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The Production and Measurement of Vacuum from Atmosphere to Ultra-High Vacuum (UHV) on accelerators

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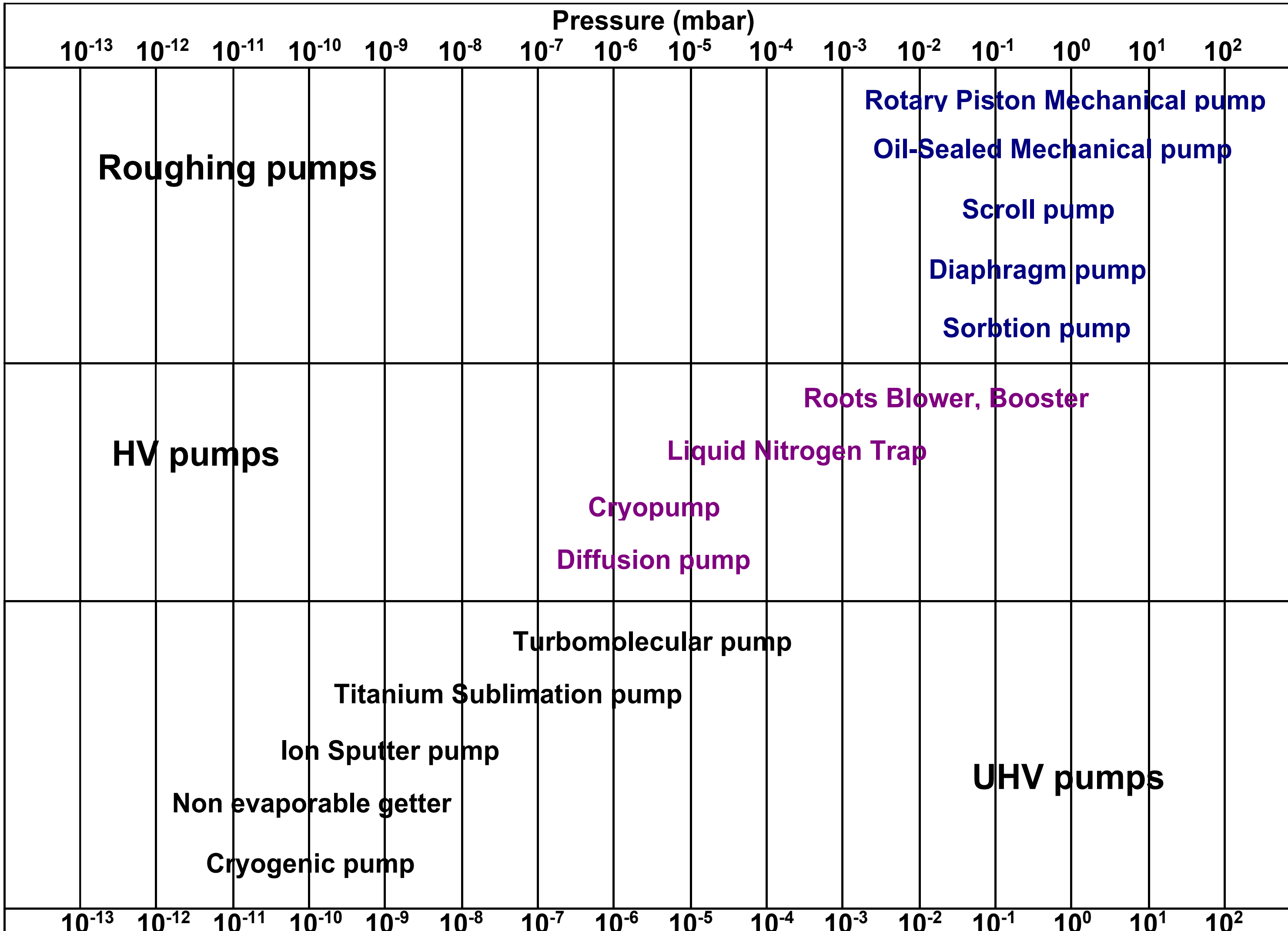
The Production and Measurement of Vacuum

Part 1 - Production

Aims

- To demonstrate the main types of vacuum pump used in accelerators
- To understand the pumping mechanisms involved
- To understand the advantages and limitations of each type of pump

Pressure Ranges of Vacuum Pumps



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Vacuum Pumps

- There are two fundamental types of pump
  - Ejection (momentum transfer) pumps
    - These are essentially compressors
  - Entrapment (chemical sorption) pumps
    - Work by binding gas molecules either chemically or physically within the pump

Pumps we will consider

- Mechanical Pumps (momentum transfer)
  - Diaphragm Pumps
  - Drag Pumps
  - Rotary Vane Pumps
  - Scroll Pumps
  - Diffusion Pumps
  - Turbomolecular Pumps
- Getter pumps (chemical sorption)
  - Cryogenic pumps
  - Ion Pumps
  - Evaporable Getters
  - Non-Evaporable Getters (NEG)

Pumping Speed

- A vacuum pump may be characterised by it's pumping speed.
- This is the volumetric flow rate of gas across a plane.
- It is usually denoted by *S*, and has units of volume/unit time e.g.:
  - l sec^{-1} for the High Vacuum, UHV and XHV pumps (~1-50,000 l/s)
  - or m^3 hr^{-1} for the Roughing pumps (~1-100 m^3/h)

Pumping

In general a pump will be attached to the vessel which we wish to pump with a tube of some sort. If this tube has a conductance C, then the net pumping speed at the vessel will be given by

$$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S_0} \quad \text{or} \quad S_{eff} = \frac{CS_0}{C + S_0}$$

The pumpdown will be given by

$$P = P_0 \exp\left(-\frac{S_{eff}}{V} t \right)$$

Mechanical pumps

Mechanical pumps (displacement pumps) remove gas atoms from the vacuum system and expel them to atmosphere, either directly or indirectly

In effect, they are *compressors* and one can define a compression ratio, *K*, given by

$$K = \frac{P_{out}}{P_{in}}$$

K is a fixed value for any given pump for a particular gas species when measured under conditions of zero gas flow.
Pumping speed, S is then given by approximately

$$S = C \cdot (K - 1)$$

Where C is the conductance through the pump

Rough Vacuum Pumps

Pumping Technology	Typical Lowest pressure (mbar)	Typical throughputs available ($m^3\ hr^{-1}$)	Comments
Diaphragm Pump	10	5	Clean. Particulate generation can be a problem
Piston Pump	10^{-2}	50	Modern versions clean (oil free). Low particulate generation possible. Possible problems when pumping particulates. Can be chemically "inert"
Claw Pump	10^{-2}	500	
Scroll Pump	10^{-2}	35	Modern versions clean (oil free) Possible problems with pumping particulates and particulate generation.
Rotary Vane (single stage)	10^{-3}	1200	Oil sealed so difficult to remove backstreaming contamination. Can use inert synthetic oils.
Rotary Vane (two stage)	10^{-4}	350	

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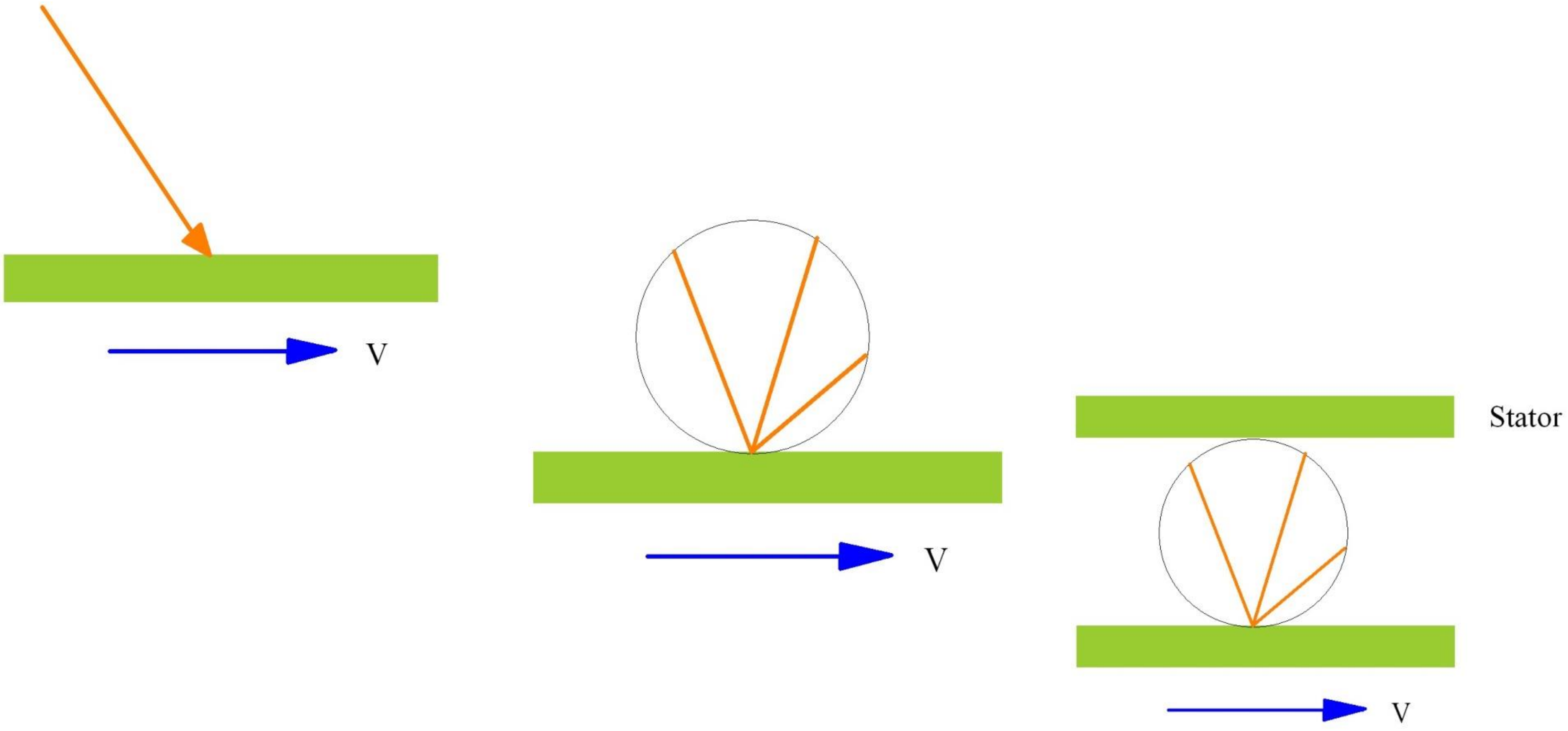
Medium to High Vacuum Pumps

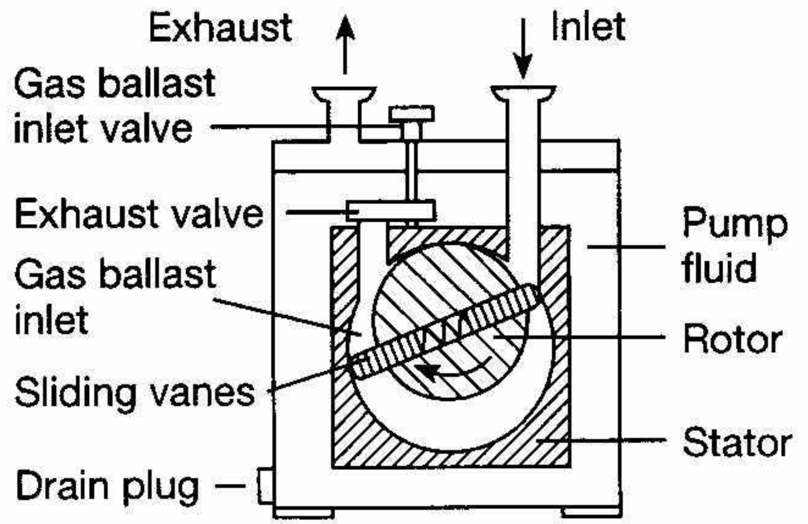
Pumping Technology	Typical pressure range (mbar)	Backing Pump max pressure (mbar)	Typical max throughput (pumping speed) available ($l\ sec^{-1}$)	Comments
Diffusion pump	$10^{-2} – 10^{-8}$	0.1	50,000	Can have very high throughputs. Can be chemically inert. Can handle particulates. Relatively cheap.
Turbomolecular pump	$10^{-3} – 10^{-9}$	10^{-3}	2,000	Good throughput. Reliable. Low particulate generation Can handle modest particulate load. Can be chemically inert
Wide-range turbomolecular pump	$10 – 10^{-10}$	10	1,500	Throughput at high pressure restricted. More sensitive to particulates.
Ion pump	$10^{-5} – 10^{-11}$	n/a	500	Species sensitive.

Drag pumps

Drag pumps (momentum transfer) work by imparting a directional velocity to the random motion of gas molecules



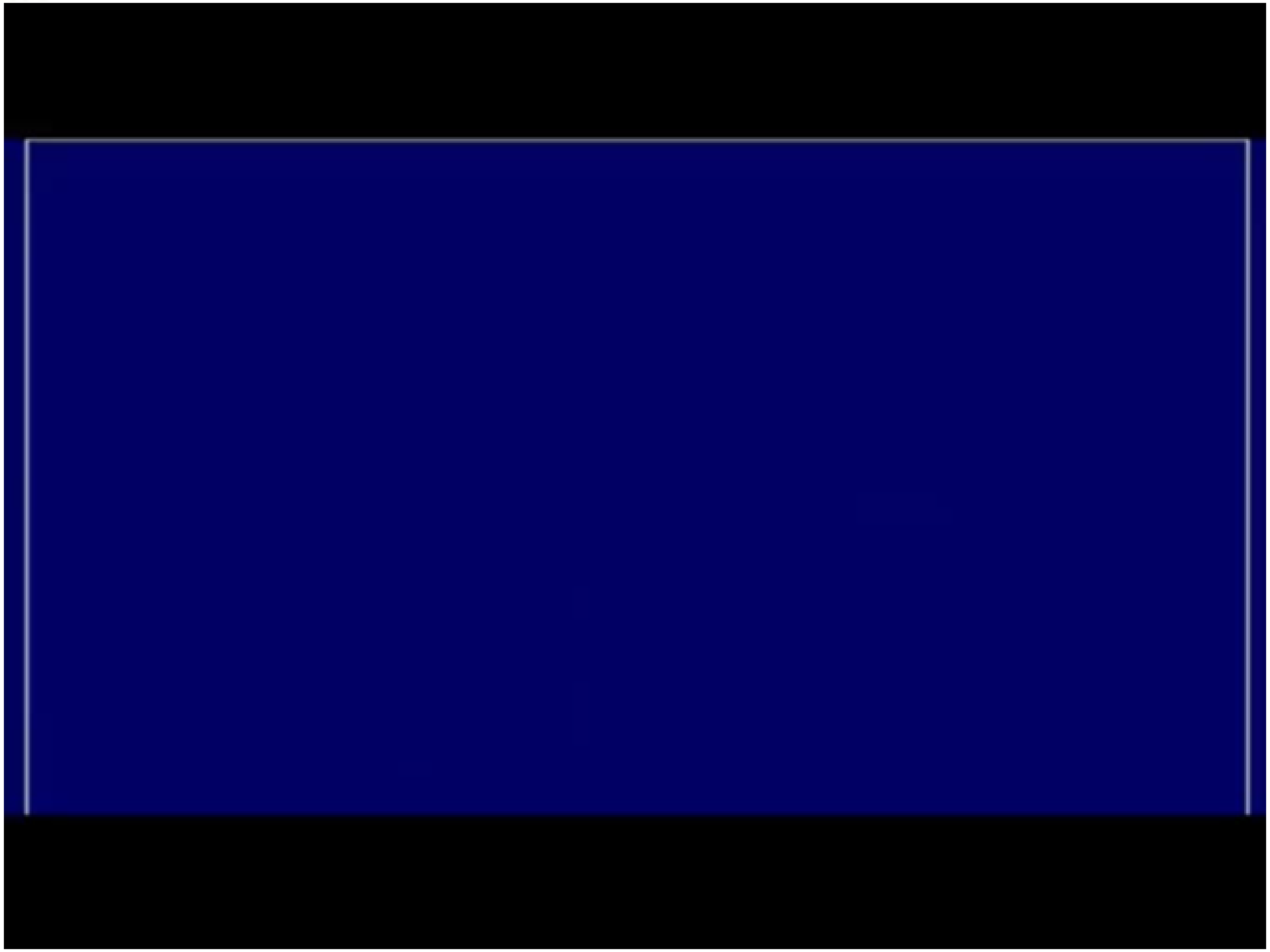
Rotary Vane Vacuum Pump



- Work in the rough vacuum range (atm – 10^{-3} mbar)
- Exhaust directly to atmosphere

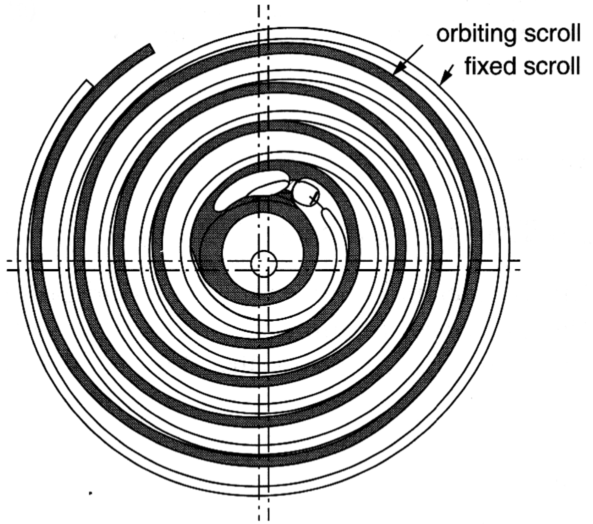
Rotary Vane Pump

Scroll Pump

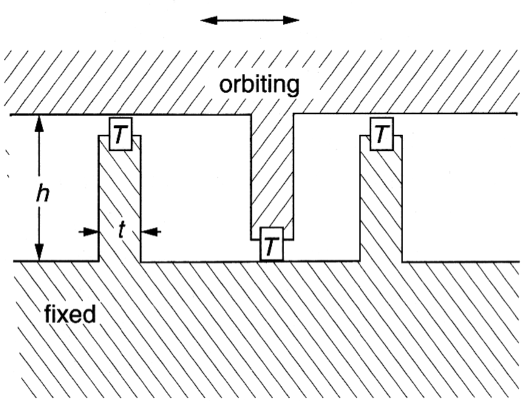


Note – The animation shows a compressor, but the principle is the same for a pump
© Copeland Engineetring

Scroll Pump



orbiting scroll
fixed scroll



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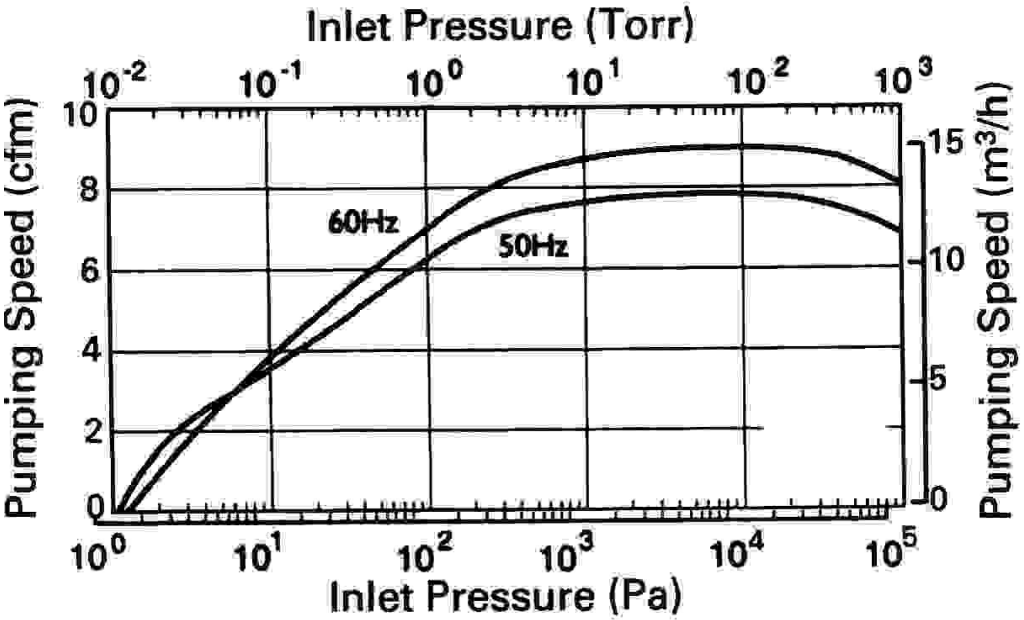


Inlet Pressure (Torr)
10⁻²
10⁻¹
10⁰
10¹
10²
10³
Pumping Speed (cfm)
10
8
6
4
2
0
60Hz
50Hz
15
10
5
0
Pumping Speed (m³/h)
10⁰
10¹
10²
10³
10⁴
10⁵
Inlet Pressure (Pa)

Medium to Ultra-High Vacuum Pumping

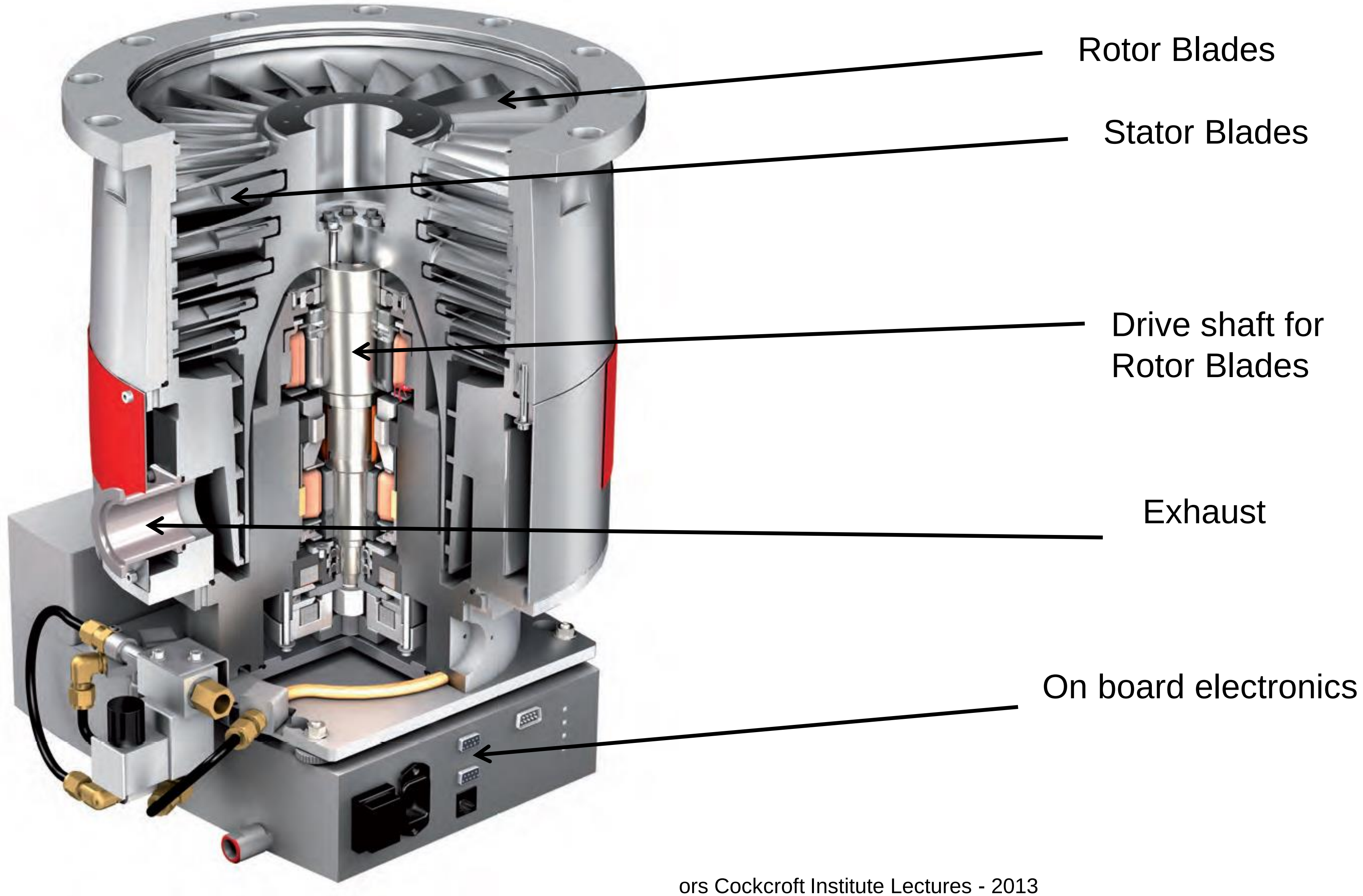
- A typical medium to ultra-high vacuum mechanical ejection pump in use on accelerators is a:
  - Turbomolecular pumps (TMP)

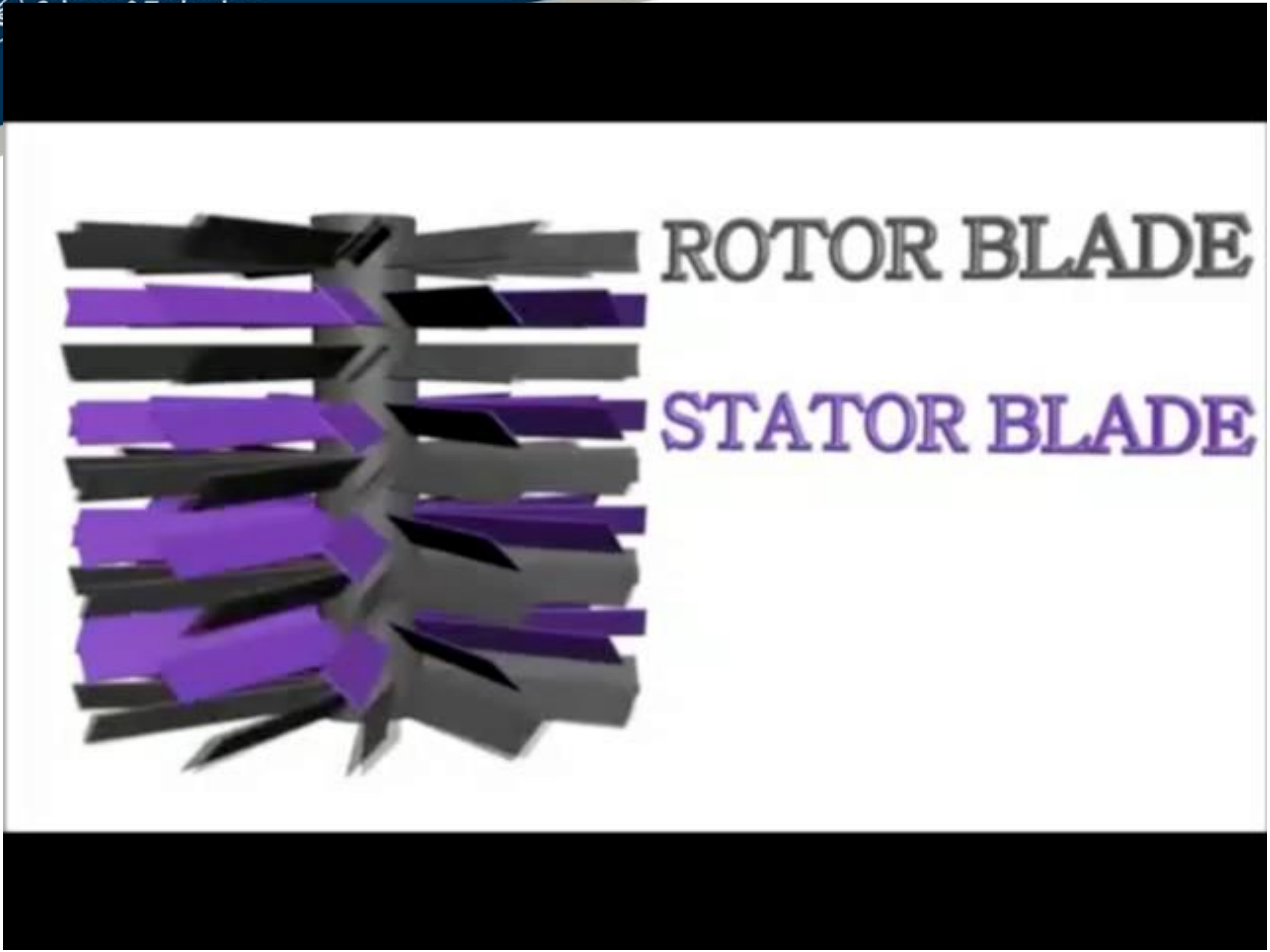
- Ultra-High Vacuum entrapment pumps include –
  - Sputter Ion Pumps (SIP)
  - Non-Evaporable Getter (NEG) pumps

Turbomolecular pumps

- These pumps cannot pump from atmosphere and cannot eject to atmosphere, so they require *roughing* (forevacuum) pumps to reduce the pressure in the vacuum system before they can be started and *backing* pumps to handle the exhaust.
- There are many types of roughing and backing pumps.
- Usually the same pump is used with a suitable valve arrangement
- Many applications using turbomolecular pumps now use clean (dry) roughing/backing pumps to avoid oil contamination in the system.

Turbomolecular pumps




ROTOR BLADE
STATOR BLADE

Turbomolecular pump principle

- To maximise the compression ratio, *K*, blade tip velocities need to be comparable to molecular thermal velocities.

For a single blade, at zero flow

$$K = \frac{P_{out}}{P_{in}} = \frac{\alpha_{12}}{\alpha_{21}}$$

where α_{12} is the forward transmission probability and α_{21} is the reverse transmission probability

It can be shown that

$$K \propto \exp\left[\frac{v_b}{\sqrt{2kN_0}}\sqrt{\frac{M}{T}}\right]$$

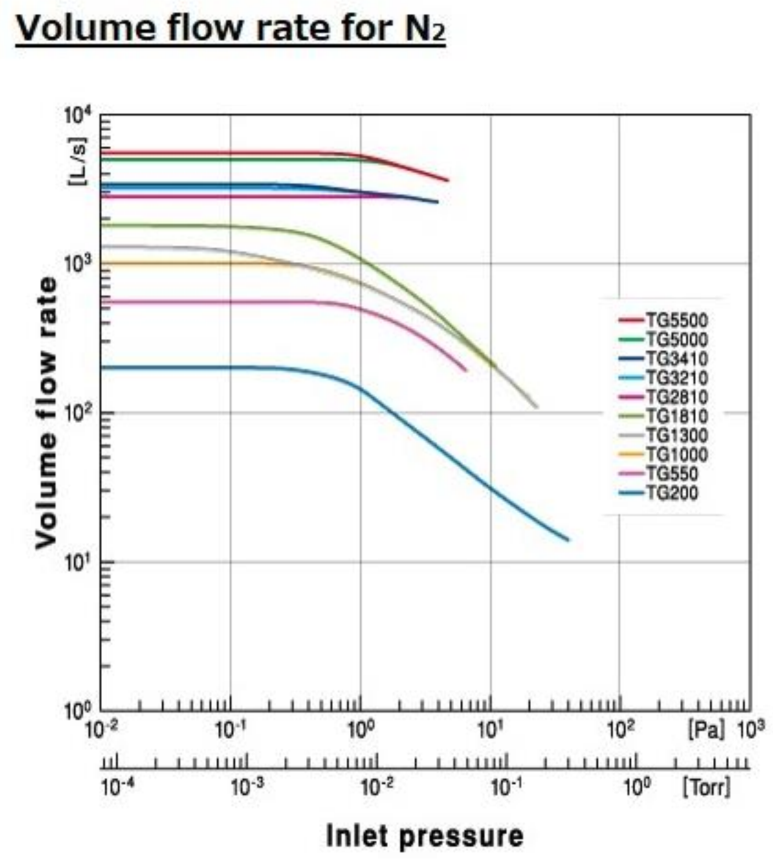
where v_b is the blade velocity

Turbomolecular pumps

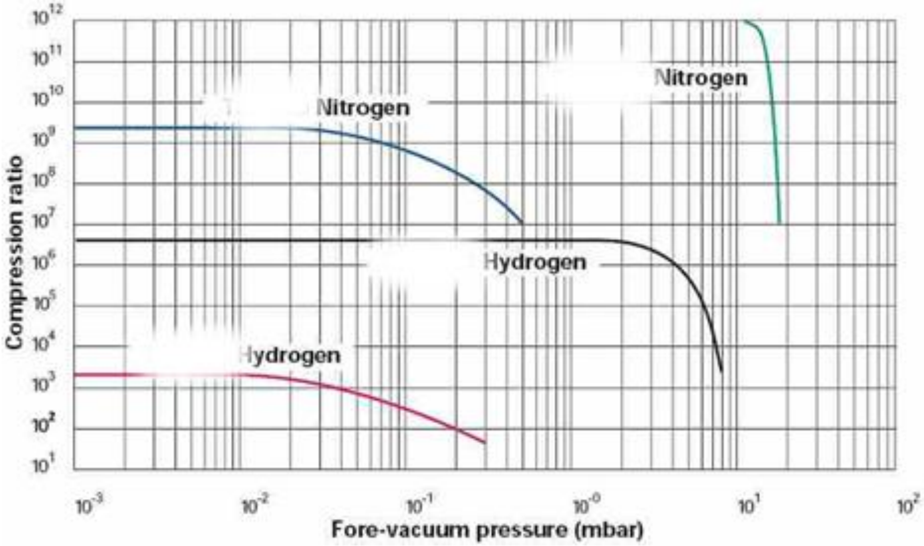
Turbo pumps come in a wide range of speeds:

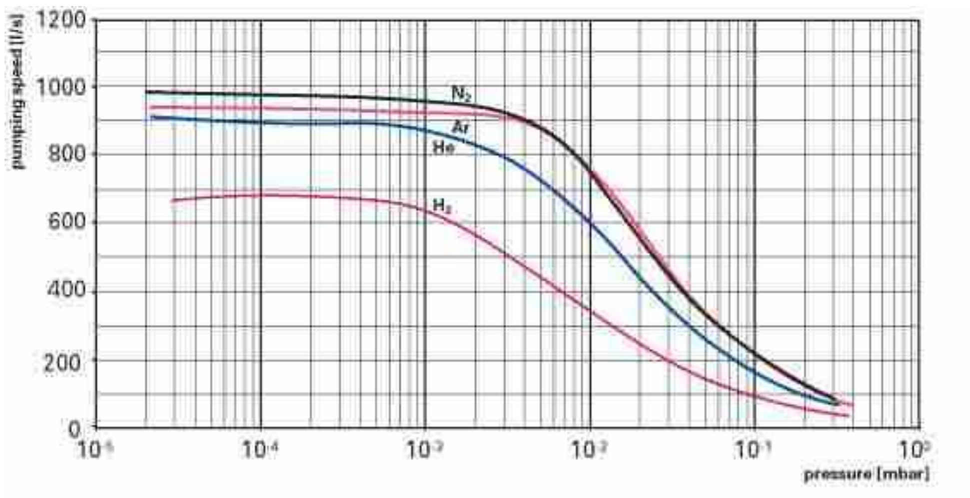
– from a few l/s to many thousands of l/s

- and operate from 10^{-3} mbar to lower than 10^{-9} mbar



Turbo drag Pumps





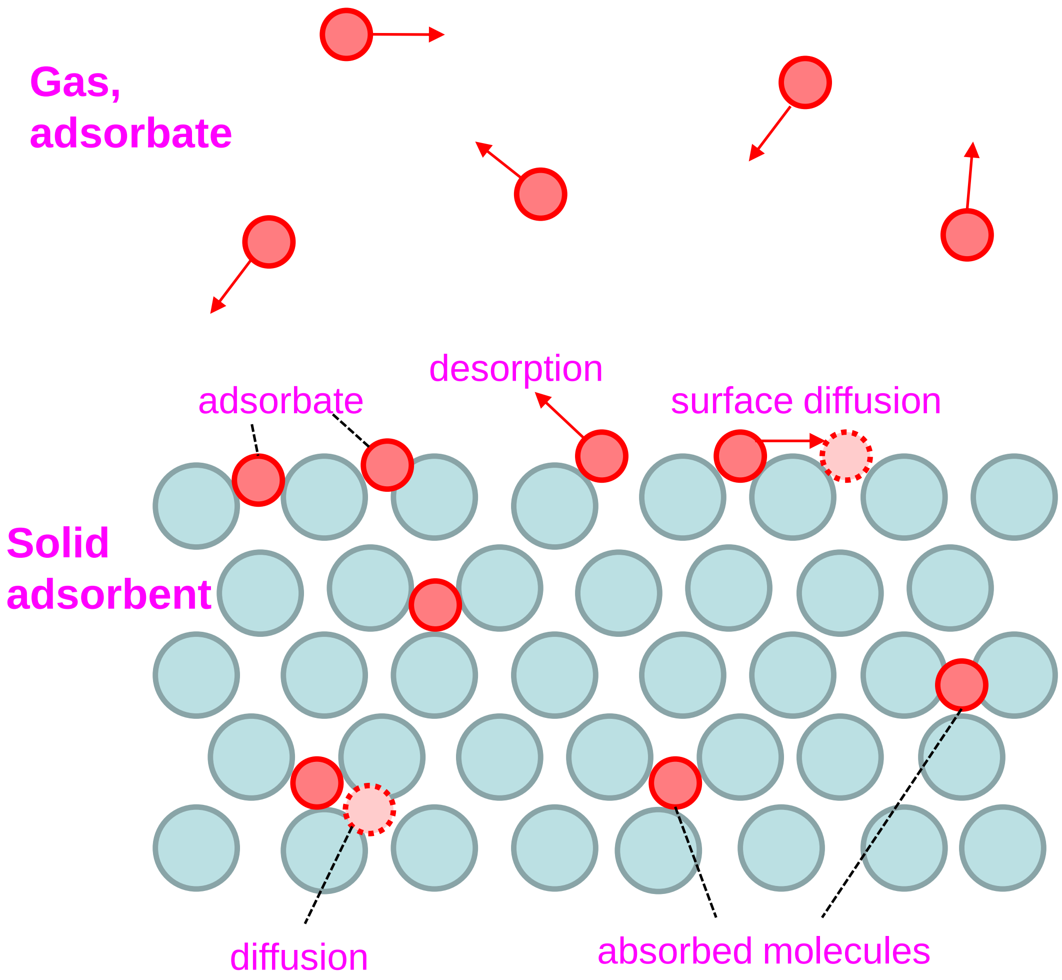
Turbomolecular Pumps

- The choice of bearing type is important
  - Oil sealed
  - Greased
  - Greased ceramic ball
  - Magnetic

Chemical Sorption pumps

Sorption and diffusion

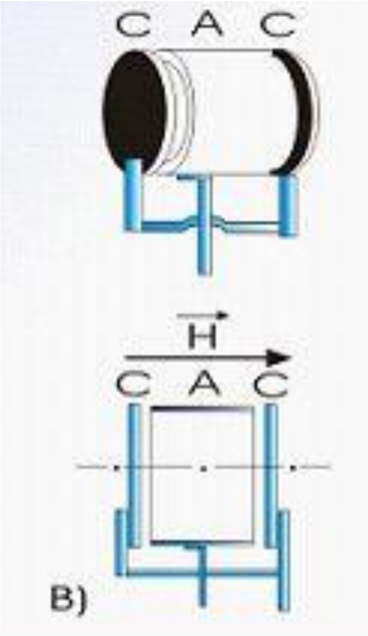
- Gas atoms or molecules (adsorbate)
- Solid surface (adsorbent)
- Sticking probability $s \leq 1$
  - Physisorption (dipole or van der Waals forces)
  - Chemisorption (covalent linkage)
  - Binding energy
- Reflecting probability $(1-s)$

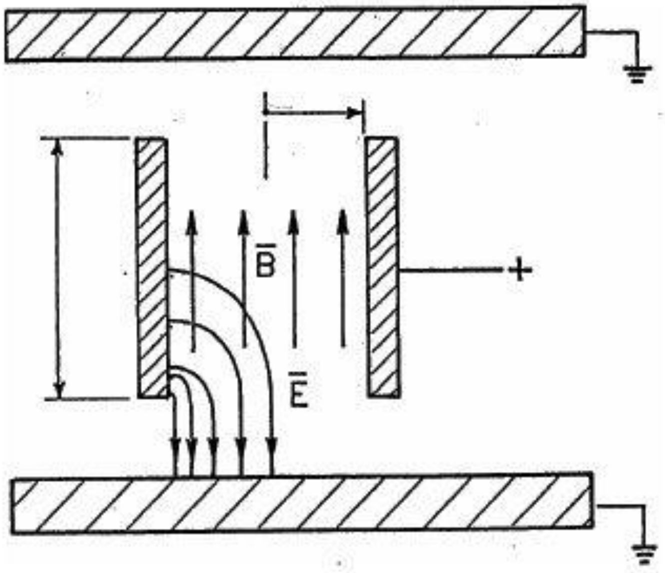


Handbook of vacuum technology. Ed. K. Jousten, Weley-VCH, Weinheim, 2008, Chapters 6,11

Sputter Ion Pumps

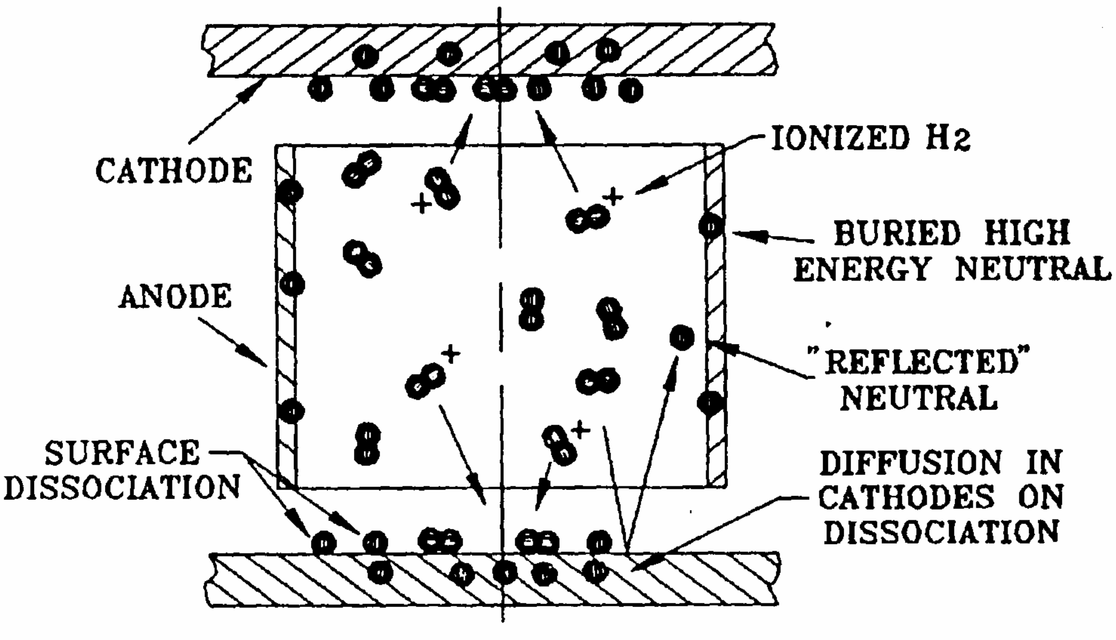
- Based on Penning Cell

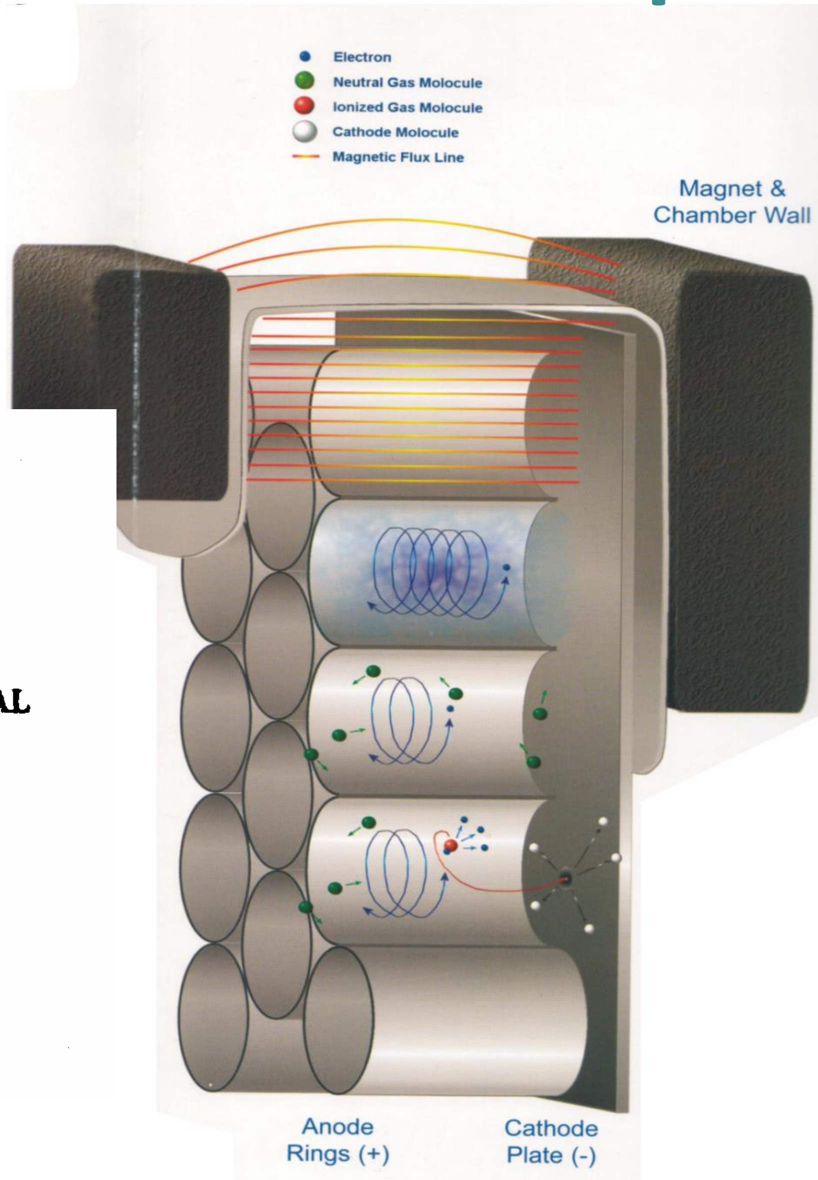




Ion Pumps

Pumping in the basic diode Penning cell



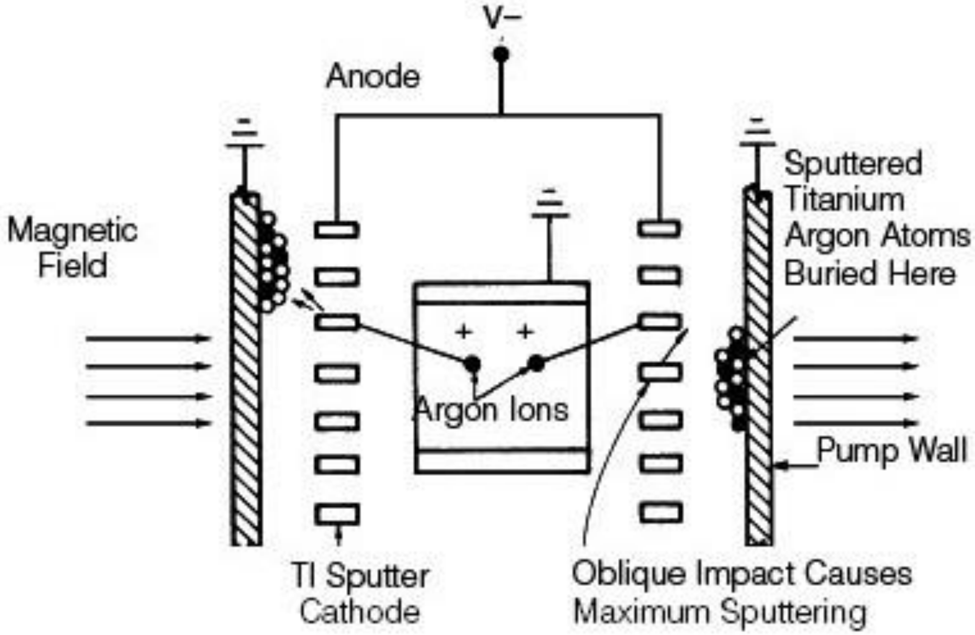


Ion Pumps

- The Diode pump has poor pumping speed for noble gases
- Remedies
  - Differential Ion; Noble Diode
    - “Heavy” cathode
  - Triode
  - Special Anode shape e.g. Starcell

Ion Pumps

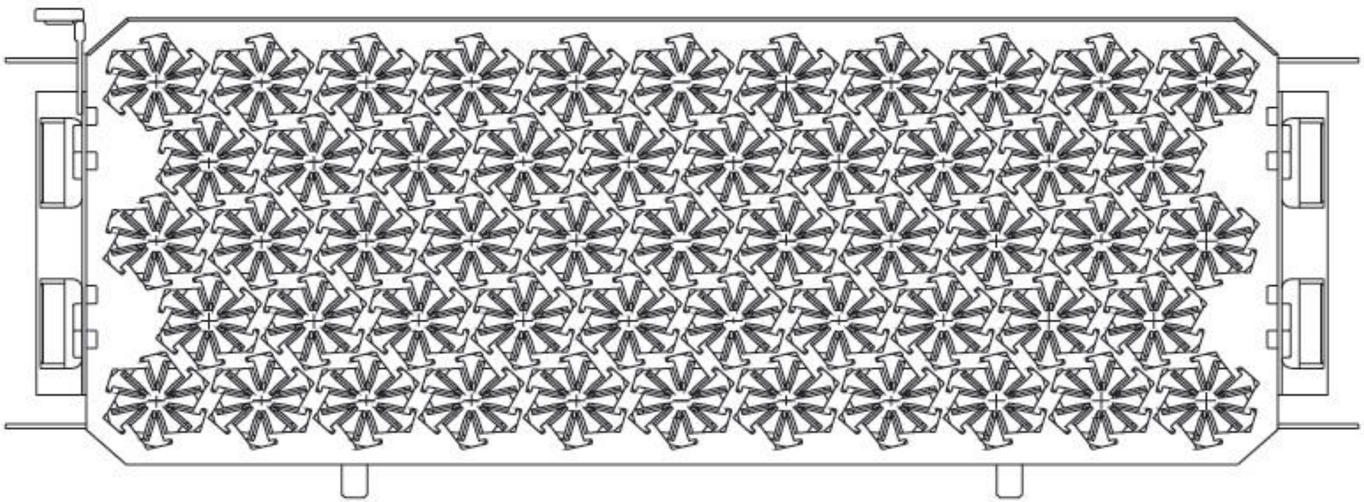
- Triode Pumps use a different design



Triode Ion Pump

Ion Pumps

- Starcell configuration



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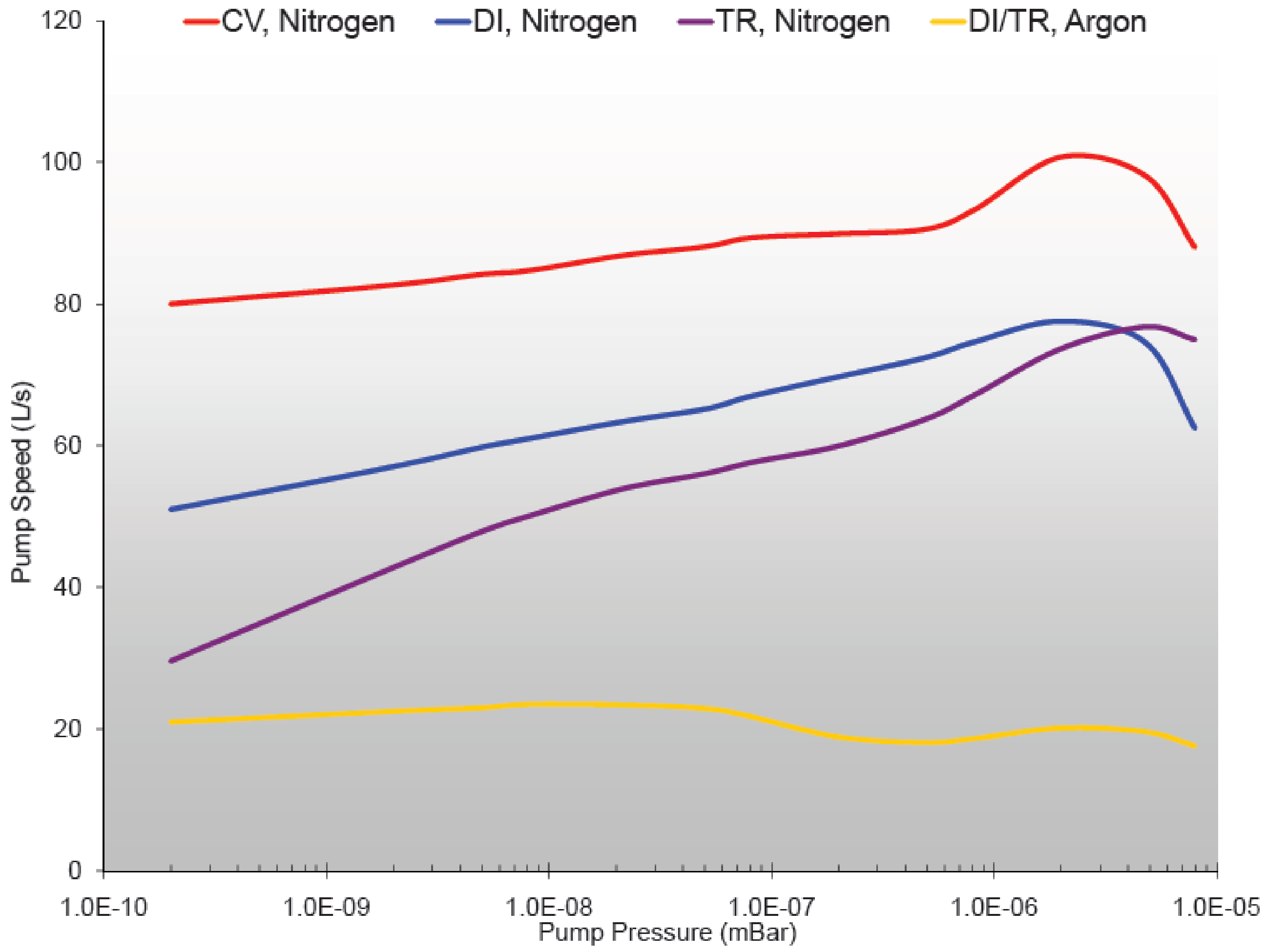
Ion Pumps



Drawbacks of Sputter Ion Pumps

- Pumping speed is species dependent
- Pumping speed is history dependent
- Previously pumped gases may be regurgitated
- Particulate generation may be a problem

Getters

Evaporation pumps

Adsorption mainly

Chemical binding at surface

Covering with a fresh material after saturation

Bulk (non-evaporable) getter pumps

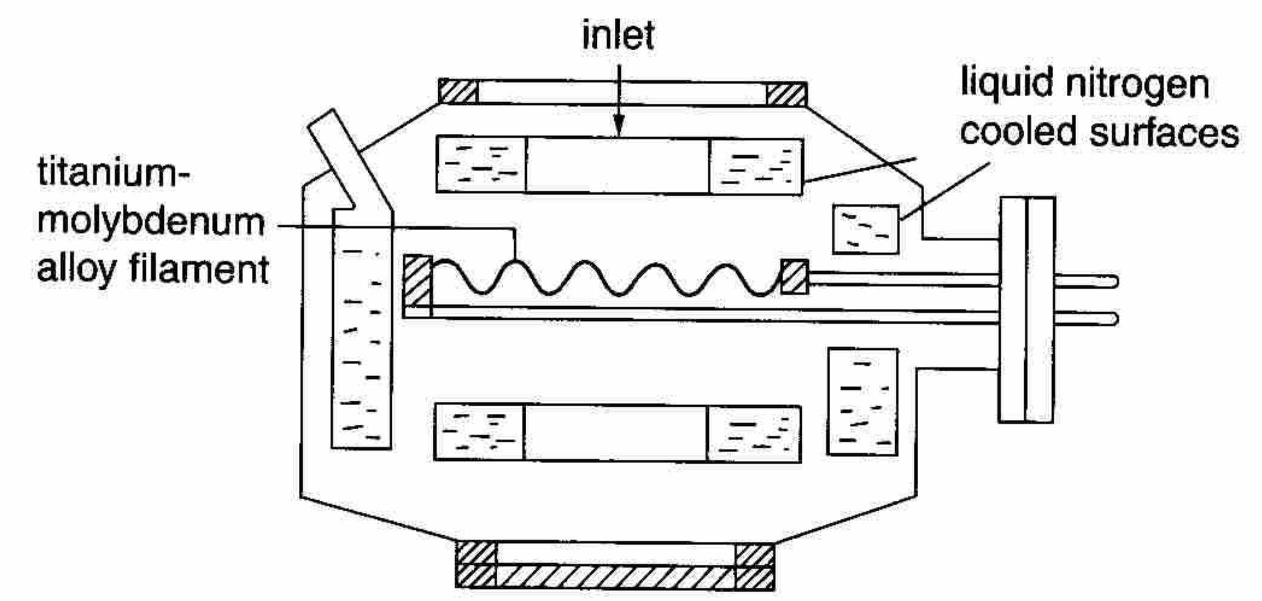
Bulk getter not only adsorb gases at the surface

but also employs an effect of gas diffusion into a getter material

Re-activation by heating to an activation temperature

Getter Pumps

- For vacuum use, the most common ‘evaporable’ getter pump is the titanium sublimation pump

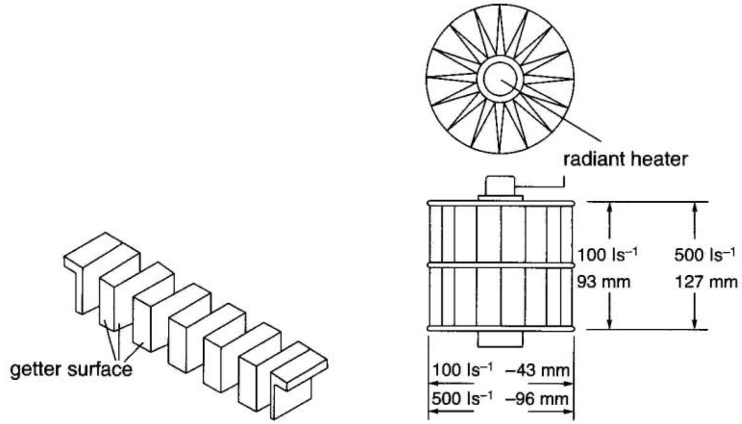


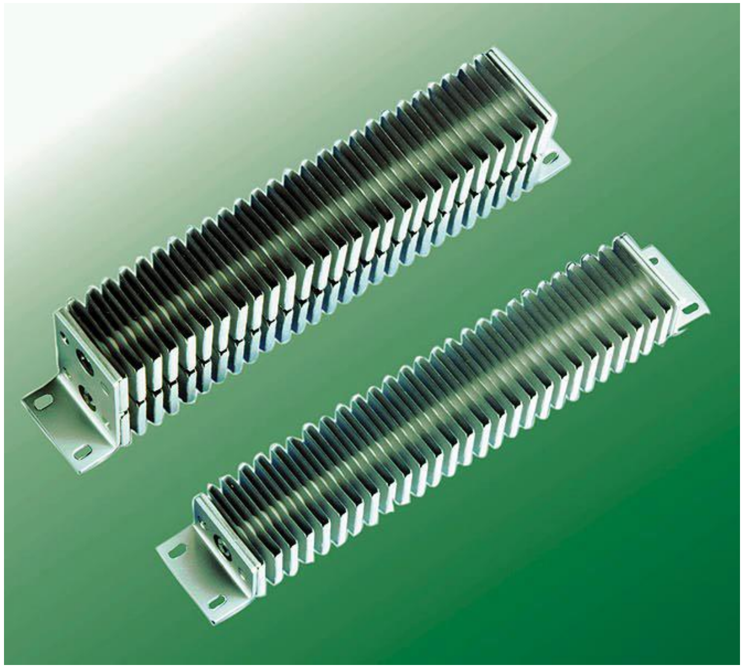
- At 10^{-10} mbar the Ti sublimation pump has to be re-sublimated every 10-12 hours

Getter Pumps

- An important class of getter pumps are the Non Evaporable Getters (NEGs)
- These are alloys of elements like Ti, Zr, V, Fe, Al which after heating in vacuo present an active surface where active gases may be gettered
- Traditionally, the getters take the form of a sintered powder either pressed into the surface of a metal ribbon or formed into a pellet

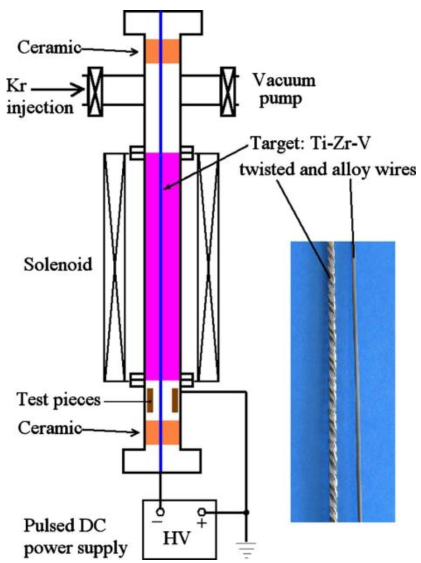
Getter Pumps



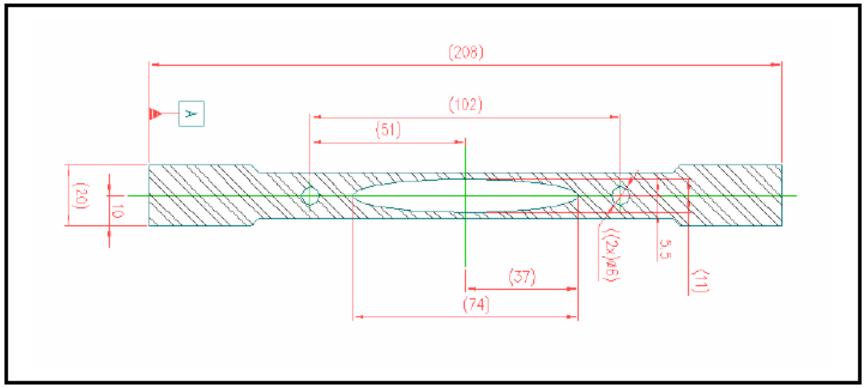


Getter pumps

- In recent times, thin films of getter material have been formed on the inside of vacuum vessels by magnetron sputtering
- These have the advantage of
  - pumping gas from the vacuum chamber by gettering
  - and of stopping gases from diffusing out of the walls of the vessels

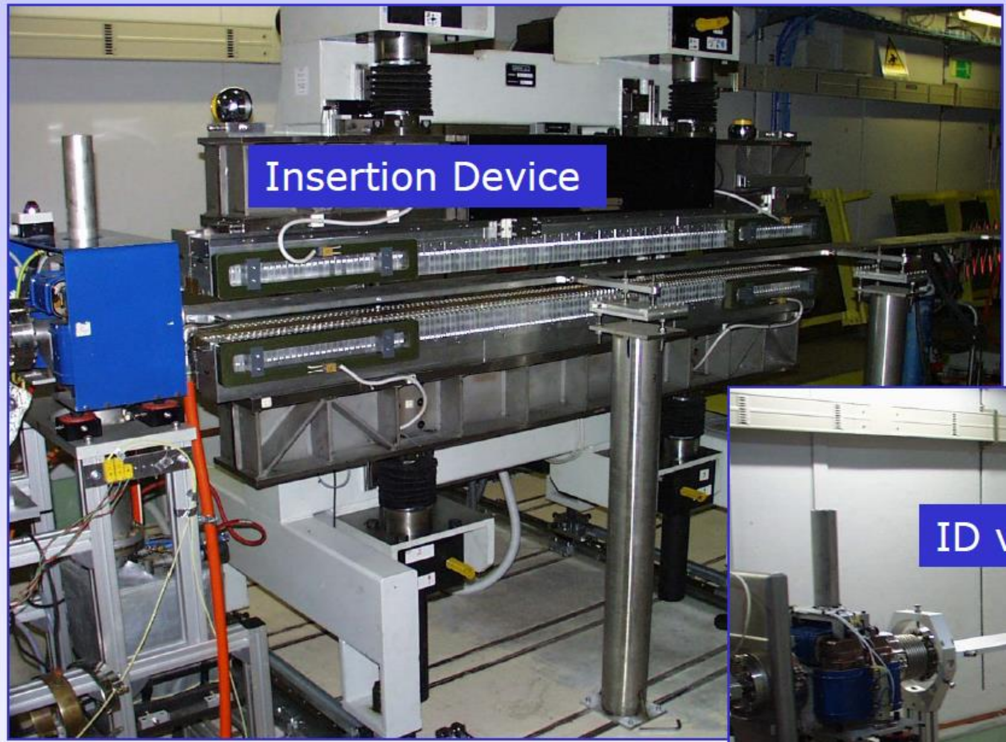


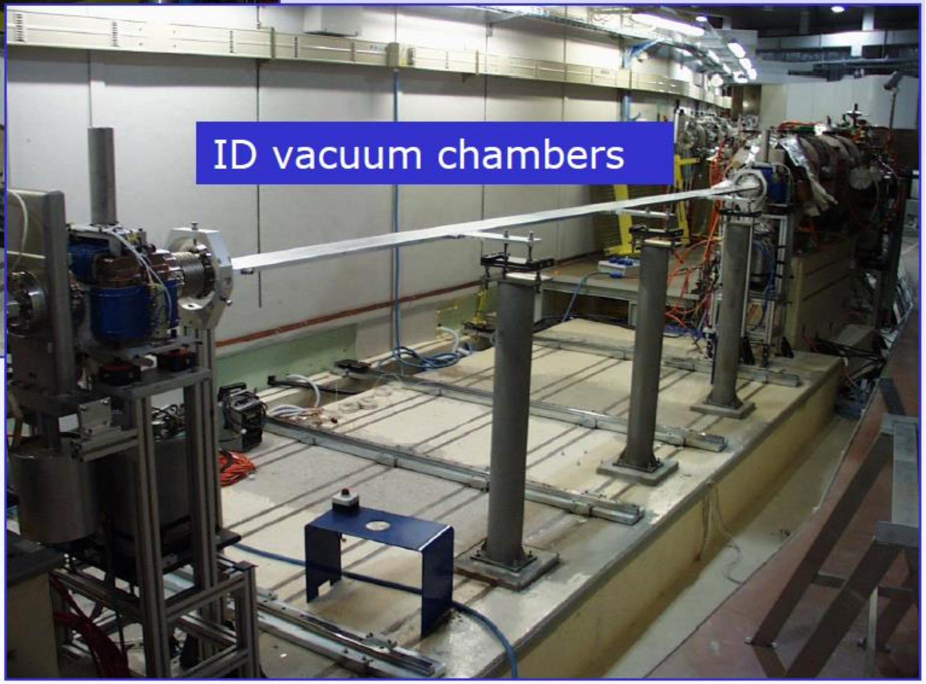
» Research work carried out here has looked at the impact of using an alloy wire as opposed to twisted wires



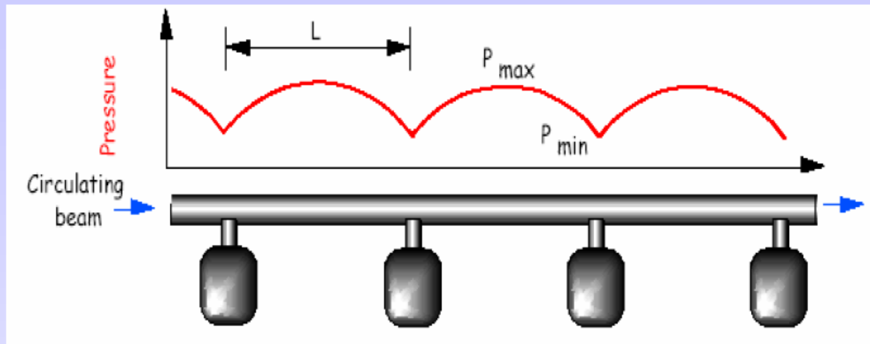
Getter Pumps

Synchrotron Light source:
vacuum chambers for
Insertion Devices

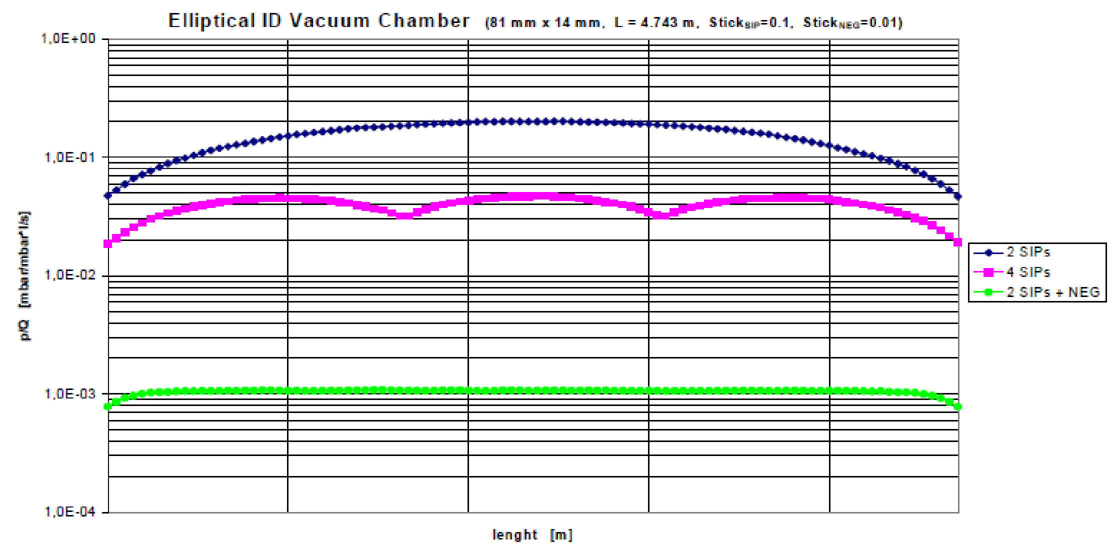


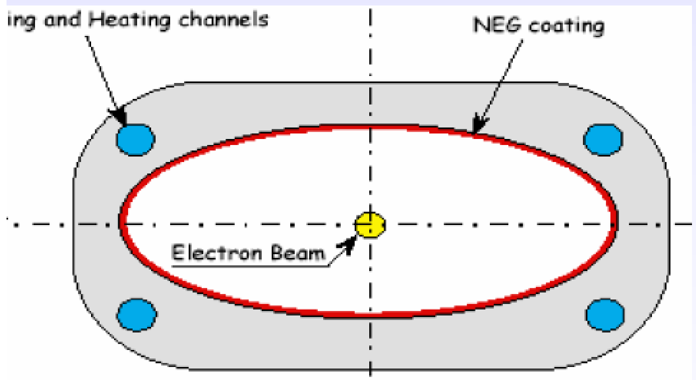


Getter Pumps



1) Discrete pump system





3) Distributed pump system (LHC)

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Choosing a pump

- What pressure are you trying to achieve?
- What is the anticipated gas load?

High $\Longrightarrow$ Gas ejection pump

Low $\Longrightarrow$ Gas capture pump

What types of gas are you pumping?

Questions

- Which of the pumps you've heard about today is the most commonly used on an accelerator – why?

- What are the main limitations of a mechanical pump – e.g. turbomolecular pump?

- Modern accelerators use NEG pumps more than Ti sublimation pumps – what are the advantages and disadvantages of that?

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The Production and Measurement of Vacuum

Part 2- Measurement

Aims

– To understand that it is normally not possible to measure pressure in a vacuum directly

– To understand how the pressure may be inferred from other types of measurement

– To understand that vacuum gauges may influence what is being measured

Pressure

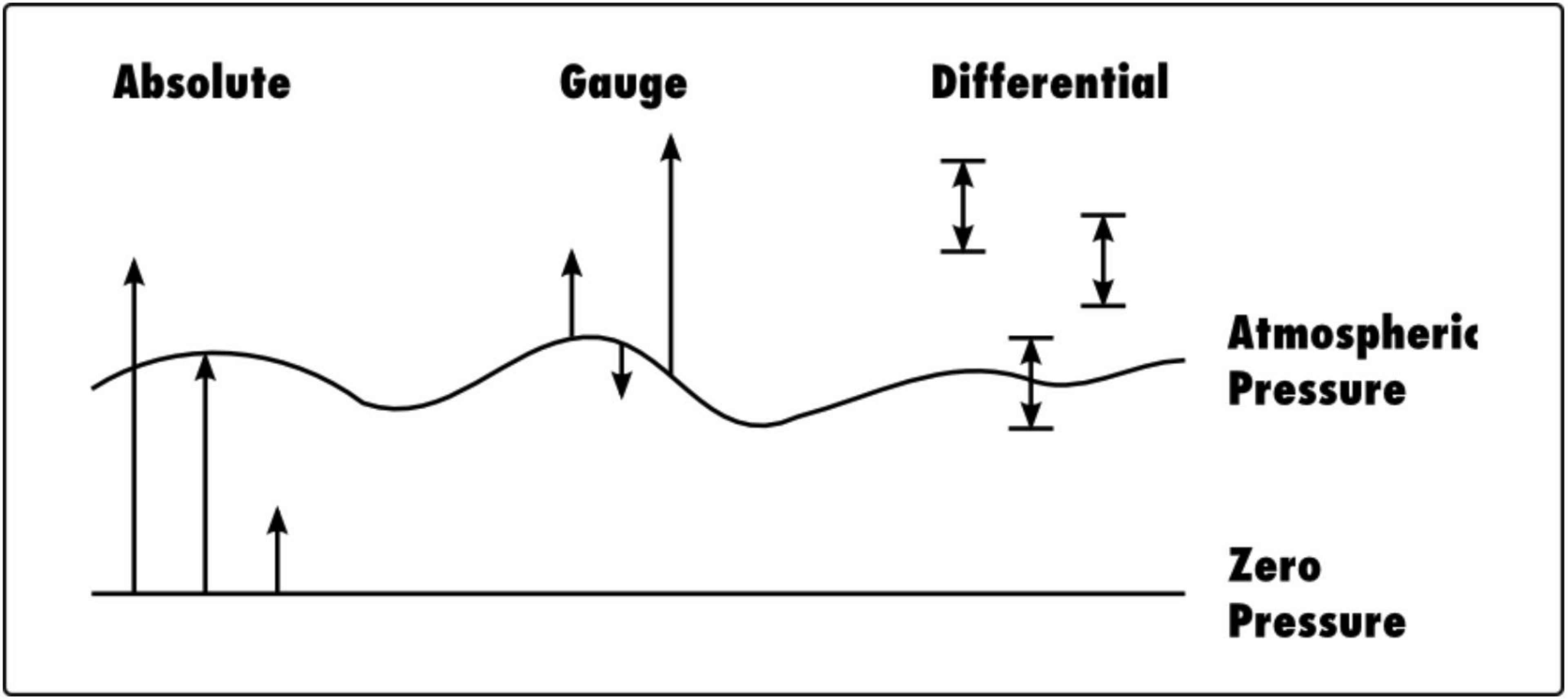
- Pressure = Force per Unit Area
- Pascal = Newton per Square Metre
  - So if we wish to measure pressure directly by measuring the force exerted on some sort of transducer, and the area of that transducer is 1 cm^2, then the force is

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

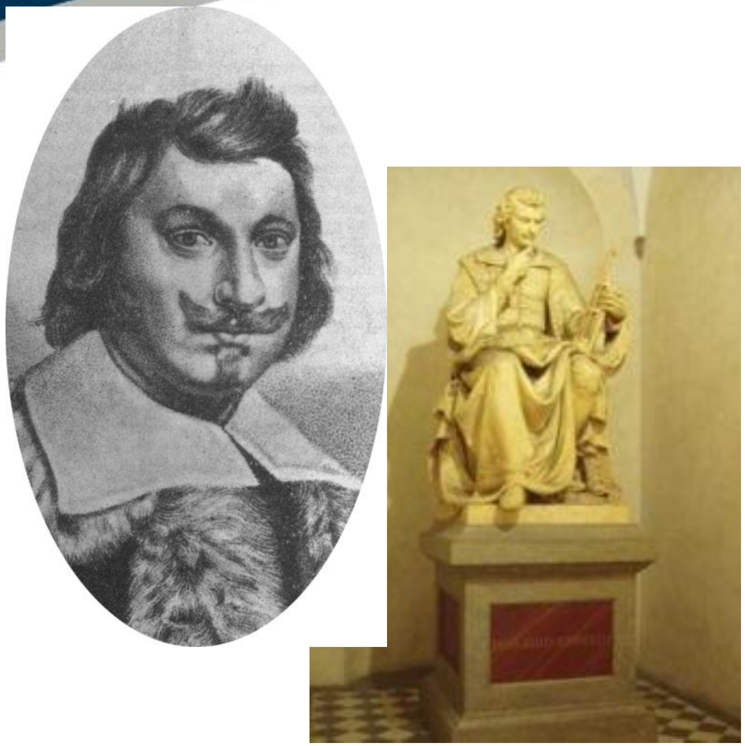
Absolute, Gauge and Differential Pressures

- When measuring pressure always be aware of what pressure you are measuring

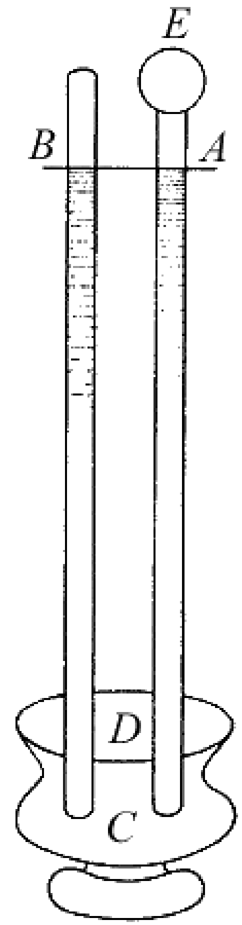
Absolute pressure = Gauge pressure + Atmospheric Pressure



The beginning



Evangelista Torricelli
(1608-1647)

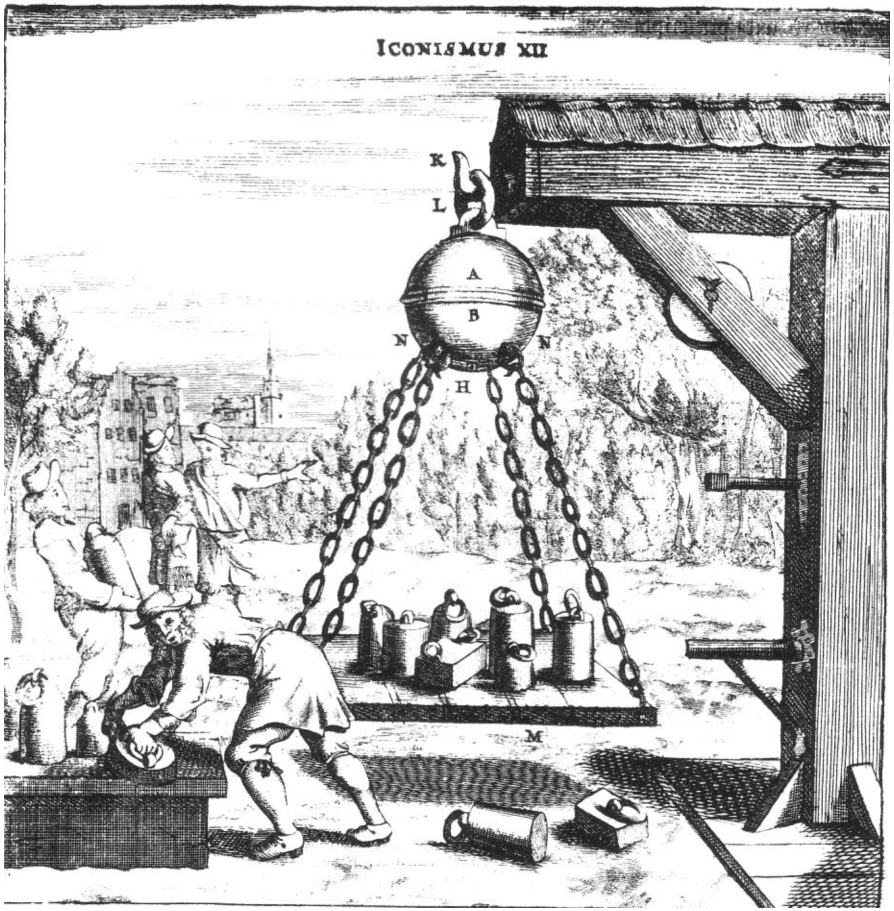


Torricelli's Barometer

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



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Magdeburg hemispheres

Guericke first demonstrated the force atmospheric pressure in 1654 for the Emperor Ferdinand III.
30 horses, in two teams of 15, were unable to pull apart the evacuated 22''-diametre hemispheres!

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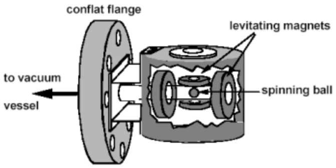
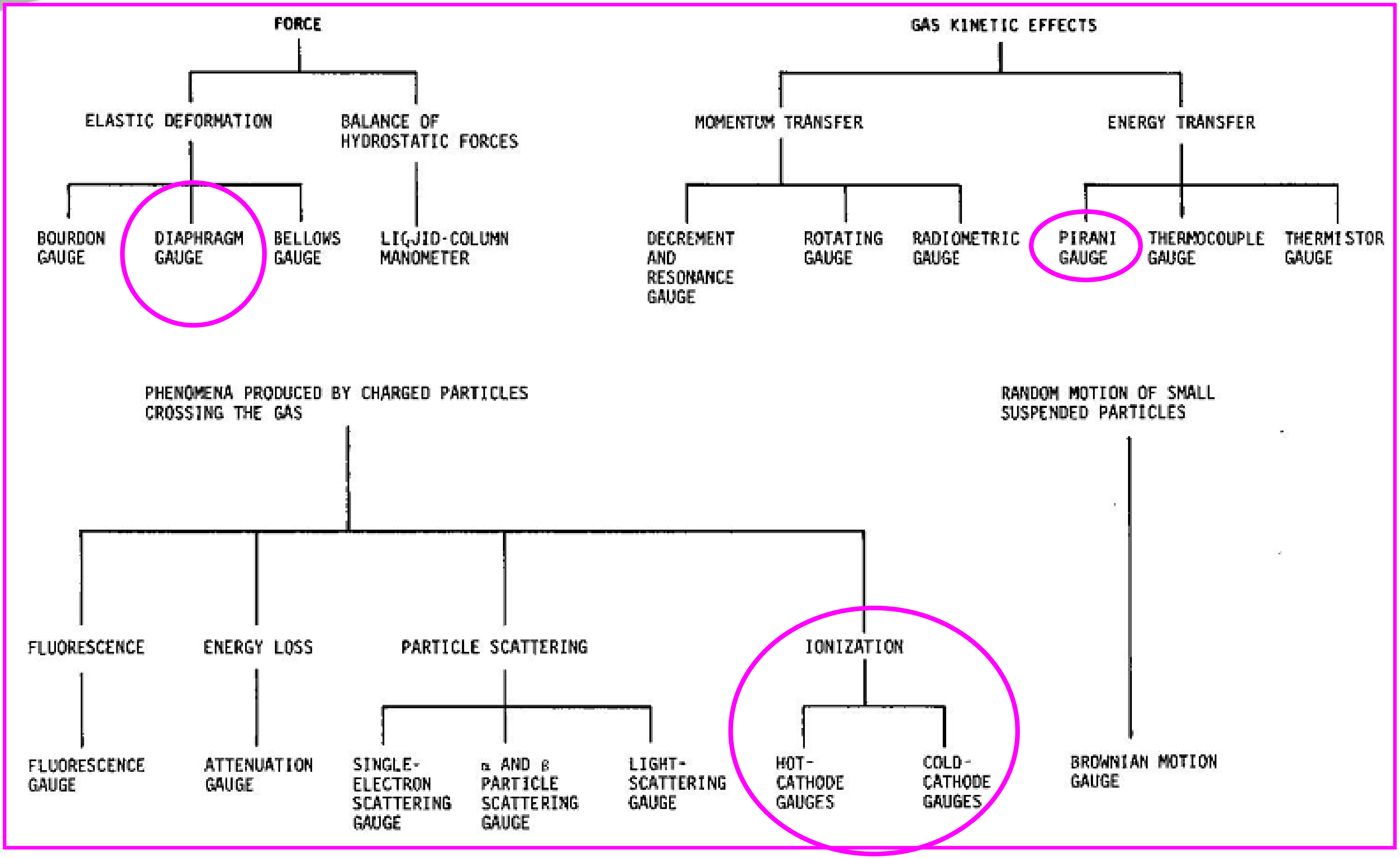
Vacuum Gauges

Commonly used gauges can be separated by the method of measurement:

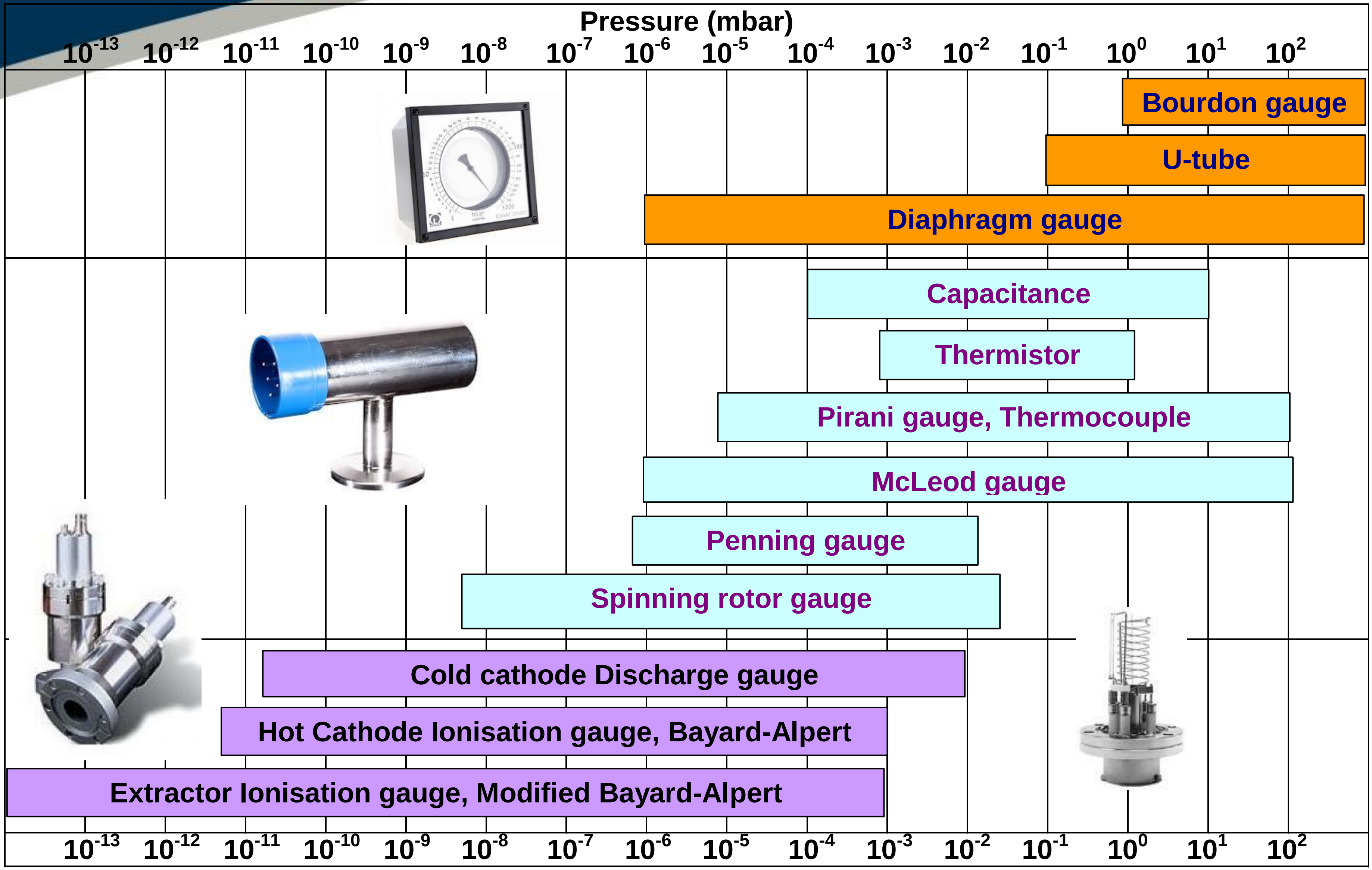
- **Deformation transducer:**
  - Bourdon tube
  - Membrane gauges
  - Capacitance manometer
- **Hydrostatic transducer (U-tube)**
- **Thermal transducer**
- **Viscosity transducer**
- **Ionisation gauges**
  - Hot cathode gauge ionisation gauge, Bayard-Alpert
  - Extractor ionisation gauge
- **Cold Cathode gauges**
  - Penning gauge
  - Inverted Magnetron gauge (SRS main gauge in recent years)



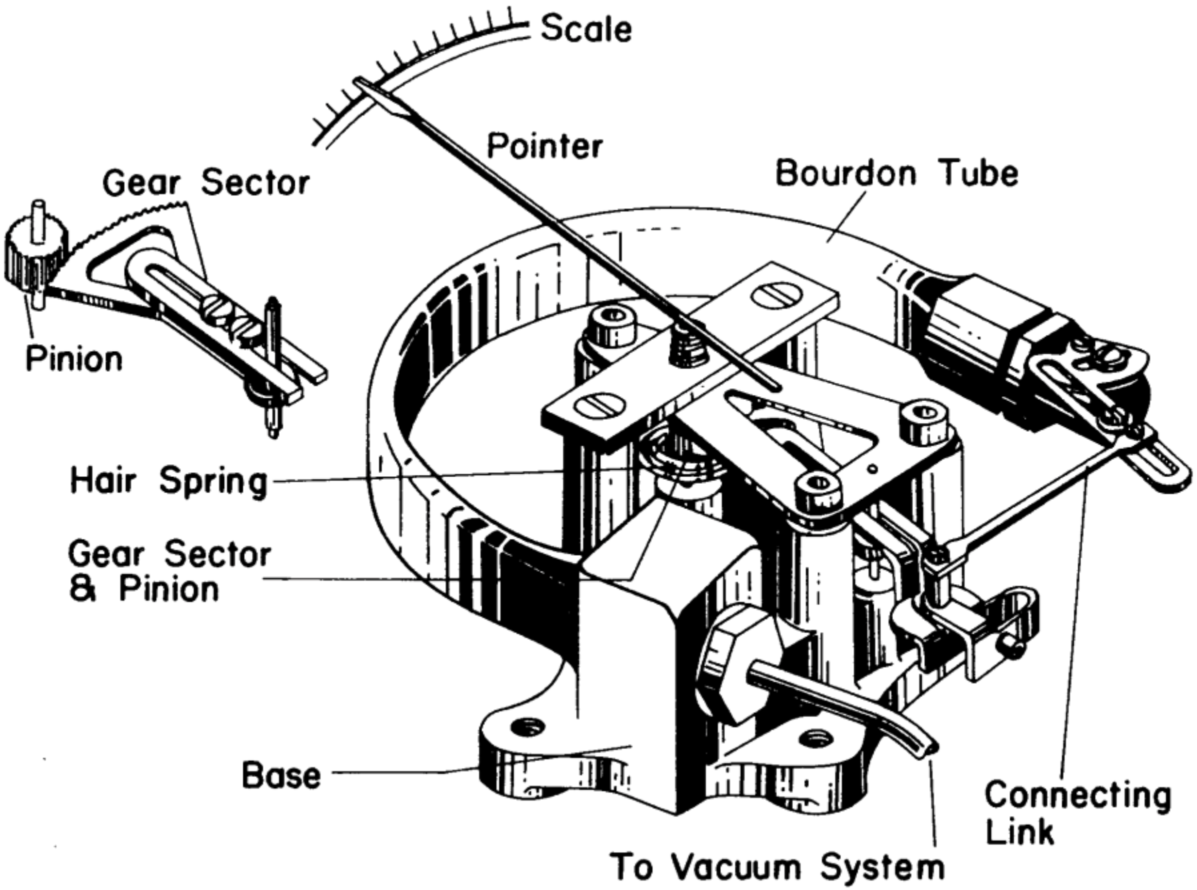
Measuring Total Pressure



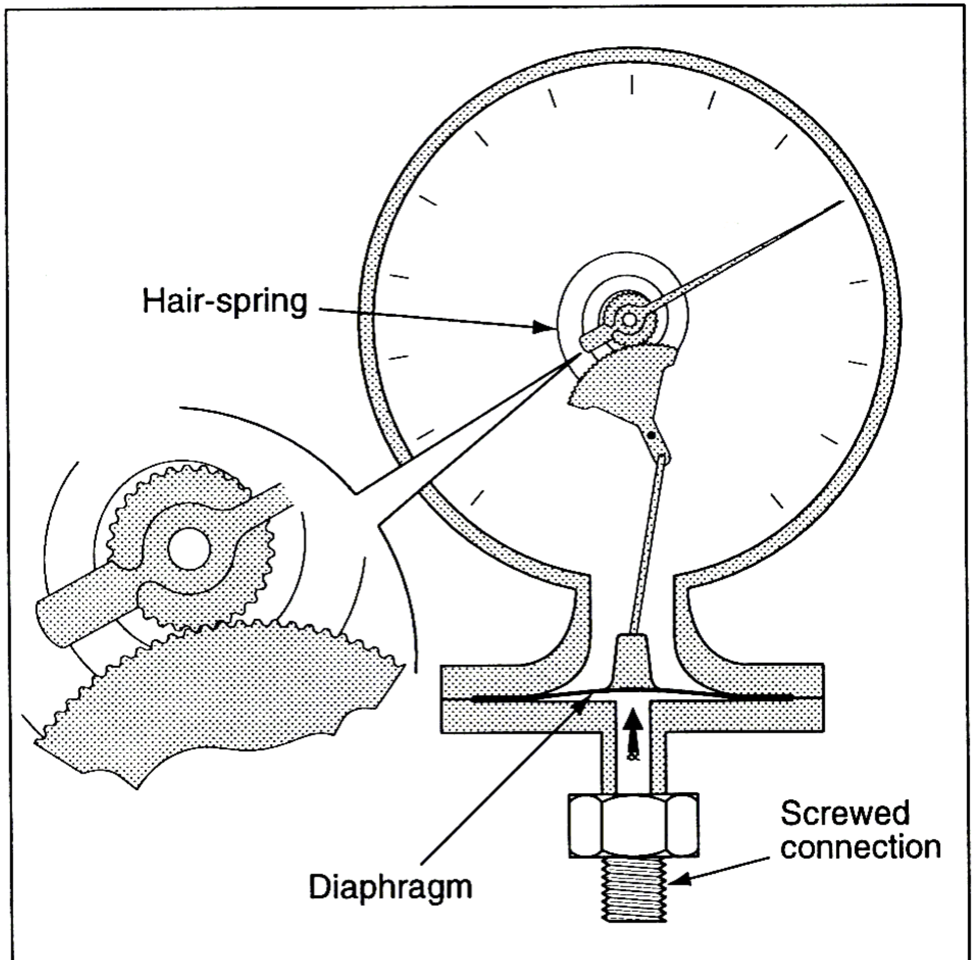
Pressure Ranges of Vacuum Gauges



Bourdon Tube Dial Gauge

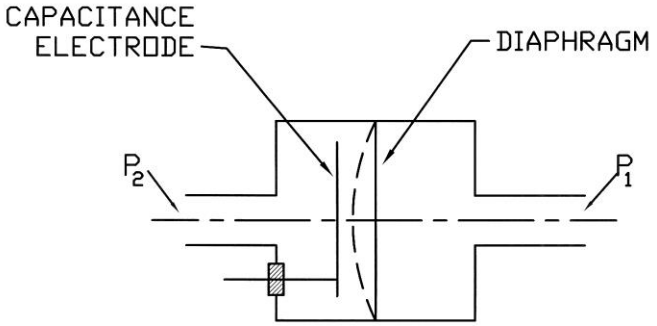


Diaphragm Dial Gauge



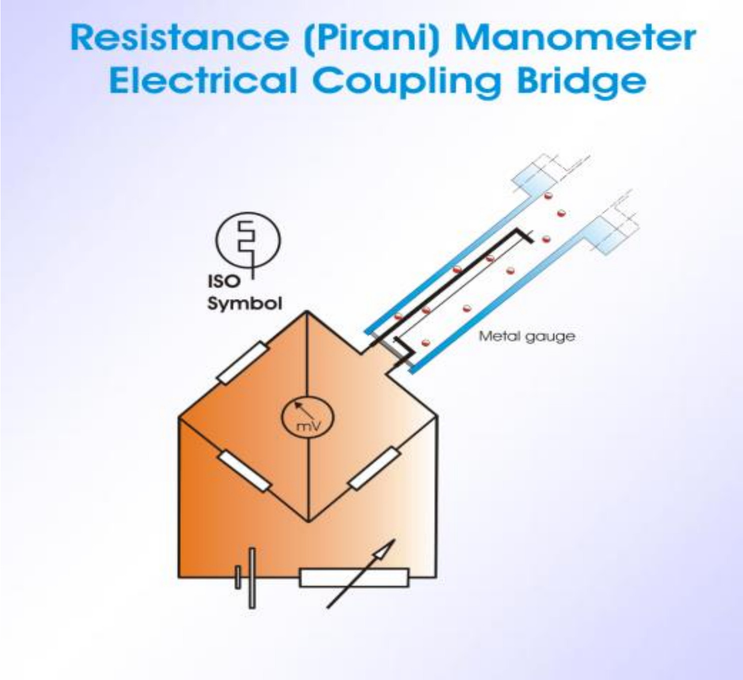
The Capacitance Manometer

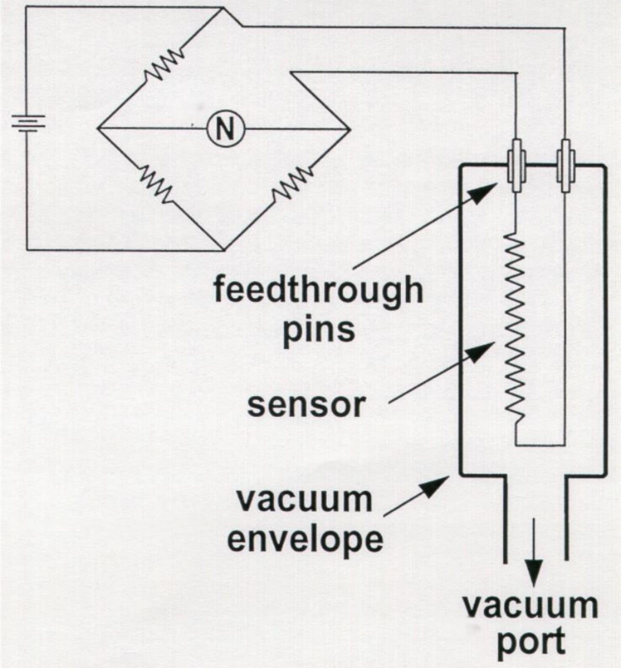
- The capacitance manometer is a form of diaphragm gauge where the diaphragm forms one plate of a capacitor. P_1 can be atmosphere or a reference vacuum. As P_2 falls the diaphragm moves towards the fixed plate of the capacitor. The change in capacitance can be related to the change in pressure.
- The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



Pirani Gauge

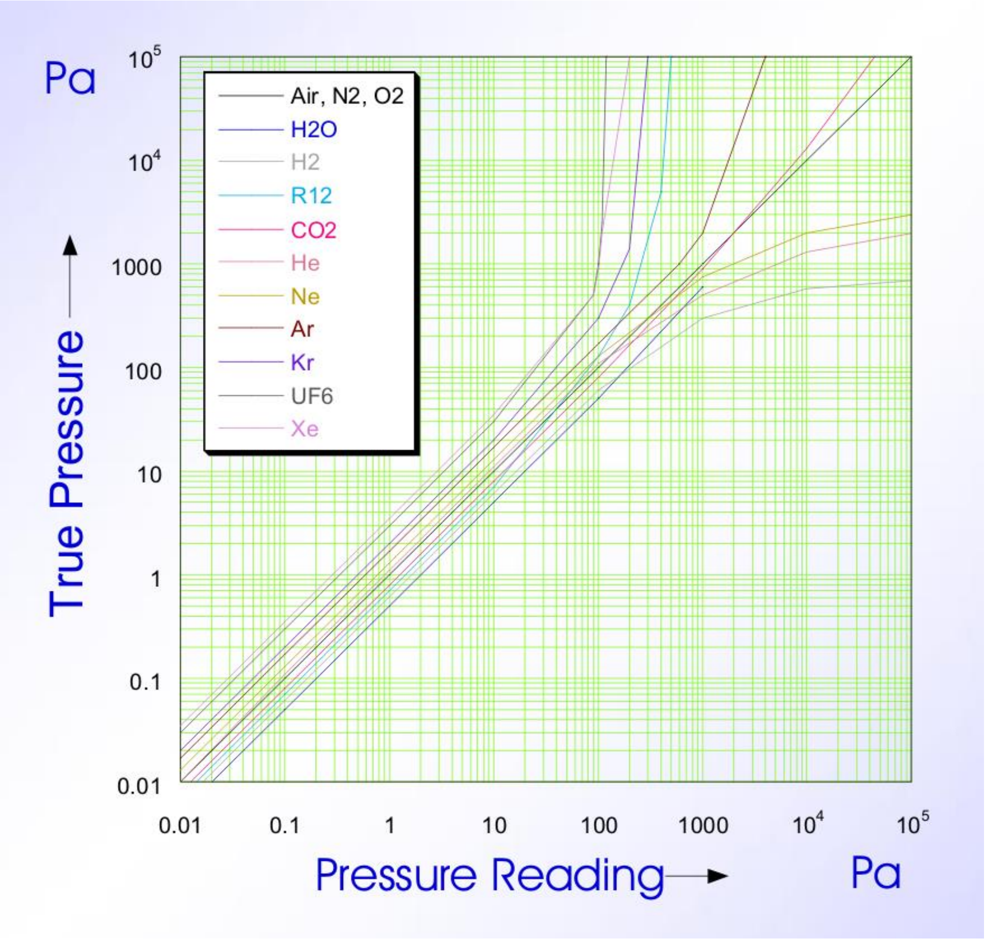
- The Pirani gauge operates at a pressure where conduction is predominant.
- In each case a Wheatstone bridge circuit is used as the indicating method. This circuit both heats the wire and measures its resistance (therefore temperature)
- The sensitivity is both pressure and gas species dependent, so calibration is essential.
- Pirani gauges operate between 100 mbar and 10^{-3} mbar.





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 the dominant factor.
- 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%



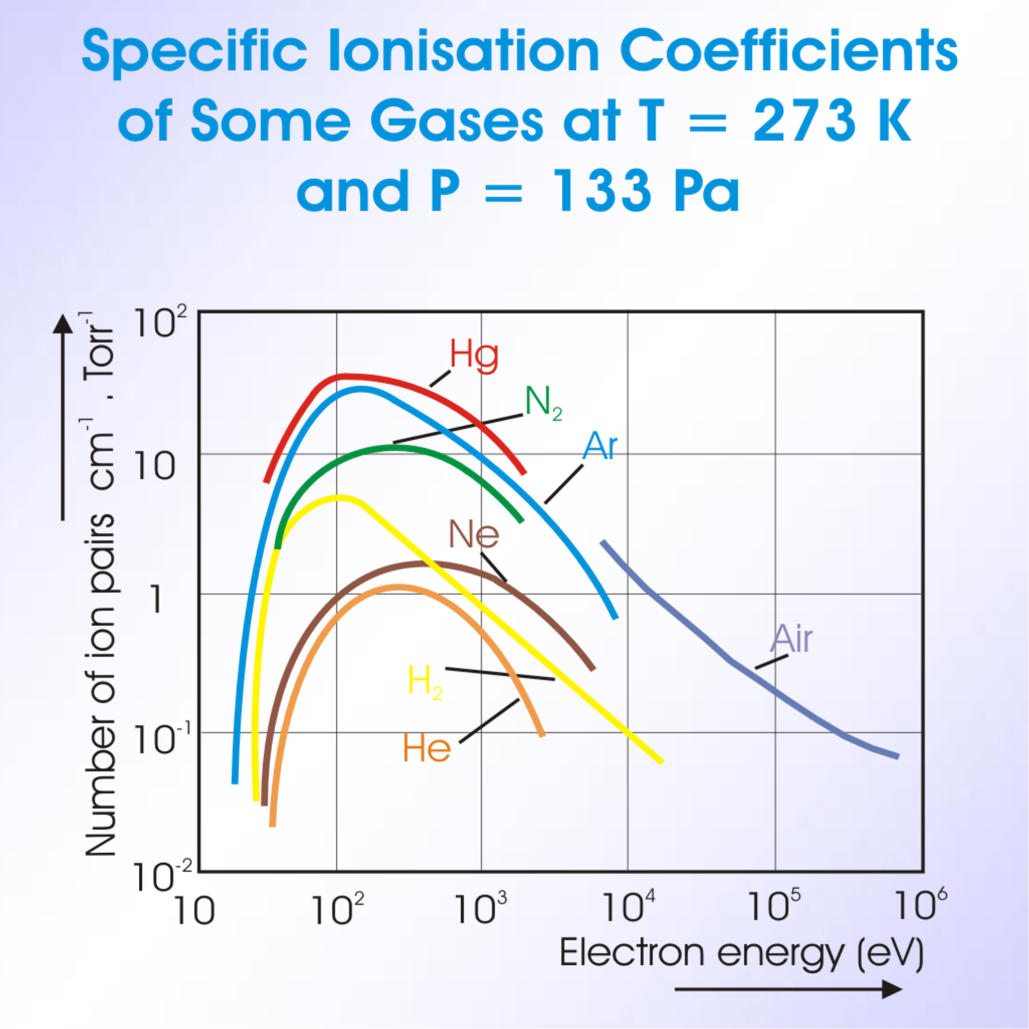
Ionisation Gauges

- The most convenient method of measuring pressures below about 0.1 Pa (10^{-3} mbar) 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)

Ionisation Processes



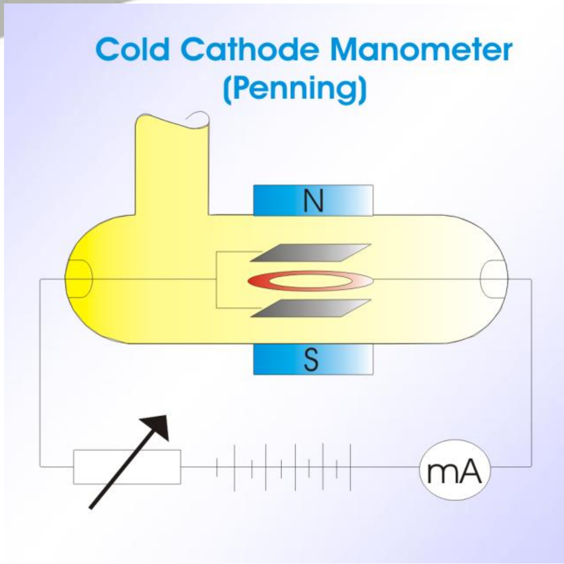
The ionisation probability for a gas atom by an electron depends not only on the species, but also on the energy of the incident electron

The ionisation probability is plotted for a number of common gases

The Cold Cathode Ionisation Gauge

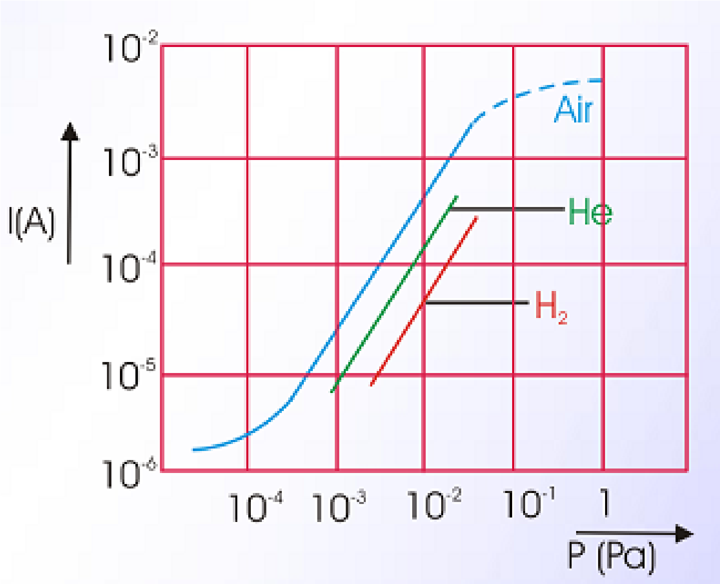
- An important class of gauge in the medium to high vacuum ranges is based on a cold gas discharge in crossed electric and magnetic fields. In such discharges, free electrons are accelerated by the electric field and are trapped by the magnetic field so that they have very long path lengths – much longer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

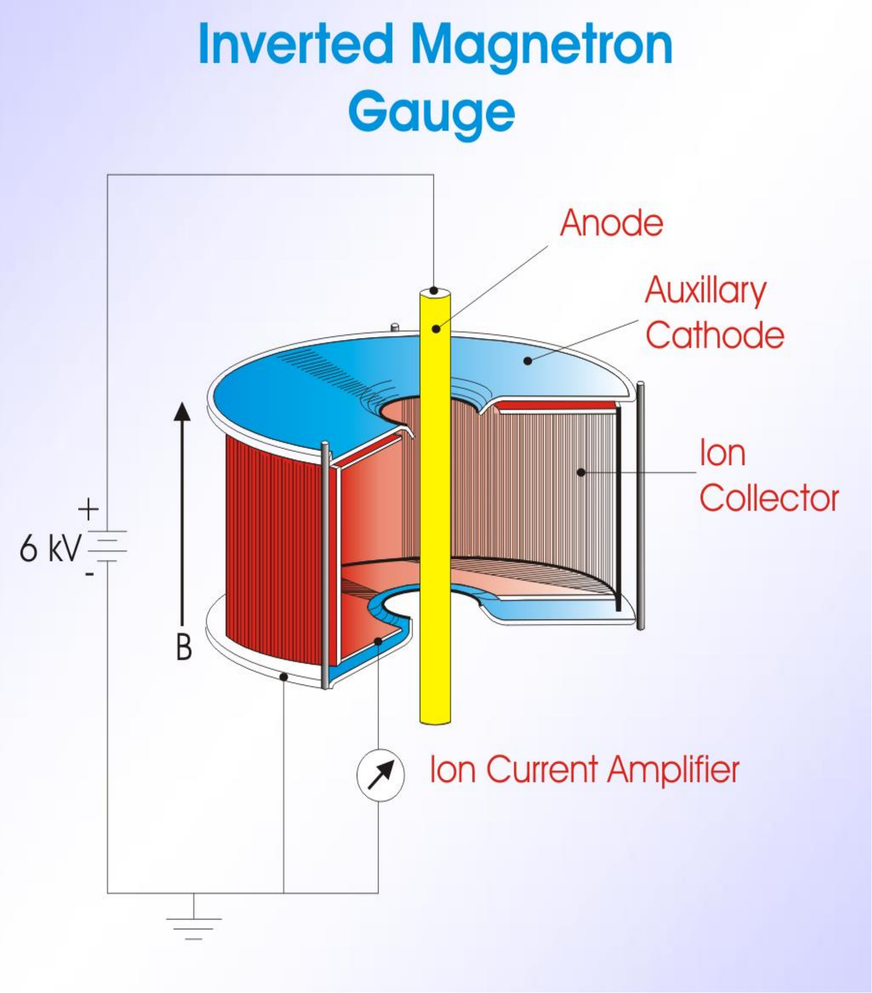
Ions are collected on the ring anode



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



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

Penning & Inverted Magnetron Gauge

- Advantages
  - No hot filaments
  - Robust & Reliable
  - IMG can operate down to 10^{-11} mbar range

- Disadvantages
  - Ion current & pressure not linearly related
  - Can be difficult to ignite a discharge to ionise gas
  - Less accurate and reproducible compared to hot cathode gauges
  - Indicated pressure may be lower than reality due to the gauge having a nominal pumping speed (up to 5 l/s)

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 need for accurate pressure measurement is not too critical

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.

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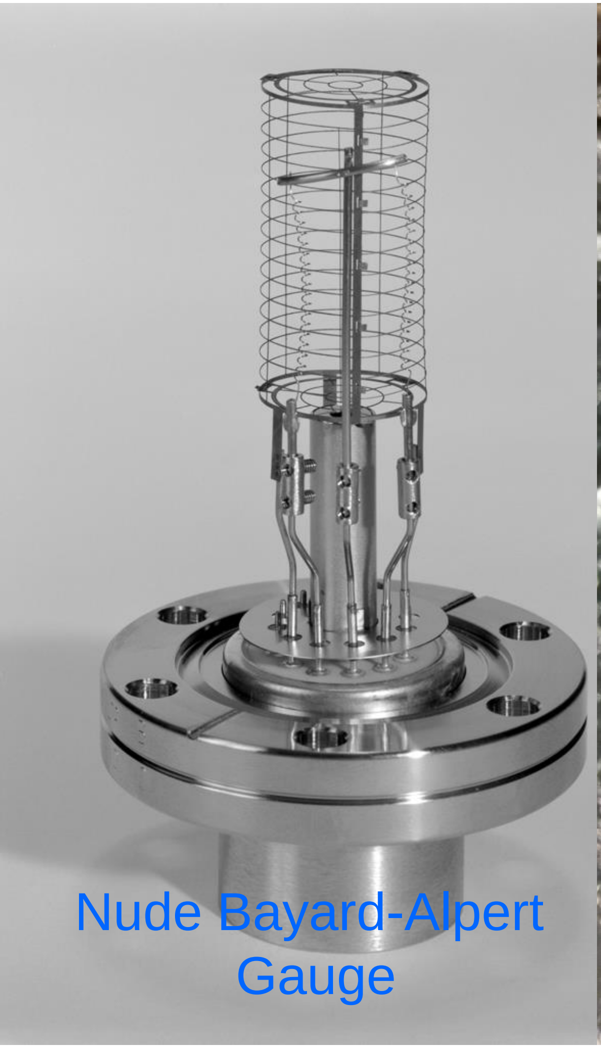
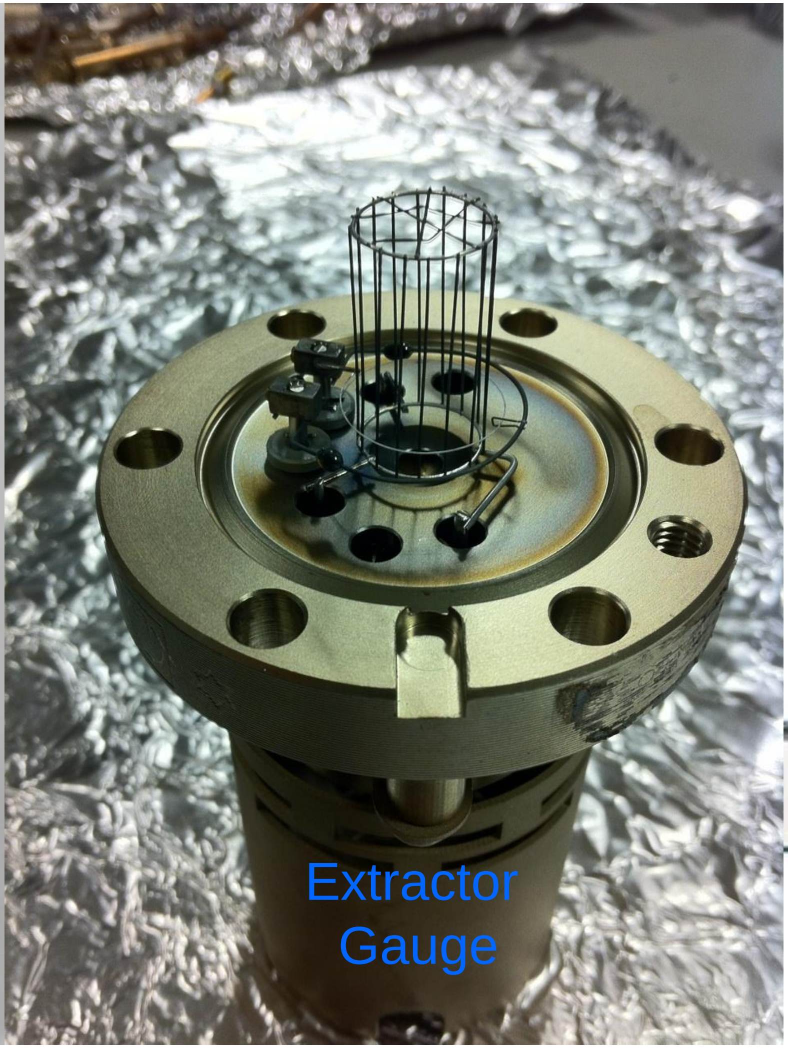
Hot Cathode Ionisation Gauges



Nude Bayard-Alpert Gauge



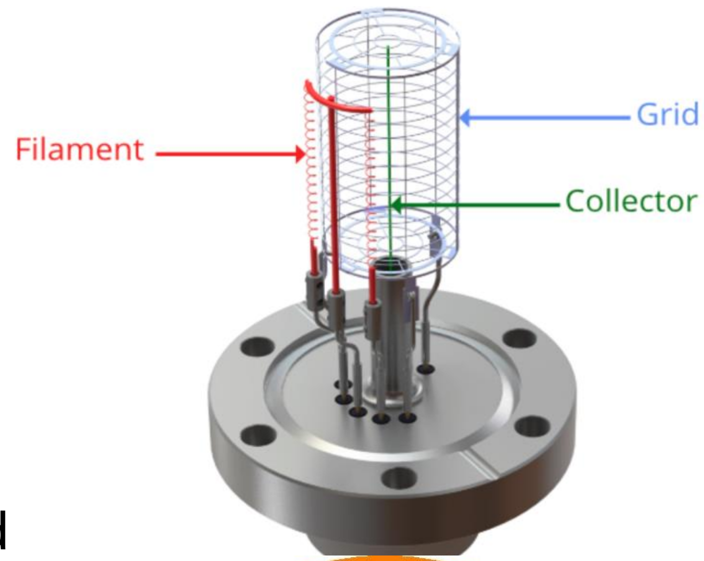
Extractor Gauge

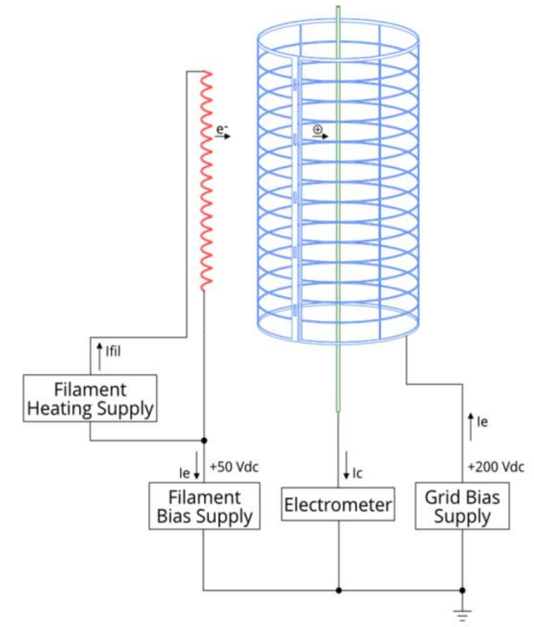
AxTran Gauge

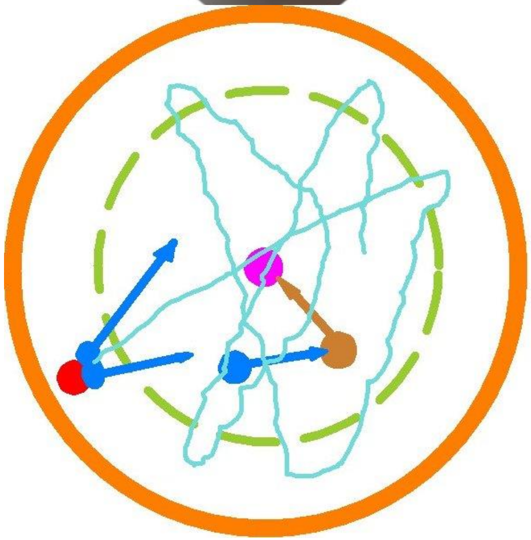
Hot Cathode Ionisation Gauges

- 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.

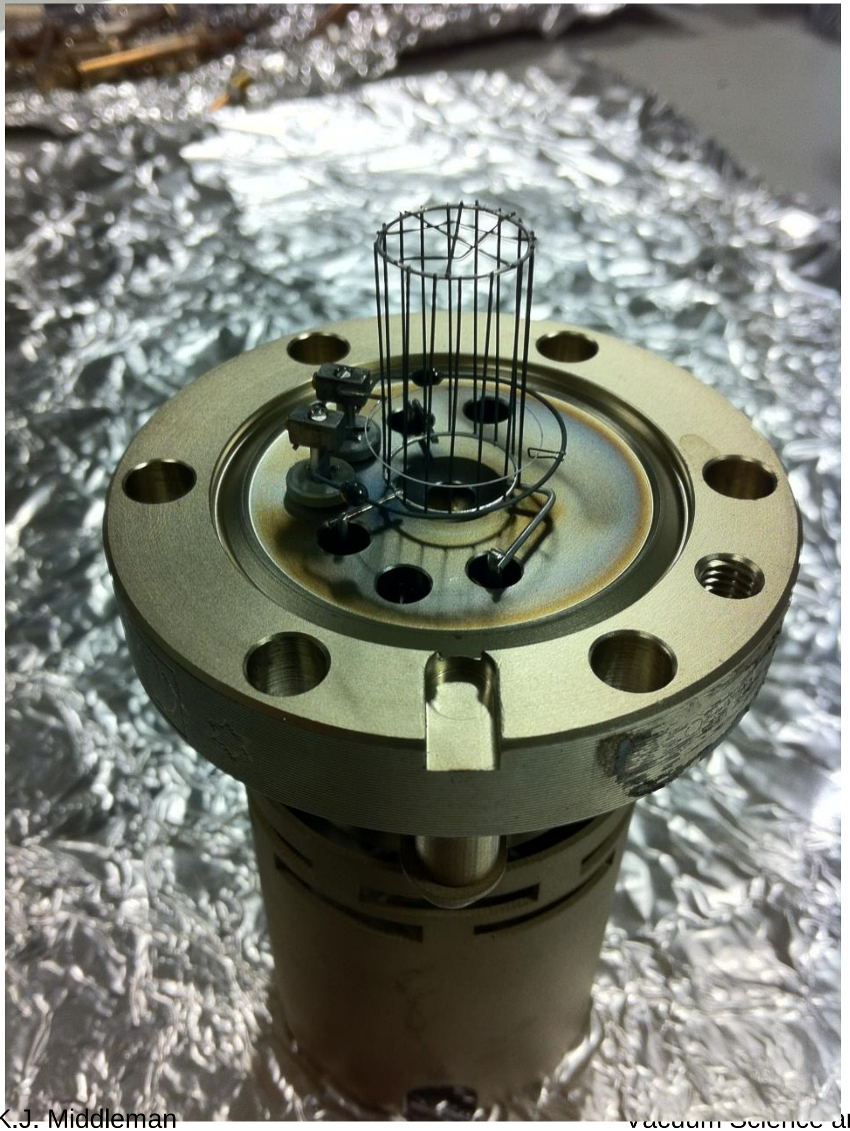
- As they travel, they generate ions from the gas molecules by impact. These ions are collected on a very thin wire, axial collector







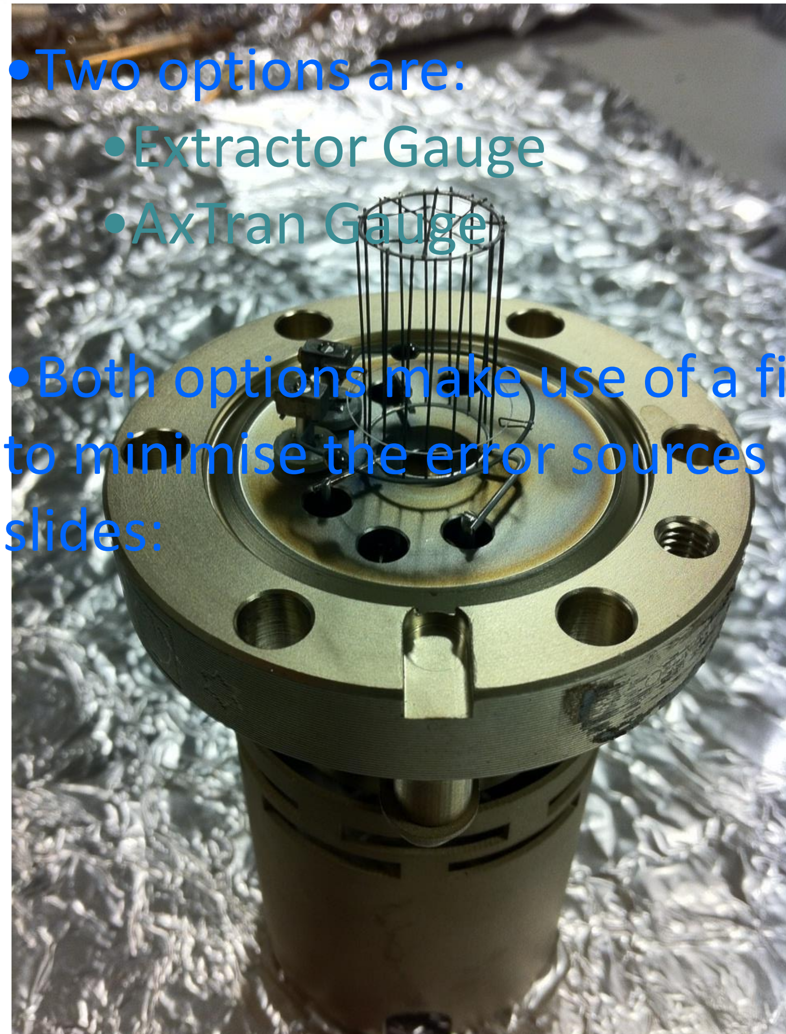
Hot Cathode Ionisation Gauges

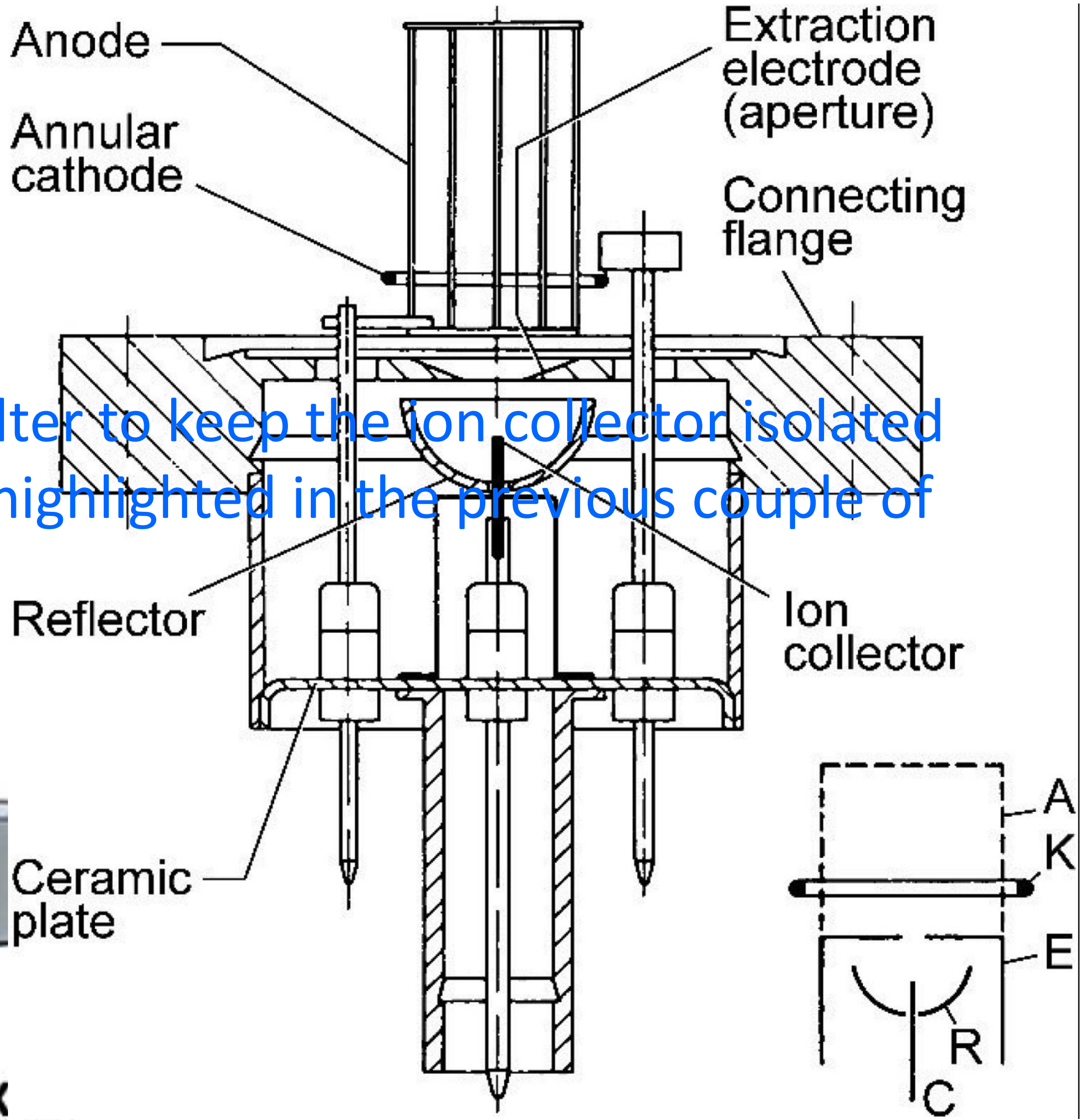


Hot cathode gauges – below 10^{-10} mbar

- Two options are:
  - Extractor Gauge
  - AxTran Gauge

- Both options make use of a filter to keep the ion collector isolated to minimise the error sources highlighted in the previous couple of slides:





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 $mbar^{-1}$

The above is often simplified such that:

$$P = \frac{I_C}{I_e * S}$$

where I_C is the ion current,

I_e is the emission current,

S is the gauge sensitivity – a constant that indicates how well a gauge creates ions

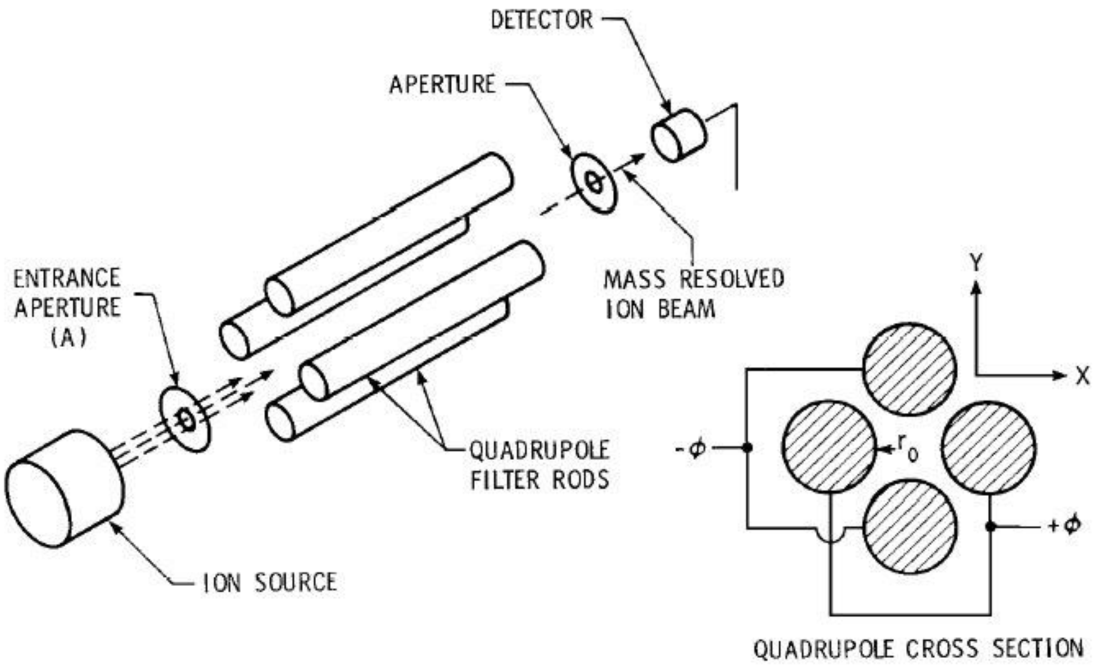
Vacuum – What's in it?

- Although it is important to know the pressure in a vacuum system i.e. the 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")



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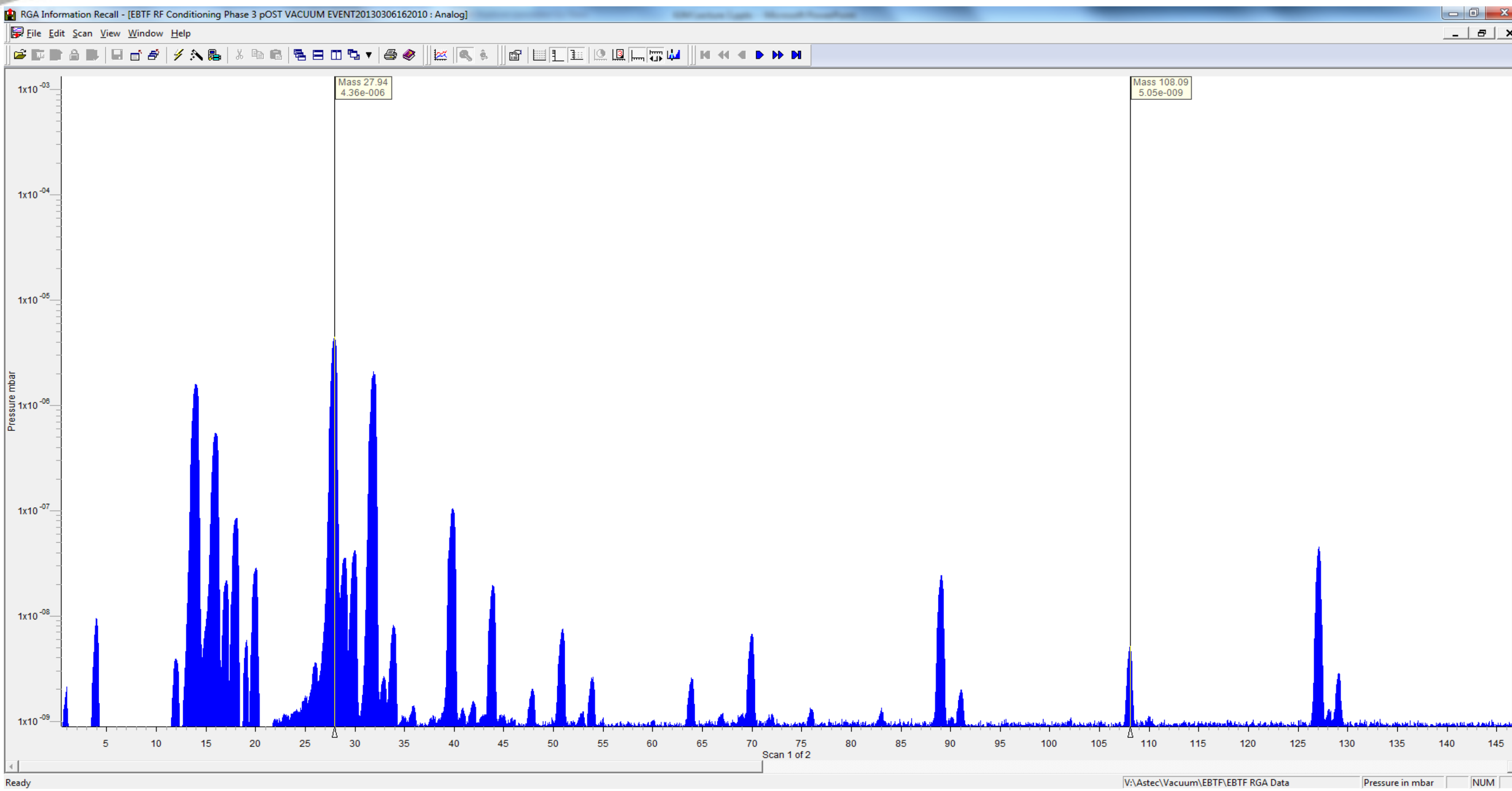
Residual Gas Analysis

Residual Gas Analysis



Peak positions give a characteristic spectrum for a given molecular species

Peak heights give information about the amount present

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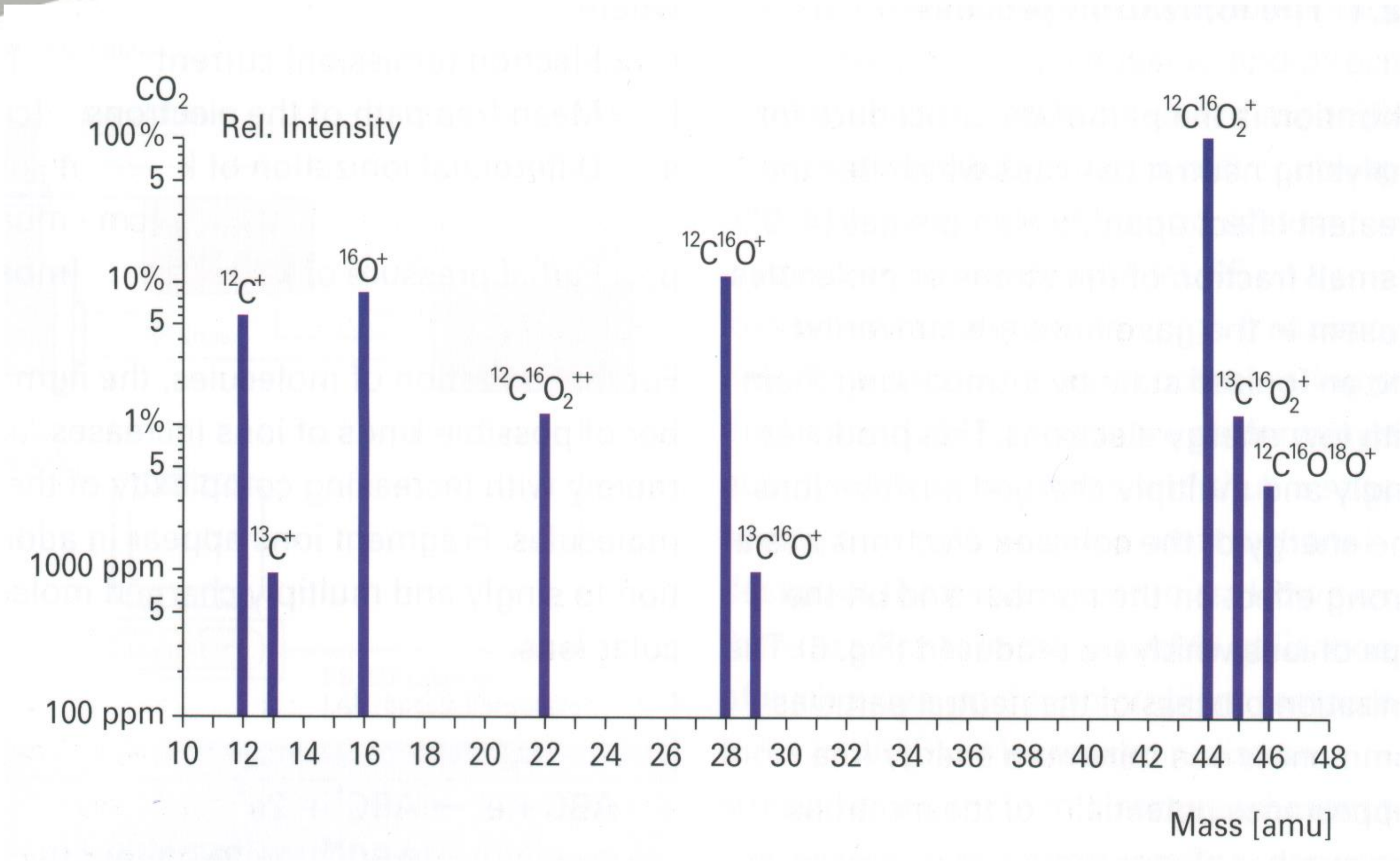
Residual Gas Analysis

- 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

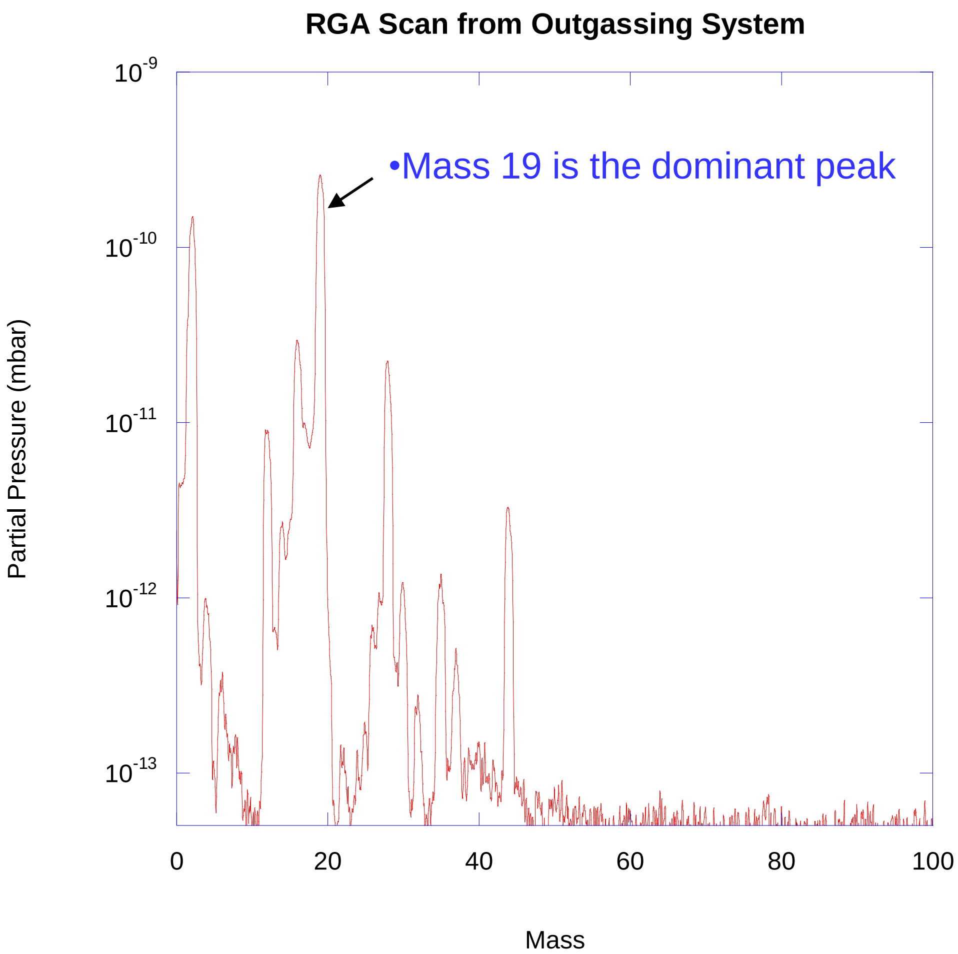
- Atomic and molecular species are identified by cracking patterns
  - Details (i.e. precise peak height ratios) vary from analyser to analyser
  - Usually tabulated for large magnetic spectrometers
  - Different species interfere
- Simple rga's are best used as monitors for changes unless the system is relatively simple and frequent in situ calibration is undertaken
- Modern systems hide this complexity inside software packages

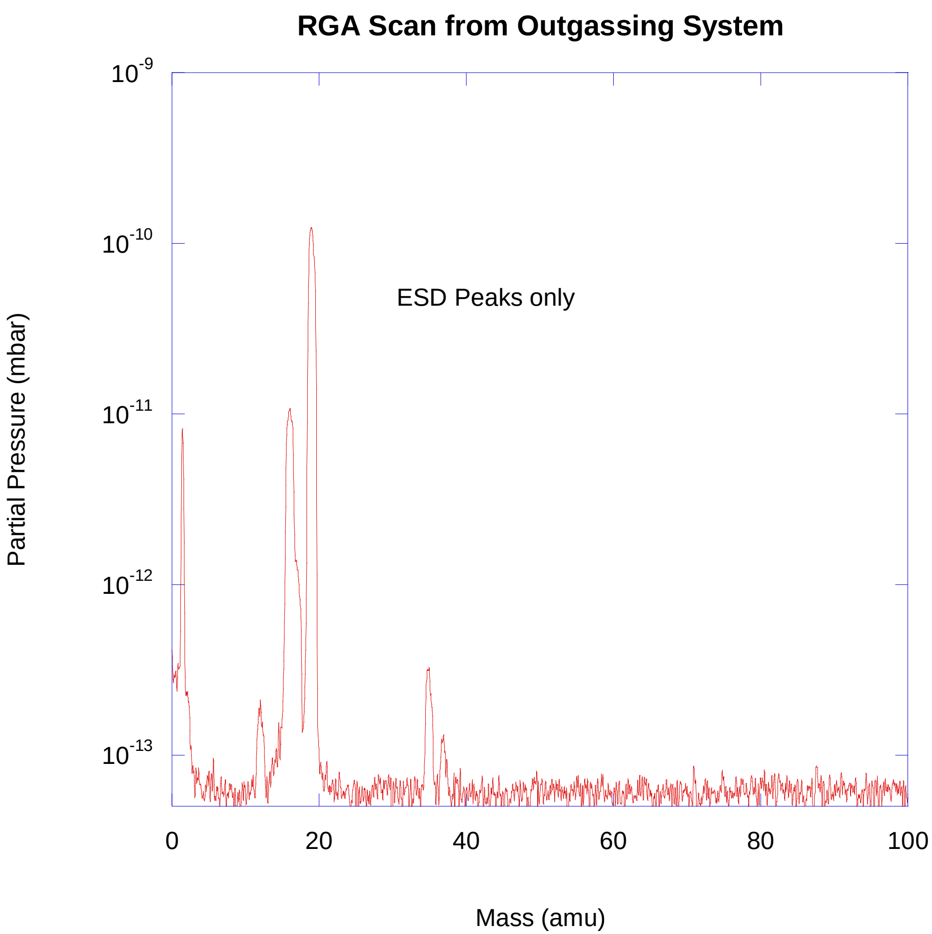
Electron Stimulated Desorption (ESD)

- Another factor to consider with RGA data at low pressure is the influence of ESD from the ion source.
- Typical ESD generated peaks include:
- H^+, O^+, F^+, $^{35}Cl^+$ and $^{37}Cl^+$
- If unaccounted for it can lead to false conclusions in interpretation of RGA data.
- This is particularly important when considering the influence of Oxygen containing species when activating GaAs photocathodes. These species are considered a contaminant and can ‘kill’ the QE of a GaAs surface.
- Suggestions are that partial pressures of < 10^{-14} mbar for such species is required.

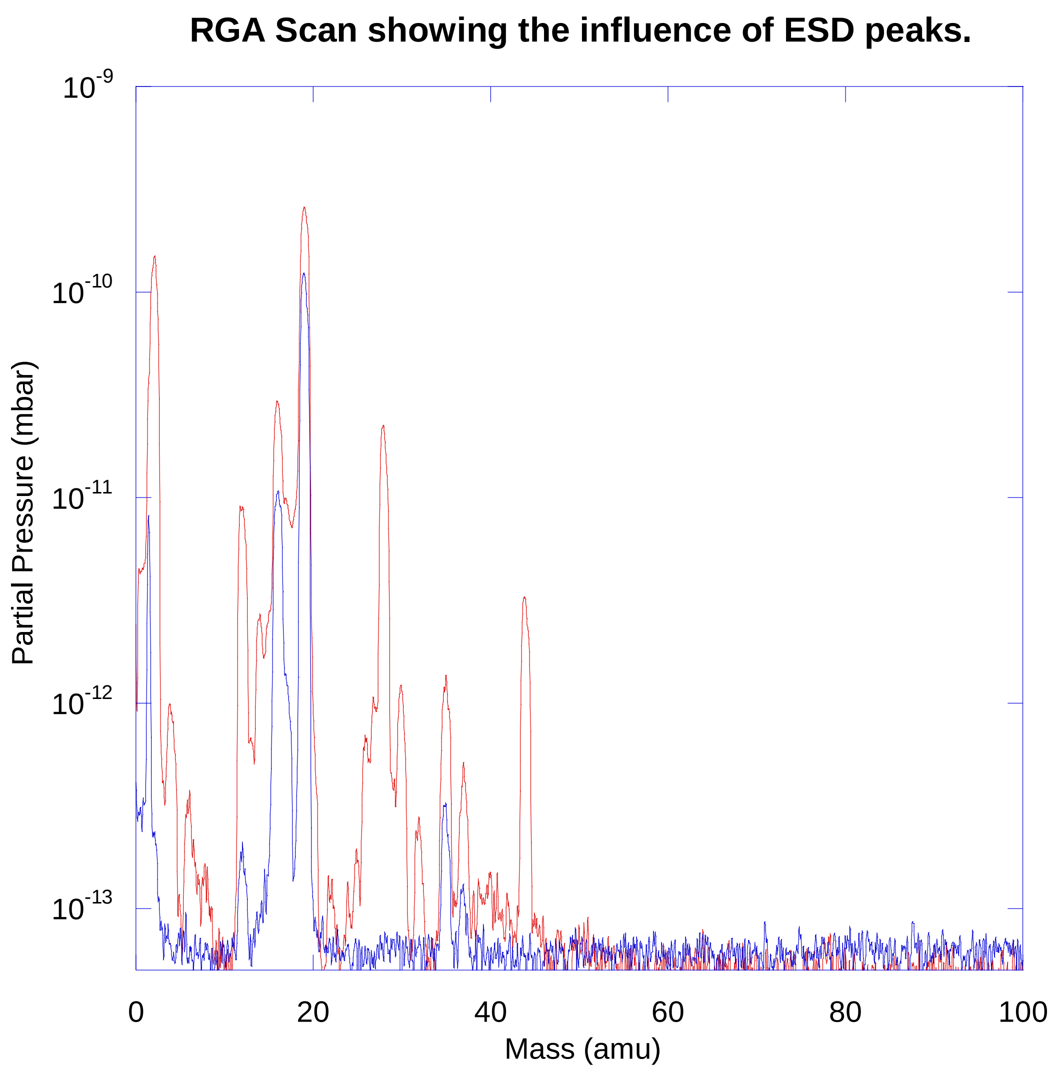
Influence of ESD Peaks in RGA Data

•Gas phase and ESD species have different energies which allow separation between the two.





Influence of ESD Peaks in RGA Data



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Summary

- In choosing a vacuum gauge, be aware of -
- The dependence of the measurement on gas species
- The dependence of the measurement on the pressure
- The role of spurious effects
- The effect of the gauge on the number density and gas specious in the measurement region.

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Further resources and reading

- Modern Vacuum Practice (3rd Edn), N Harris, (2005). ISBN 0955150116
- A User's Guide to Vacuum Technology (3rd Edn), J F O'Hanlon, Wiley-Interscience, 2003. ISBN 0-471-27052-0
- Basic Vacuum Technology (2nd Edn), A Chambers, R K Fitch, B S Halliday, IoP Publishing, 1998, ISBN 0-7503-0495-2
- Modern Vacuum Physics, A Chambers, Chapman & Hall/CRC, 2004, ISBN 0-8493-2438-6
- Handbook of Vacuum Technology, Ed. K Jousten , Wiley- VCH, 2008. ISBN 3527407235
- F. Sharipov, Rarefied Gas Dynamics. Fundamentals for Research and Practice. Wiley- VCH, 2016. ISBN 978-3-527-41326-3
- Vacuum Science and Technology, Pioneers of the 20th Century, AIP, 1994, ISBN 1-56396-248-9
- Vacuum Science World: an educational and information portal for all things relating to vacuum science https://www.vacuumscienceworld.com/
- Manufacturers' data
- Google !