

# Radiation Detection and Measurement

Lecture 11

Chapter 5: Ionization chambers

# The ionization process in gases

- The ionization chamber has come to mean, exclusively, the type of detector in which ion pairs are collected from gases.
- After a neutral atom is ionized, the resulting positive ion and free electron are called an ion pair.
- Practically we use the number of ion pairs created along a track of radiation, note table 5.1 shows various values for several gases.
- W value is the average energy absorbed per ion pair, which accounts for several processes of differing energies ( $\sim 10$  eV for weakest bound electron and processes which don't produce an ion pair).

# Fano factor

- If we assume the foundation of ion pairs is a Poisson process, the number of fluctuations associated with the number of ion pairs formed should go as the square root of the average number of pairs formed.
- The fano factor is an empirical constant one must multiply by the predicted variance to obtain the experimentally observed variance.

# Fano factor

- In gases the fano factor is observed to be  $<1$  so that the fluctuations are smaller than what would be predicted by the Poisson distribution.
- The significance of the fano factor is only in pulse mode operation, since an ionization chamber is generally run in current mode, we postpone this discussion until proportional counters, where energy resolution and pulse mode operation are more important factors.

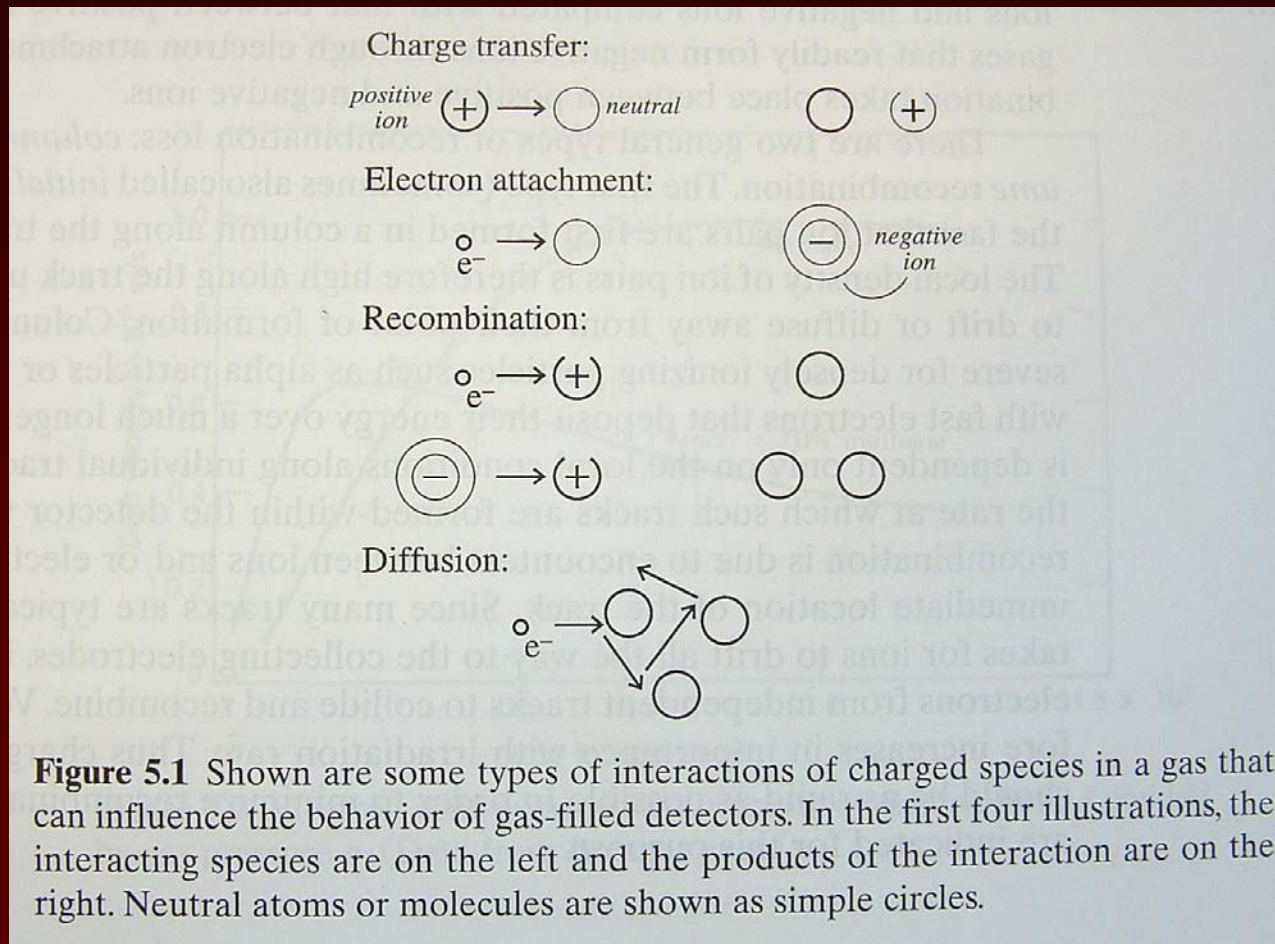
# Diffusion, charge transfer and recombination

- Ions have a tendency to diffuse away from areas of high density through random thermal motion, which is more pronounced in free electrons since their average thermal velocity is much greater.
- A point-like collection of free electrons will spread out into a Gaussian spatial distribution where  $\sigma = \sqrt{2Dt}$ , where  $t$  is the elapsed time and  $D$  the diffusion constant predicted from kinetic gas theory.

# Diffusion, charge transfer and recombination

- Several charge transfer collisions (Fig. 5.1) can also occur after ionization:
  - Charge transfer- the positive ion interacts with a neutral atom transferring the positive charge.

# Charge transfer collisions



**Figure 5.1** Shown are some types of interactions of charged species in a gas that can influence the behavior of gas-filled detectors. In the first four illustrations, the interacting species are on the left and the products of the interaction are on the right. Neutral atoms or molecules are shown as simple circles.

# Diffusion, charge transfer and recombination

- electron attachment - the electron attaches to a neutral atom and forms a negative ion (Oxygen)
- Recombination - an electron interacts with a positive ion and produces a neutral atom or a positive and a negative ion interact to form two neutral atoms.



# Diffusion, charge transfer and recombination

- Since the collision frequency is proportional to the product of the concentration of the 2 species involved the recombination rate can be written as:

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

- Where  $n^{+(-)}$  is the number density of the positive (negative) species and  $\alpha$  is the recombination coefficient.

# Diffusion, charge transfer and recombination

- There are two types of recombination loss, columnar or initial and volume.
- Columnar is highest along the high density of ion pairs formed along the initial track and is worse for highly ionizing particles ( $\alpha$ ).
- Columnar is only based on local conditions and not on the rate of which the tracks are formed.
- Volume is recombination after the ions have diffused away from the initial track and increases with importance with irradiation rate.

# Charge migration and collection

- The drift velocity of ions in a gas can be accurately (fairly) predicted by  $v = \mu E / p$ , where  $\mu$  is the mobility,  $E$  the electric field strength, and  $p$  the gas pressure.
- $\mu$  tends to remain fairly constant over wide ranges of  $p$ ,  $E$  and charge sign of the ion. Typical values are between 1 and  $1.5 \times 10^{-4}$  m<sup>2</sup>atm/(V\*s) for detector gases of medium atomic number.
- A typical ion transit time for  $E = 10^4$  V/m at 1 atm is 10 ms.

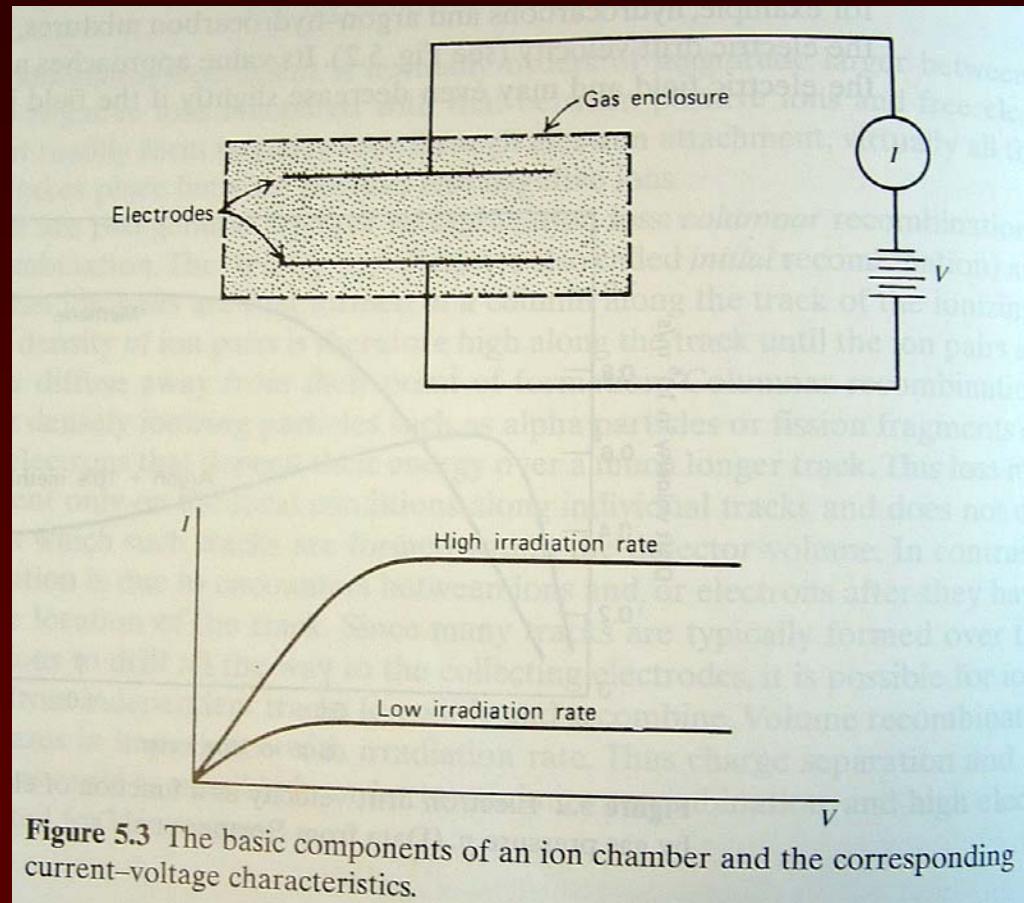
# Charge migration and collection

- Free electrons are lighter than ions so  $\mu$  tends to be  $\sim 1000$  time greater pushing typical collection time to  $\mu\text{s}$ .
- For free electrons, in some cases electrons may reach a saturation effect (reduction of drift velocity with increasing  $E$  strength) and with increasing  $E$  field there may result an anisotropy in  $D$  between the parallel and perpendicular direction with respect to the electric field direction. Such diffusion will result in a spread in position when reaching the collecting electrode.

# The ionization current

- In the presence of an electric field the drift of ions or  $e^-$  constitutes a current.
- Under the conditions where recombination is negligible and the ions are collected efficiently, the steady state current is an accurate measure of the rate at which ion pairs are formed in the volume.
- Measurement of this current is the basis for a DC ion chamber (schematic seen in Fig. 5.3).

# The ionization current



# The ionization current

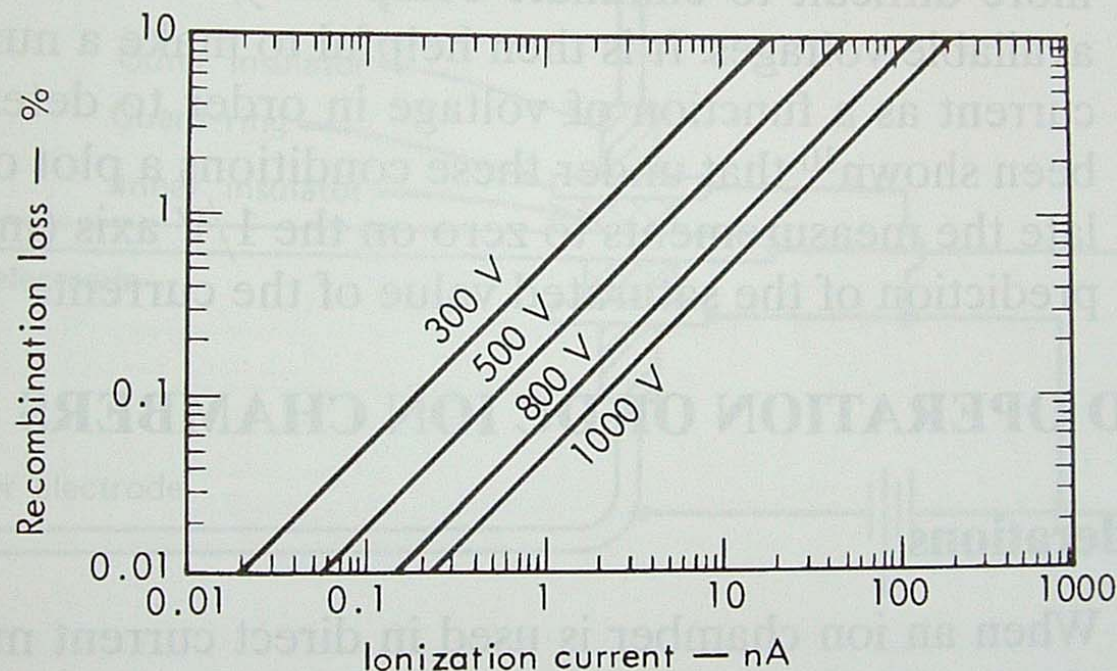
- Increasing the voltage (electric field strength) will increase the current of the system, and at low voltages the ion pairs will undergo recombination or diffusion.
- Once a high enough voltage is reached, all the ion pairs are collected and no increase in current is observed. This is the ion saturation region and the current is then an accurate representation of the rate of ion pairs formed. This is conventionally the region ionization meters are run in.

# Factors affecting the saturation current

- Recombination (minimized when a large enough electric field is everywhere in the chamber).
- Chambers run with ambient air as the gas will also be affected by moisture in the air (humidity).



# Factors affecting the saturation current



**Figure 5.4** Losses due to recombination in an ion chamber filled with argon at 1 atm. These losses are minimized at high values of the applied voltage as shown. (From Colmenares.<sup>8</sup>)

# Factors affecting the saturation current

- As the positive charges drift to the cathode negative charges toward the anode, the increase in density and the electrodes will produce a diffusion gradient (away from the electrode and opposite the applied electric field) and produces a perturbation in the ionization current given by:

$$-\frac{\Delta I}{I} = \frac{\epsilon kt}{eV}$$

# Factors affecting the saturation current

$$-\frac{\Delta I}{I} = \frac{\varepsilon k T}{e V}$$

- Where  $\varepsilon$  is the ratio of the average energy of the charge carrier with the  $E$  field present to that without the  $E$  field present,  $k$  is the Boltzmann constant,  $T$  is temperature,  $e$  is the electron charge, and  $V$  is the applied voltage between the electrodes.

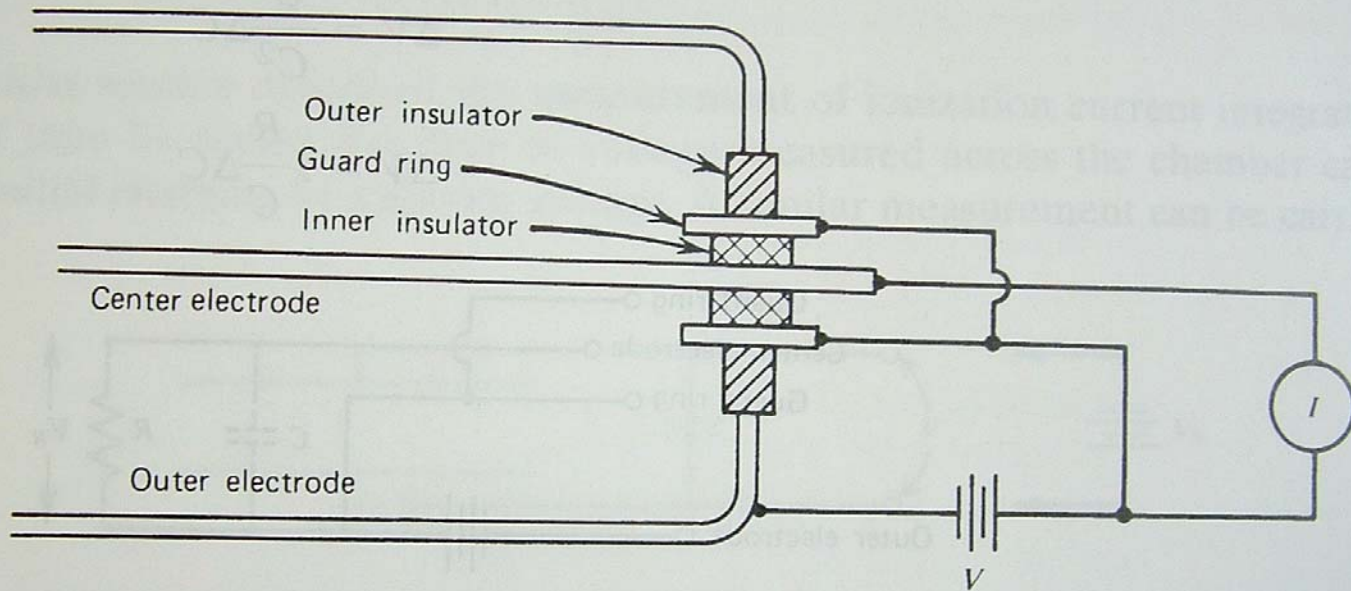
# Factors affecting the saturation current

- A plot of the  $I$  vs.  $1/V$  can be used to extrapolate the true saturation current of a chamber by determining a value for infinite applied voltage (0 on the  $1/V$  axis).

# Design and operation of DC chambers

- General Considerations:
  - One can modify many parameters to suit ones needs including fill gas, geometry, applied voltage, and recombination effects of the intended radiation and gas.

# Insulators and guard rings



**Figure 5.5** Cross-sectional view of one end of a cylindrical ion chamber that utilizes guard ring construction. Most of the applied voltage  $V$  appears across the outer insulator, for which the resulting leakage current does not contribute to the measured current  $I$ .

# Insulators and guard rings

- Due to the small values of ionization current, leakage current must be smaller.
- A guard ring is designed to be at the same potential as the central electrode, to minimize the leakage current.
- Any leakage through the insulator is returned to the voltage source without going through the current meter (ammeter).
- Thus only ionization current passes through the ammeter and the leakage current does not affect the measurement.

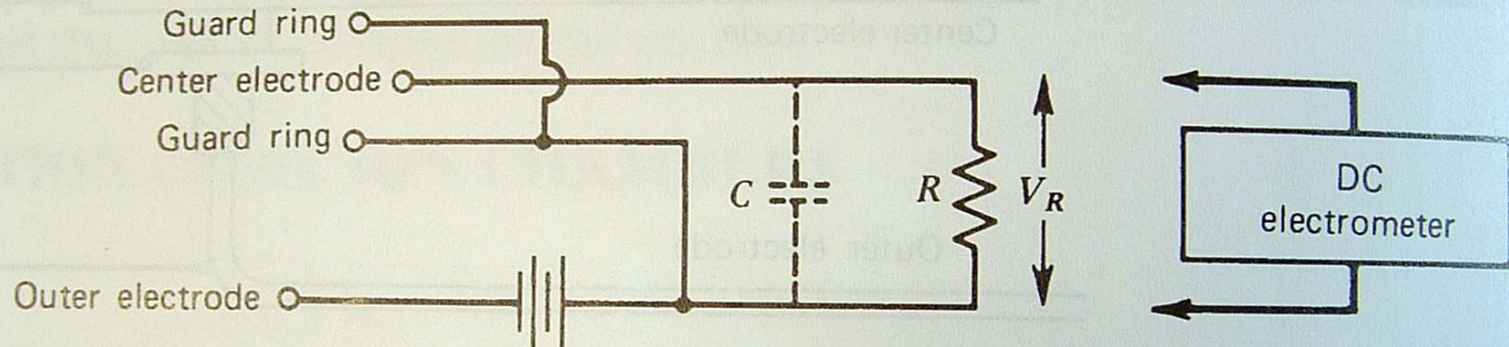


# Insulators and guard rings

- In practice the current is measured indirectly by an electrometer, which measures the voltage across a series resistor  $V_R$  (Fig. 5.6).
- The chamber capacitance and any stray line or current capacitance is represented by  $C$ . if the ion current remains constant over several measurement time constants ( $RC$ ) the steady state value of  $I = V_R/R$ .
- One can also get more stable amplification of the signal by using a dynamic capacitor or vibrating reed electrometer seen in Fig. 5.7.

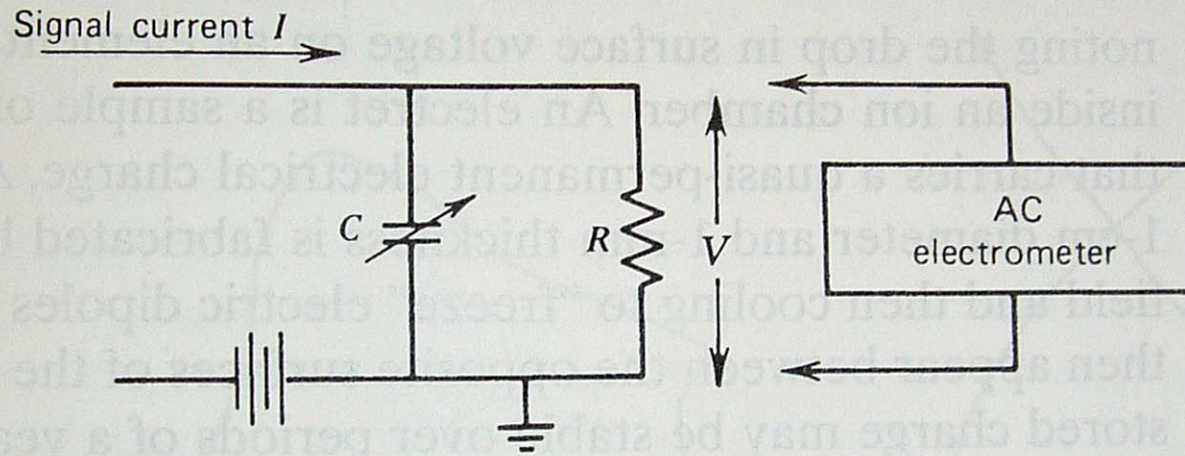


# Insulators and guard rings



**Figure 5.6** Measurement of small ion currents through the use of a series resistance  $R$  and an electrometer to record the resulting dc voltage  $V_R$ . The chamber capacitance plus any parallel stray capacitance is represented by  $C$ . Provided the ion current does not change for several values of the measurement time constant  $RC$ , its steady-state value is given by  $I = V_R/R$ .

# Insulators and guard rings



**Figure 5.7** Principle of the vibrating reed electrometer. Oscillations of the capacitance induce an ac voltage that is proportional to the steady-state signal current  $I$  [see Eq. (5.7)].

# Insulators and guard rings

- The  $V$  oscillations across the RC circuit are then measured (assuming a long RC time constant) and proportional to the steady-state signal current  $I_{ss}$ .
- At equilibrium:  $V=I_{ss}R$  and the charge stored in the capacitor is  $Q=VC$ .
- We now allow the capacitance to change rapidly with the time constant, the corresponding change in  $V$  across  $C$  is given by:

$$\Delta V = \frac{Q}{C^2} \Delta C = I_{ss} \frac{R}{C} \Delta C$$

# Insulators and guard rings

- If  $C$  is varied sinusoidally about an average value  $C$  ( $\Delta C = \sin(\omega t)$ ) then the amplitude of the AC voltage is proportional to  $I_{ss}$ .
- If we make  $R = \infty$  (Fig. 5.6) any ionization current from the chamber is integrated across the capacitance  $C$ . the total voltage across  $C$  is a measure of the integrated ionization current or total charges created.

# Electret

- This is a piece of dielectric material with a charge “frozen” in place. (One heats the material, applies an electric field, i.e. 1000 V, then cools the piece). One might use Teflon of 1 cm. diameter by 1 mm. thick disk.
- The electret is then placed in contact with the outer electrode of the chamber, producing an electric field in the chamber.

# Electret

- By measuring the voltage change on the electret before and after measurement, the electret can be calibrated in terms of the ionization change produced in the chamber.
- Electrets (with proper encapsulation) can be stable for over a year or more, even in the presence of high humidity.