Vacuum Science and Technology in Accelerators

Ron Reid

Consultant

ASTeC Vacuum Science Group

(ron.reid@stfc.ac.uk)

Session 3

The Measurement of Vacuum

Aims

- To understand that it is not in general possible to measure pressure in a vacuum directly
- To understand how the pressure may be inferred from other types of measurement
- To understand the influence of vacuum gauges on what is being measured

Pressure

- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

Pressure	Force (N)	Force (gf)

Pressure

- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

Pressure	Force (N)	Force (gf)
1 atmos	10	1020

Pressure

- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

Pressure	Force (N)	Force (gf)
1 atmos	10	1020
1 mbar	10^{-2}	1

Pressure

- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

Pressure	Force (N)	Force (gf)
1 atmos	10	1020
1 mbar	10^{-2}	1
10^{-6} mbar	10^{-8}	10^{-6}

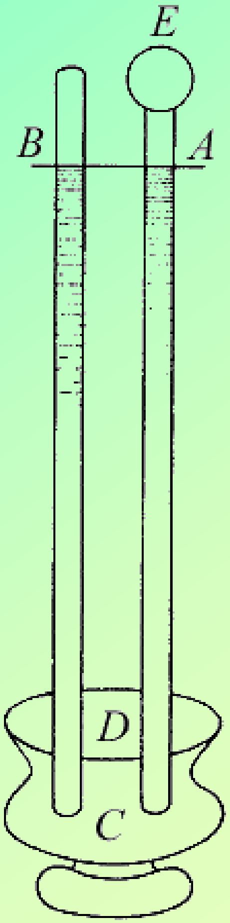
Pressure

- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

Pressure	Force (N)	Force (gf)
1 atmos	10	1020
1 mbar	10^{-2}	1
10^{-6} mbar	10^{-8}	10^{-6}
10^{-9} mbar	10^{-11}	10^{-9}

The beginning

Evangelista Torricelli
(1608-1647)

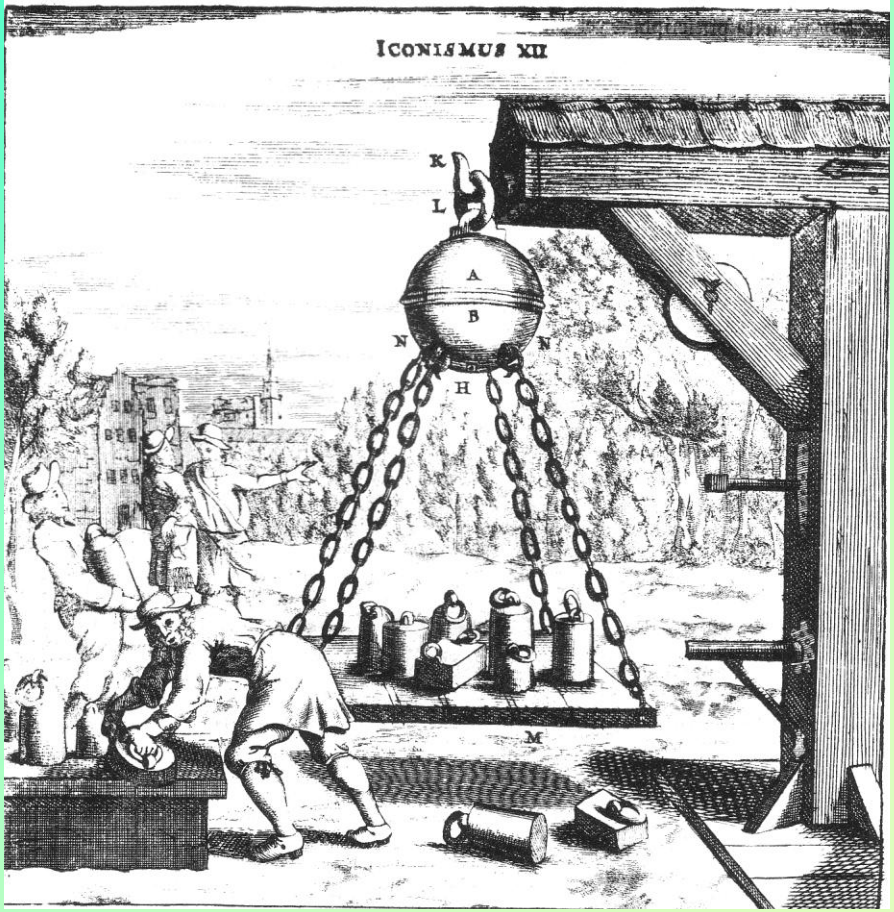


Torricelli's Barometer

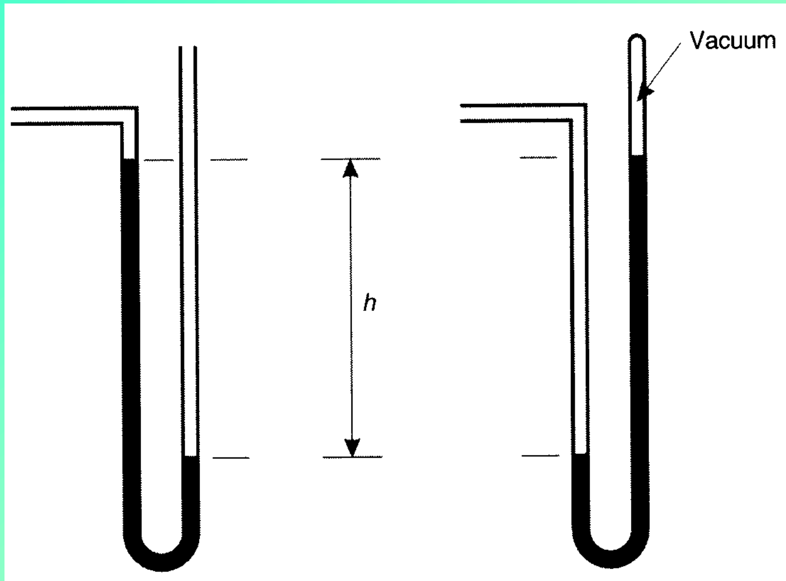
Direct and Indirect Measurements

- Direct measurements measure the force exerted by the gas on a surface of some sort
- Indirect measurements measure a physical property of the gas (e.g. heat transfer) or measure the number density by counting the gas molecules

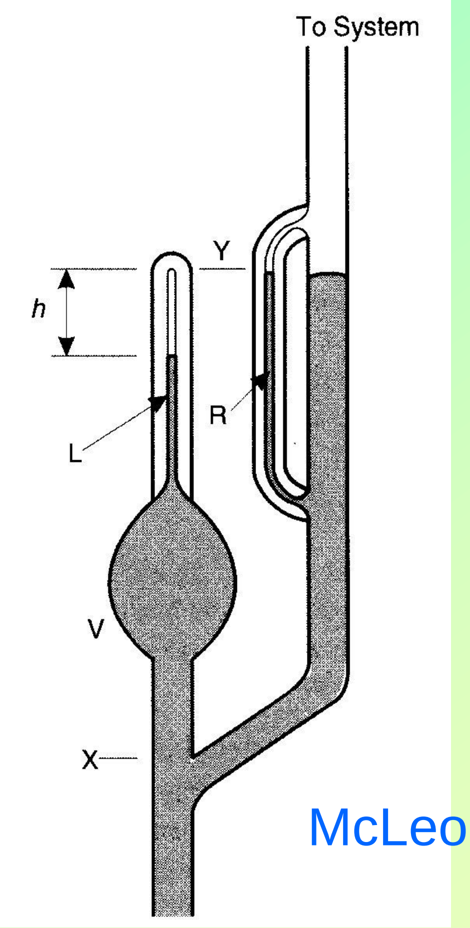
Direct measurement of pressure



Direct measurement of pressure

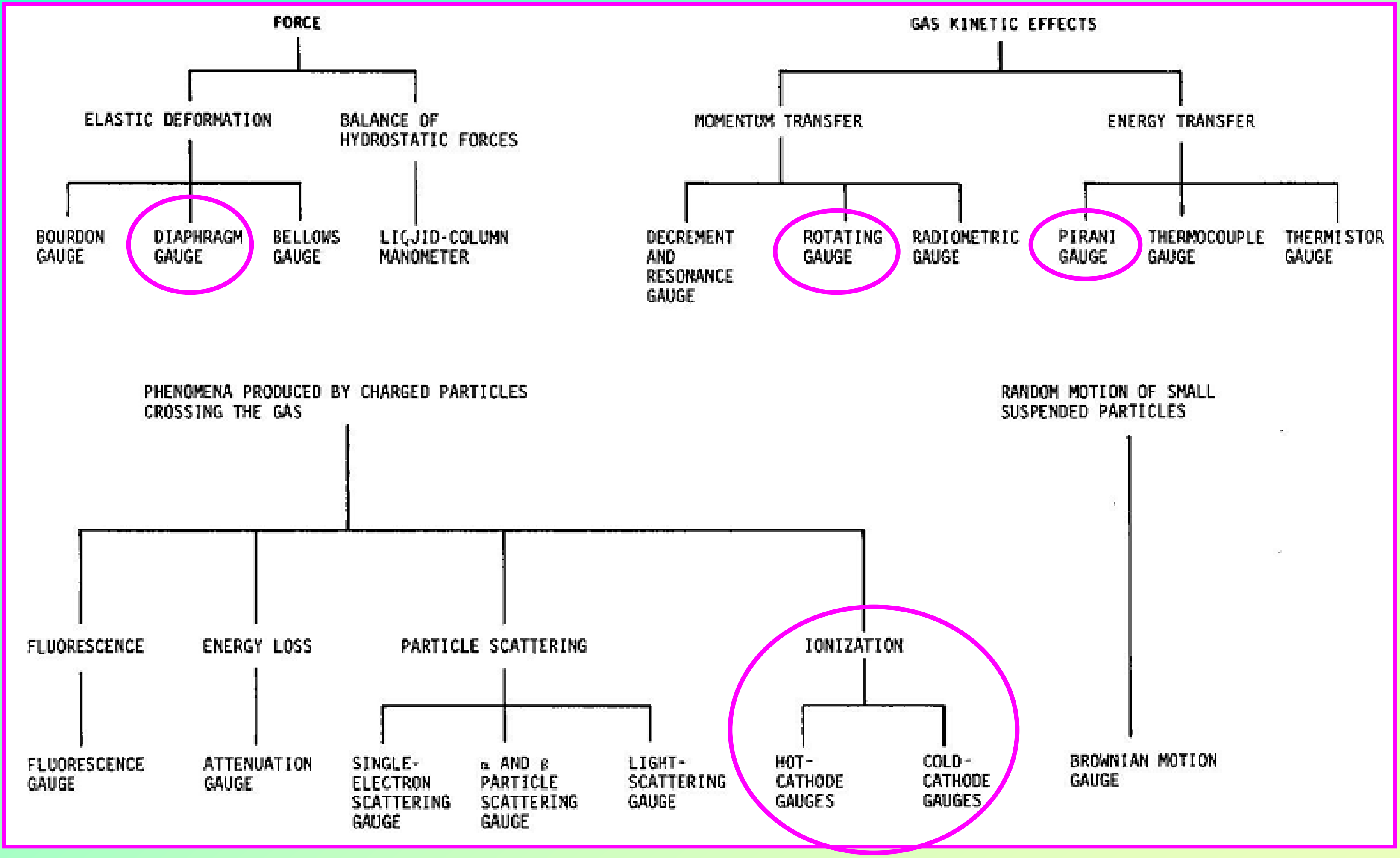


U-tube manometer

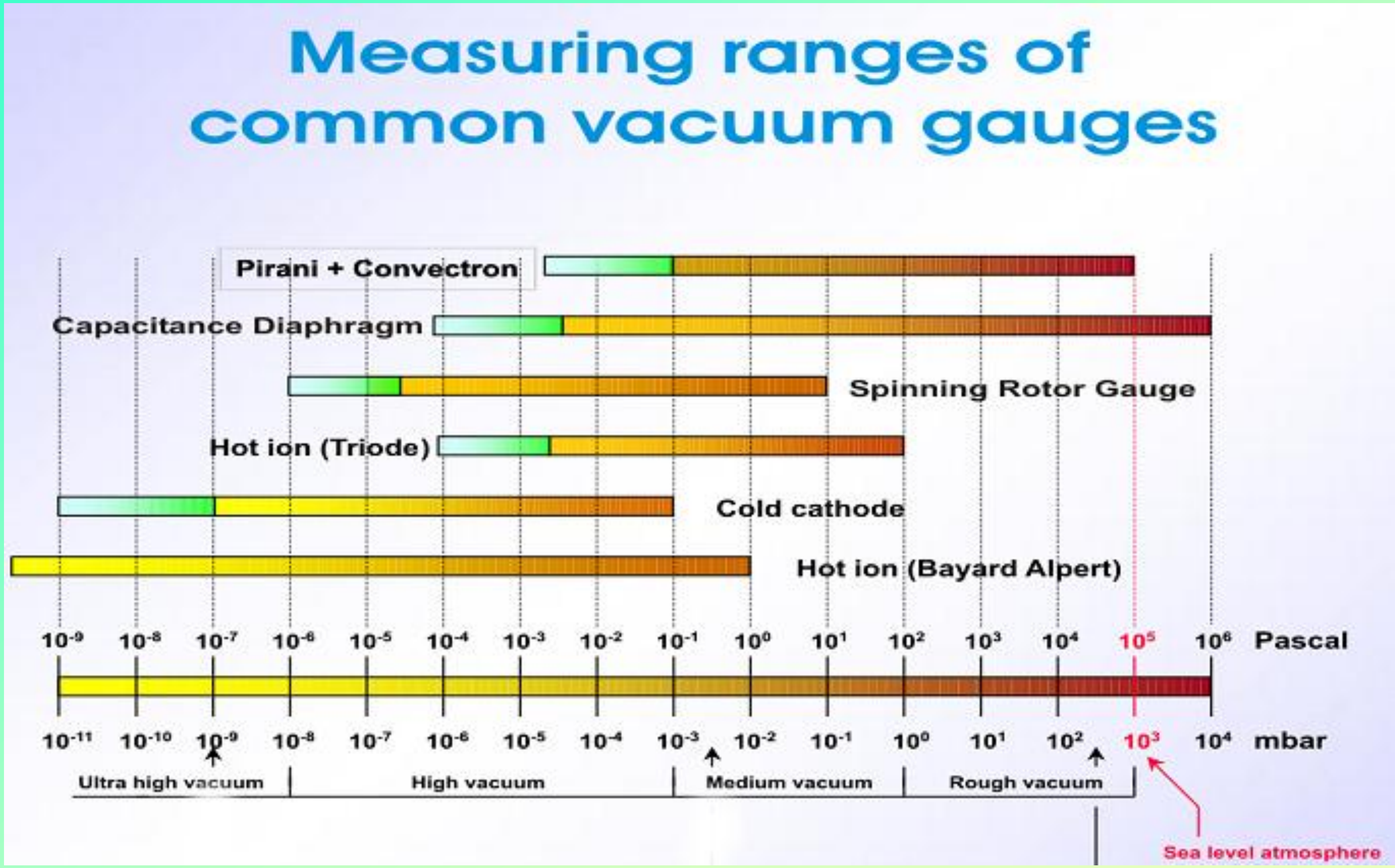


McLeod gauge

Measuring Total Pressure



Measuring Total Pressure



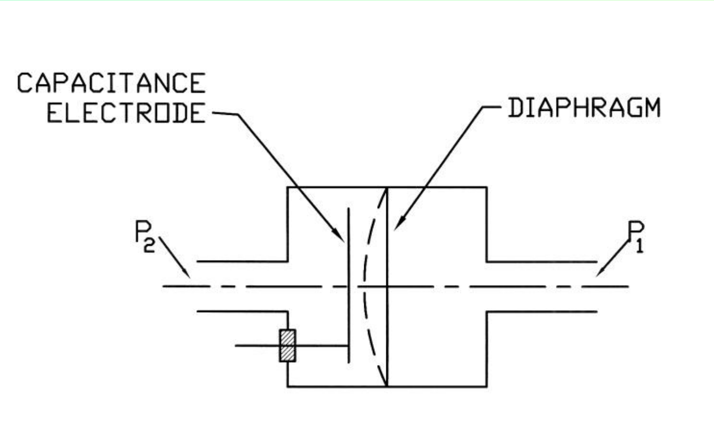
The Capacitance Manometer

The capacitance manometer is a form of diaphragm gauge where the diaphragm forms one plate of a capacitor. P_1 can be atmosphere or a reference vacuum. As P_2 falls the diaphragm moves towards the fixed plate of the capacitor. The change in capacitance can be related to the change in pressure.

The measurement is independent of gas species, but calibration is required.

The main source of error is temperature variation in the gauge, so high accuracy gauges operate at a modest temperature (~40^{o}C)

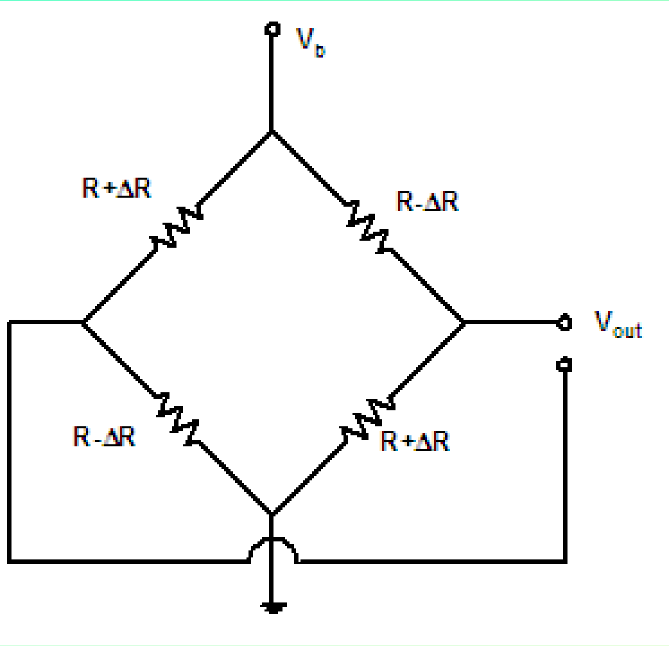
High quality gauges can measure down to better than 10^{-4} mbar with accuracies of 0.2%

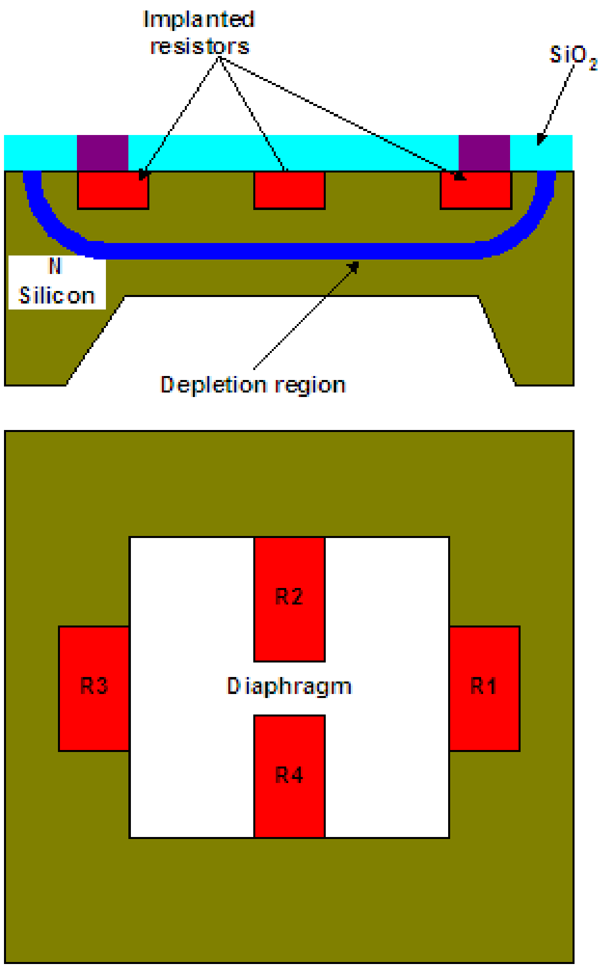


A modern diaphragm gauge

Grown Piezoresistive Sensor

Bridge Measurement Schematic





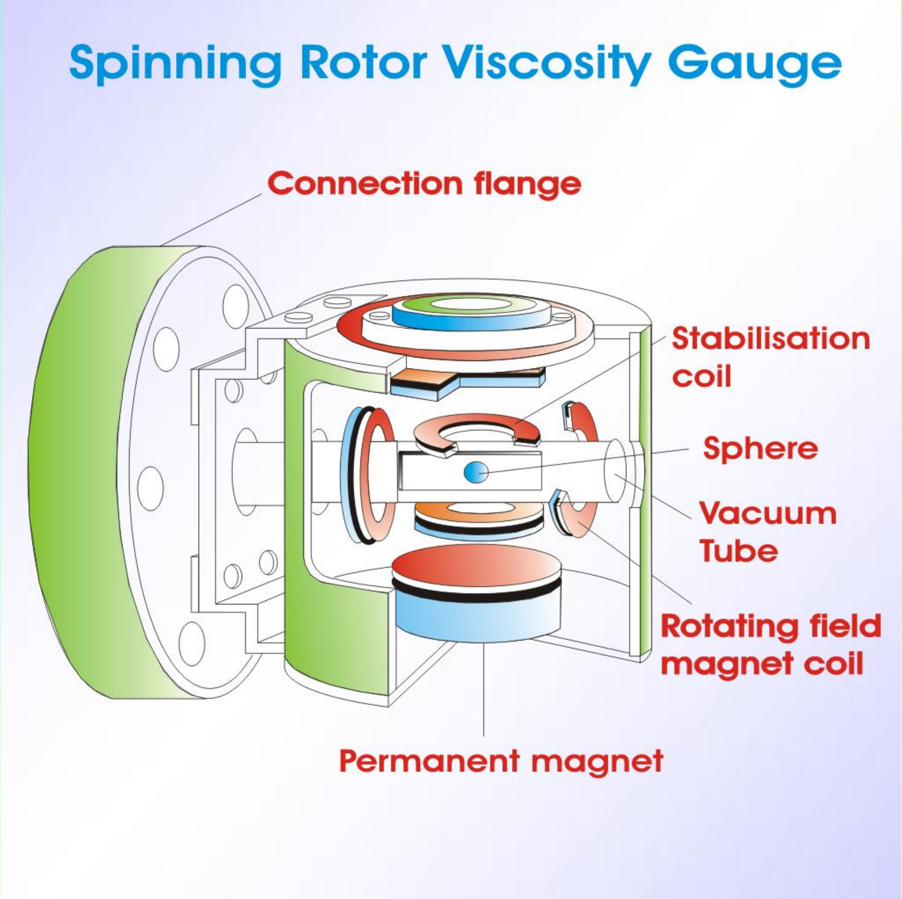
The Spinning Rotor Gauge

In this gauge, a steel ball is set spinning and its deceleration due to viscous drag measured. The rotation of the ball – which has a small magnetic moment – is sensed by a pickup coil

The sensitivity of the gauge is relatively independent of gas species and is very stable - the uncertainty is better that 3% and stability better than 2% per annum

The gauge can be used as a transfer standard for calibration

The operating pressure range is 0.1 mbar to 10^{-6} mbar



The Pirani Gauge

Thermal gauges utilise *thermal transfer* as an analogue of pressure. A filament heated in vacuum loses heat by convection, conduction and radiation.

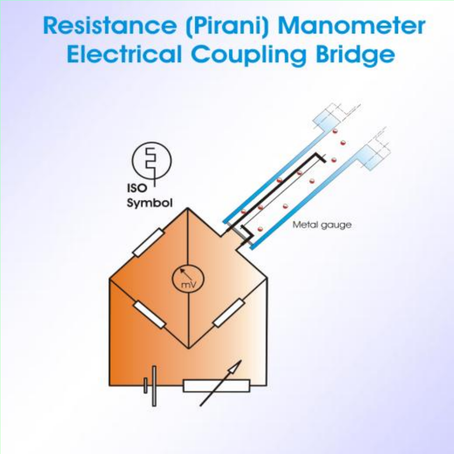
The Pirani gauge operates in the pressure regime where conduction is predominant. There are two modes of operation

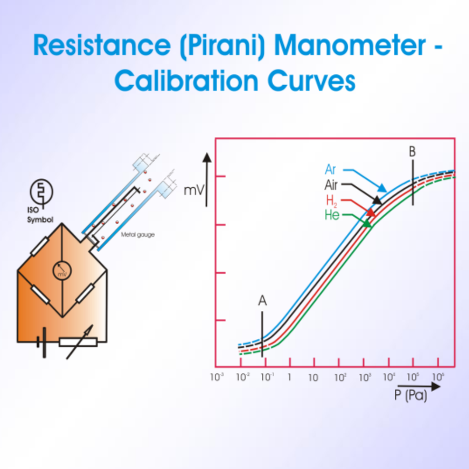
- the filament is maintained at a constant temperature (i.e. resistance)
- a constant voltage is applied to the filament

In each case a Wheatstone bridge circuit is used as the indicating method.

The sensitivity of the gauge is both pressure dependent and gas species dependent, so calibration is essential.

Pirani gauges operate between about 100 mbar and 10^{-3} mbar.





The Pirani Gauge

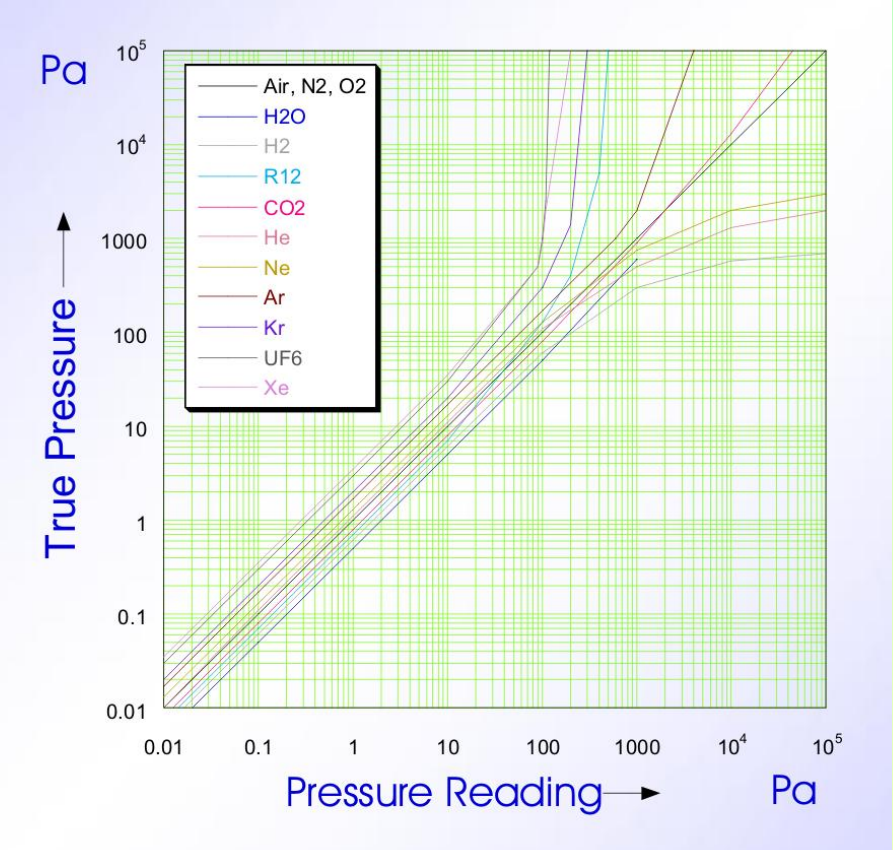
Here we see in more detail a set of calibration curves for a Pirani gauge operated in constant temperature mode.

Sensitivities are plotted relative to that for nitrogen.

The divergence at higher pressures is due to convection becoming more important.

These are not high accuracy gauges and contamination of the filament can cause serious shifts in sensitivity, but clean gauges can exhibit reproducibility of the order of 10%

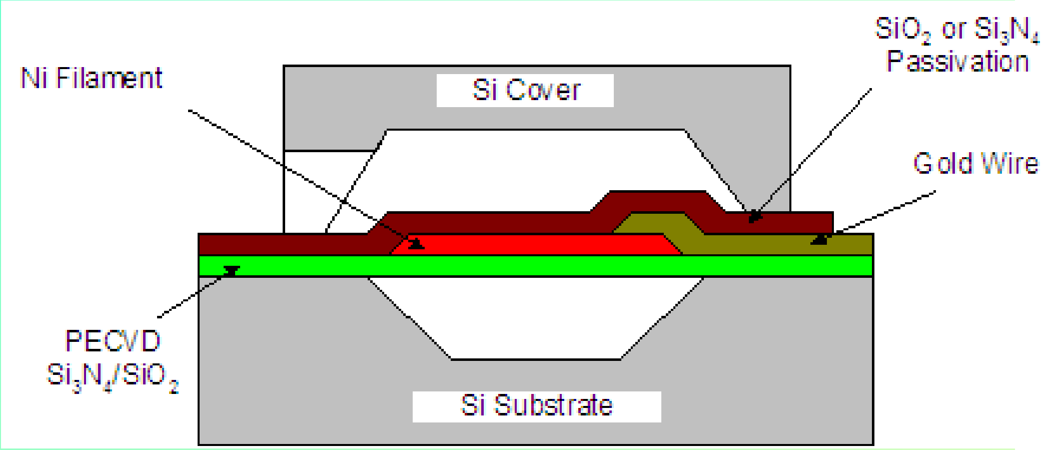
Any thermal gauge will have a relatively long time constant

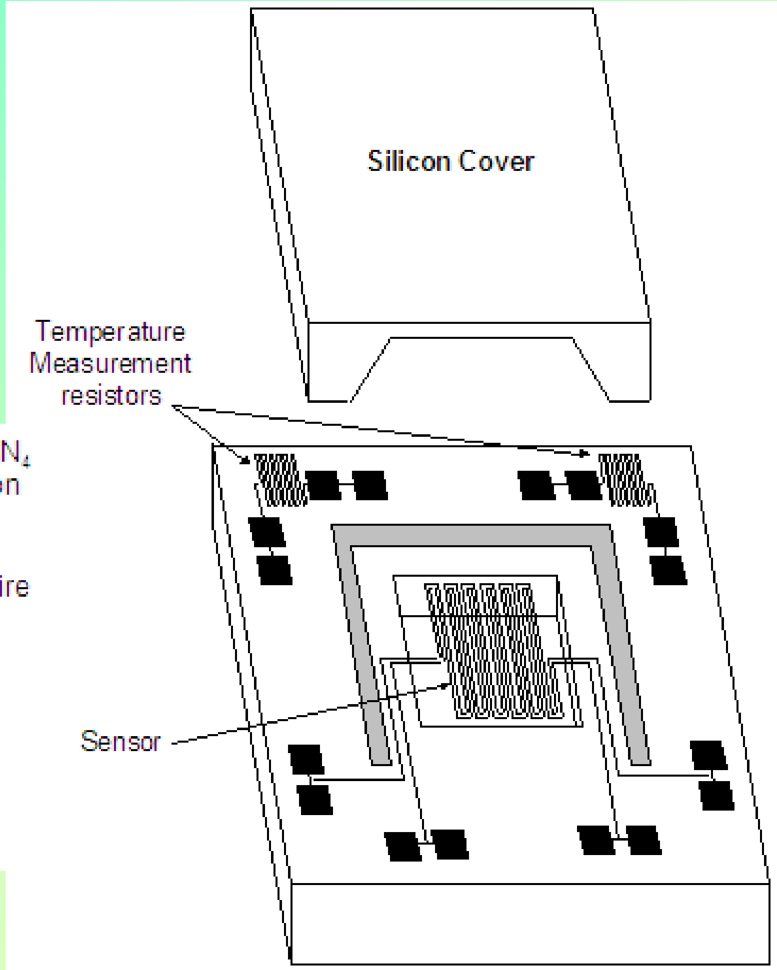


A Solid State Pirani Sensor

Construction of the sensor

Cross section of the sensor





Ionisation Gauges

The most convenient method of measuring pressures below about 0.1 Pa is to ionise the remaining gas molecules, collect the ions and measure the ion current

Ionisation can be effected by various means but the two most common are to use either

- a plasma (gas) discharge of some sort
- a beam of low energy electrons, often between 50eV and 250eV

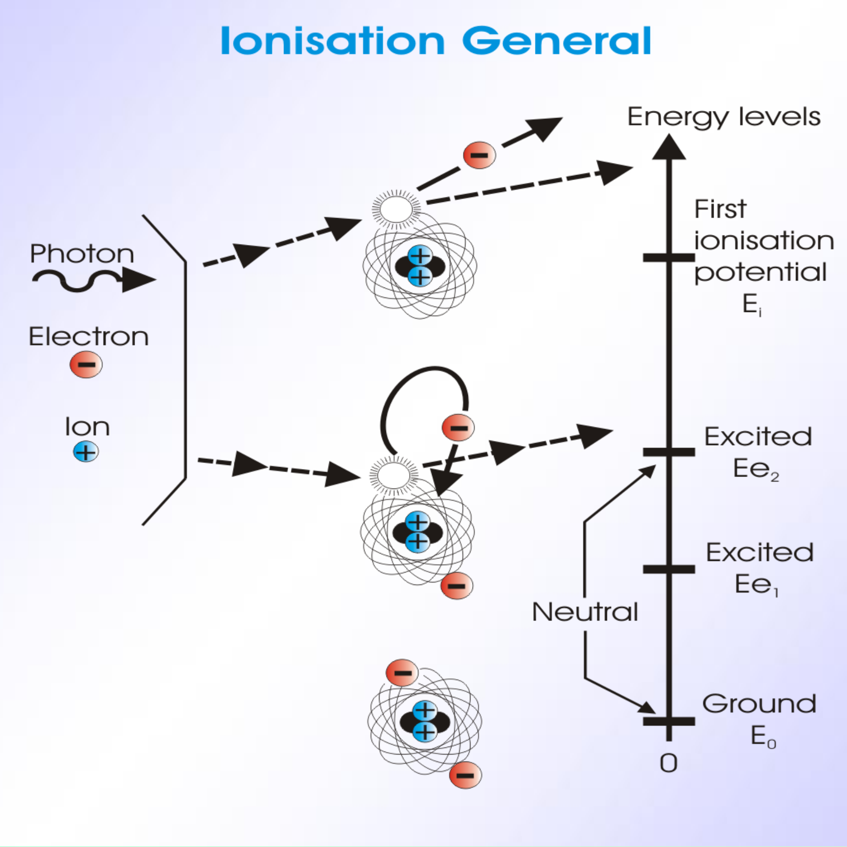
There are two important points to note when using gauges based on gas ionisation

- Such gauges measure number density of gas molecules, not pressure, therefore they must be calibrated
- Ionisation cross sections are species dependent, so such gauges will give readings which are dependent on the gases present

Ionisation Gauges

- Cold Cathode Discharge Gauges
  - Penning Gauge
  - Inverted Magnetron Gauge
- Hot Cathode
  - Bayard Alpert Gauge (BAG)
  - Extractor gauge

Ionisation



Ionisation removes one or more electrons from a gas atom, so it becomes positively charged.

Multiply charged ions may be formed.

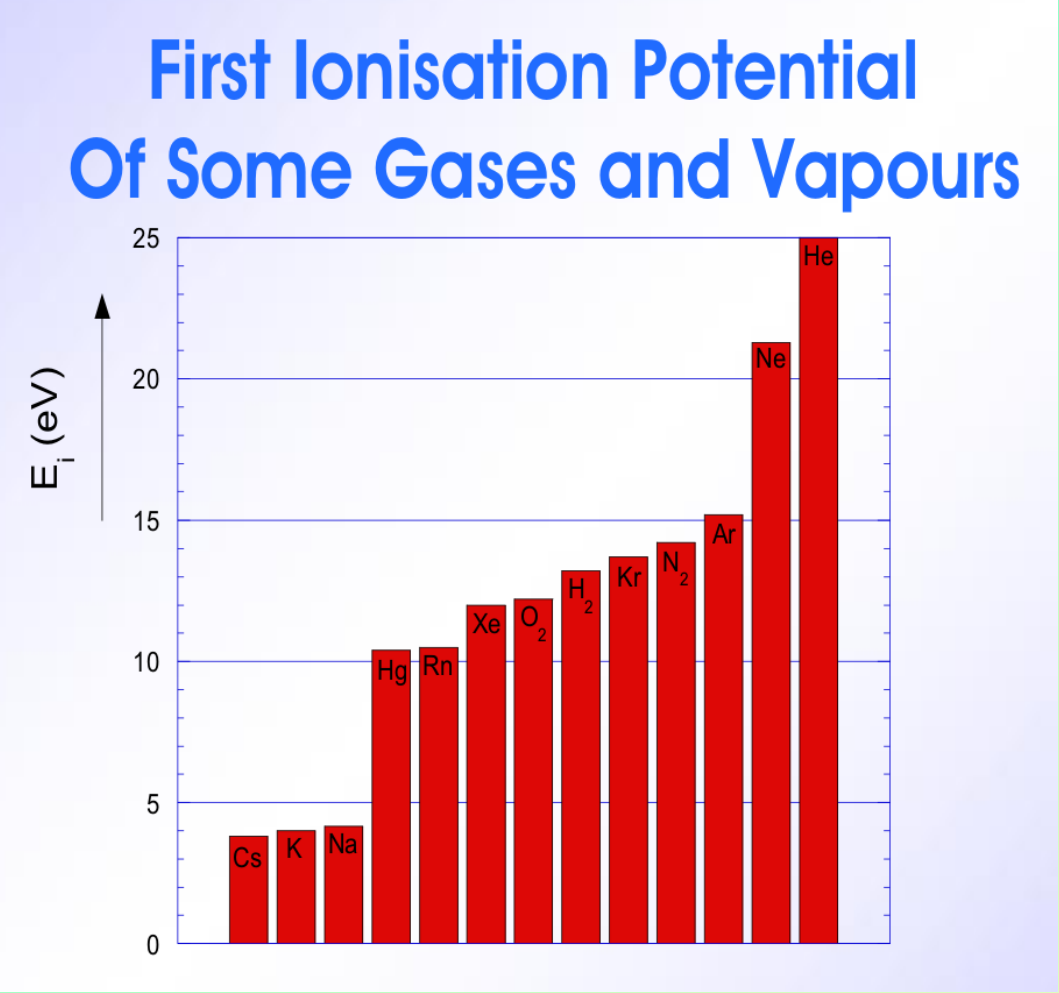
Polyatomic molecules may break up giving ion fragments and neutrals

Excited atoms may decay with the emission of photons

These phenomena are dependent on the energy of the exciting electron, photon, etc

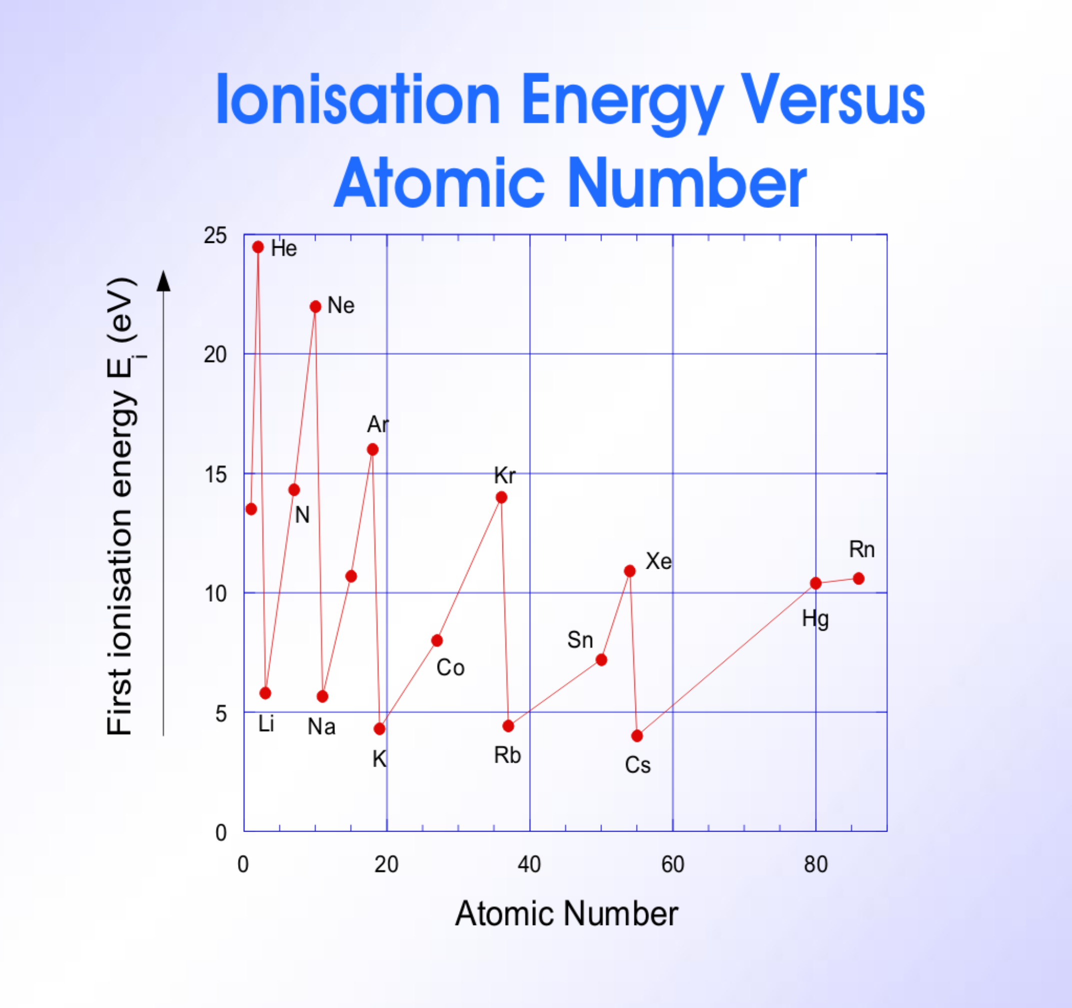
The Measurement of Vacuum

Ionisation Processes



Here, we can see how the energy required to create a singly charged positive ion varies for some selected atomic species (not all are gases)

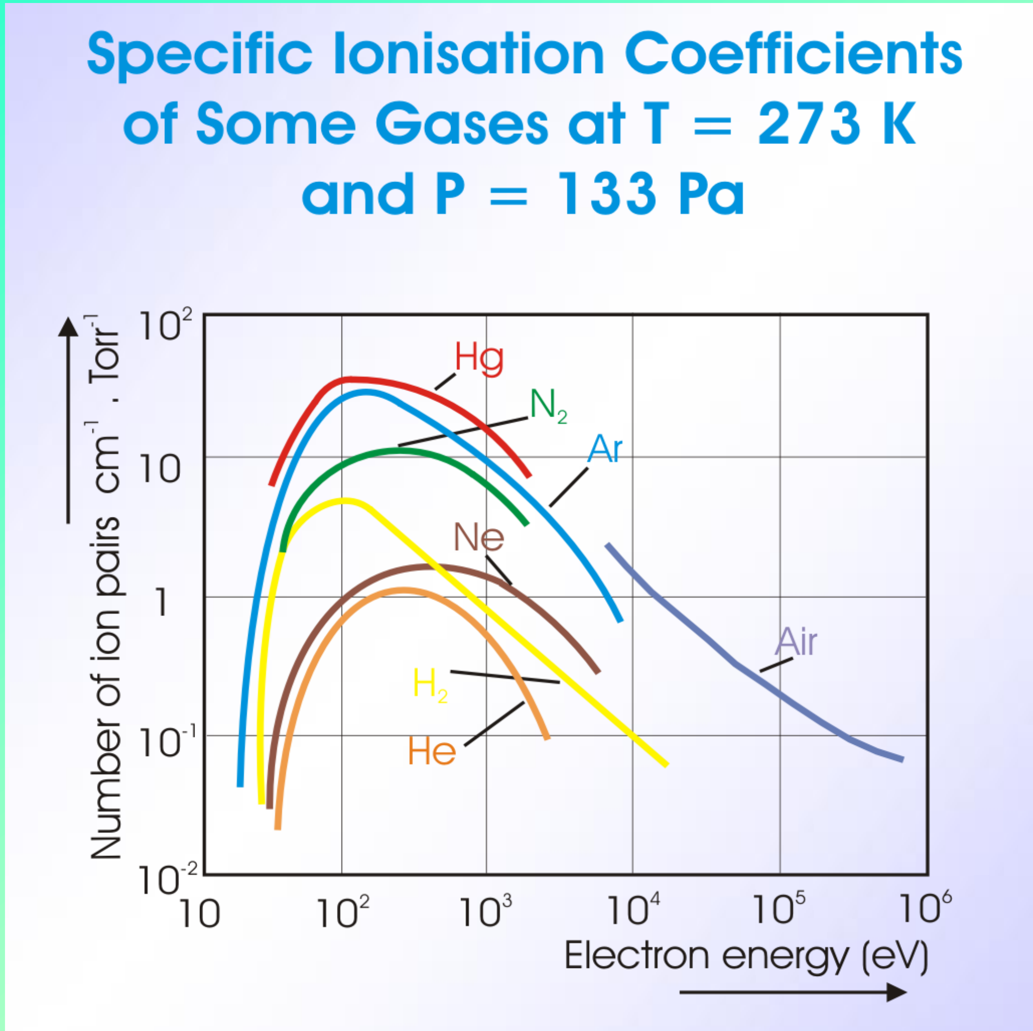
Ionisation Processes



This is a plot of the first ionisation energy for a wide range of elements – some are identified

The local maxima correspond to atoms where all electron energy shells are full

Ionisation Processes



The ionisation probability for a gas atom by an electron depends not only on the species, but also on the energy of the incident electron

The ionisation probability is plotted for a number of common gases

The Cold Cathode Ionisation Gauge

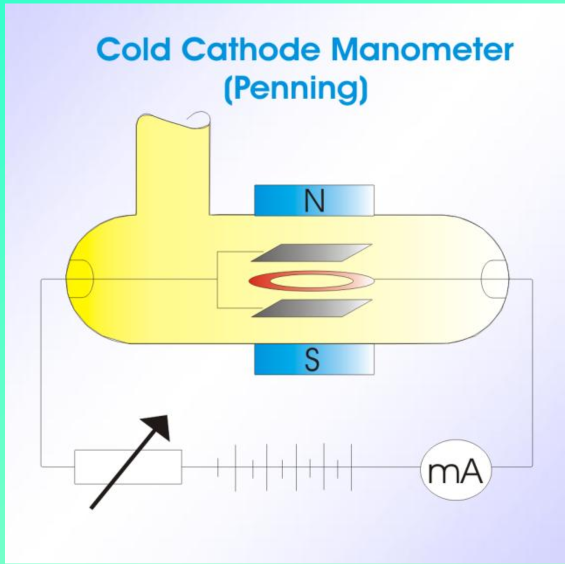
An important class of gauge in the medium to high vacuum ranges is based on a cold gas discharge in crossed electric and magnetic fields. In such discharges, free electrons are accelerated by the electric field and are trapped by the magnetic field so that they have very long path lengths – much longer than the gauge dimensions

This means that even at low pressures, these electrons have a good chance of ionising a gas molecule

Many configurations are possible for such gauges which are often referred to as Penning Gauges, since the most popular configurations are based on the Penning discharge.

Discharge gauges have a significant pumping speed, so indicated pressures may be lower than true pressures in some circumstances.

The Cold Cathode Ionisation Gauge

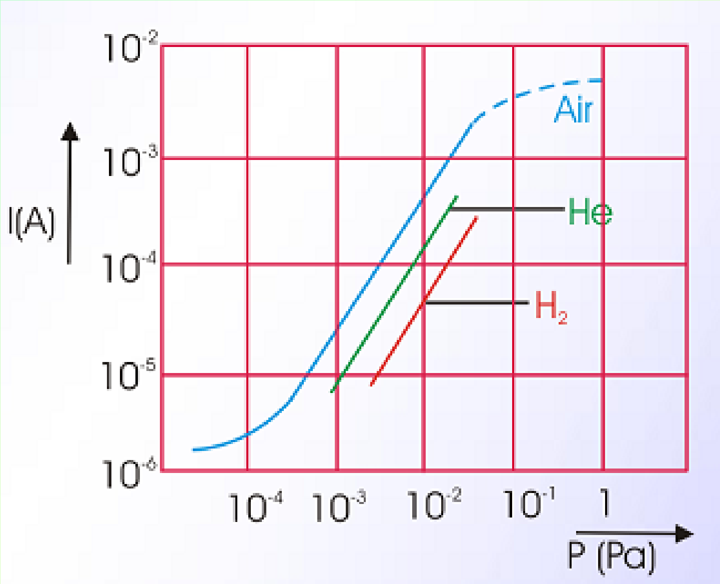


This is the classic Penning discharge configuration. It operates at fixed voltage and fixed magnetic field

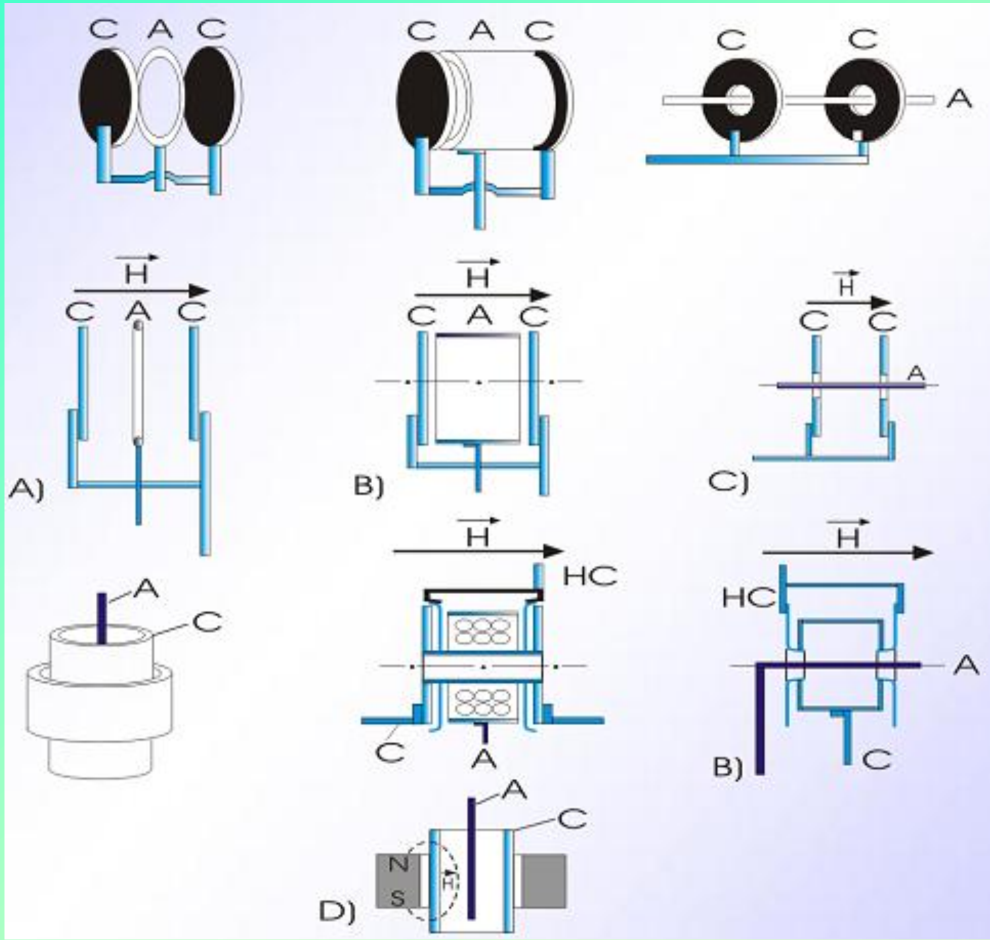
Ions are collected on the ring anode

The gauge characteristic is .shown as a function of pressure for a few gas species

At low pressures the discharge is unstable and the calibration can change abruptly

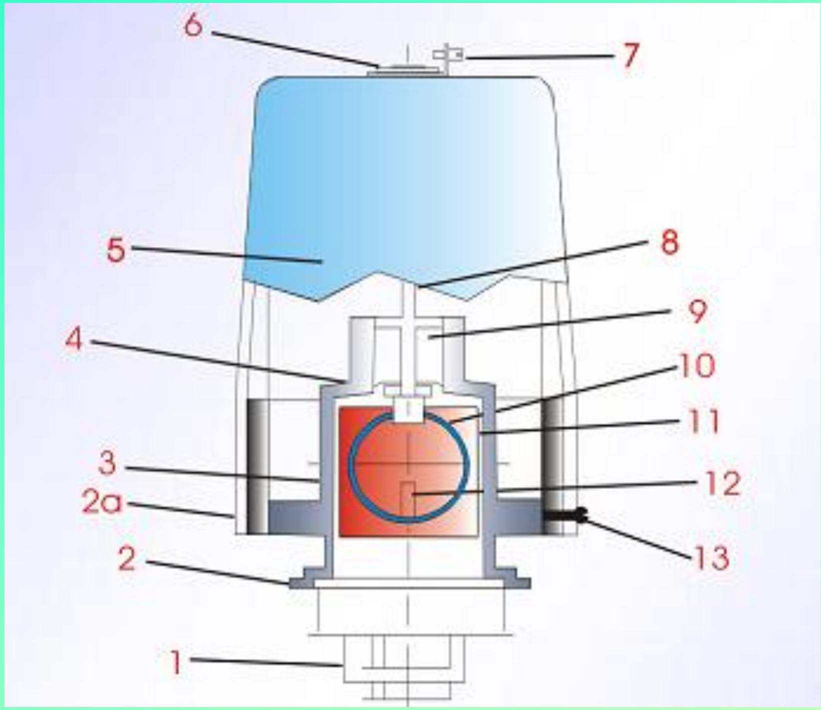


The Cold Cathode Ionisation Gauge



Various Penning cell configurations

The Cold Cathode Ionisation Gauge



This a commercial realisation of the Penning gauge

The useful range of standard Penning gauges is between 10^{-3} mbar and 10^{-8} mbar, or in special versions, 10^{-9} mbar. The accuracy of Penning gauges is not very good, especially at low pressures and large changes in sensitivity are not uncommon

They are susceptible to contamination leading to errors in pressure measurement.

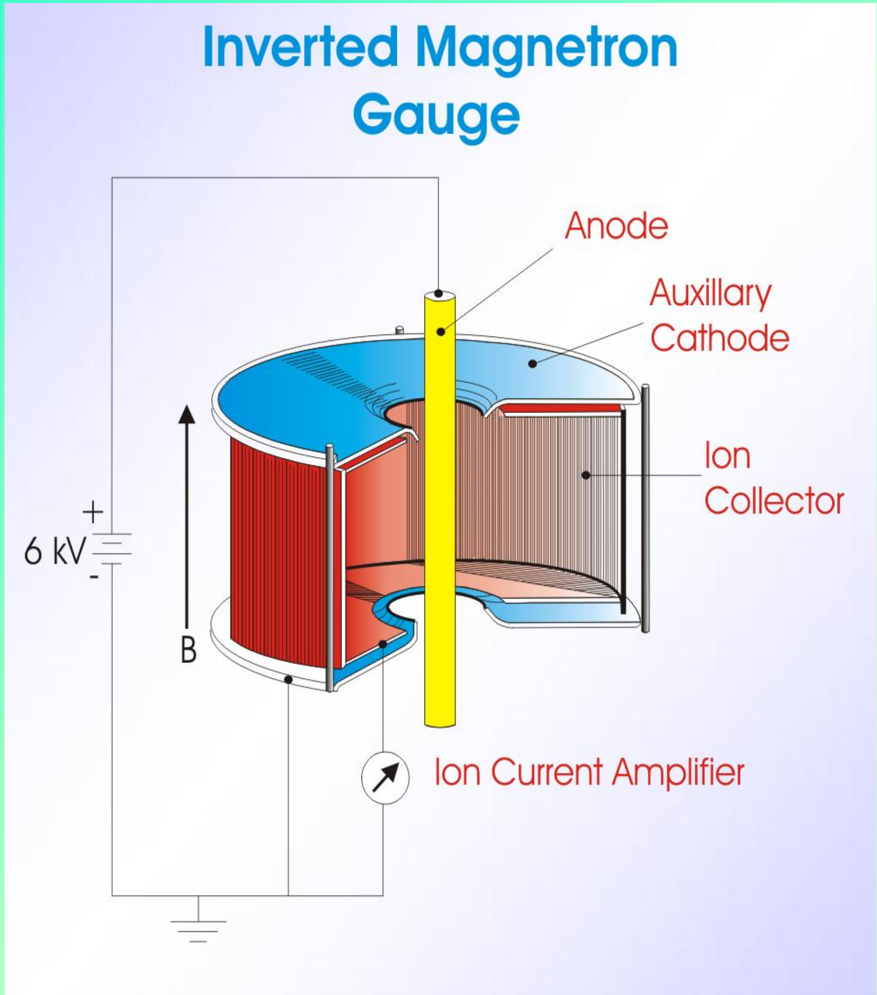
The Cold Cathode Ionisation Gauge

A development of the cold cathode gauge based on a different configuration known as the Inverted Magnetron Gauge has become quite popular. This gauge can operate down to 10^{-11} mbar or lower.

The accuracy and repeatability are similar to the Penning gauge. However, like all discharge gauges, the discharge can be reluctant to strike at very low pressures.

Starting times (i.e. before the gauge actually measures pressure) can be quite long, often several hours, which may, or may not be a problem.

The Cold Cathode Ionisation Gauge



This is the construction of the Inverted Magnetron Gauge as proposed by Redhead

Inverted Magnetron Gauge

For accelerators operating at UHV pressures, the inverted magnetron gauge (IMG) has largely become the gauge of choice.

This is because

- It operates in the desired pressure regime (and can be paired with a low cost low vacuum gauge to cover the full pressure range)
- It is robust and reliable
- In most accelerators, contamination is not a serious problem
- The problems of low pressure starting are not an issue
- It is (relatively) cheap

The Hot Cathode Ionisation Gauge

The hot cathode ionisation gauge was developed to provide a convenient method of measuring pressures in the high vacuum and later the ultra high vacuum regimes.

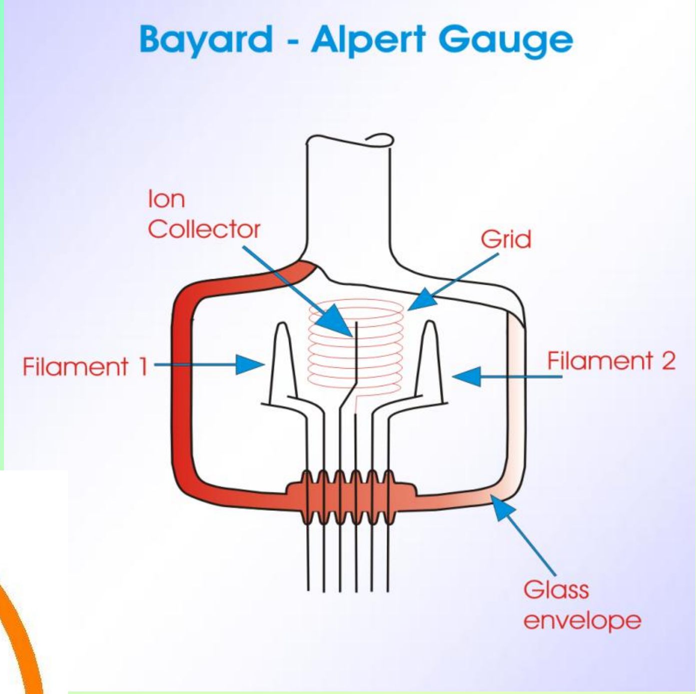
In such a gauge, a heated filament generates a beam of electrons which ionise the gas molecules.

The ions are collected on a negatively biased collector and the resultant current is a measure of the pressure.

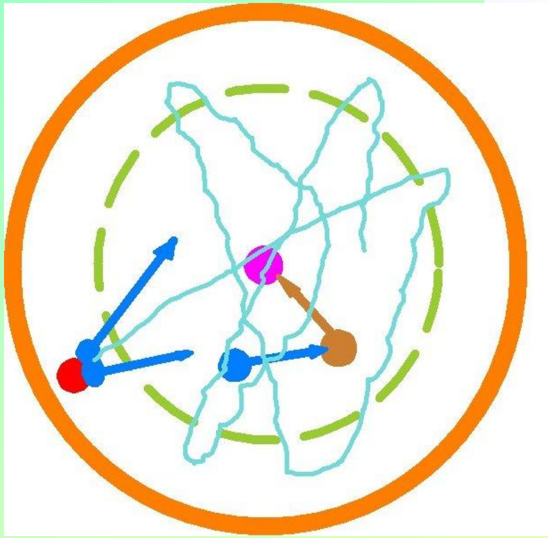
There are various configuration, but in this lecture we discuss only one, the Bayard-Alpert gauge (BAG) which is a true UHV gauge.

The Measurement of Vacuum
Hot Cathode Ionisation Gauges

Electrons are emitted from a heated filament and are attracted into an open grid structure, which is at a positive potential. In this space they oscillate back and forth until they eventually are collected on the grid.



As they travel, they generate ions from the gas molecules by impact. These ions are collected on a very thin wire, axial collector



Hot Cathode Ionisation Gauges

Because it is a hot filament gauge, the BAG has an upper pressure limit of about 10^{-3} mbar to avoid filament burn out.

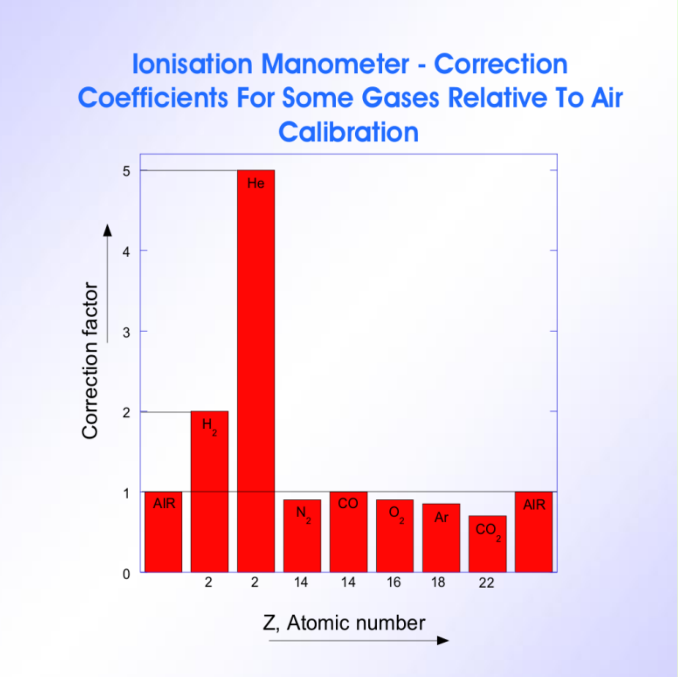
Its lower limit is about 10^{-11} mbar, for reasons discussed later

It is delicate, prone to damage and susceptible to contamination

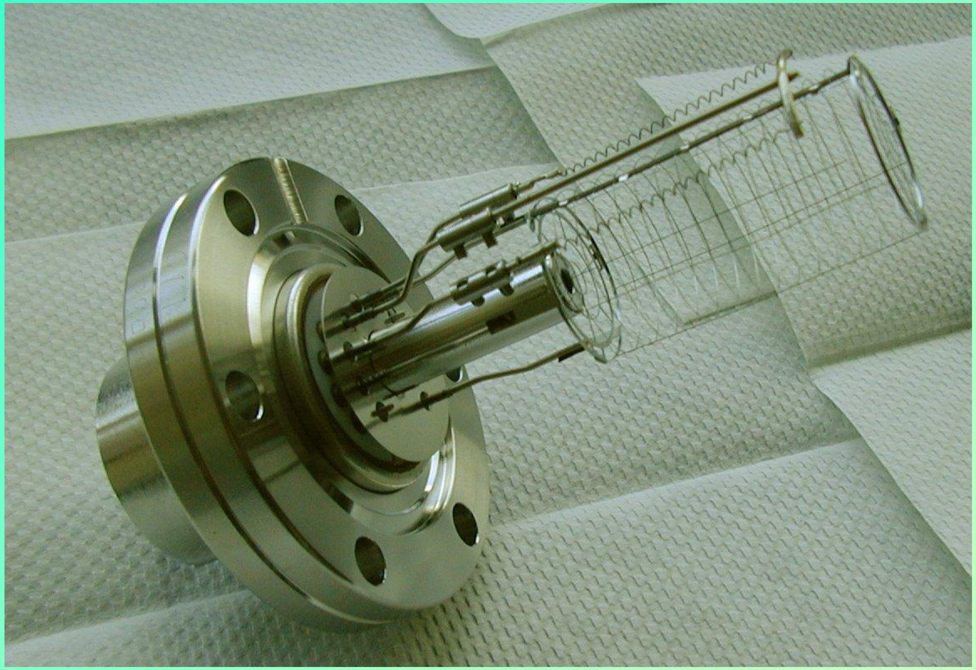
Like all ionisation gauges, its sensitivity is species dependent (and at higher pressures, pressure dependent) and so it must be calibrated

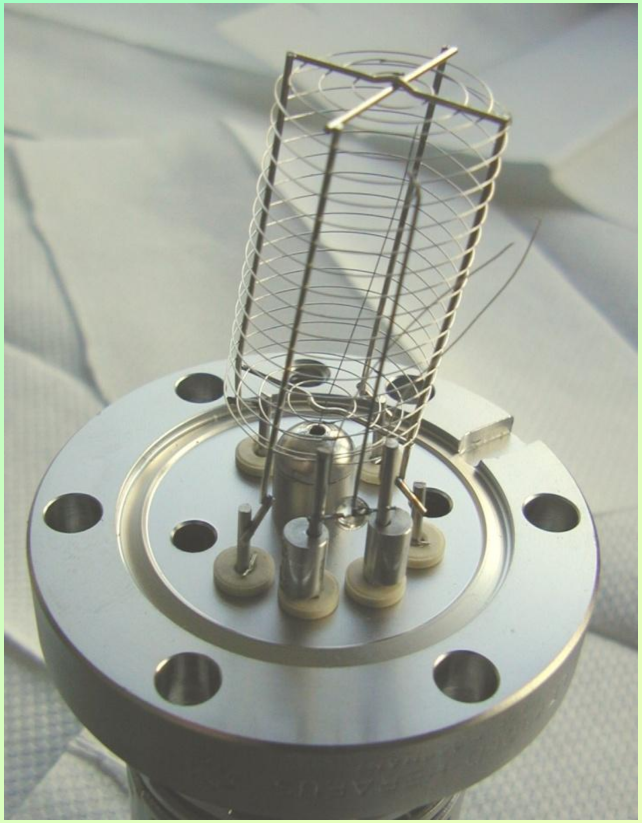
Its calibration may change, especially after exposure to atmosphere – variations of 50% have been observed

Sensitivity can vary from gauge to gauge for nominally identical gauges by a factor of 2 or more



Hot Cathode Ionisation Gauges





Hot Cathode Ionisation Gauges

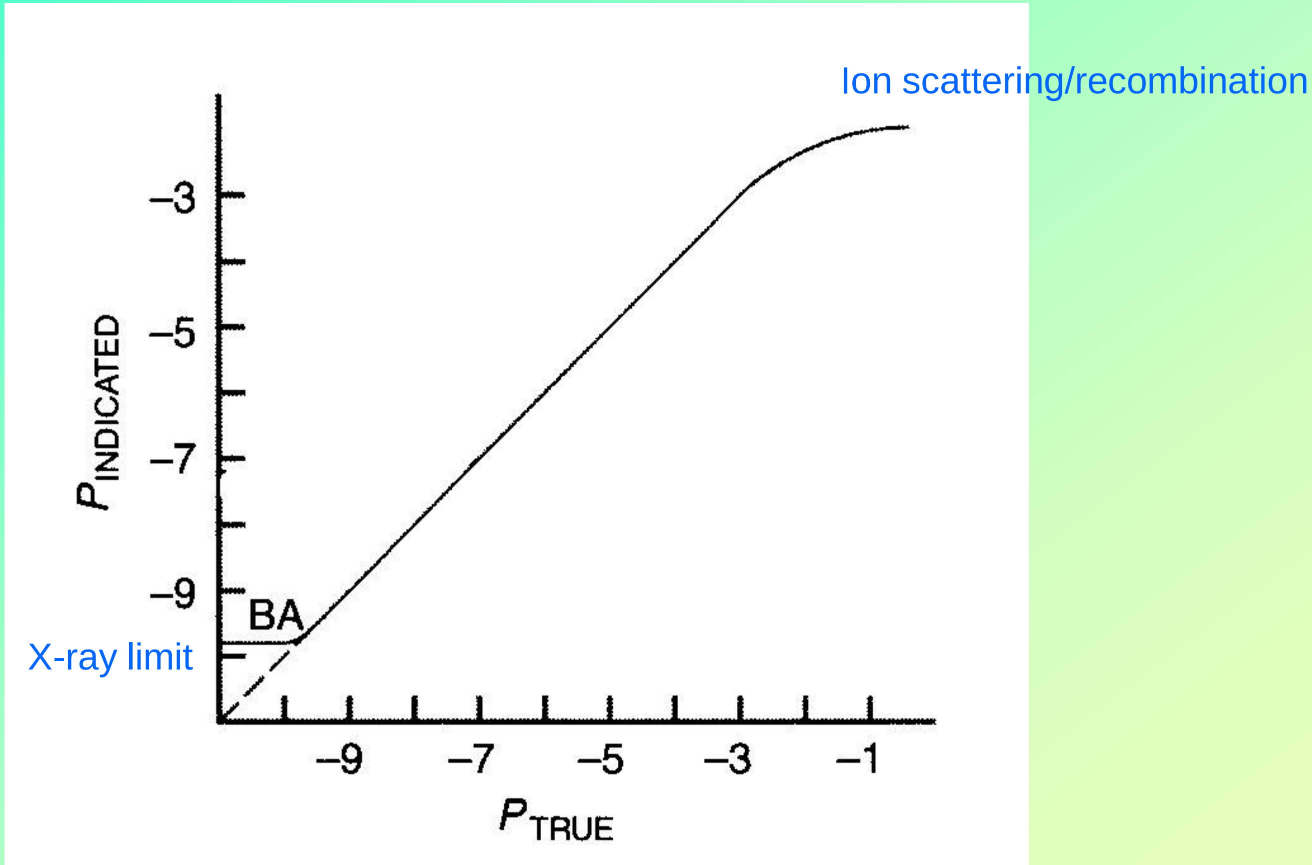
The ion current i^+ is proportional to the emission current i^- and the pressure p, so that

$$i^+ = \varepsilon i^- p = Kp$$

where ε is a gauge constant with units of $mbar^{-1}$ and K is the gauge sensitivity with units of Amp $mbar^{-1}$

ε is typically between 10 and 30 $mbar^{-1}$

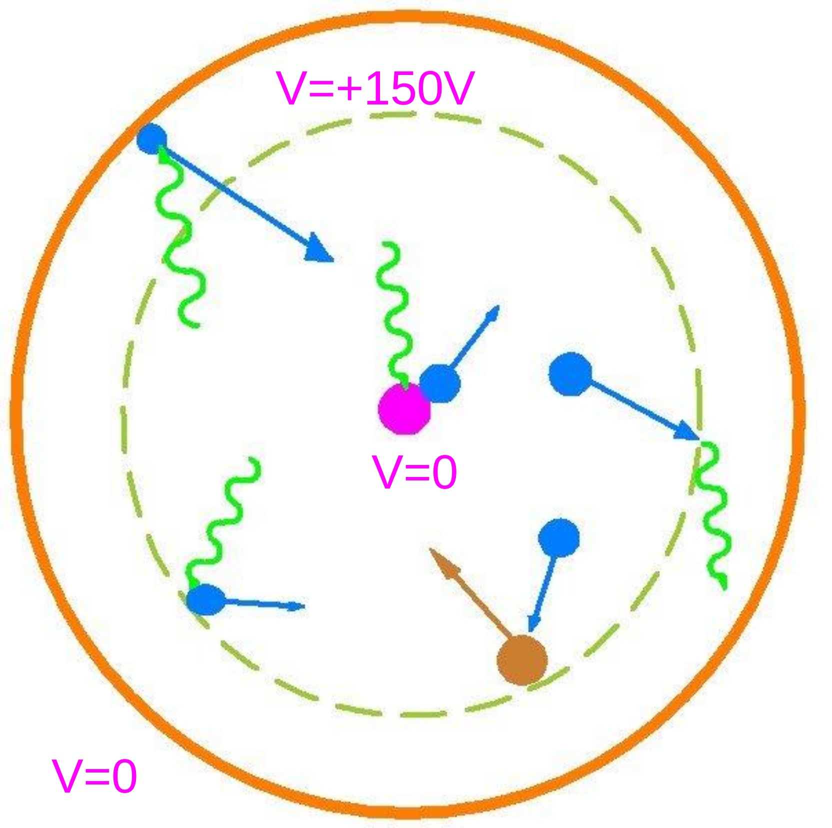
Hot Cathode Ionisation Gauges



Hot cathode gauges – error sources

Some of the physical processes which occur in a hot cathode ionisation gauge which lead to errors on pressure measurement are

- Soft X-ray emission
- Photoemission
- Electron Stimulated Desorption



Hot cathode gauges – error sources

The apparent pressure p_m is given by

$$p_m = \frac{1}{K}(i^+ + i_R + i^+_{des})$$

Where K is the gauge constant

i^+ is the "real" ion current

i_R is a current due to X ray photoemission

i^+_{des} is a current from a local pressure increase due to desorption

Hot cathode gauges – error sources

Other sources of error include

- The hot cathode causes local heating of the vacuum system and therefore outgassing from the walls, giving an apparent increase in pressure.
- The created ions can be buried in the collector and so the gauge can “pump”
- A lot of chemistry happens at a hot filament, so the gas composition can change

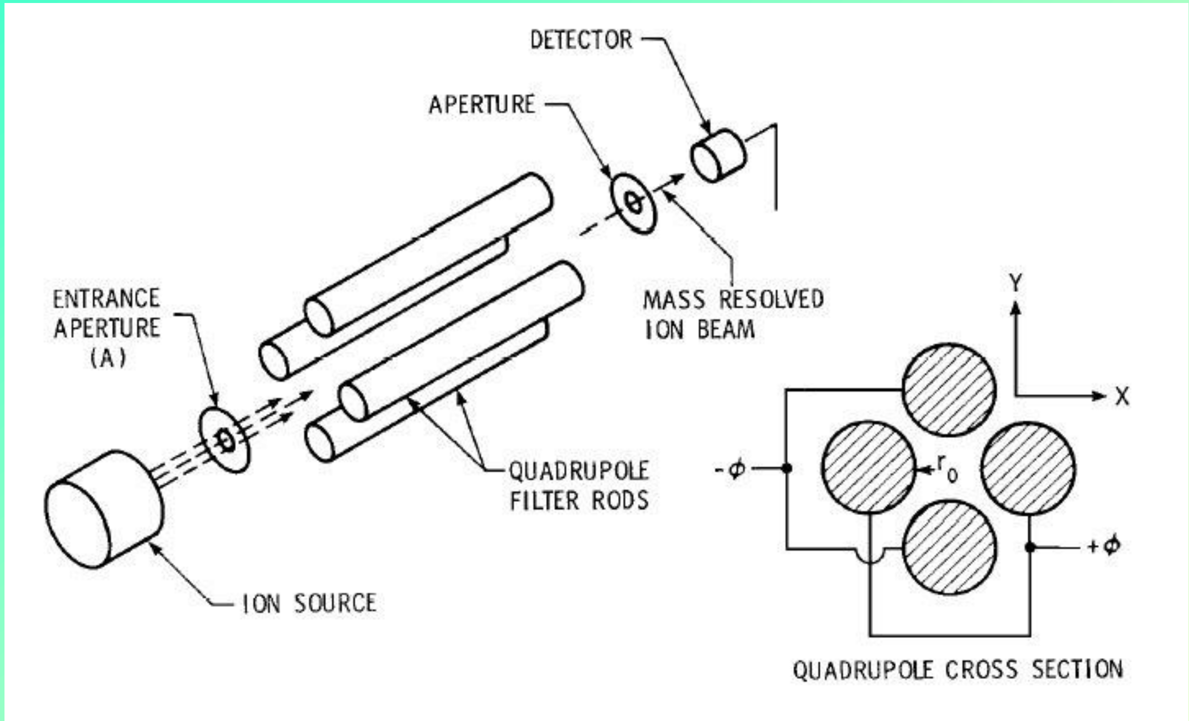
Vacuum – What's in it?

In accelerators, although it is important to know the pressure I.e. number density of residual gas molecules, it is often just as important to know the number densities of individual gas species.

We therefore need a means of performing residual gas analysis.

Residual Gas Analysis

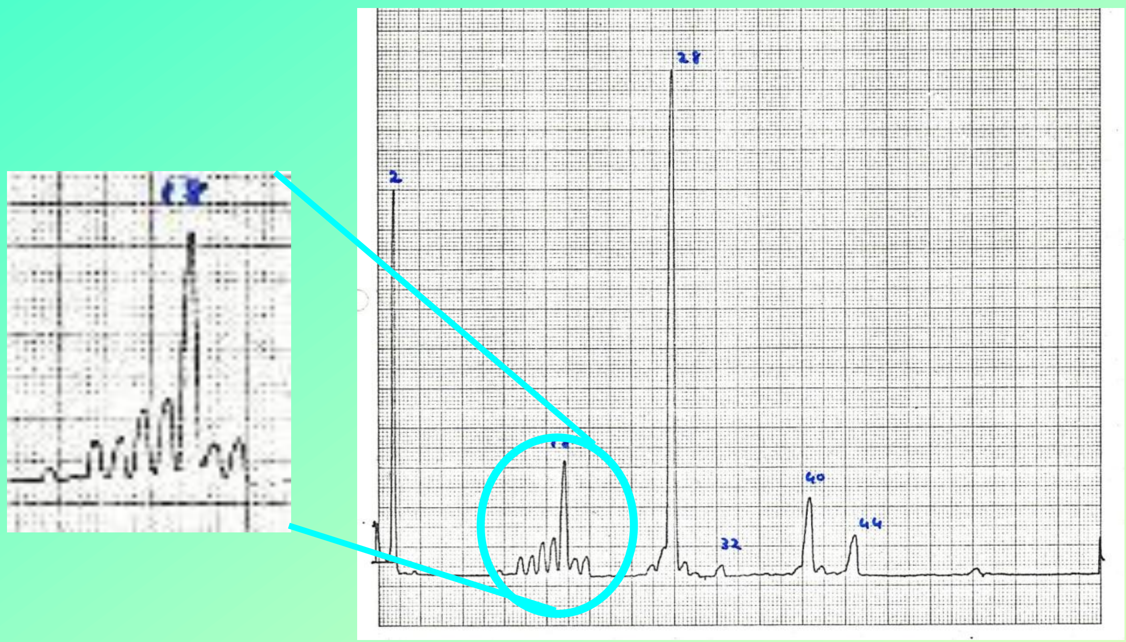
A common RGA- The quadrupole radio frequency analyser ("Quad")



$$\phi = U + V\cos\omega t$$

Residual Gas Analysis

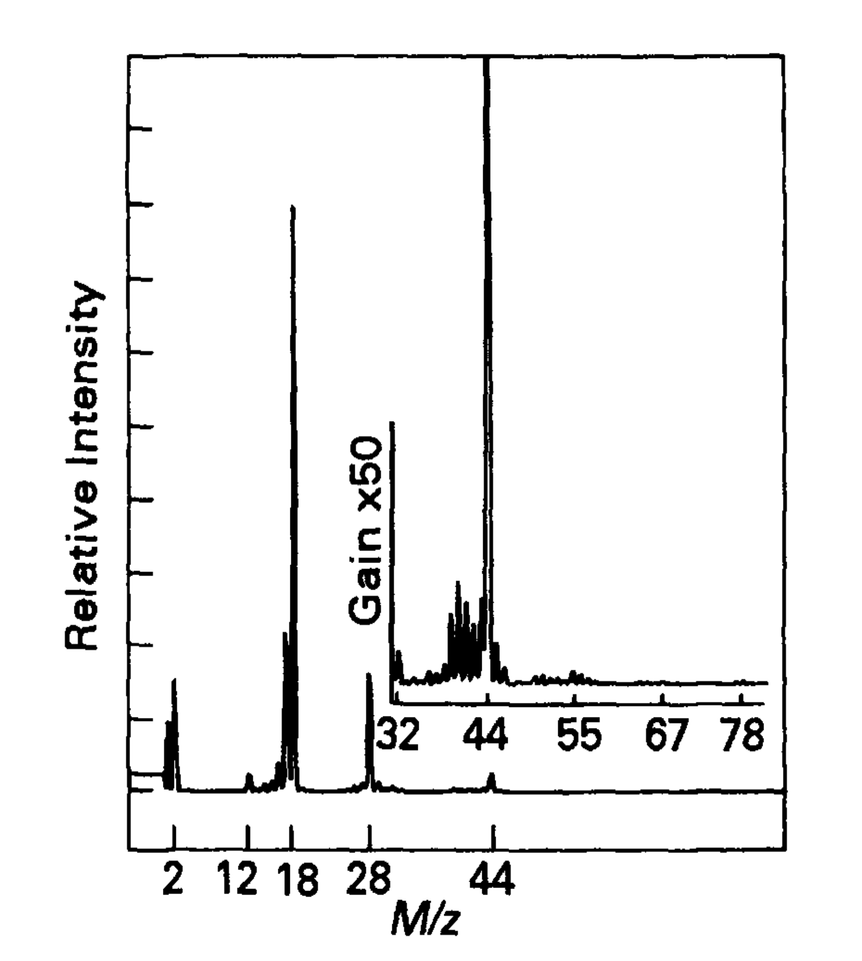
Residual Gas Analysis



Peak positions give a characteristic spectrum for a given molecular species

Peak heights give information about the amount present

The Measurement of Vacuum
Residual Gas Analysis



A mass spectrum taken by a quadrupole rga in a system pumped by a diffusion pump

The mass scale is linear and the peaks are of constant width

This is typically how such instruments are set up

Residual Gas Analysis

Since the ion source of this type of rga is similar to a hot cathode ionisation gauge, the characteristics and sources of error are also similar.

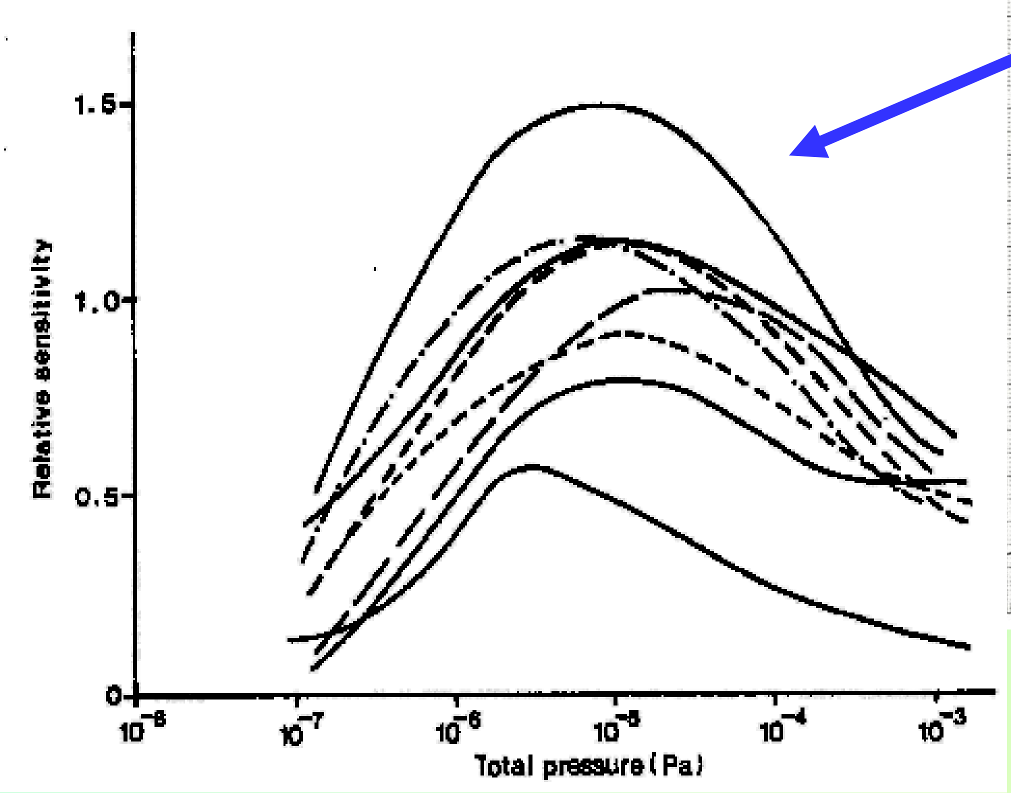
- Sensitivity is species dependent
- At low pressures, esd may give rise to spurious peaks
- At high pressures, scattering and recombination of ions may give rise to sensitivity changes (important for trace analysis)

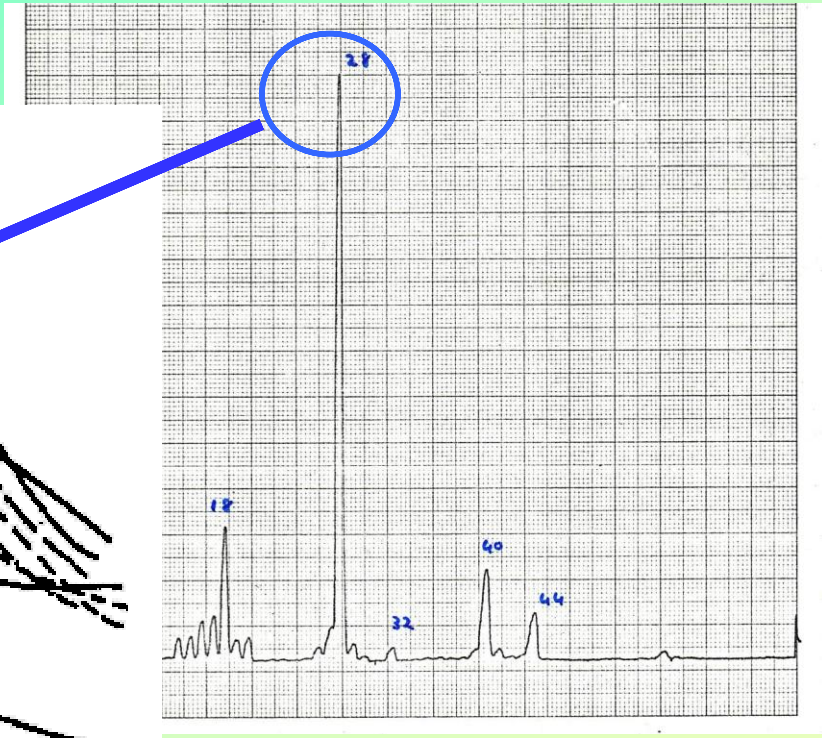
Transmission through the mass filter is mass dependent (Mass discrimination).

Therefore each analyser must be calibrated (preferably in situ) for accurate analytical work.

Residual Gas Analysis

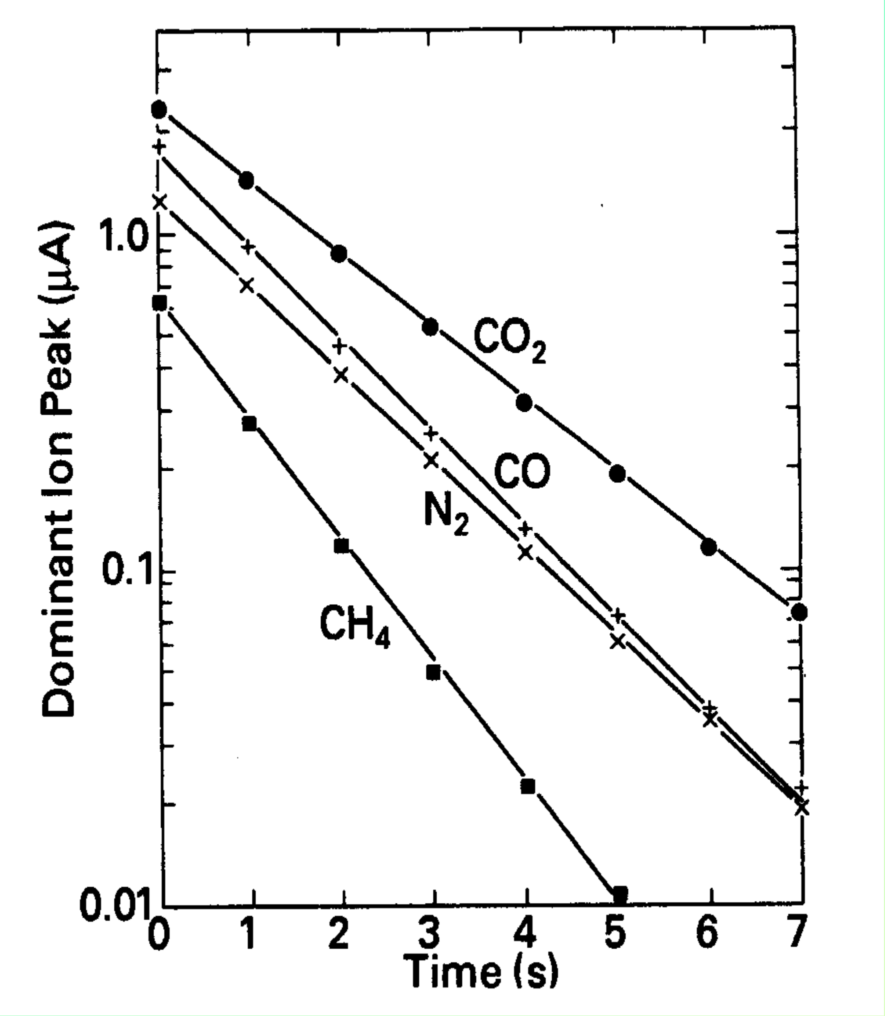
Sensitivity may vary with pressure and from analyser to analyser





Sensitivity of a range of nominally identical rga's for nitrogen

The Measurement of Vacuum
Residual Gas Analysis



A pulse of gas of known composition is admitted to a small vacuum system

The measured peak height of each species can then determine the relative sensitivities of the analyser for each species

The decay of each peak can give the pumping speed of the system for each species

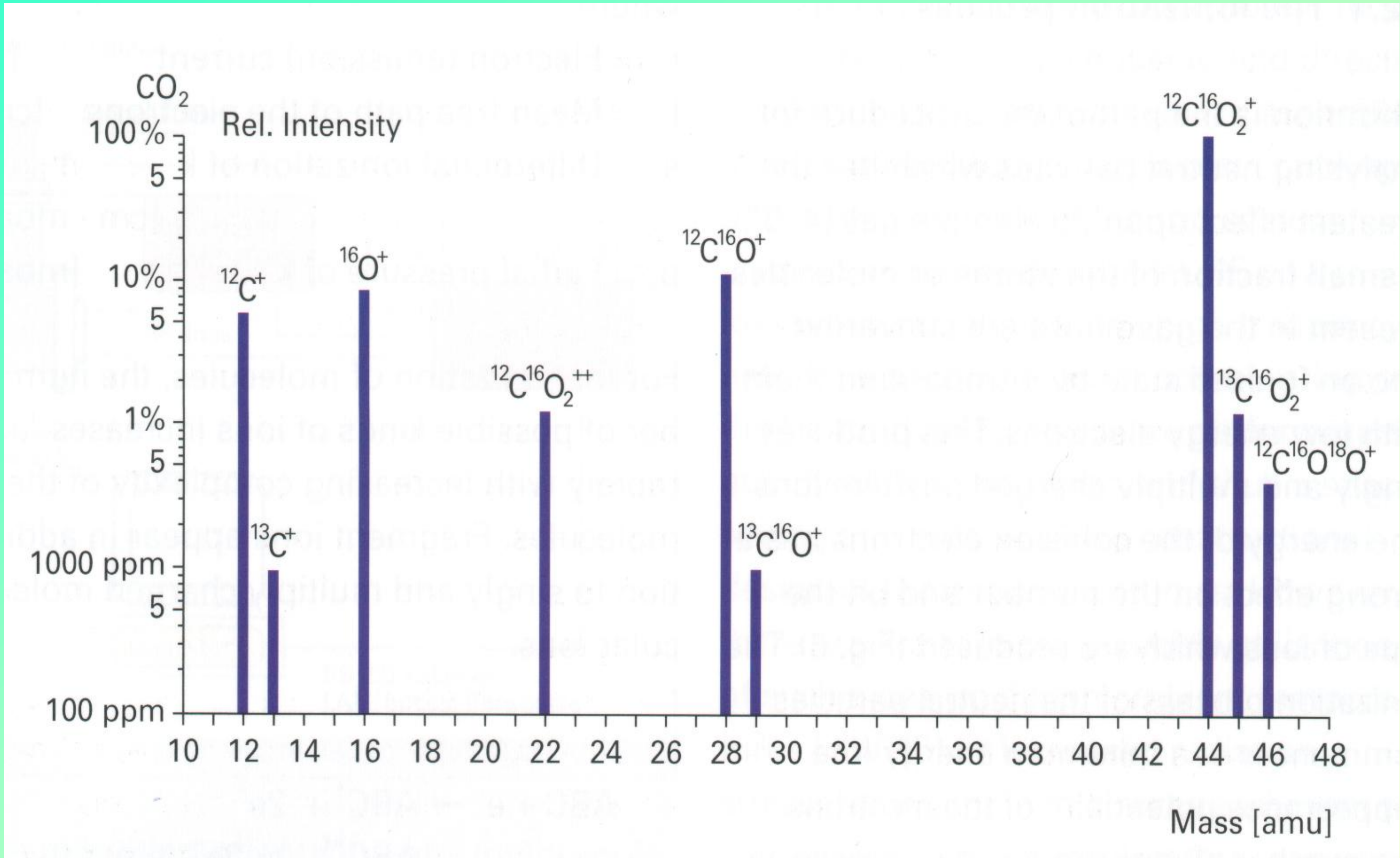
Residual Gas Analysis

Atomic and molecular species are identified by their so called cracking patterns

These are the relative peak heights in the spectrum of each fragment ion after the molecule is broken up by electron impact

They will also reflect the isotopic composition of each atomic species present

Residual Gas Analysis



The cracking pattern of CO_2 after ionisation by 70eV electrons

Residual Gas Analysis

Atomic and molecular species are identified by cracking patterns

- Details (i.e. precise peak height ratios) vary from analyser to analyser
- Usually tabulated for large magnetic spectrometers
- Different species interfere
  - Simple linear superpositions have considerable uncertainty
  - Complicated matrices may be set up for these superpositions and solutions fitted by a least squares type minimisation

Simple rga's are best used as monitors for changes unless the system is relatively simple and frequent in situ calibration is undertaken

Modern systems hide this complexity inside software packages

Residual Gas Analysis

As noted earlier, the ion source of an rga has some of the same problems as a hot cathode ion gauge.

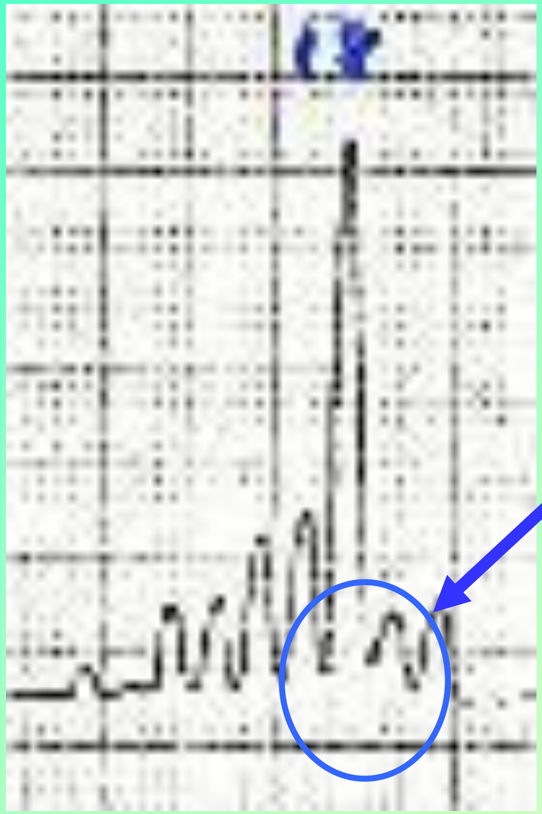
One particularly troublesome spurious effect is caused by electron stimulated desorption or by surface ionisation.

Here, an ion which does not come from the gas phase is created in a region where the potential is not the same as that in the region where the gas phase ions are formed.

The energy of the ion will therefore be different from that of a gas phase ion and this may be used to differentiate them

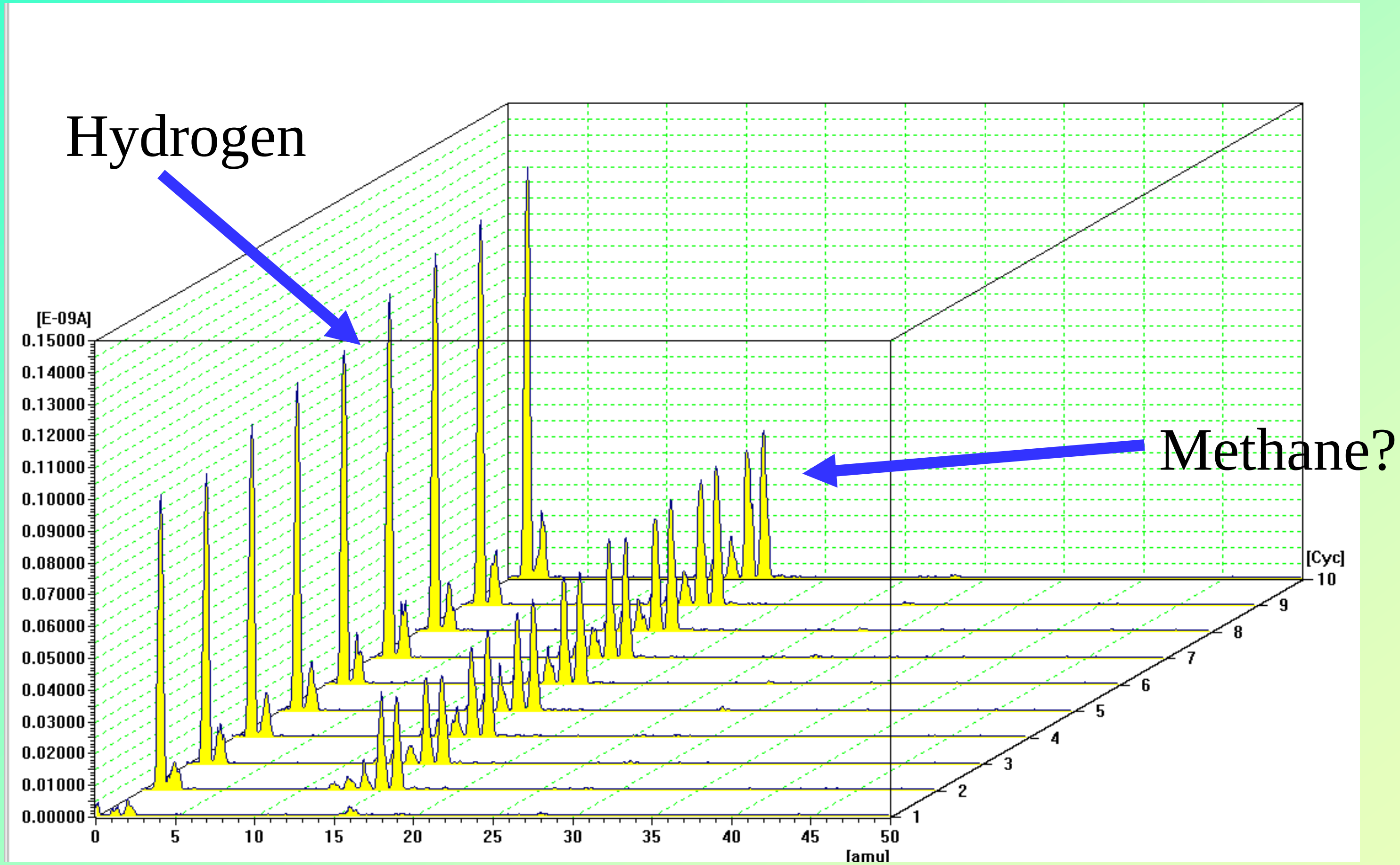
Residual Gas Analysis

Spurious peaks caused by esd



Is mass 19 Fluorine?

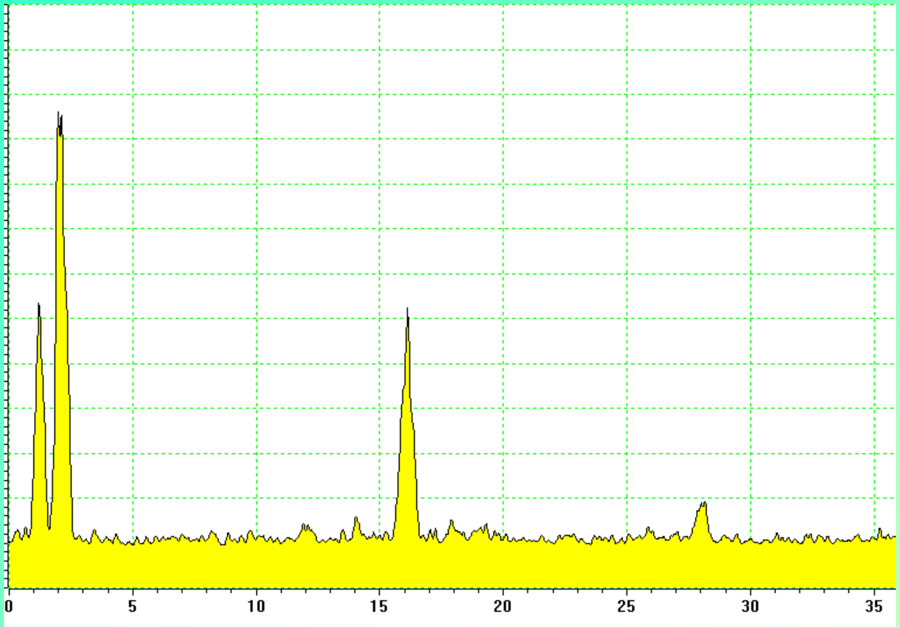
The Measurement of Vacuum
Residual Gas Analysis



The evolution of methane in a large sealed-off vacuum system

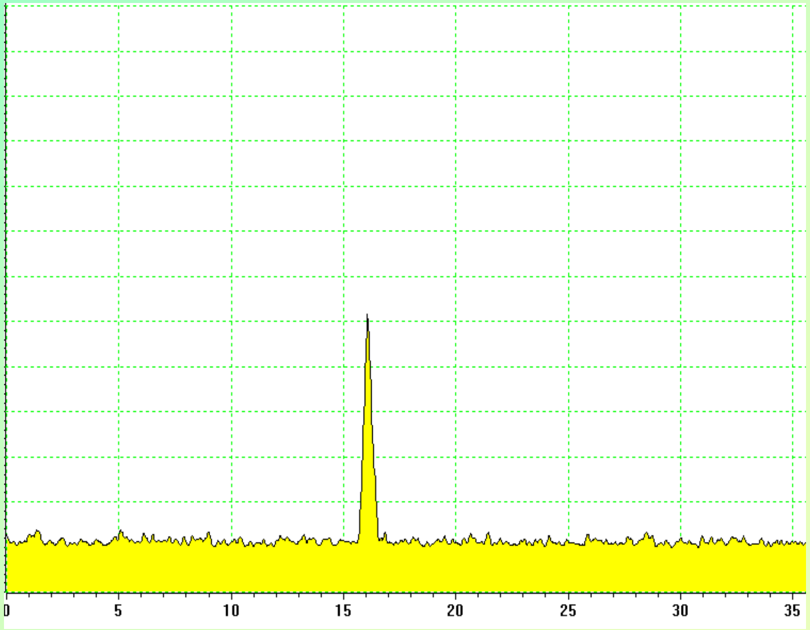
Residual Gas Analysis

Spurious peaks caused by esd

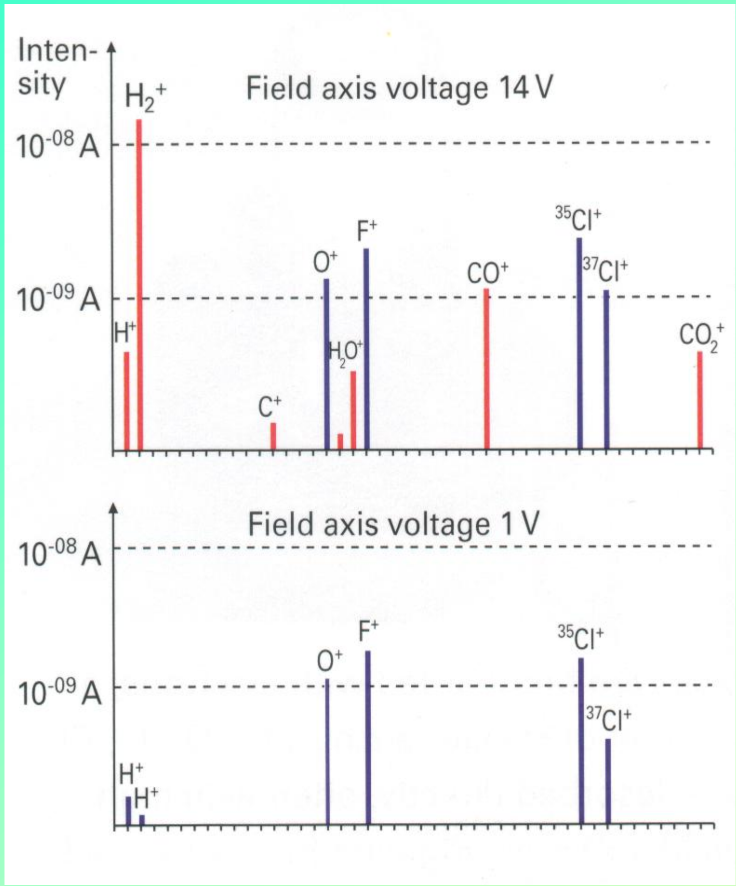


Ion extraction energy 6.25 V

Ion extraction energy 0 V



Residual Gas Analysis



Adjusting the extraction energy of ions from the ion source can discriminate against ion phase ions

Commonly observed peaks are shown here