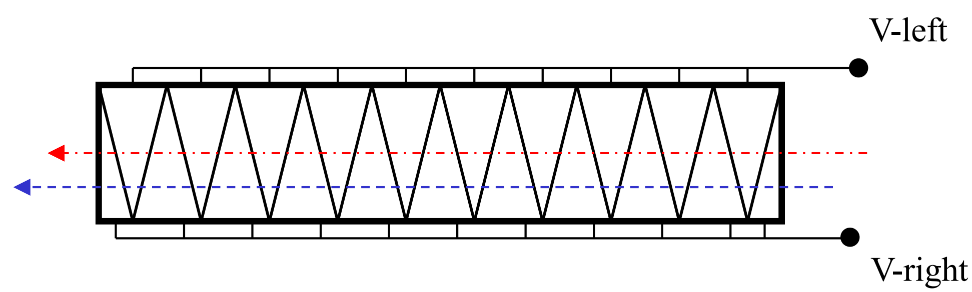


Position-sensitive gas ionization detectors

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

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





- Wedged cathode:

  Red signals (middle) $V_{left} = V_{Right}$

  Blue signals (lower edge) $V_{left} < V_{Right}$

Ion Chambers – Drift Direction

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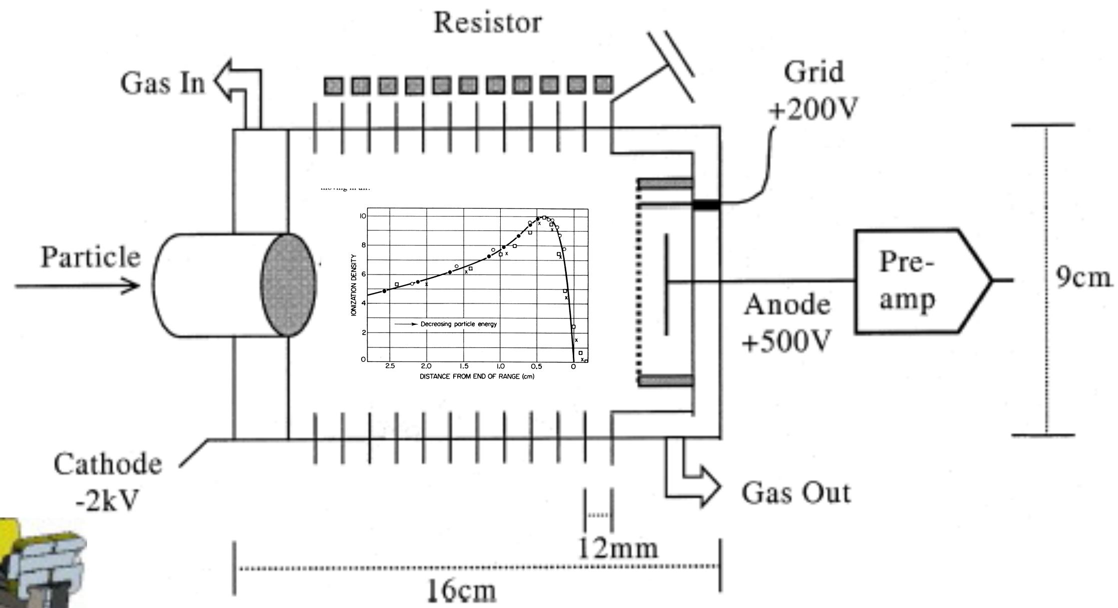
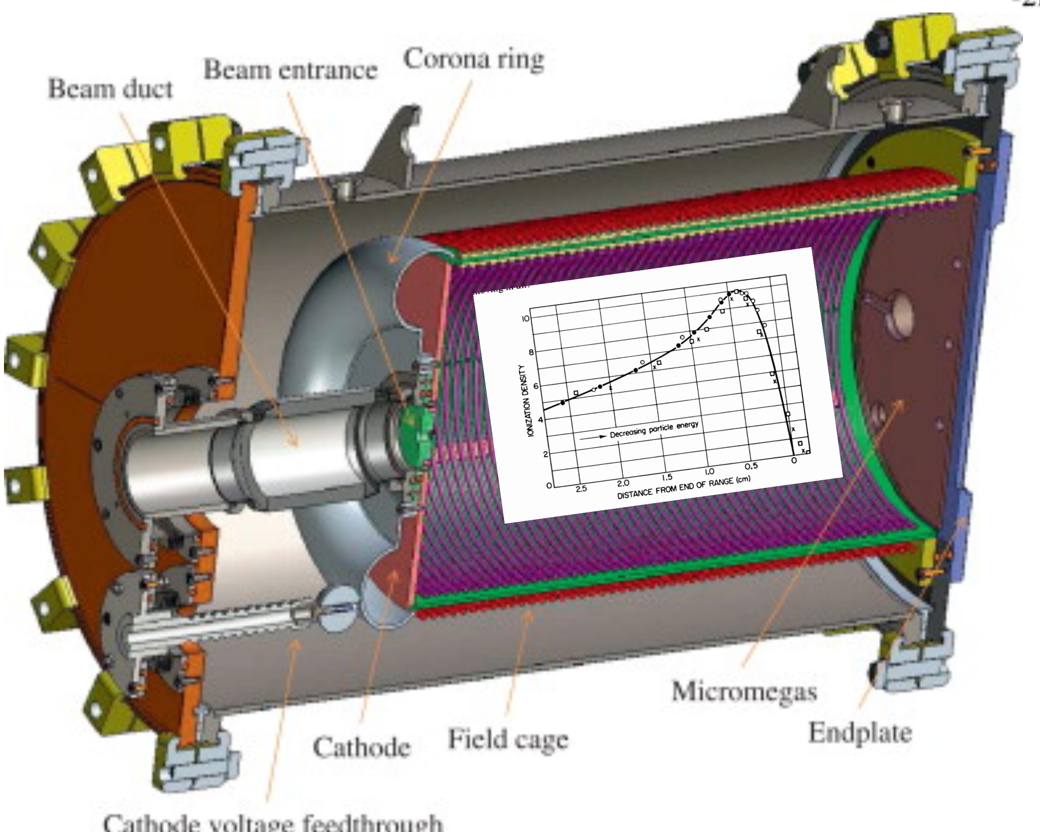
Bragg Curve Detector for AMS

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





Commissioning of the Active-Target Time Projection Chamber

by *Bradt, et al. NIM A 875 (2017) 65*

1m x ~0.3m diameter, ~10^4 V bias