# TRAINING COURSE ON RADIATION DOSIMETRY:

## Instrumentation 1 –

# Gas detectors / Part 1

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*University of Ontario Instutute of Technology*

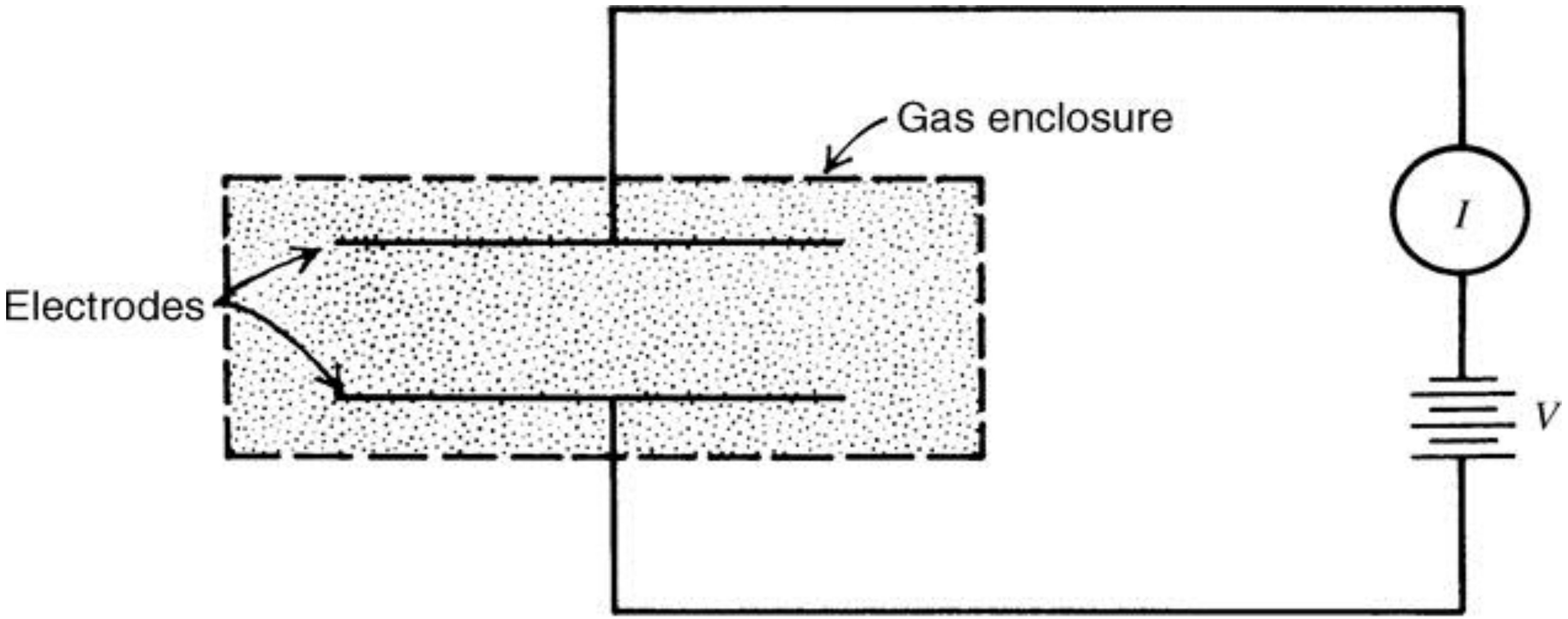
*Wed. 21/11/2012, 15:00 – 16:00 pm, and 16:30 – 17:30 pm*

# GAS-FILLED DETECTORS

- **One of the oldest and most widely used radiation detectors**

- **Gas-filled detectors sense the direct ionization created by the passage of charged particles caused by the interaction of the radiation with the chamber gas**
  - Ion Chambers
  - Proportional Counters
  - Geiger-Mueller Counters

# BASIC COMPONENTS OF AN IONIZATION CHAMBER



Common Fill Gases: Ar, He, $H_2$, $N_2$, Air, $O_2$, $CH_{4,}$ TE

# IONIZATION IN GASES

**To create an ion pair, a minimum energy equal to the ionization energy of the gas molecule must be transferred**

**Ionization energy between 10 to 25 eV for least tightly bound electron shells for gases of interest**

- **Competing mechanisms such as excitation leads to incident particle energy loss without the creation of ion pair**

**W-value: average energy lost by incident particle per ion pair formed**

**Typical W-values are in the range of 25 – 35 eV/ion pair**

# CHARGE COLLECTION

**Under steady-state irradiation, rate of ion-pair formation is constant**

- **For a small test volume, rate of formation will be exactly balanced by rate at which ion pairs are lost from volume due to recombination, diffusion or migration from the volume.**

# CHARGE COLLECTION

**For ions in a gas,**

$$v_{drift} = \frac{\mu \mathcal{E}}{p}$$

$v_{drift}$ – drift velocity of ions
$\mu$ – mobility
$\mathcal{E}$ – electric field strength
$p$ – gas pressure

+ve and –ve charges are swept towards their respective electrodes with $v_{drift}$

By increasing $v_{drift}$ concentration of ions within the gas volume decreases suppressing volume recombination within the gas volume.

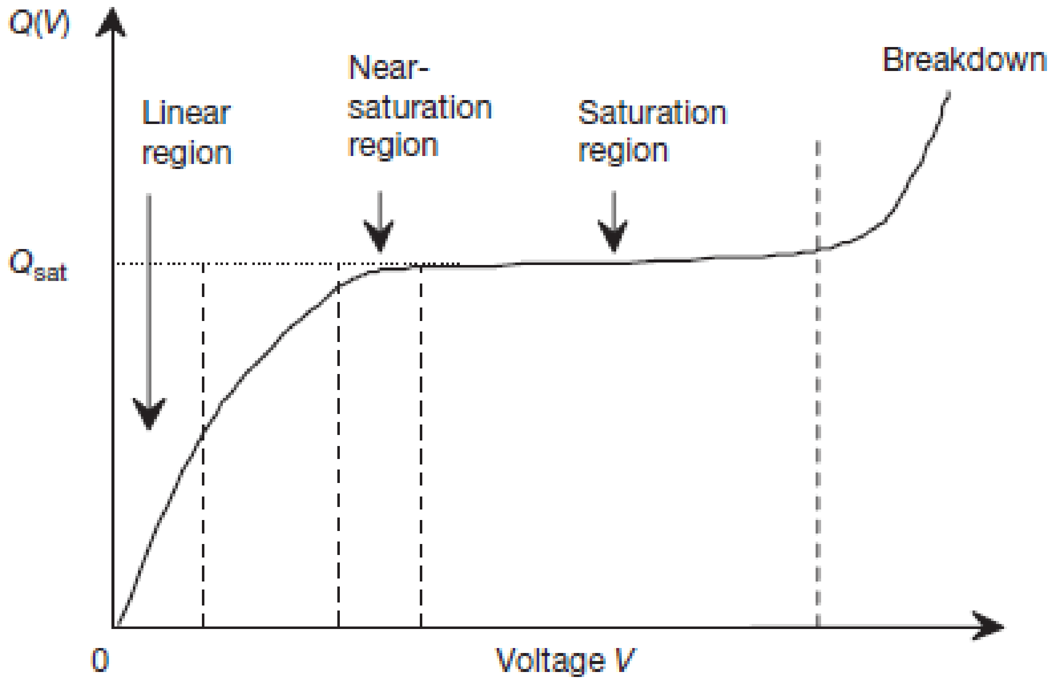
# RECOMBINATION

**Two types of recombination:**

- Columnar (or initial) recombination
  - Increases with LET of Radiation
- Volume recombination
  - Increases with dose-rate

$$\frac{dn^{+}}{dt} + \frac{dn^{-}}{dt} = -\alpha n^{+} n^{-}$$

# CHARGE COLLECTION



# IONIZATION CHAMBER – FARMER CHAMBER

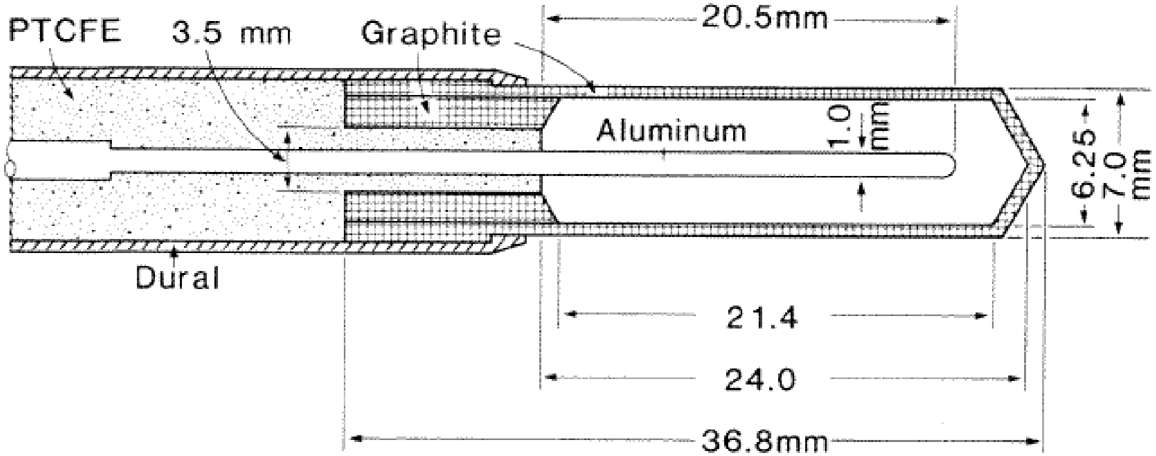


**FIG. 6.10.** Farmer graphite/aluminum chamber. Nominal air volume, 0.6 ml. PTCFE, polytrichlorofluorethylene. (Redrawn from Aird EGA, Farmer FT. The design of a thimble chamber for the Farmer dosimeter. *Phys Med Biol* 1972;17:169.)

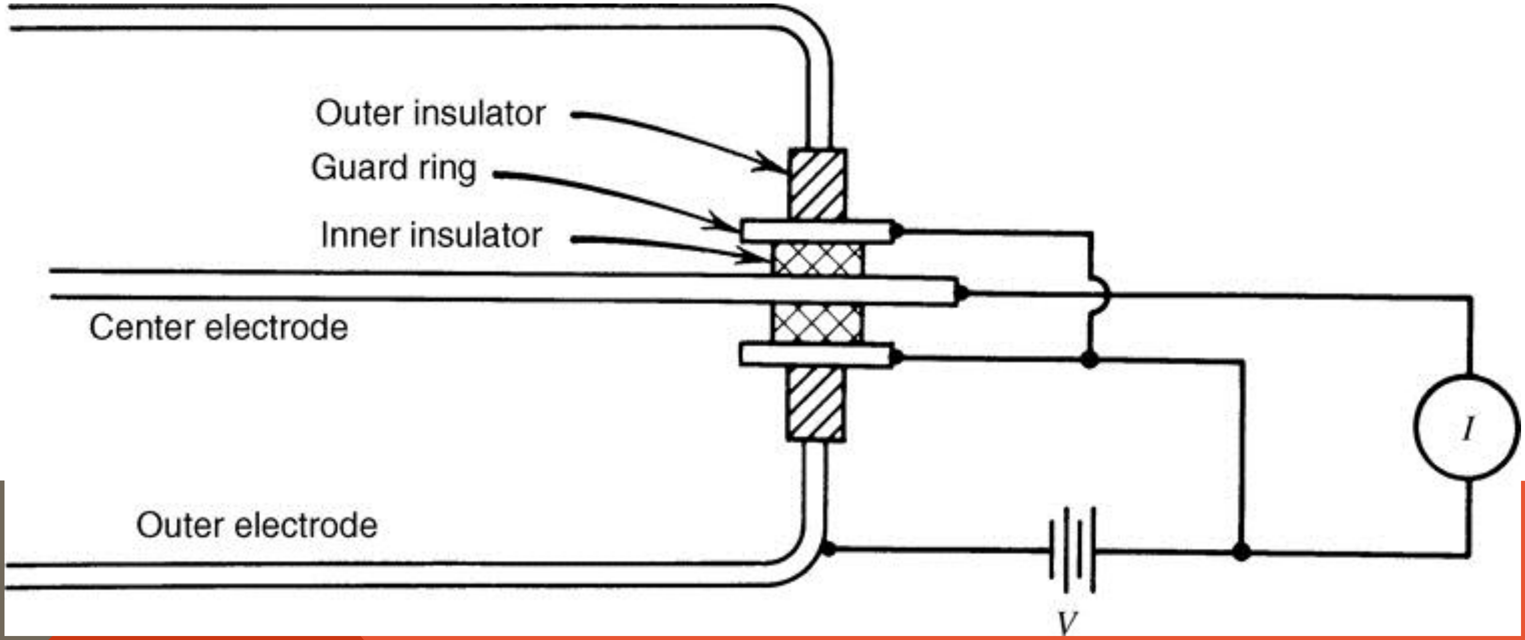
# IONIZATION CHAMBERS

What ionization current would we expect to measure in a Farmer chamber placed in a high energy photon radiotherapy beam where the dose rate to air is 10 Gy per minute.

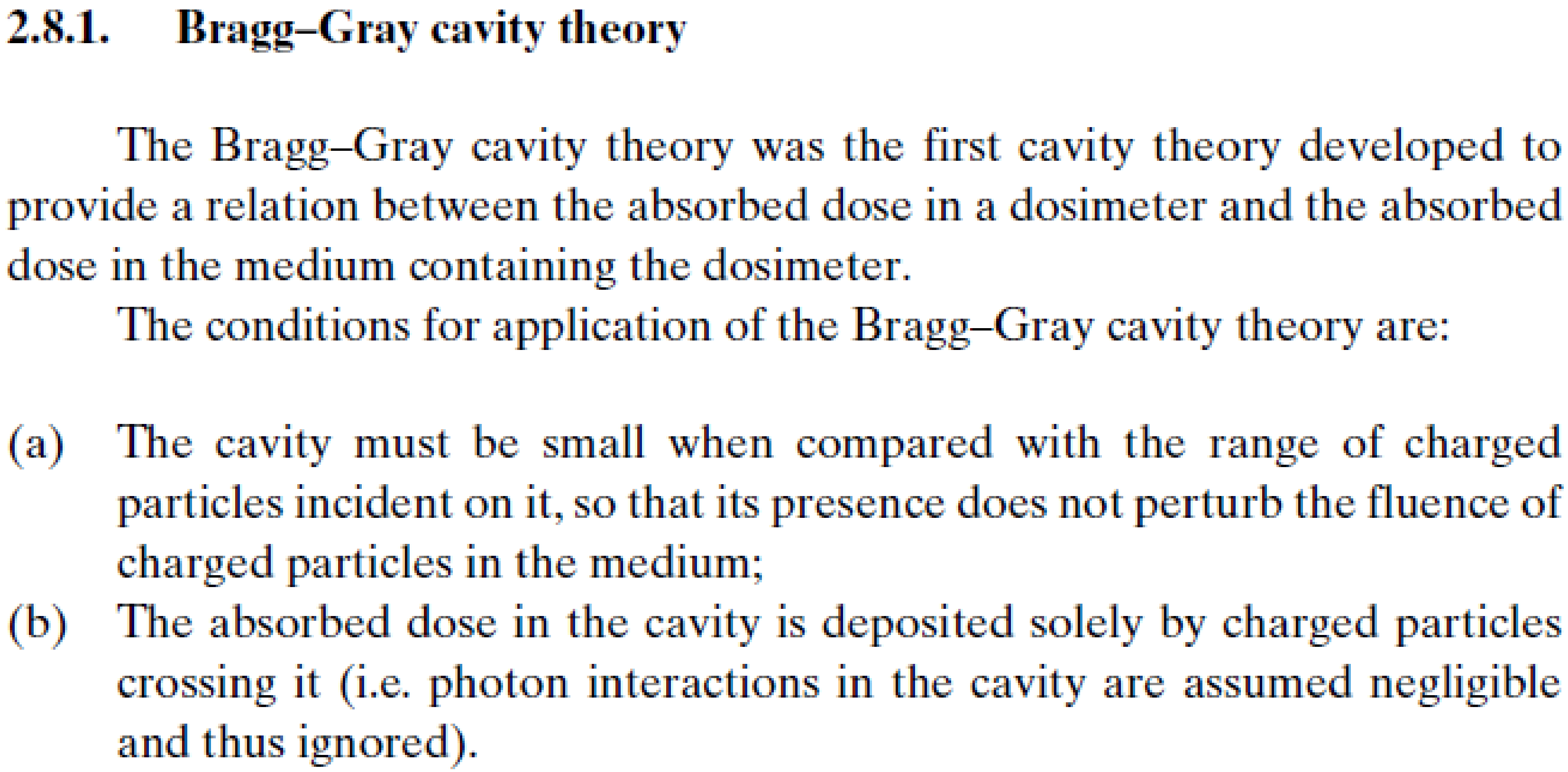
# INSULATORS AND GUARD RINGS

**Typical ionization currents are extremely small.**

**Require good insulation and guard rings to ensure leakage current does not interfere with ionization current**



# IONIZATION CHAMBER DOSIMETRY



## 2.8.1. Bragg–Gray cavity theory

The Bragg–Gray cavity theory was the first cavity theory developed to provide a relation between the absorbed dose in a dosimeter and the absorbed dose in the medium containing the dosimeter.

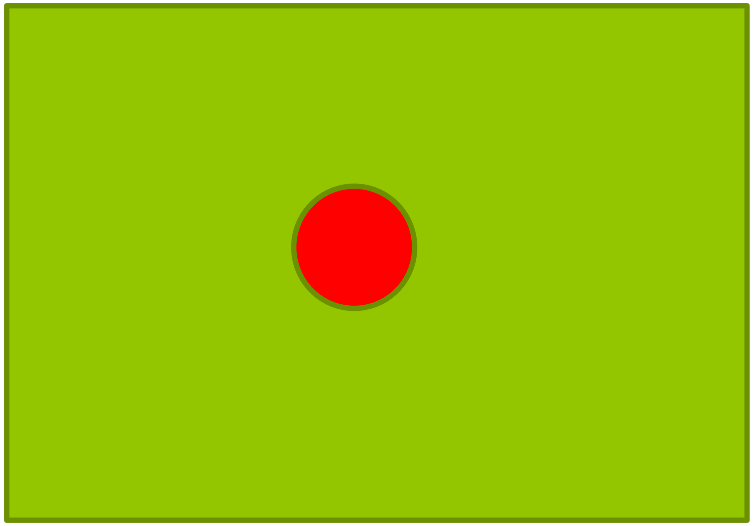
The conditions for application of the Bragg–Gray cavity theory are:

(a) The cavity must be small when compared with the range of charged particles incident on it, so that its presence does not perturb the fluence of charged particles in the medium;

(b) The absorbed dose in the cavity is deposited solely by charged particles crossing it (i.e. photon interactions in the cavity are assumed negligible and thus ignored).

# DOSIMETRY WITH IONIZATION CHAMBERS

$$D_{matter} = D_{cavity} \cdot \left\{\frac{S}{\rho}\right\}_{\frac{matter}{cavity}}$$



# FANO’S THEOREM

*In an infinite medium of given atomic composition exposed to a uniform field of indirectly ionizing radiation, the field of secondary radiation is also uniform and independent of density of the medium, as well as density variations from point to point.*

**This means that if an ionization chamber is constructed of a wall material and filled with gas of the same atomic composition the dose to the wall material will be the same as the dose measured to the gas regardless of the size of the chamber**

# IONIZATION CHAMBER DOSIMETRY - CALIBRATION

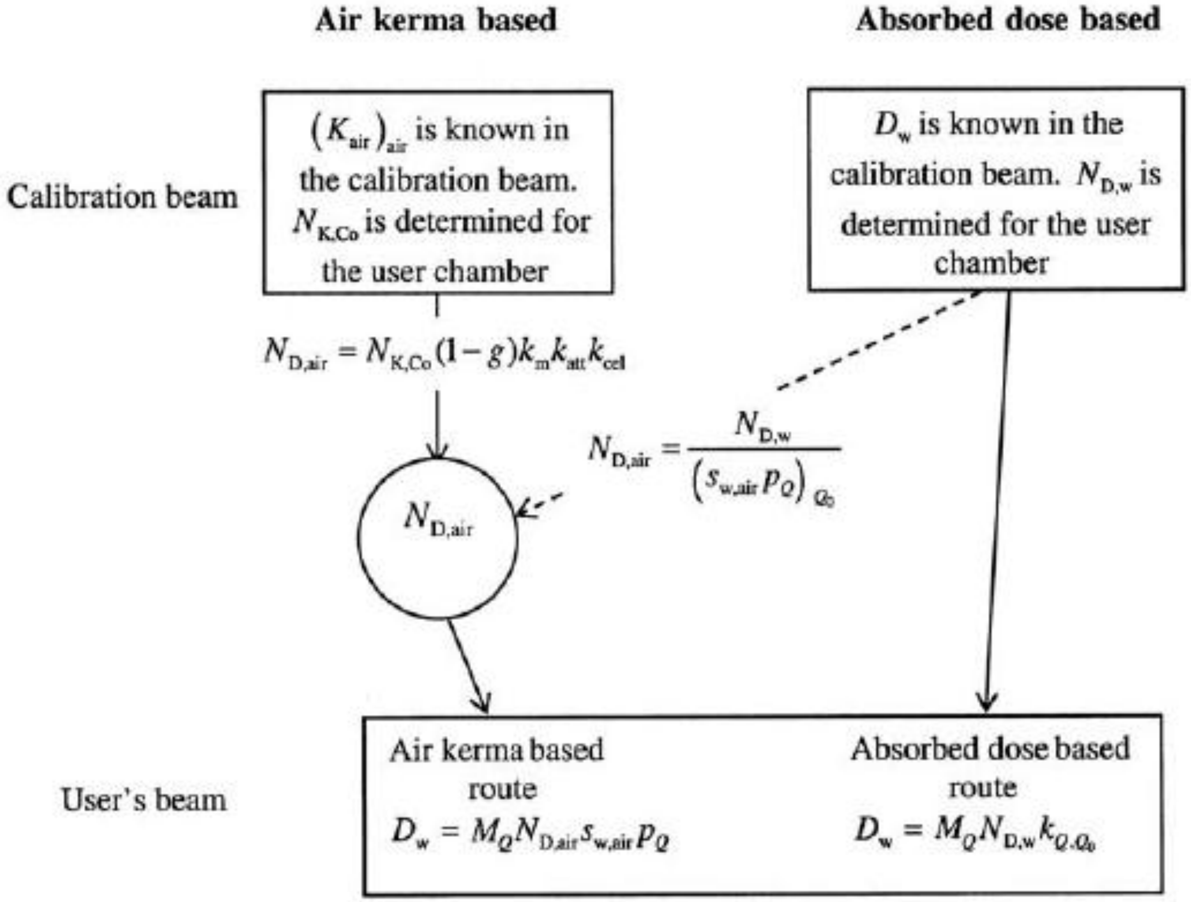
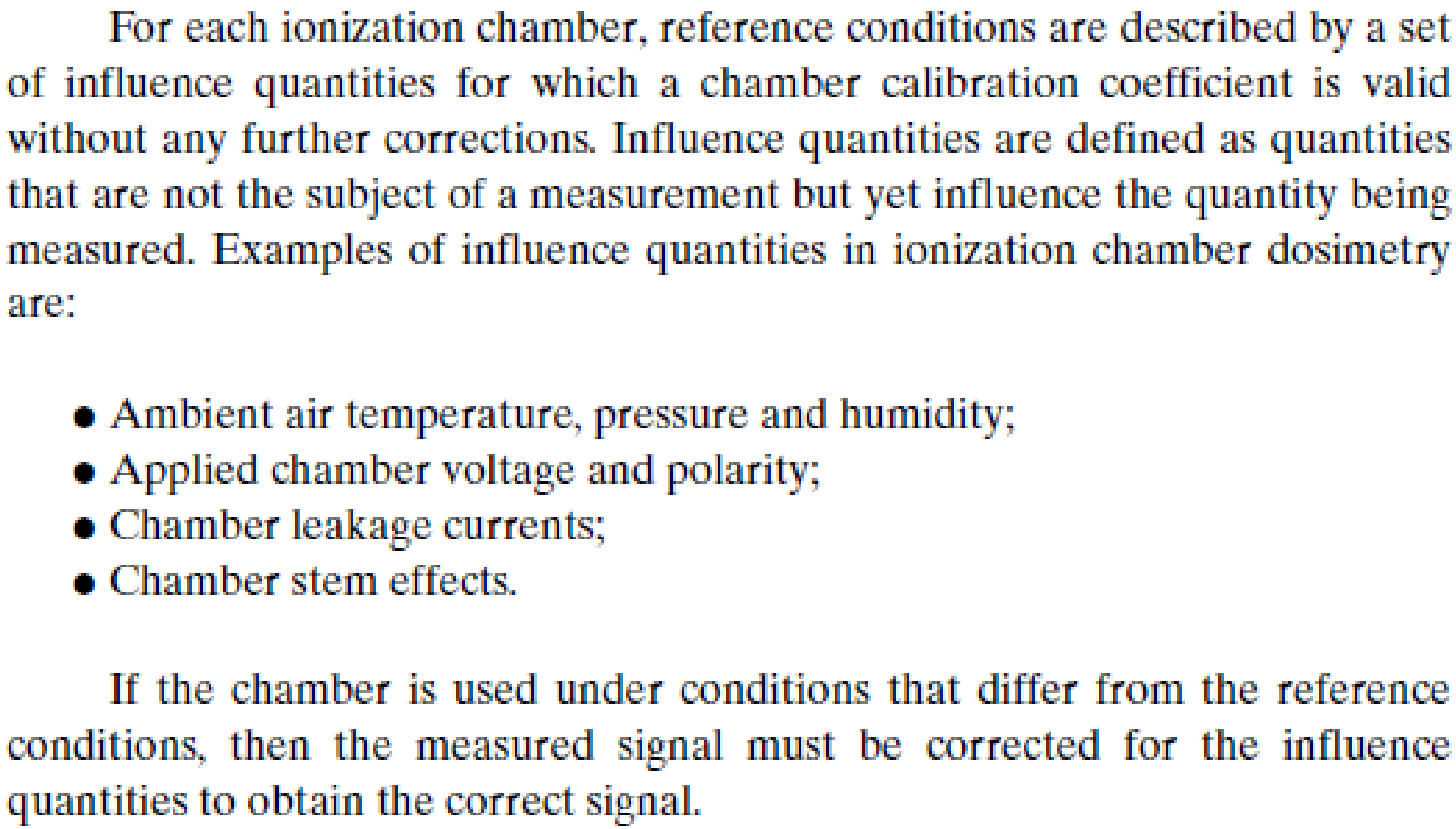


*FIG. 9.4. Steps involved in ionization chamber based reference dosimetry: (a) air kerma in air based, (b) absorbed dose to water based.*

# IONIZATION CHAMBER DOSIMETRY



For each ionization chamber, reference conditions are described by a set of influence quantities for which a chamber calibration coefficient is valid without any further corrections. Influence quantities are defined as quantities that are not the subject of a measurement but yet influence the quantity being measured. Examples of influence quantities in ionization chamber dosimetry are:

- Ambient air temperature, pressure and humidity;
- Applied chamber voltage and polarity;
- Chamber leakage currents;
- Chamber stem effects.

If the chamber is used under conditions that differ from the reference conditions, then the measured signal must be corrected for the influence quantities to obtain the correct signal.

# DOSIMETRY WITH GAS IONIZATION DEVISES

## TISSUE EQUIVALENT PROPORTIONAL COUNTERS

## TEPC

# ATOMIC COMPOSITION OF TISSUE AND TE GAS

- **Methane based**
  - $CH_4$ (64.4% partial pressure)
  - $CO_2$ (32.4% partial pressure)
  - $N_2$ (3.2% partial pressure)
  - By %weight: H (10.2); C (45.6); N (3.5); O (40.7)

- **Propane based**
  - $C_3H_8$ (% partial pressure)
  - $CO_2$ (% partial pressure)
  - $N_2$ (%partial pressure)
  - By %weight: H (10.3); C (56.9); N (3.5); O (29.3)

**ICRU Tissue (Muscle) atomic composition by % weight**

| H | C | N | O |
|---|---|---|---|
| 10.2 | 12.3 | 3.5 | 72.9 |
| | | | |

# TISSUE EQUIVALENT PLASTIC

**The main tissue equivalent plastic used in dosimetry is A150.**

**The atomic composition of A150 is close to tissue but has a higher percentage by weight of carbon, which makes it conductive.**

**A150 TE-plastic atomic composition by % weight**

| H | C | N | O |
|---|---|---|---|
| muscle (10.2) | muscle (12.3) | muscle (3.5) | muscle (72.9) |
| **10.1** | **77.6** | **3.5** | **5.2** |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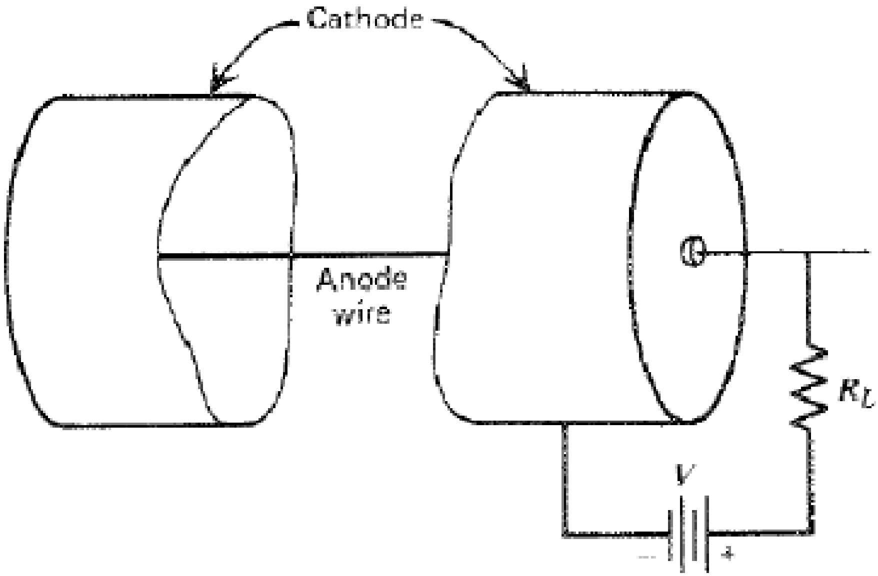
# GAS-GAIN IN PROPORTIONAL COUNTERS

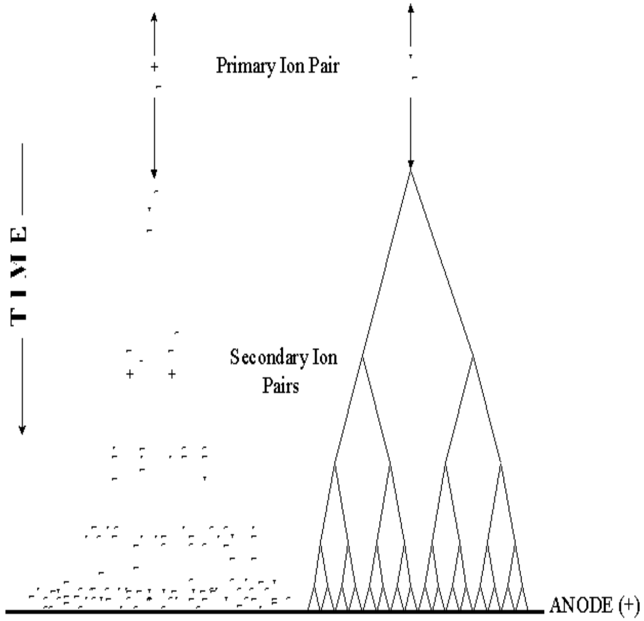
**A proportional counter is a gas-ionization device consisting of a cathode, thin anode wire and fill-gas. Ionization in the fill gas is multiplied providing an amplified signal proportional to the original amount of ionization.**



# GAS GAIN

**The gas-gain achievable in a proportional counter is determined by the first Townsend coefficient α for the counter fill gas used**

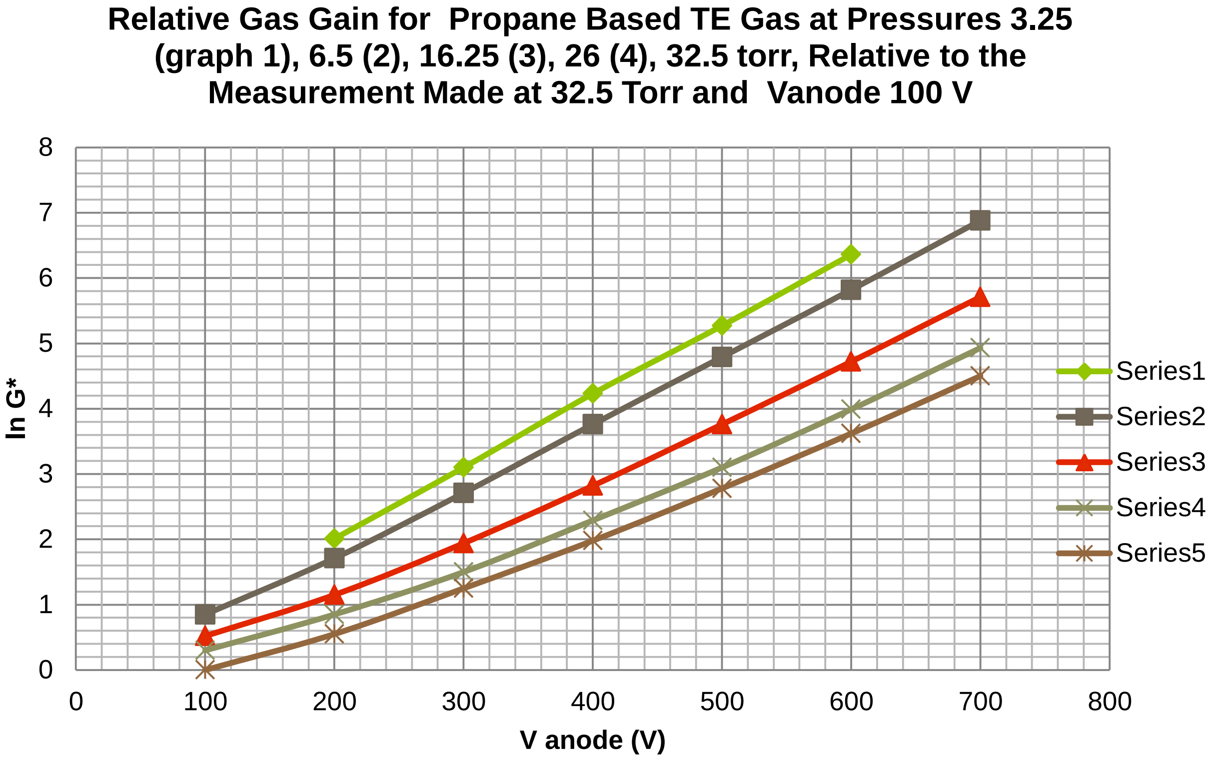
**α itself depends on the reduced electric field in the counter, which is determined by the applied voltage and counter geometry**



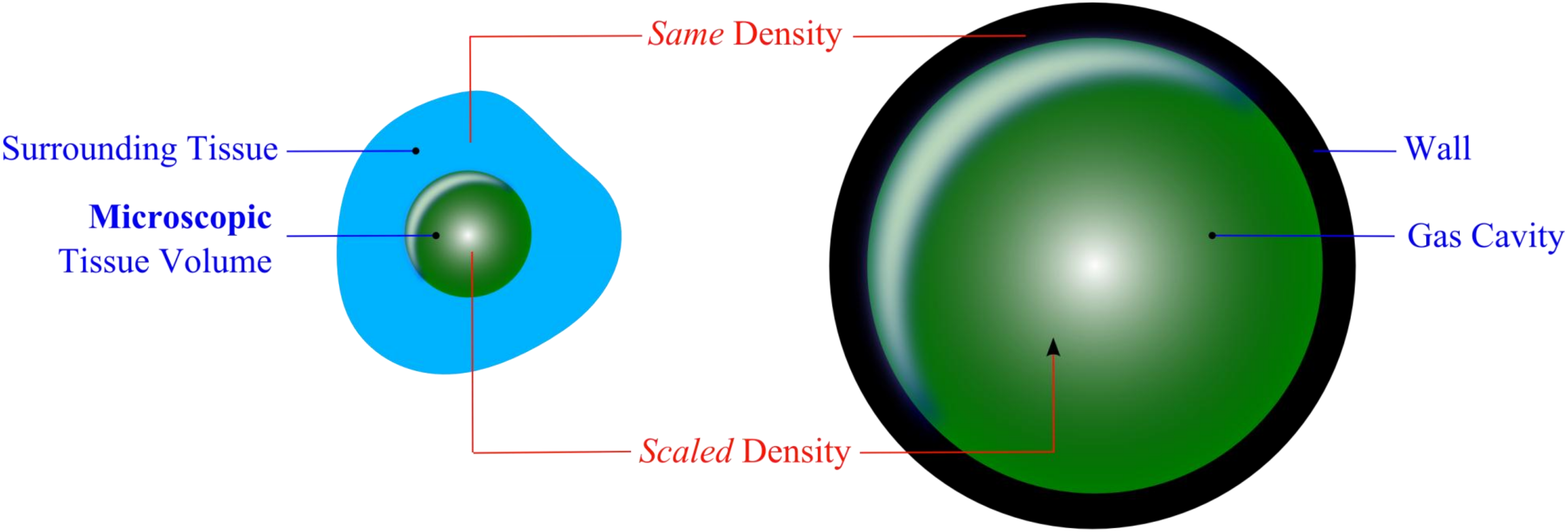
$$\ln(G) = \alpha * d$$

# GAS GAIN

To a first approximation the relationship between the logarithm of gas-gain and applied anode voltage is linear

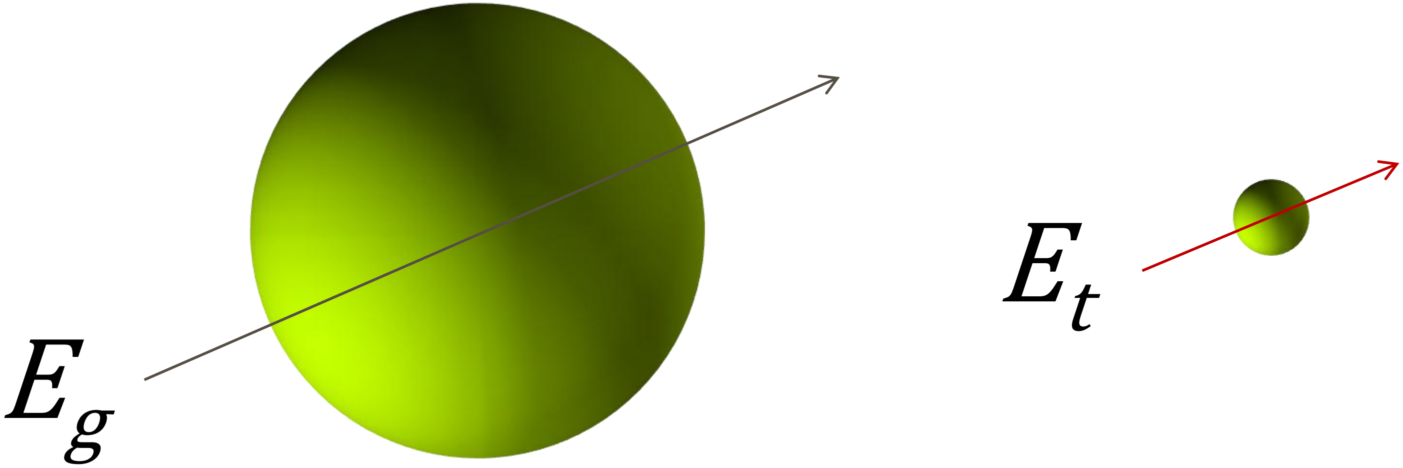


# SIMULATION USING A GAS CAVITY



# SITE-SIZE SIMULATION

**Energy deposited in the gas cavity by a charged particle crossing the cavity equals energy deposited in tissue site by an identical particle**



# SITE-SIZE SIMULATION

$$E_g = Et$$

$$\left(\frac{1}{\rho}\cdot\frac{dE}{dx}\right)_{gas}\cdot\rho_g\cdot\Delta_g = \left(\frac{1}{\rho}\cdot\frac{dE}{dx}\right)_{tissue}\cdot\rho_t\cdot\Delta_t$$

# SITE-SIZE SIMULATION

**The density of the gas in the cavity is adjusted to equal the ratio of the tissue site diameter to the gas cavity diameter**

Diameter of Tissue Site

$$\rho_g = \left( \frac{\Delta X_t}{\Delta X_g} \right) \rho_t$$

Density of Gas

Density of Tissue Site (1000 kg.m$^{-3}$)

Diameter of Gas Cavity

# EXAMPLE

What is the density of propane TE gas required for a 1 cm cavity to simulate a tissue sphere of 1 µm.

$$\boldsymbol{\rho_g = (10^{-6}/10^{-2}).\,\rho_t}$$

$$\boldsymbol{\rho_g = 10^{-4}\ .\ 1000\ \mathrm{kg.m^{-3}}}$$

$$\boldsymbol{\rho_g = 0.1\mathrm{kg.m^{-3}}}$$

# EXAMPLE

**What pressure of propane TE gas is required for a density of 0.1 kg.m$^{-3}$**

$$\rho_g = 1.798\ kg.m^{-3} at\ 100\ kPa\ and\ 20^oC$$

$$\rho_{PT} = \rho_{PoTo} \cdot \frac{P}{Po} \cdot \frac{To}{T}$$

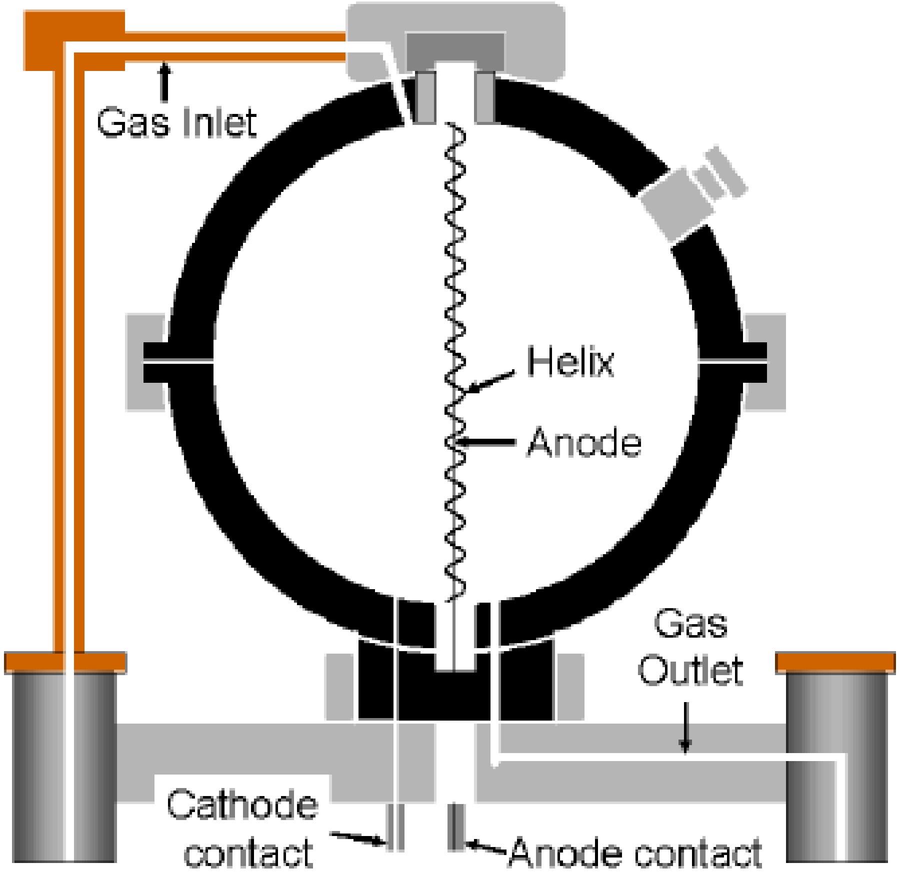
At 20 $^o$C:

$$0.1 = 1.798. \frac{P}{100} \cdot \frac{293}{293}$$

$$P = 5.562\ kPa$$

(41.72 torr)

# Rossi Counter



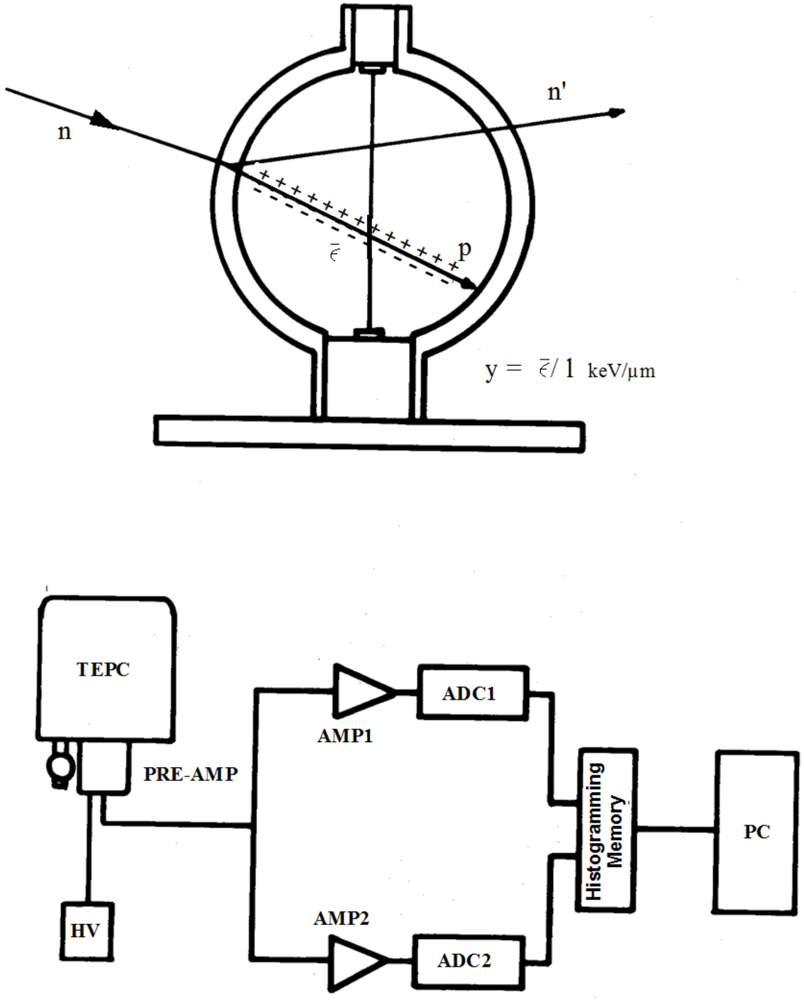


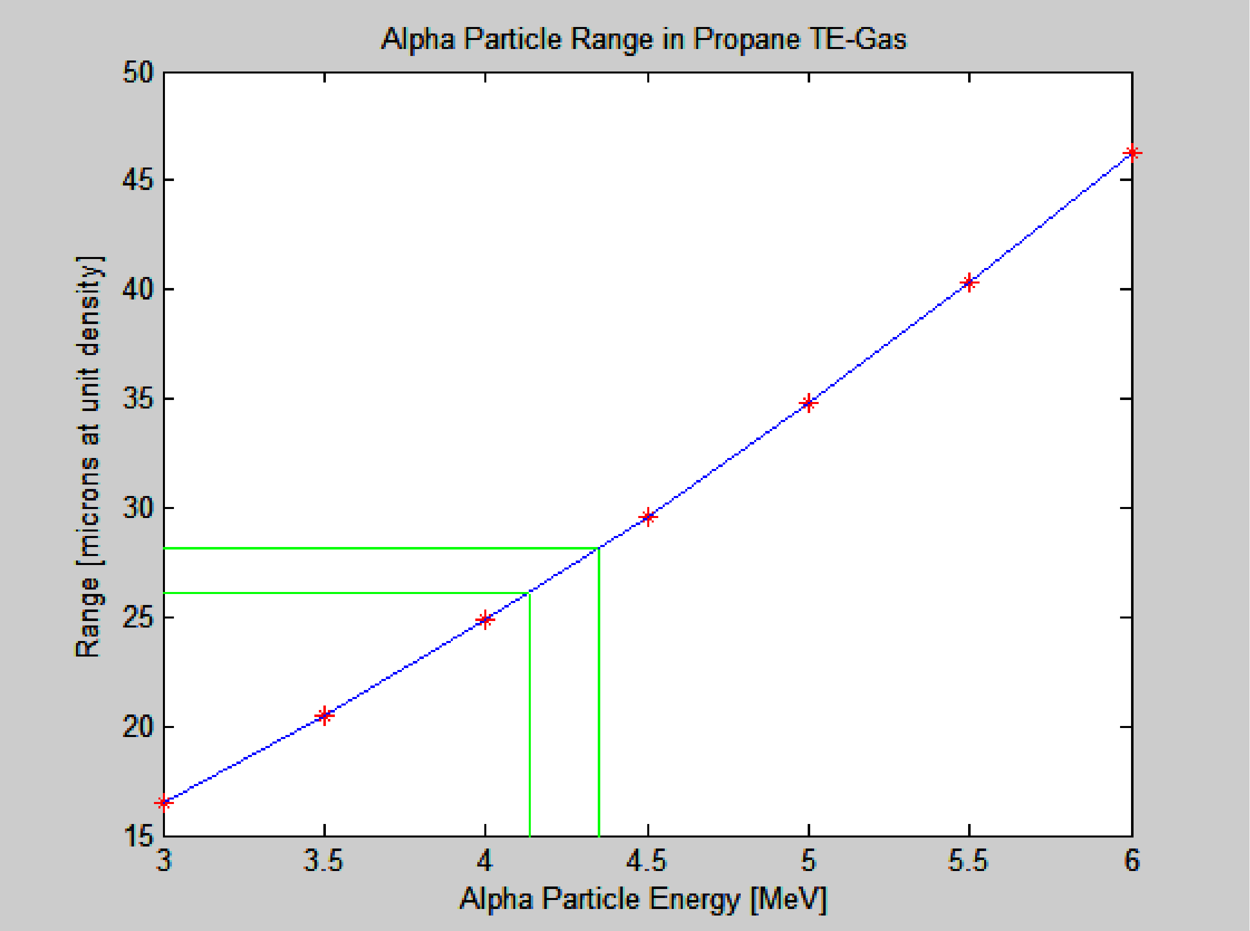
Figure 1. The principles of operation and measurement with TEPCs

# TEPC CALIBRATION

## INTERNAL ALPHA SOURCES

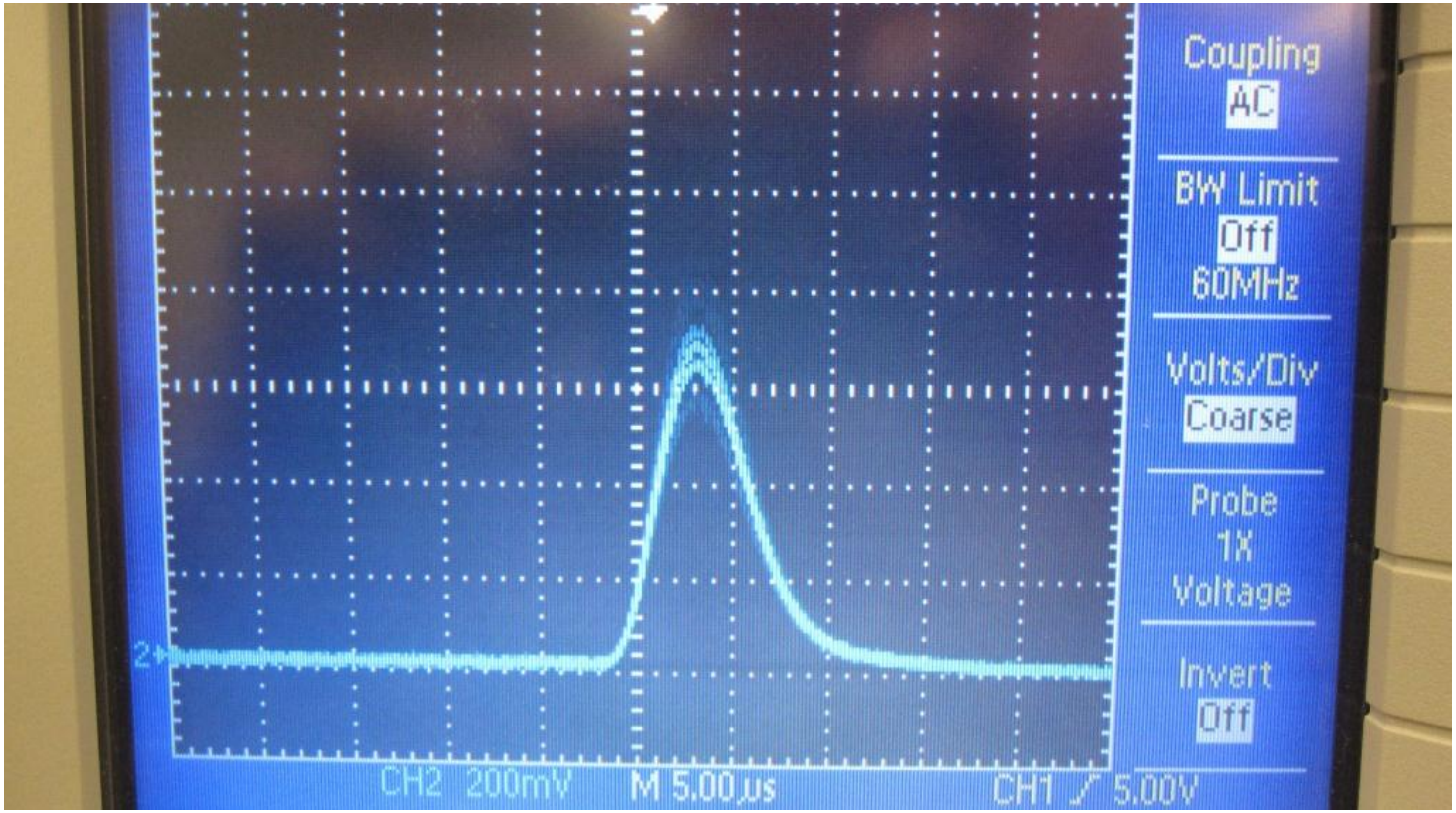
# INTERNAL SOURCE CALIBRATION

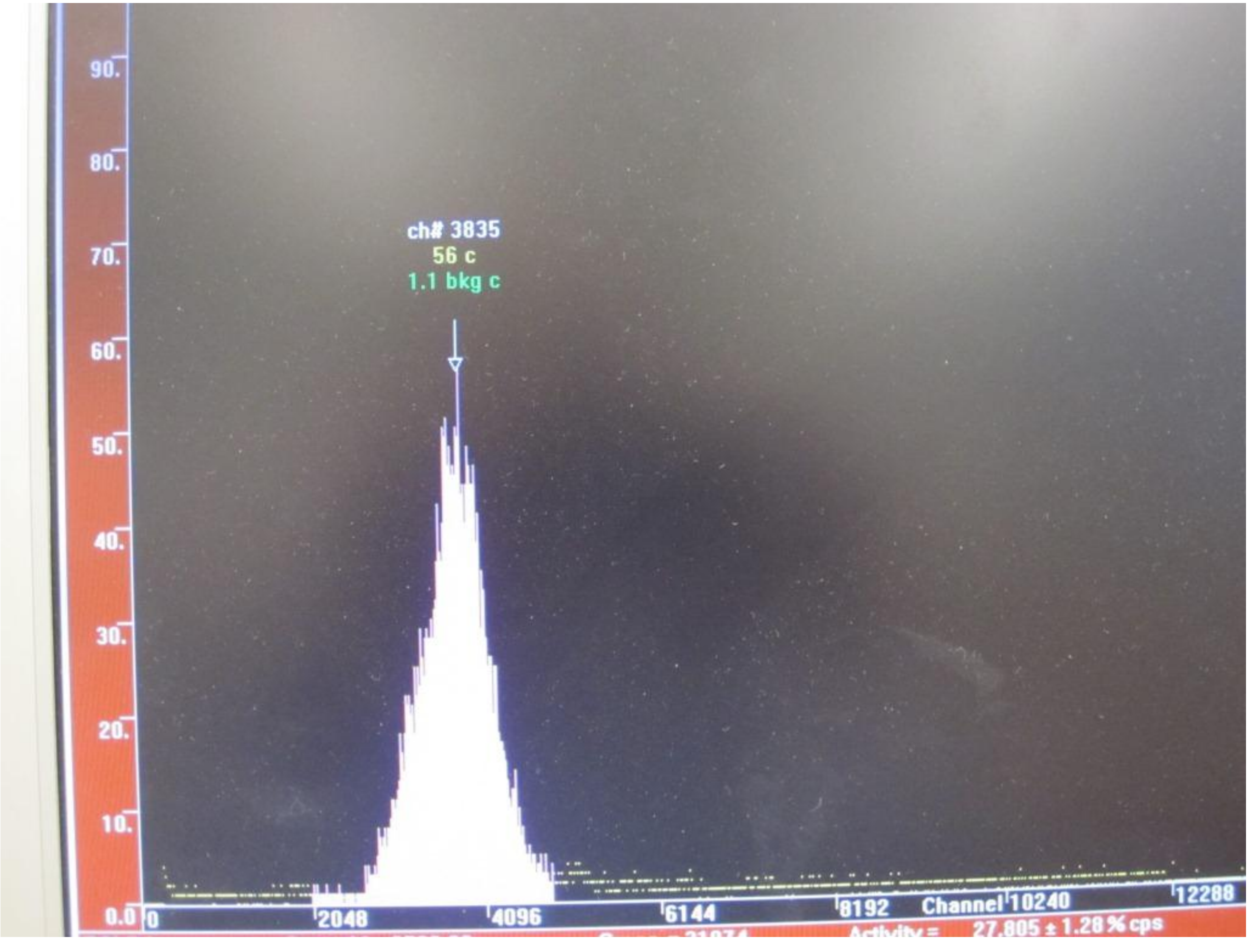
**In crossing the TEPC an alpha particle will lose an average amount of energy that can be calculated using range-energy data**



# INTERNAL SOURCE CALIBRATION

**Each alpha particle crossing the counter generates a pulse height proportional to the energy deposited; the mean of this distribution is associated with the mean energy deposited in the counter**




ch# 3835
56 c
1.1 bkg c
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.0
0
2048
4096
6144
8192
Channel
10240
12288
Activity = 27.805 ± 1.28 % cps

# EXAMPLE

**Using range-energy data for propane based TE gas for a 2 micron simulated diameter and a Cm-244 internal alpha source of energy 5.8 MeV.**

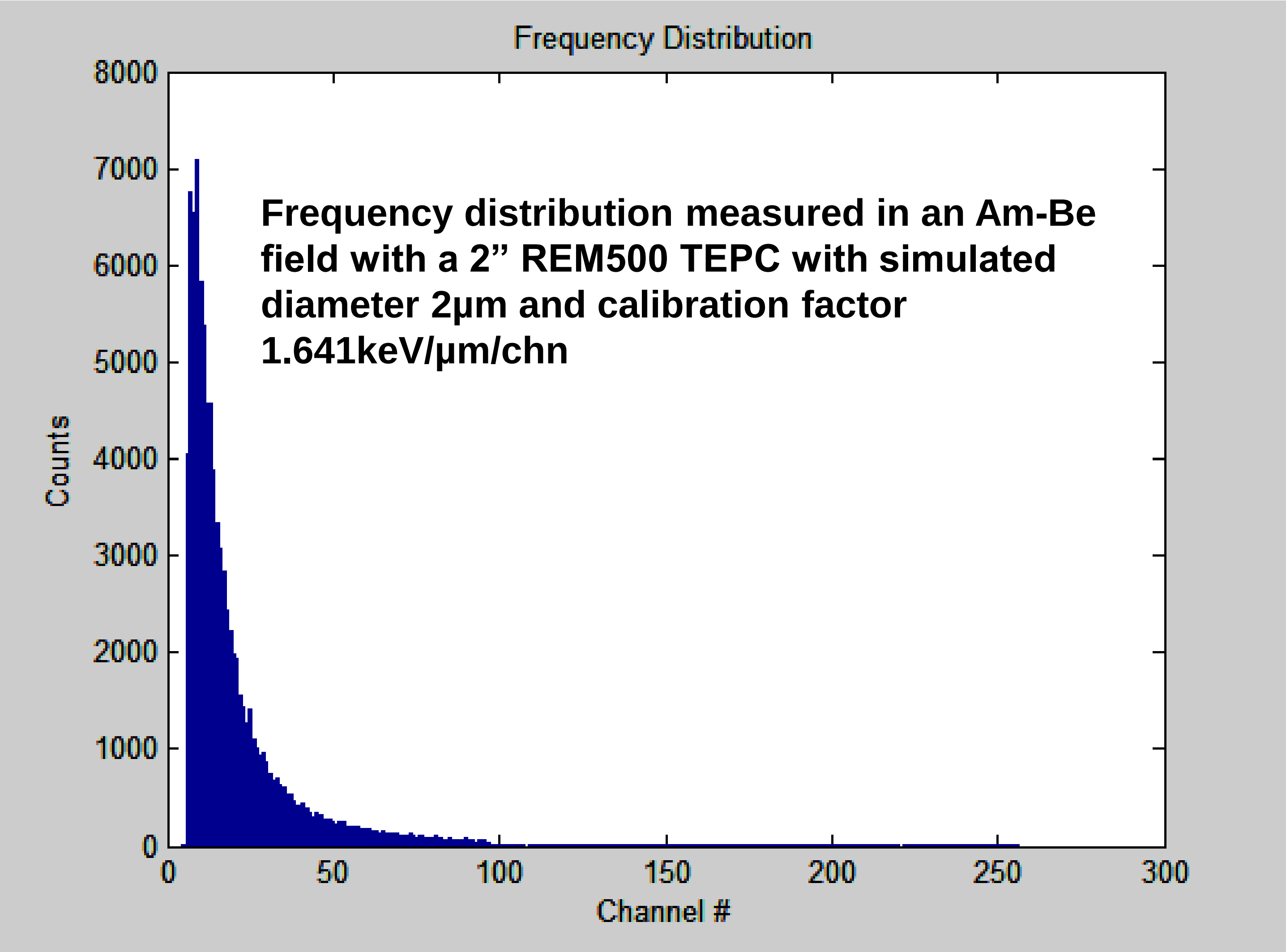
**Applied Voltage 750V; amplifier gain 10**

**Mean energy lost 168.48 keV**

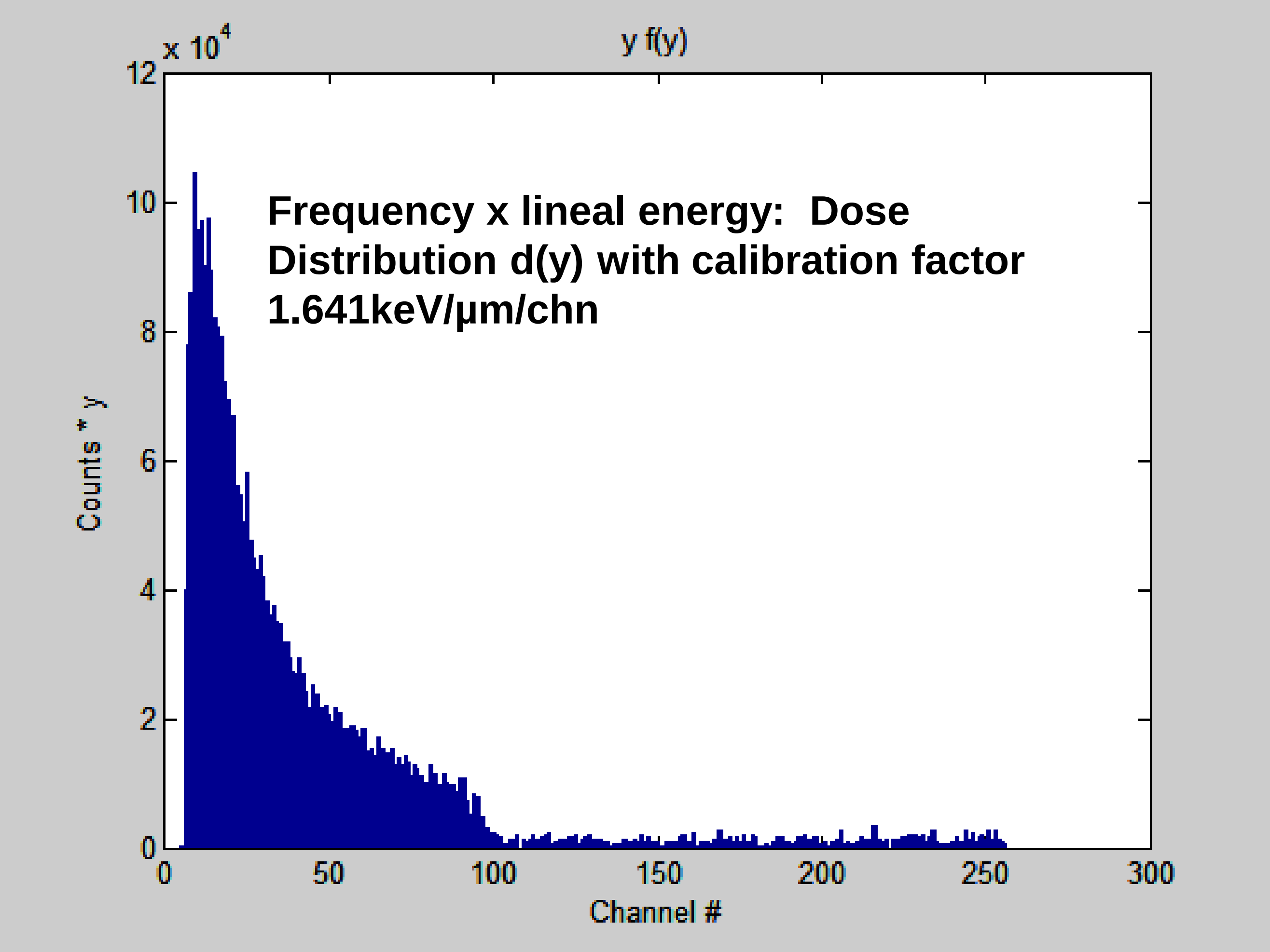
**Mean chord-length 1.33 µm**

**Channel 3835 corresponds to 126.68 keV/µm**

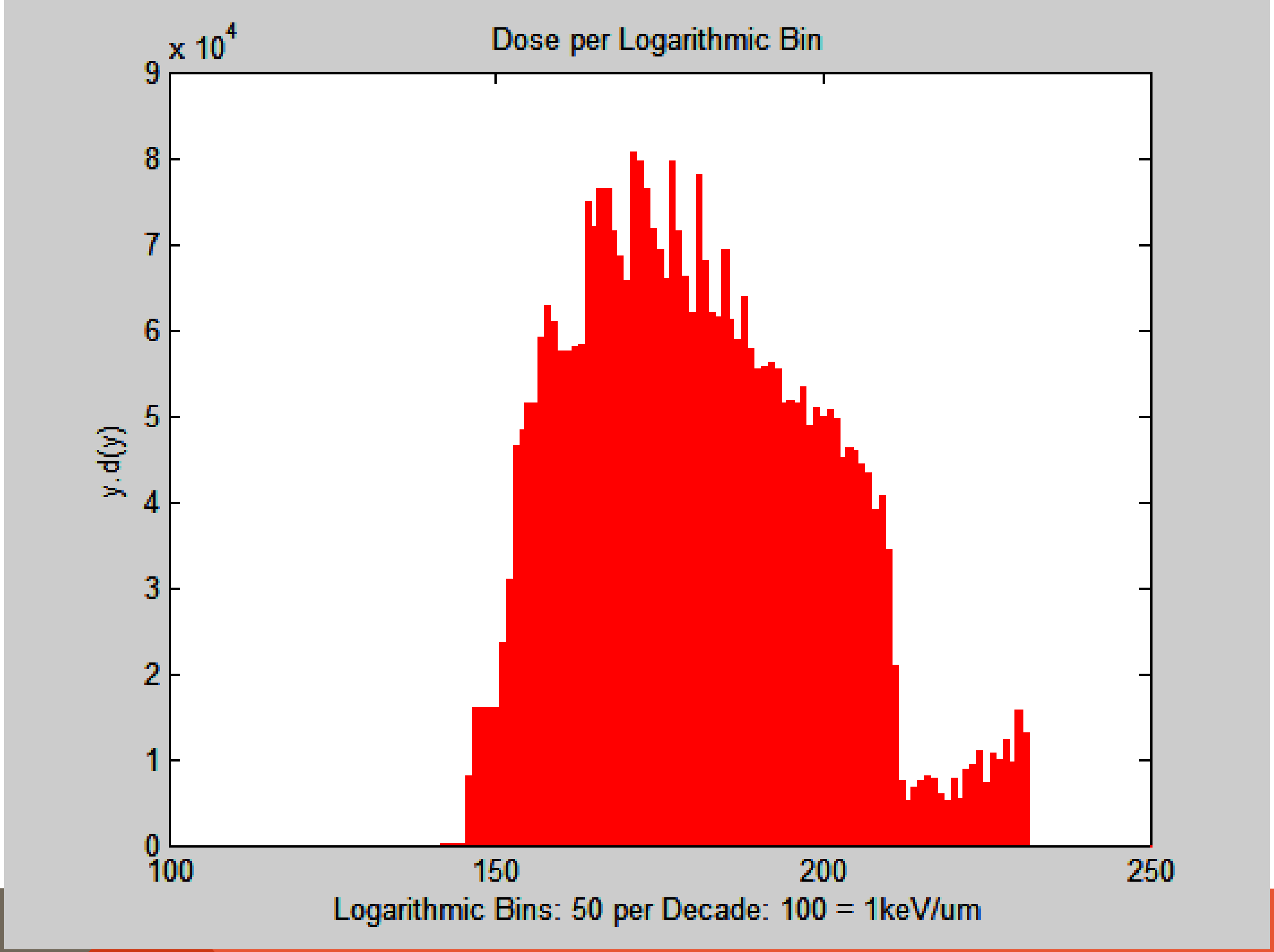
**Calibration Factor for amplifier setting of 10 (126.68/3835) = 0.03303 keV/µm/channel**



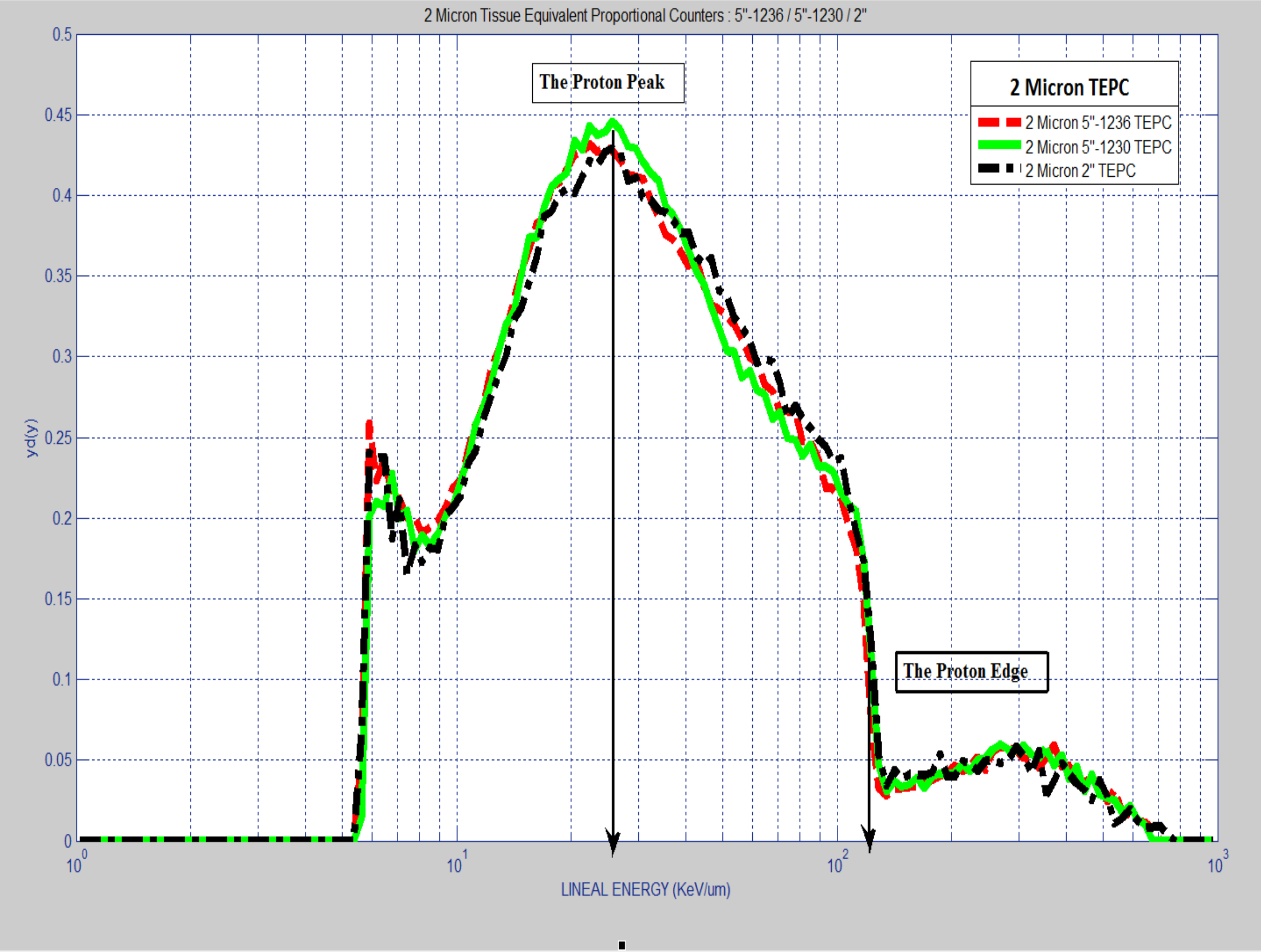
Frequency distribution measured in an Am-Be field with a 2” REM500 TEPC with simulated diameter 2μm and calibration factor 1.641keV/μm/chn



**Frequency x lineal energy: Dose Distribution d(y) with calibration factor 1.641keV/μm/chn**



y.f(y) data plotted in equal logarithmic intervals, 50 per decade



The Proton Peak

The Proton Edge

# TEPC MEASURABLE QUANTITIES

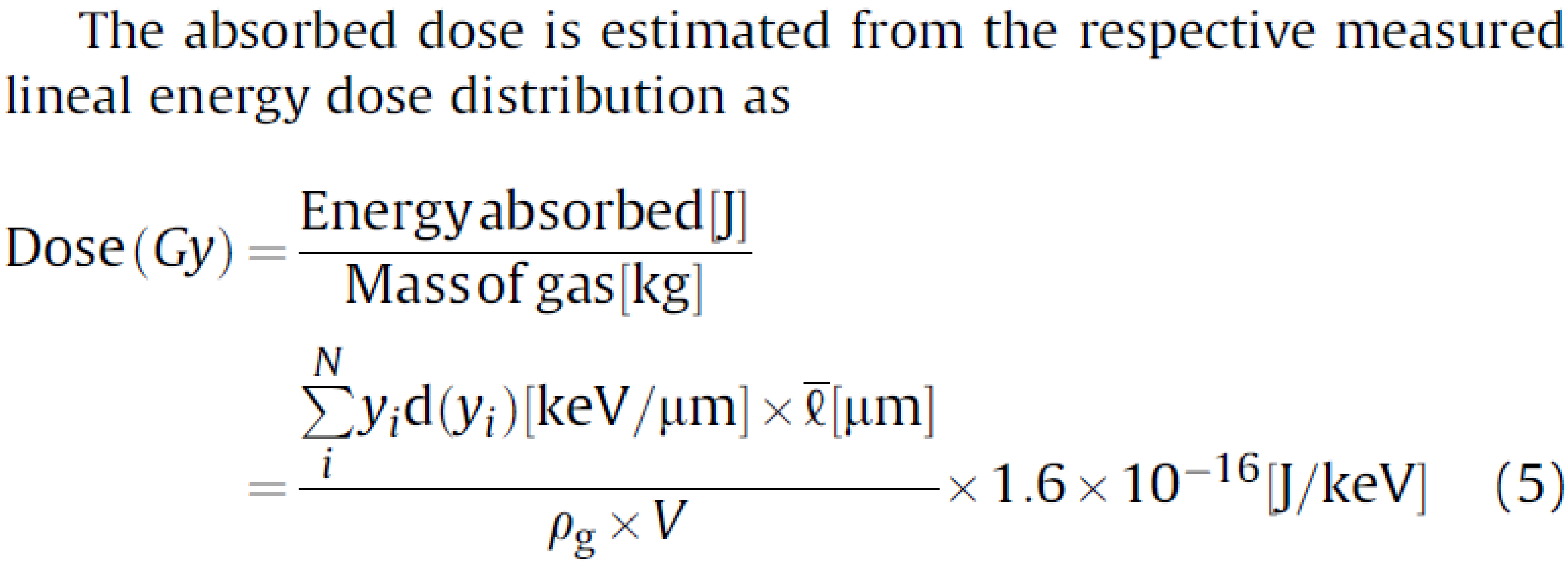
# MEASUREABLE QUANTITIES – AMBIENT DOSE EQUIVALENT

$$H^*(10) = D^*(10).\bar{Q}$$

**Estimated directly from the measured event-size spectrum**

**Determined from the shape of the event-size spectrum and assuming Q(y) = Q(L)**

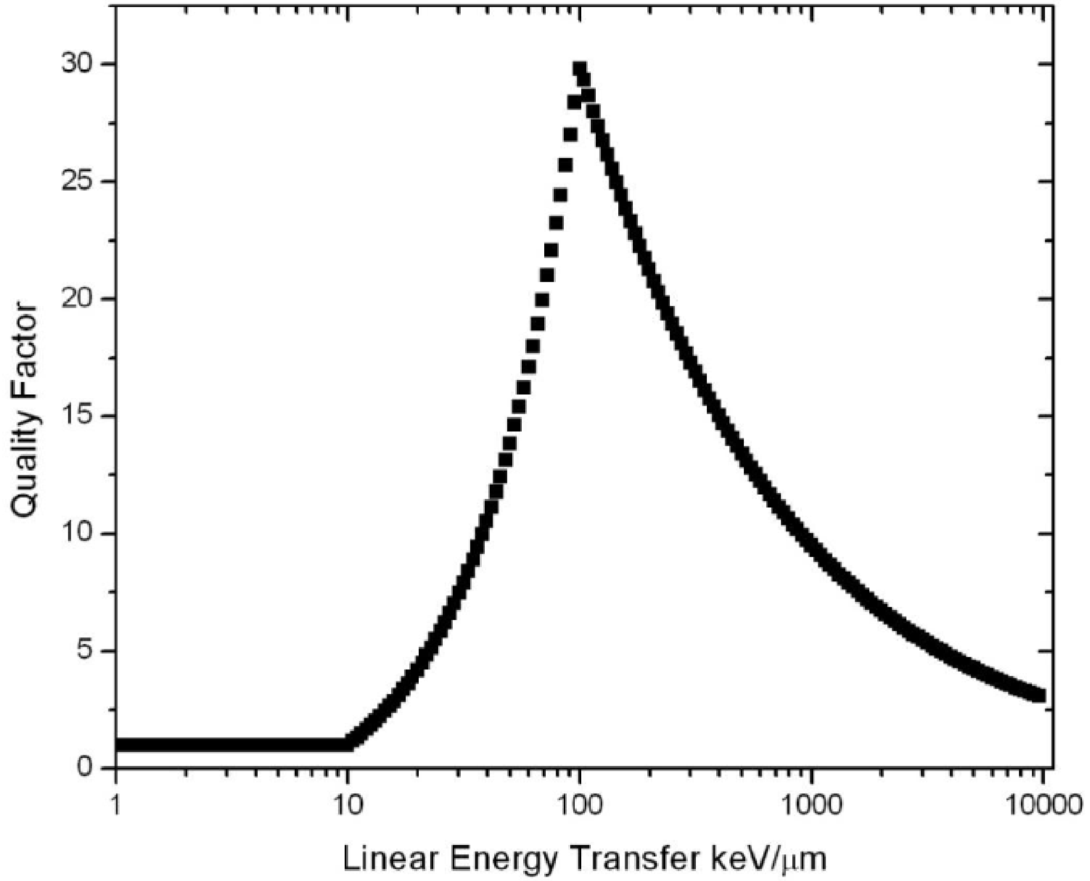
# TEPC MEASUREABLE QUANTITIES – ABSORBED DOSE



The absorbed dose is estimated from the respective measured lineal energy dose distribution as

$$\mathrm{Dose}\,(Gy) = \frac{\mathrm{Energy\,absorbed}\,[\mathrm{J}]}{\mathrm{Mass\,of\,gas}\,[\mathrm{kg}]} = \frac{\sum_{i}^{N} y_i \mathrm{d}(y_i)\,[\mathrm{keV}/\mu\mathrm{m}] \times \bar{\ell}\,[\mu\mathrm{m}]}{\rho_{\mathrm{g}} \times V} \times 1.6 \times 10^{-16}\,[\mathrm{J}/\mathrm{keV}] \qquad (5)$$

# From ICRP 60



$$Q(L) = \begin{cases} 1, & L < 10\ keV/\mu m \\ 0.32L - 2.2, & 10 \le L \le 100\ keV/\mu m \\ \frac{300}{\sqrt{L}}, & L > 100\ keV/\mu m \end{cases}$$

# Assuming that Lineal Energy y is equal to Linear Energy Transfer L

$$\bar{Q} = \frac{\int_0^\infty Q(y)d(y)dy}{\int_0^\infty d(y)dy} = \frac{\int_0^\infty Q(y)yd(y)d(\log y)}{\int_0^\infty yd(y)d(\log y)}$$

$$\cong \frac{\sum_{i=1}^{N} Q(y_i)y_i d(y_i)\Delta(\log y_i)}{\sum_{i=1}^{N} y_i d(y_i)\Delta(\log y_i)} = \frac{\sum_{i=1}^{N} Q(y_i)y_i d(y_i)}{\sum_{i=1}^{N} y_i d(y_i)}$$

# TEPC RESPONSE – KERMA

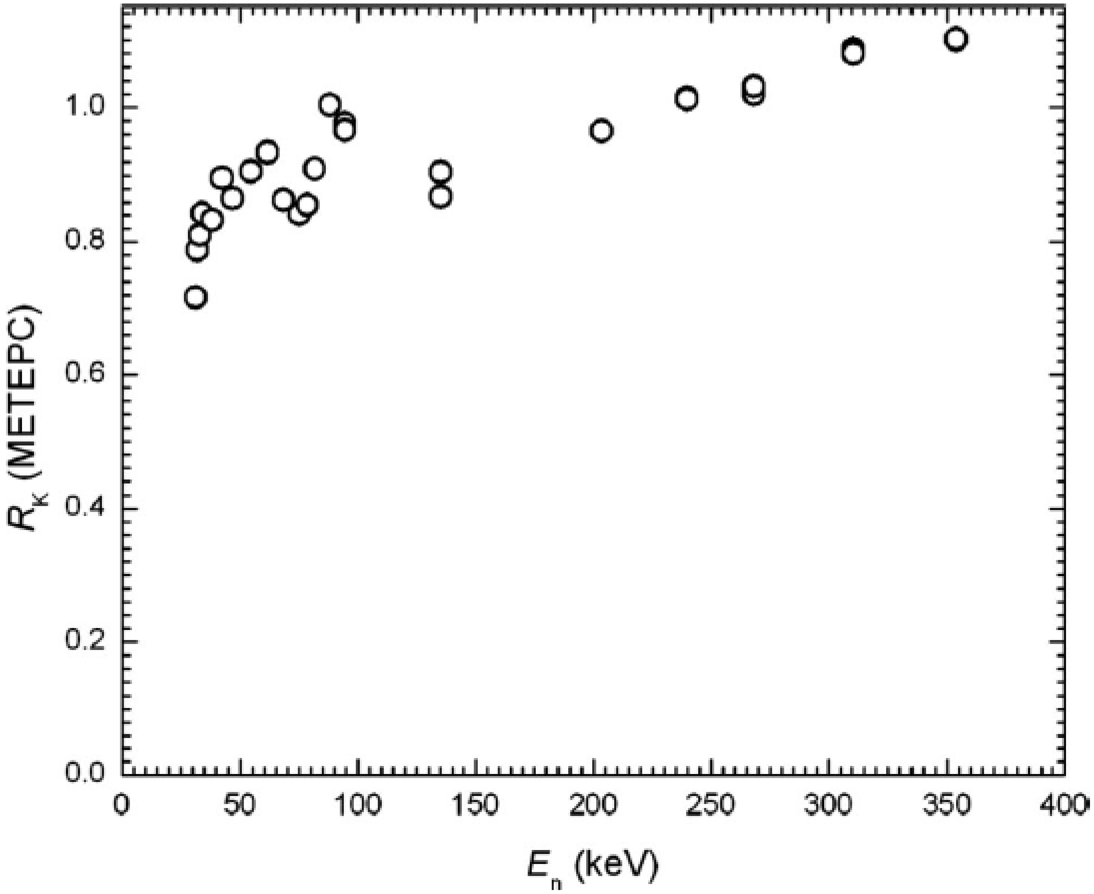


**Fig. 10.** Kerma response of METEPC at a depth of 10 mm in an ICRU tissue sphere.

# TEPC ENERGY RESPONSE – QUALITY FACTOR

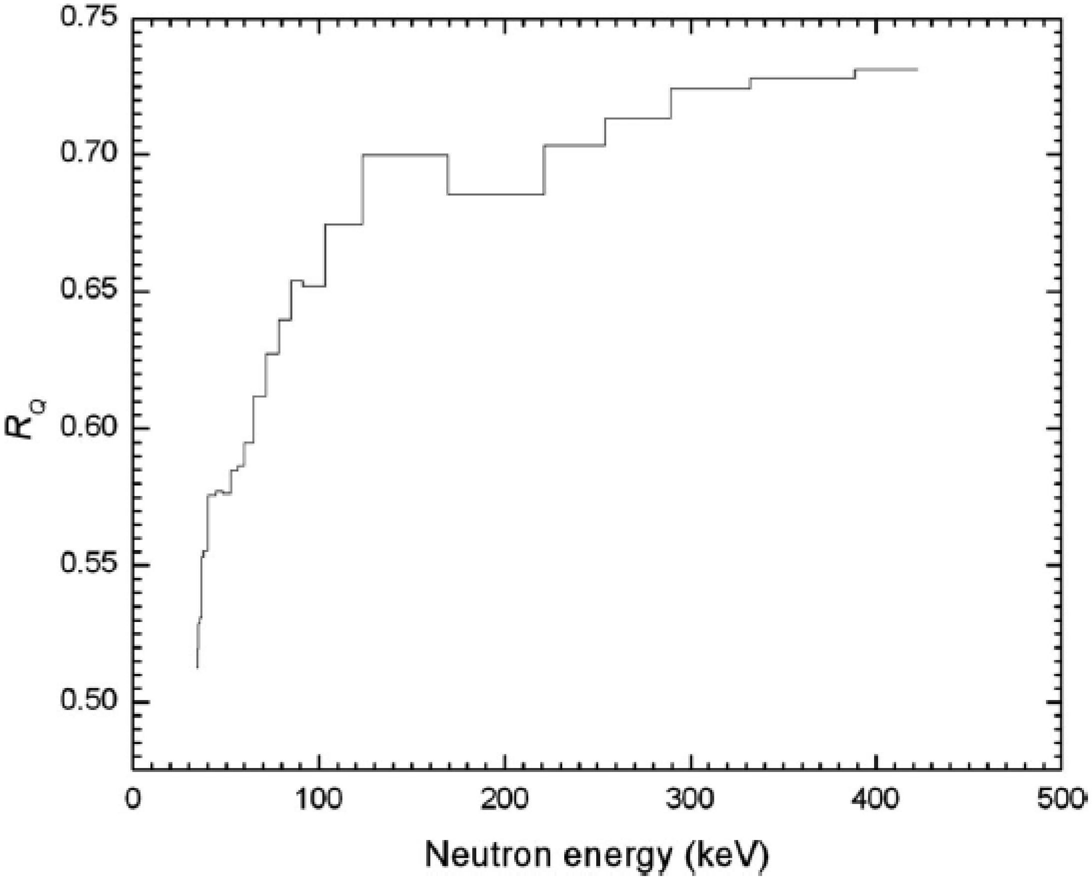
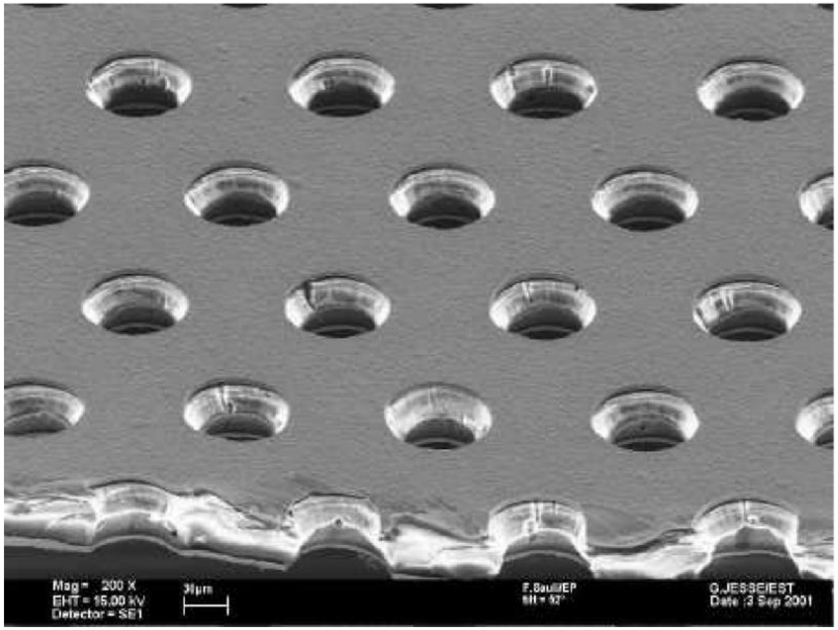


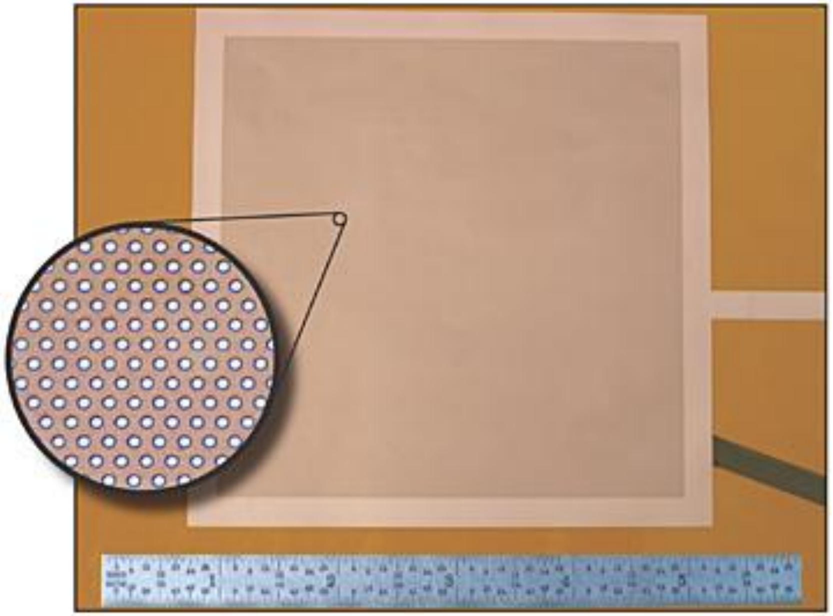
**Fig. 7.** Quality factor response, $R_Q(E_n)$, of METEPC simulating a 2 $\mu$m diameter simulated tissue cylinder.

# DETECTORS OTHER THAN TEPCs

GAS ELECTRON MULTIPLIERS

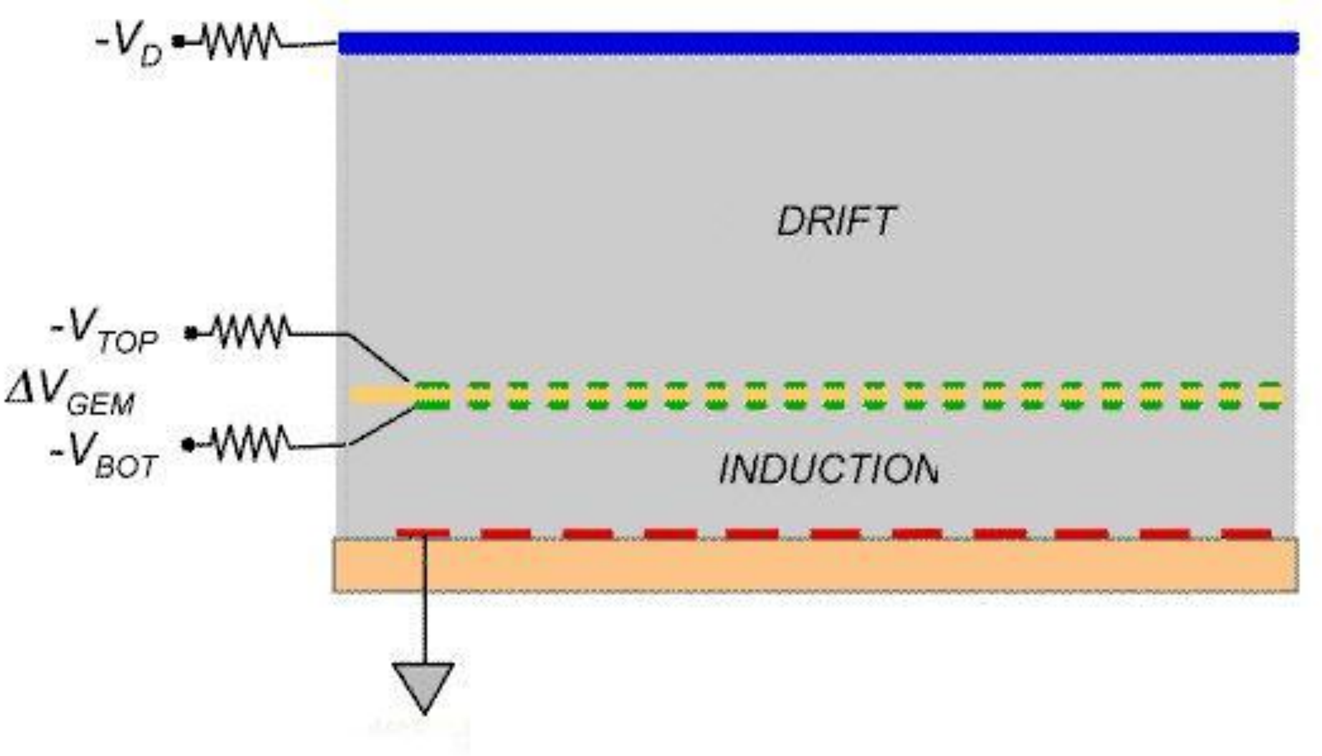
# GEMS

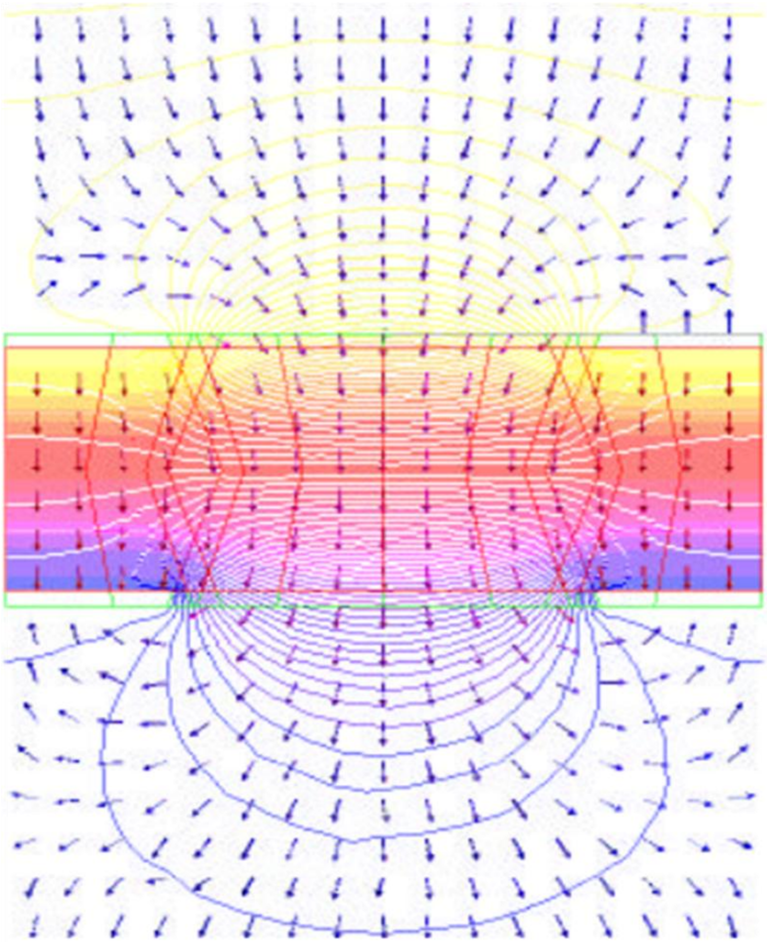

Mag = 200 X
EHT = 15.00 kV
Detector = SE1
30μm
F.Sauli/EP
tilt = 57°
G.JESSE/EST
Date :3 Sep 2001

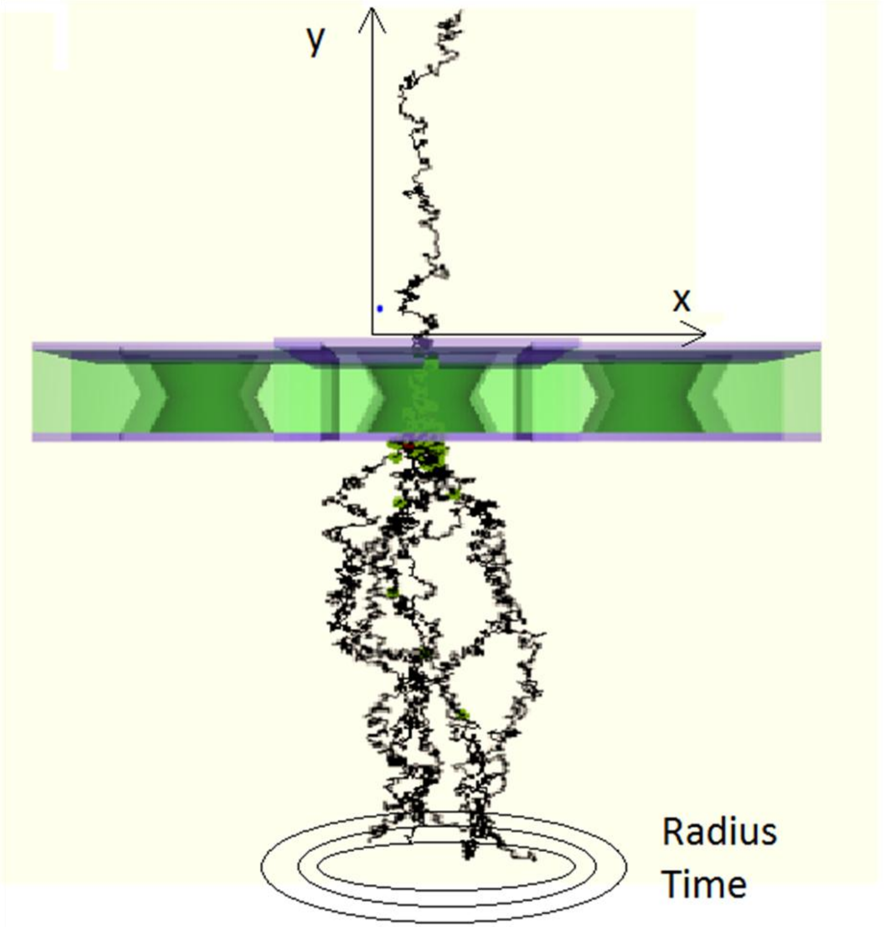


# GAS ELECTRON MULTIPLIER

Operates as proportional counter except multiplication takes place between the top and bottom surfaces of the GEM structure through microscopically etched holes






y
x
Radius
Time

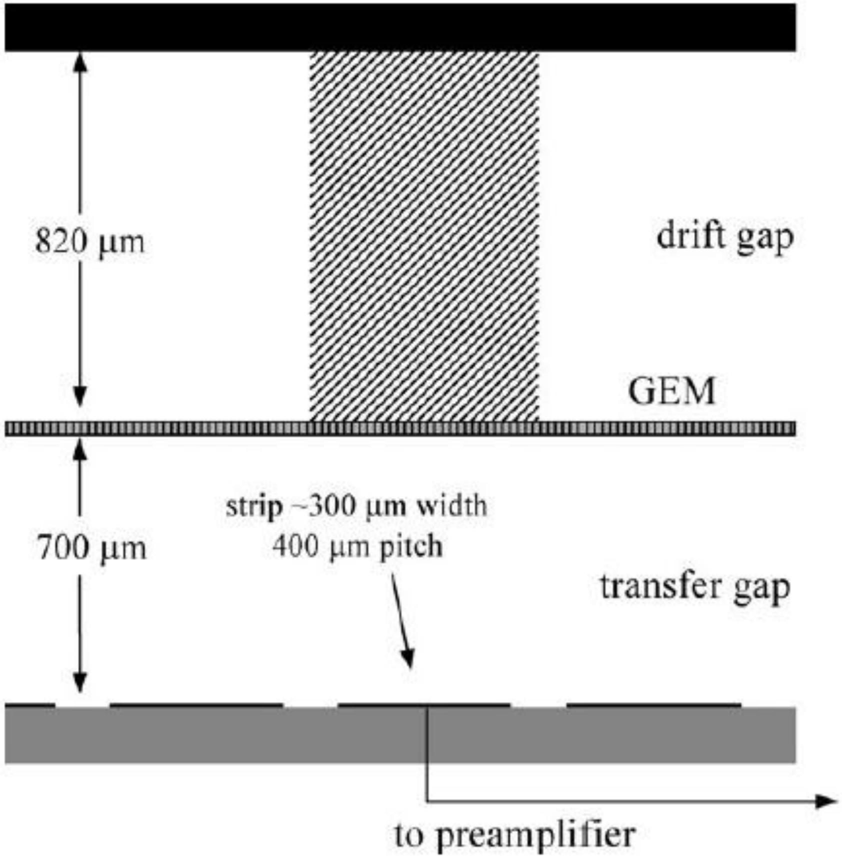


Figure 2. Profile of a GEM configured for microdosimetry.

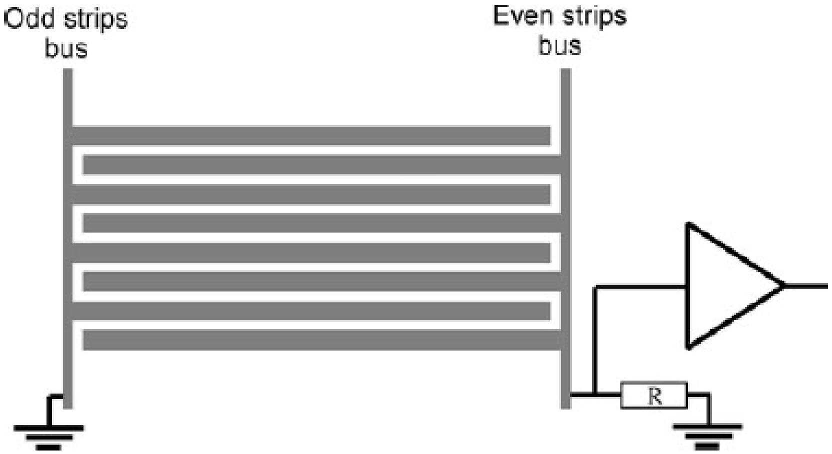


Figure 3. Details of the coupling between the readout strips and the front end electronics for the '1 in 2 strips' configuration.

Dubeau and Waker Radiat. Prot. Dosim. 128(4), 2008

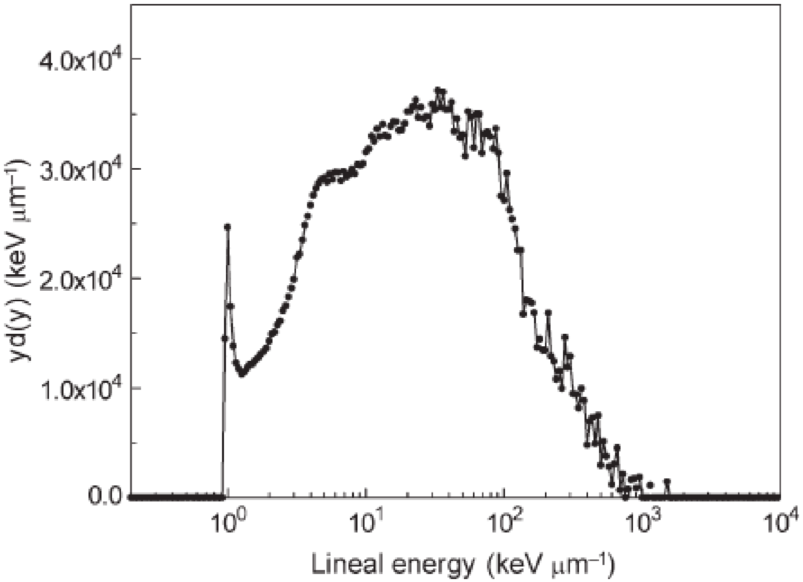


Figure 7. Lineal energy distribution for 2.8 MeV neutrons as measured by 64 strips of the TE-GEM.

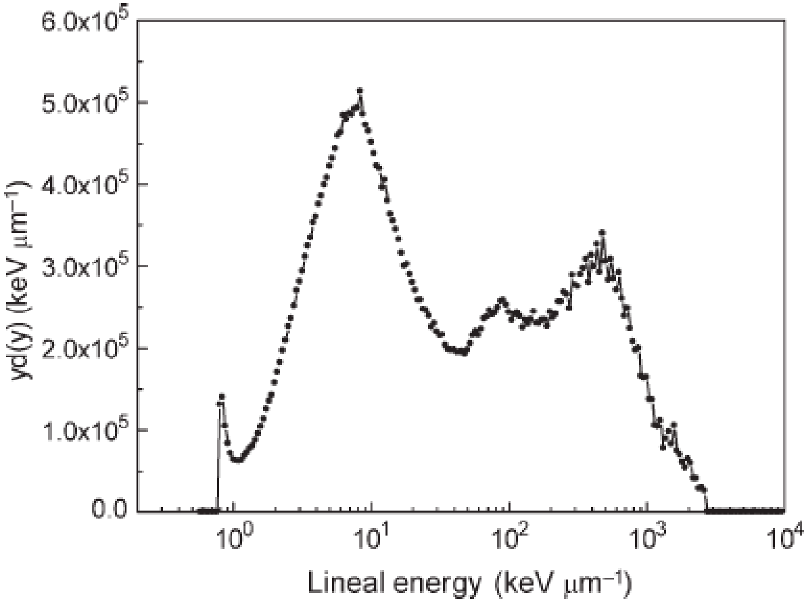


Figure 8. Lineal energy distribution for 14.8 MeV neutrons as measured by 64 strips of the TE-GEM.

Dubeau and Waker Radiat. Prot. Dosim. 128(4), 2008

# GEM SUMMARY

- **GEMs can be configured to operate as TEPC and have the advantage of**
  - **smaller physical size for each detecting element and smaller simulated diameters for improving dose equivalent response (better LET spectrometers)**

  - **Potential for basis as a personal neutron dosimeter**

- **Particle tracking capability depending on read-out pattern of anode**

- **Much work still to be done!**