UNIT 4 :

ULTRA HIGH VACUUM INSTRUMENTATION

- In vacuum technology pressures are measured either directly (force acting on surfaces) or indirectly.

  The force measurement is at best limited to 10^{-7} N / cm². This gives a lower limit to the pressure measurement : $10^{-4} \div 10^{-5}$ Torr. In general in particle accelerators, the pressure is much lower. The direct methods are never used for the beam pipes.

- The indirect pressure measurements are obtained :

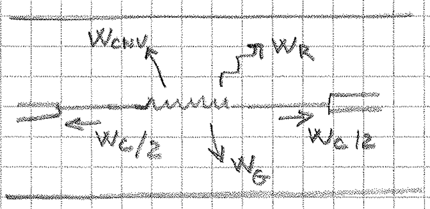
  1) by considering the thermal conductivity dependence on gas pressure (Thermal conductivity vacuum gauges),

  2) by ionizing the gas and detecting the density of ions (ionization gauges).

- In the first group of gauges, a filament is heated by ohmic effect. The current, voltage or temperature are monitored.

Filament radius: r_1

length L



There are 4 different thermal transport phenomena :

1) Thermal conduction at the end of the filament :

$$\frac{1}{2} W_C = \pi r_1^2 K_{wire} \cdot \frac{dT}{dt}$$

2) Thermal irradiation

$$W_R = \varepsilon_1 (2\pi r_1 L) \sigma (T_1^4 - T_2^4) \quad \text{Stefan-Boltzmann}$$

3) Gas convention for P > 10 Torr ; do not depend on pressure.

4) Thermal conduction in the gas.

$$W_G = F \cdot P$$

where F is a function of the gas characteristics and, in first approximation, independent of pressure

Comparing the 4 heat transport mechanisms, it comes out that:

- for low pressure (low 10^{-3} Torr) the thermal transport is dominated by pressure independent processes (radiation + solid conduction)
- for high pressure (> 10 Torr) the gas convection dominates the thermal balance ⇒ pressure independent

Therefore the thermal conductivity gauge gives significant reading in the range:

$$\sim 10^{-3} < P < \sim 10 \text{ Torr}$$

The signal from the filament can be obtained in 2 different ways:

1) Measuring the resistance or dissipated power. The temperature of the filament is maintained constant and the required heating power is measured. Reversely the heating current is kept constant and the resistivity variation is measured.

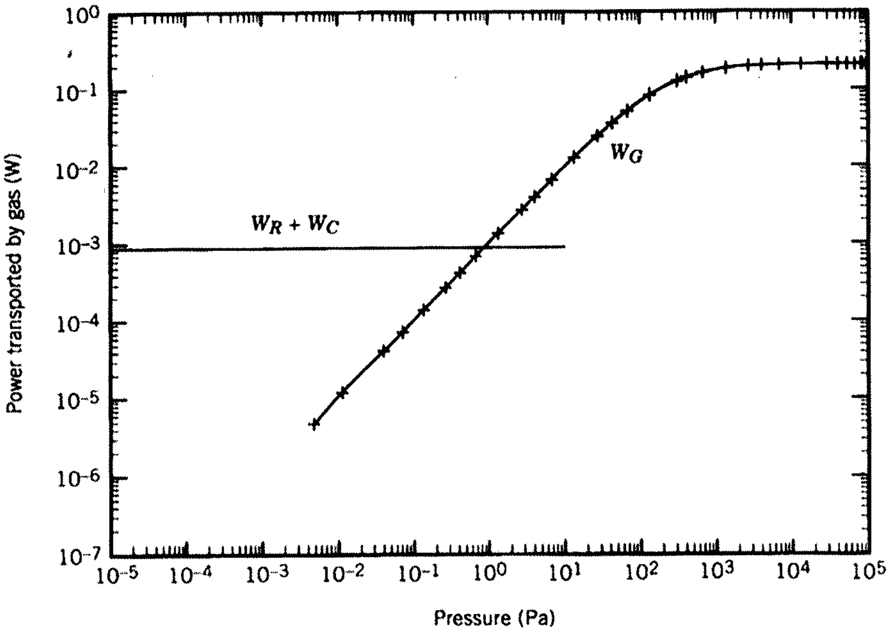
⇒ PIRANI GAUGES

The filament is part of a Wheatstone bridge, which increases sensitivity.

2) The temperature of the filament is measured by a thermocouple

⇒ THERMOCOUPLE GAUGES

Thermal conductivity gauges are used in particle accelerators to measure the first part of the pumpdown process and the pressure on mechanical pumps.



Power transported by gas (W)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$W_R + W_C$
W_G
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Pressure (Pa)

4.1 IONIZATION GAUGES

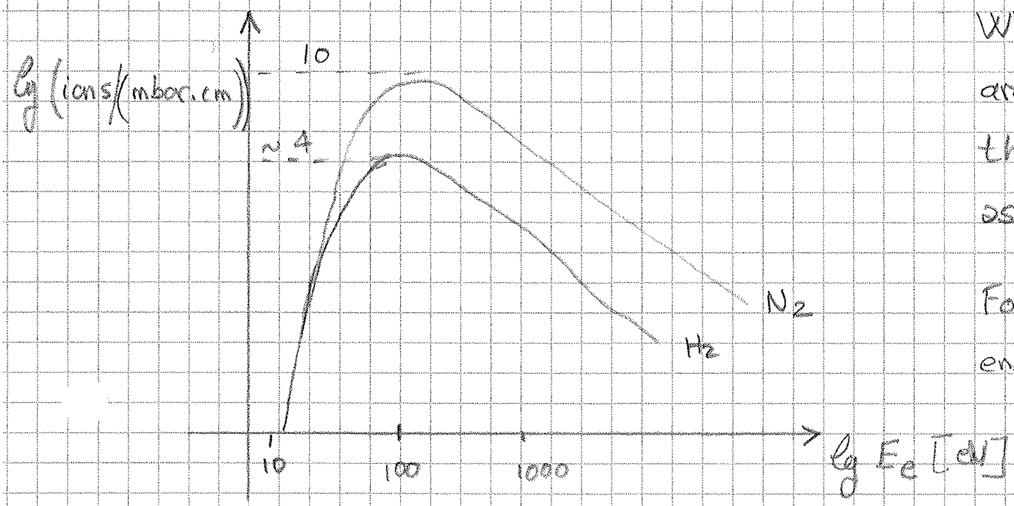
The pressure is proportional to the gas density n:

$$PV = N k_B T \rightarrow P = n k_B T$$

The simplest way to measure n at low pressure is ionize the gas molecules by electron impact and collect the ions.

Electrons are emitted by a hot filament (thermoionic current) or extracted from a Penning discharge. The first family of gauges is called hot cathode gauges, the second cold cathode (or Penning) gauges.

The ionization process is characterized by the ionization cross section, which depends on electron energy and nature of the gas.



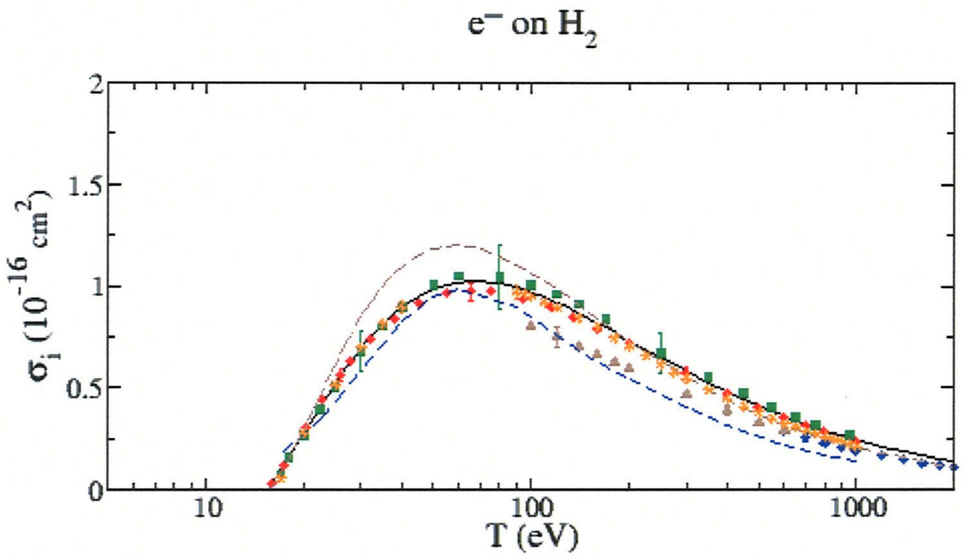
When in a vacuum system there are more than a single gas, the pressure reading is given as N_2 equivalent.

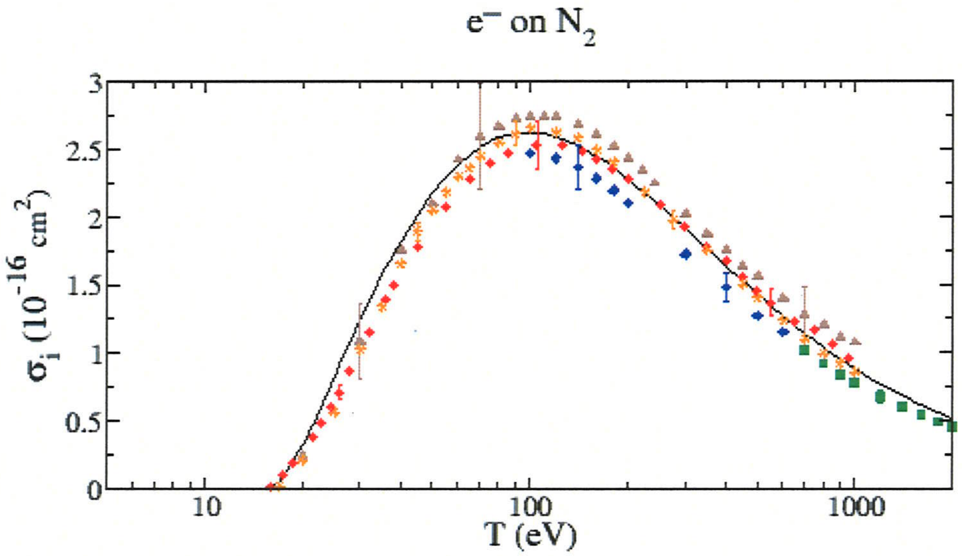
For a fixed value of electron energy, the ratio of the cross sections is constant and is independent of the gauge geometry.

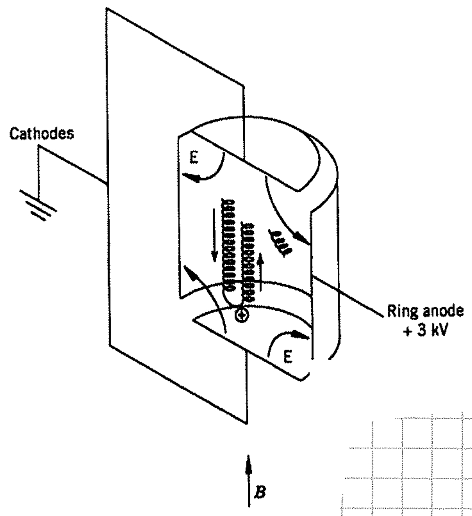
4.1.1 COLD CATHODE GAUGES

The working mechanism is similar to the one of sputter ion pumps.
A magnetic field force electron to move onto spiral paths leading to higher ionization probability. An electric field accelerates electrons and pushes the ions on a collector.

- magnetic field ~ 0,1 ÷ 0,2 T
- voltage ~ 3000 V


e⁻ on H_2
σ_i (10^{-16} cm^2)
0
0.5
1
1.5
2
10
100
1000
T (eV)

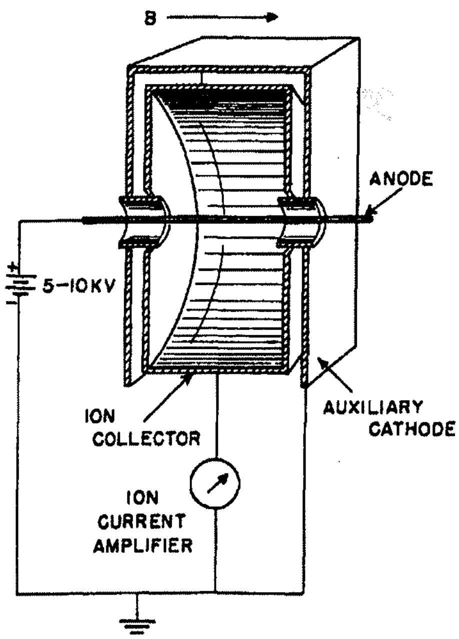

e⁻ on N_2
σ_i (10^{-16} cm^2)
0
0.5
1
1.5
2
2.5
3
10
100
1000
T (eV)



Secondary electrons produced by ions and electron impingement nourish the discharge.
The ion current is a measurement of pressure:

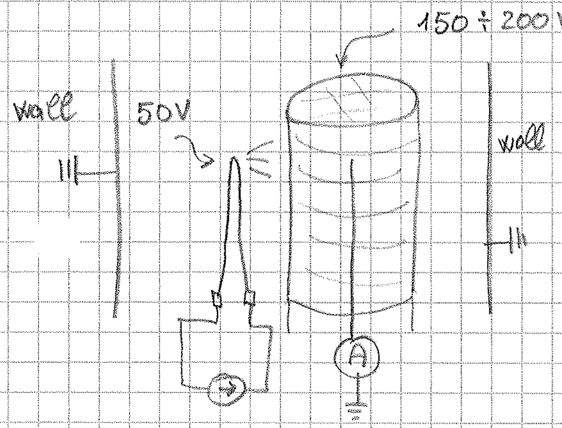
$$P \propto I_+^m \qquad 1 \leq m \leq 1,4 \quad \text{(depends on gauge design)}$$

The gauge configuration used nowadays is the inverted magnetron one.



Inverted magnetron gauges are used for pressure measurement in the range $10^{-4} \div 10^{-10}$ Torr.
Most of the gauges in particle accelerators are inverted magnetron gauges. They are extensively employed for interlock purpose for the protection of delicate components (for example kickers and RF cavities).

4.1.2 HOT CATHODE GAUGES (BAYARD-ALPERT GAUGE)



The electrons are extracted from a filament by thermoionic effect and accelerated toward a very transparent grid by an electric field.

The electrons cross the grid and, once outside it, they are decelerated and return in the grid.
They continue to move back and forth until they collide with a molecule or impinge on the grid.
The ion are collected by a very thin wire placed at the centre of the grid.

- The collected current is given by:

$$I^+ = \sigma \cdot L \cdot n \cdot I^-$$

- n: gas molecule density
- I^-: electron emission current
- σ: ionization cross section
- L: the average path length of the electrons in the grid

$$I^+ = \sigma L \cdot \frac{P}{K_B T} \cdot I^- = \Sigma \cdot P \cdot I^-$$

$$\Sigma = \text{gauge sensitivity} = \frac{1}{K_B T} \cdot \sigma \cdot L$$

(σ: gas nature; L: gauge geometry)

$$I^- \sim 10^{-3} A$$
$$\Sigma \sim 10 \text{ Torr}^{-1}$$
$\Rightarrow$ For 10^{-11} Torr $I^+ = 10^{-13} A$!

Typical values

$$I^- = 4 \times 10^{-3}$$
$$\Sigma = 45 \text{ Torr}^{-1}$$
For 10^{-11} Torr $I^+ = 1,8 \times 10^{-12} A$

(Best Bayard-Alpert gauges)

In addition to gas ions, other sources of collector current are measured.

$$I^+ = \Sigma P I_e^- + I_R^-$$ ← residual current pressure independent

I_R →
a) photoelectron current extracted by soft X-ray.
b) electron stimulated desorption of positive ion.

a) electrons impinging on the grid produce bremsstrahlung radiation; the photons strike the central collector; photoelectron are extracted → equivalent to collected positive charges. (X-ray limit)

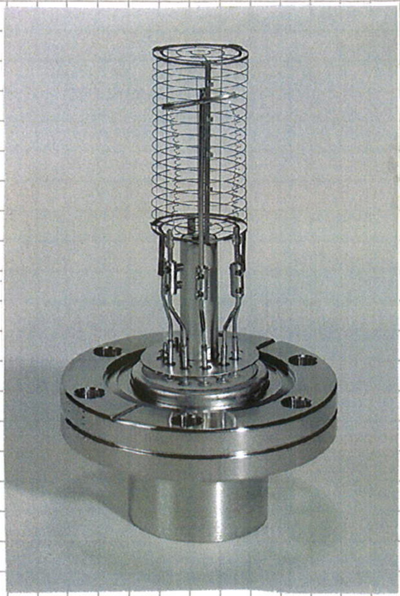
b) electrons impinging on the grid extract positive ions by electron stimulated desorption; the energetic ESD ion in direct view of the collector are counted.

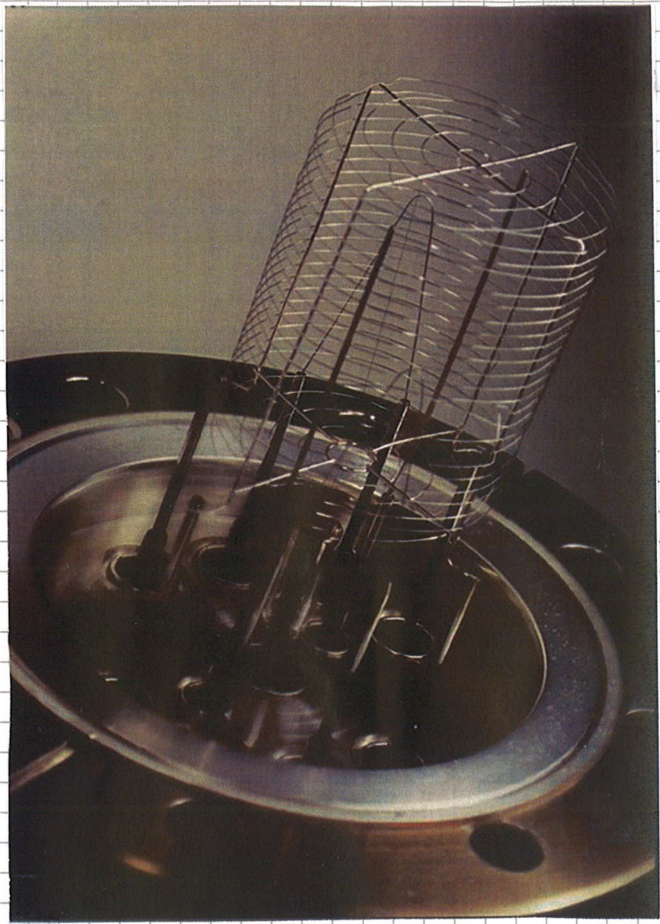
The X-ray limit can be reduced by retracting the collector outside the grid. The ions are pushed outside the grid toward the collector by electrostatic plates: extractor gauge and Helmer gauge.

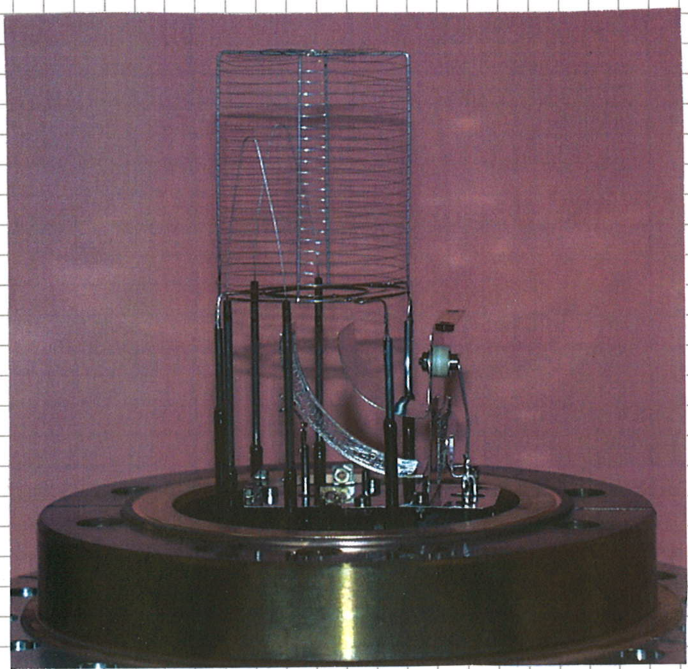
Bayard-Alpert gauges of optimized design attain X-ray limit in the low 10^{-12} Torr range. Extractor and Helmer gauges lower the limit down to 10^{-14} Torr.

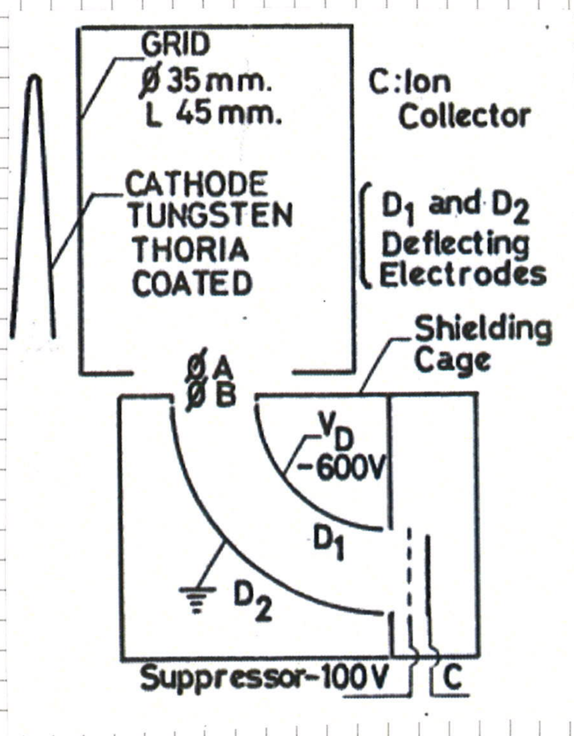
Modified Helmer gauges produced at CERN measured 2×10^{-14} Torr.

– The accuracy of hot cathode gauge is much better than that of cold cathode. In addition they are stable and do not undergo sudden instability.








GRID
Ø 35 mm.
L 45 mm.
C: Ion Collector
CATHODE TUNGSTEN THORIA COATED
D1 and D2 Deflecting Electrodes
Shielding Cage
ØA
ØB
VD -600V
D1
D2
Suppressor-100V
C

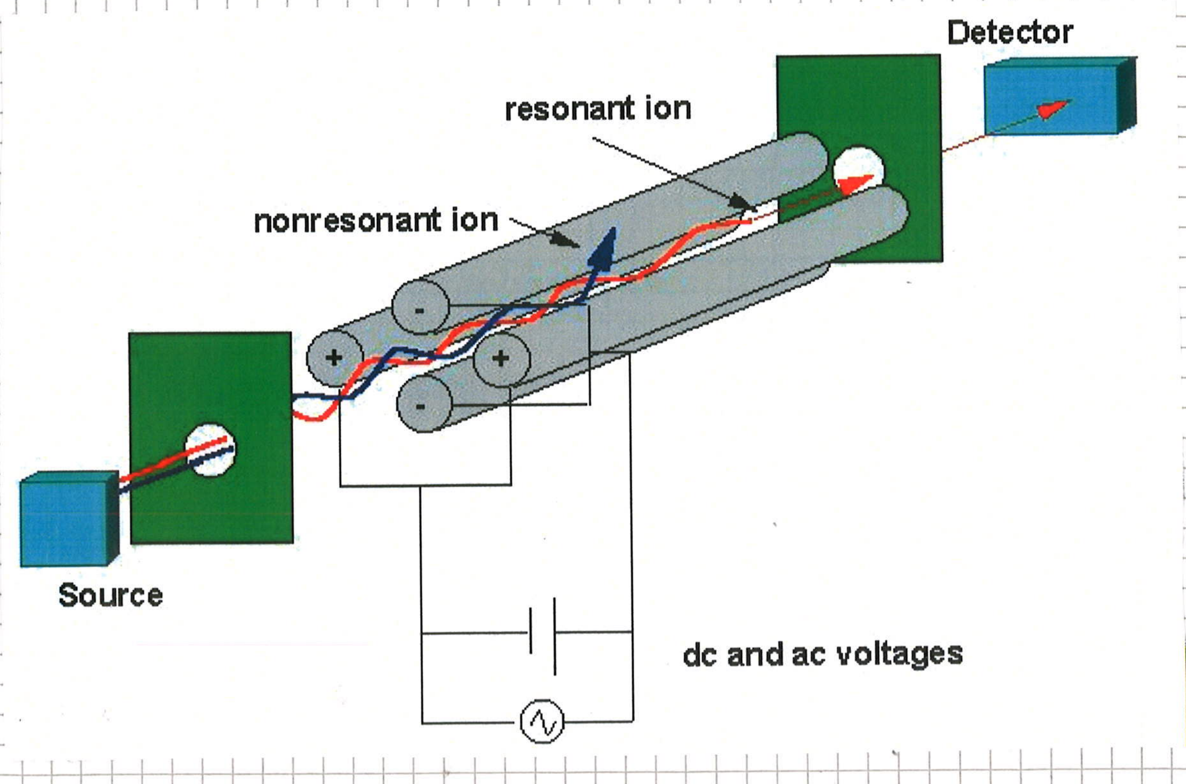
4.2 RESIDUAL GAS ANALYSERS

- It is important to know the nature of the residual gas in vacuum system. Residual gas analysers ionize all gas molecules and select them by a radiofrequency filter. Only the molecules with the selected mass get out from the filter and are detected.

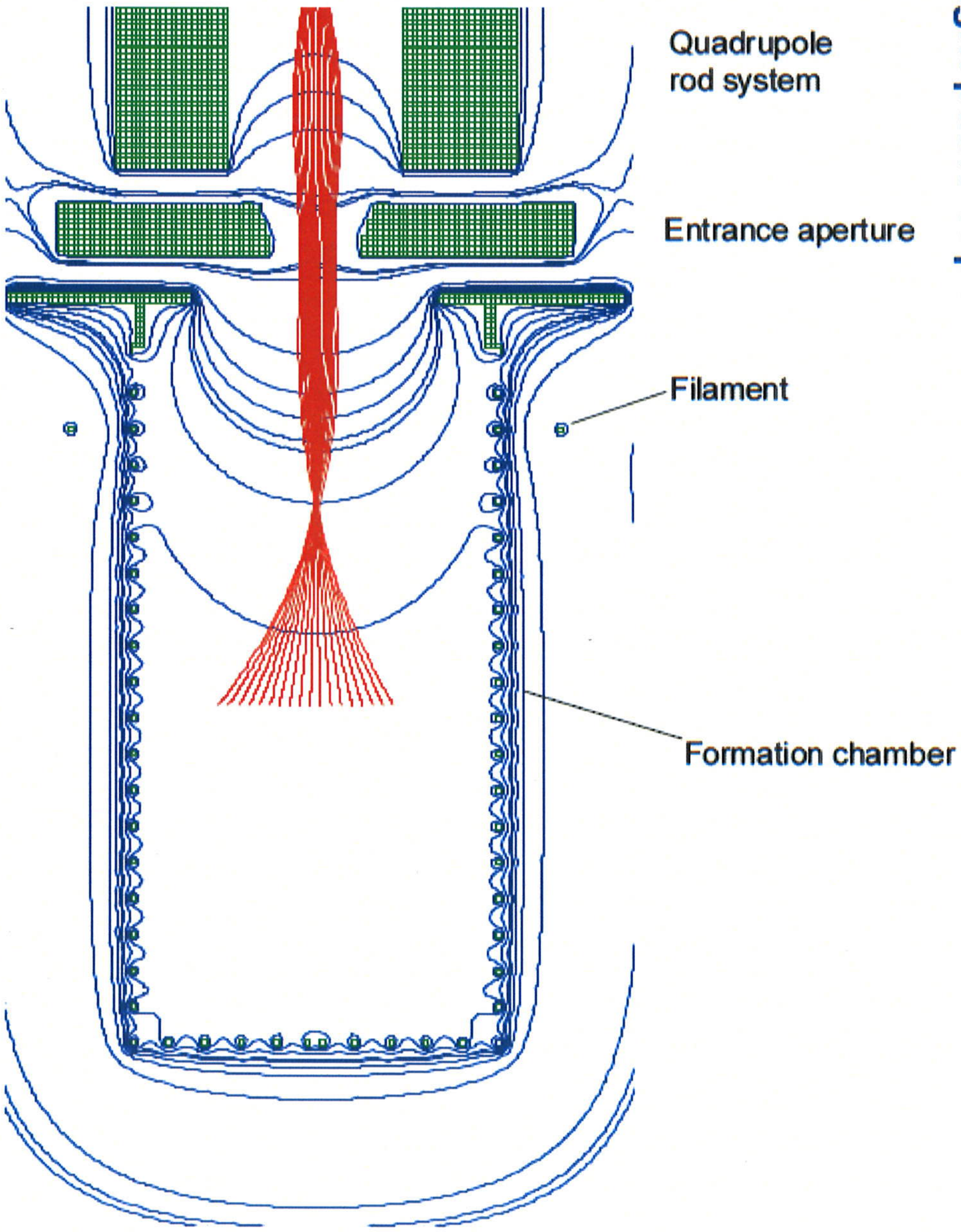
- The electron bombardment causes fragmentation of the molecules in addition to ionization. The molecular dissociation is not an unwanted complication; the fragmentation pattern (cracking pattern) facilitates the identification of the gas nature.

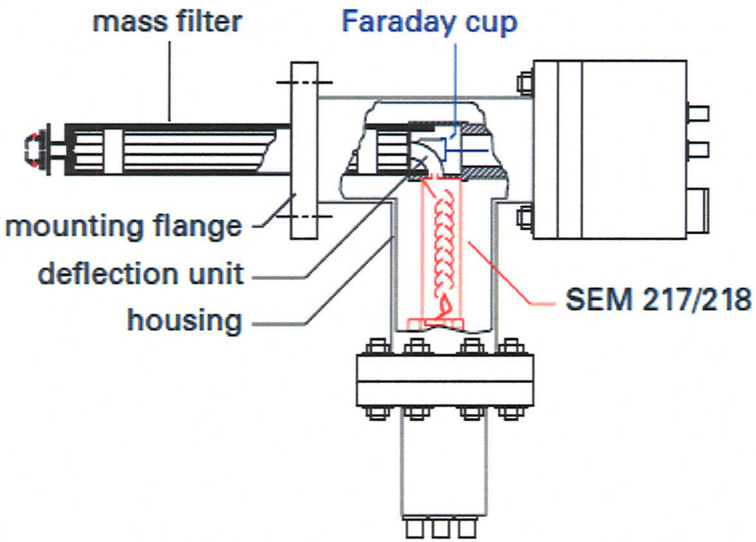
- The ionization is produced, as in hot cathode gauges, in a grid. The ions are extracted by polarized plates and injected into the filter with a defined energy.

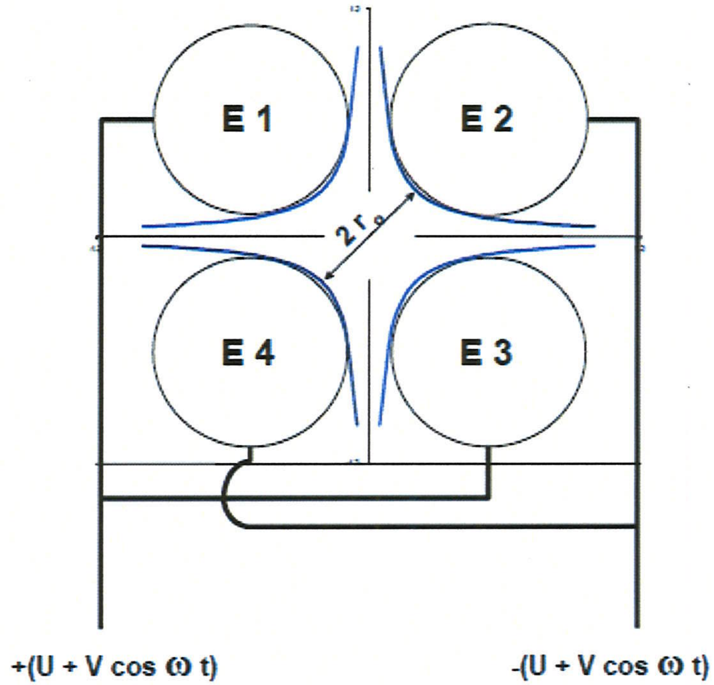
- The filter is a quadrupole mass filter invented by W. Paul. It consists of a set of four cylindrical electrodes.

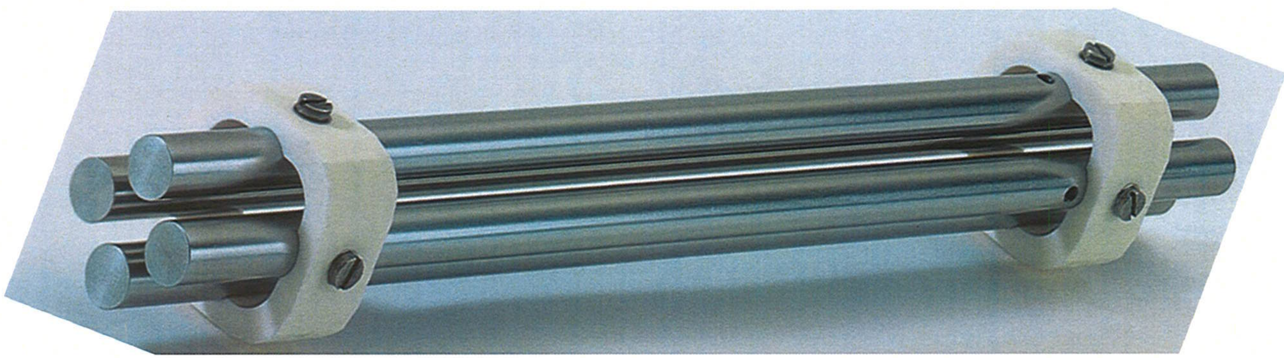


Flight paths of positive ions



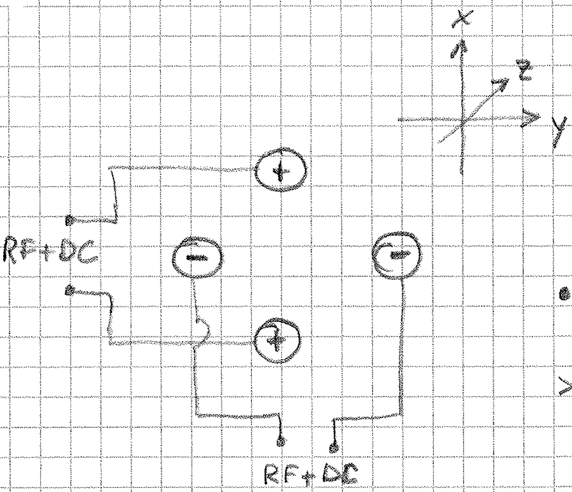

mass filter
Faraday cup
mounting flange
deflection unit
housing
SEM 217/218

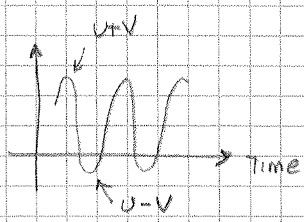

E 1
E 2
E 3
E 4
2 r₀
+(U + V cos ω t)
-(U + V cos ω t)



The filter action is obtained superposing a DC to a time periodic potential.

$U + V\cos\omega t$





- In the x-z plane:

> the positive DC potential focus the ions on the central axis

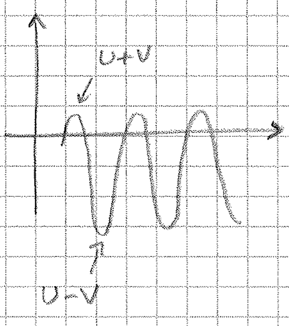
> when the RF field is superposed, for a short time, the two electrodes become negatively biased

> during this time, light ions can promptly react and be defocused and lost

> heavy ions do not have time to react and continue their trajectory close to the axis.

⇒ In the x-z plane the quadrupole is a high-pass filter.

- In the y-z plane:



> the negative DC potential defocuses all ions from the central axis

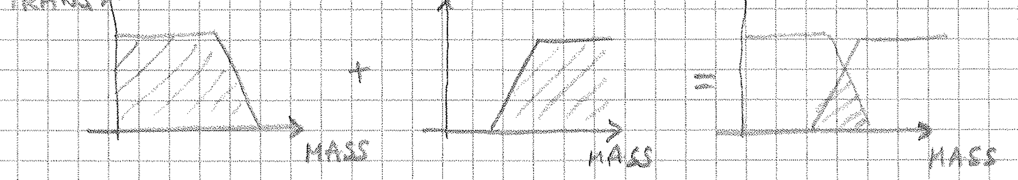
> when the RF field is superposed, for a short time the two electrodes become positively biased

> light ions react rapidly and are refocused and possibly they do not strike on the electrods

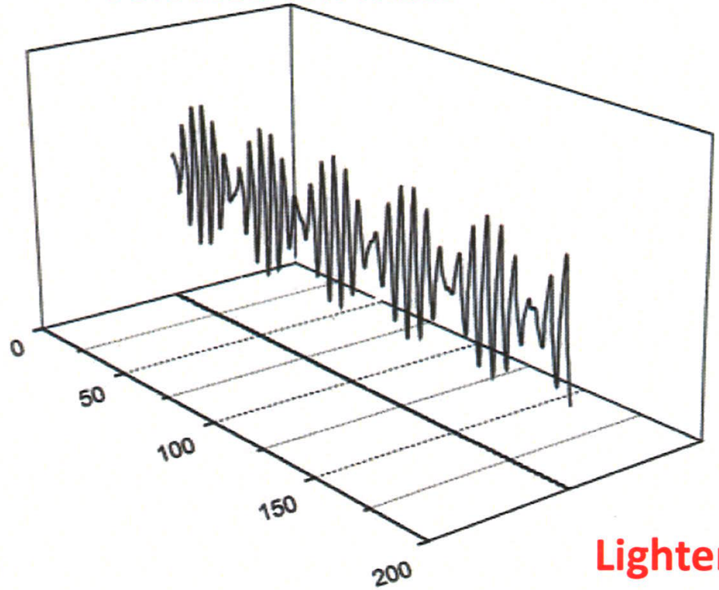
> heavy ions do not have time to react and are lost

⇒ In y-z plane the quadrupole is a low-pass filter.

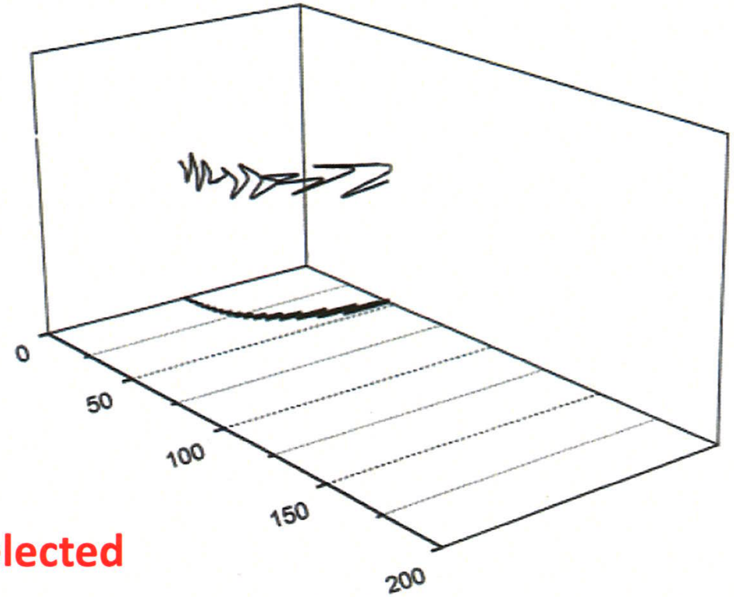
Superposing the two effects a band-pass filter is obtained.



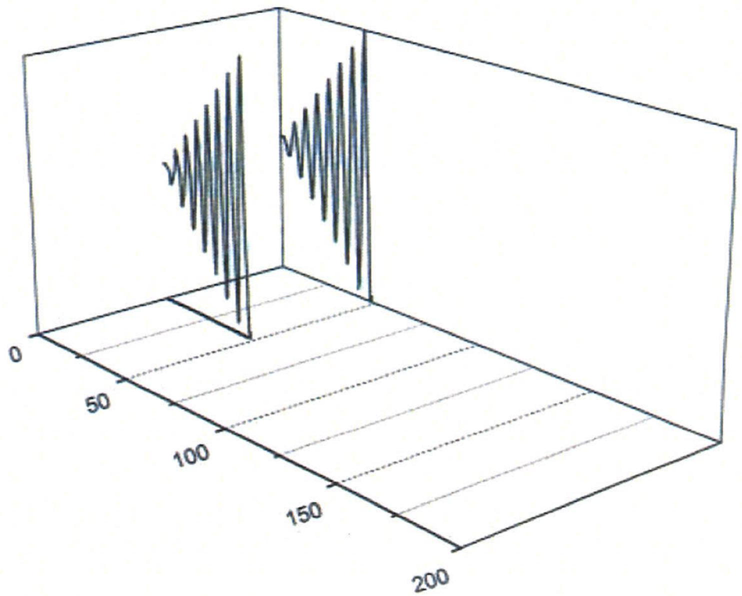
Selected ion mass



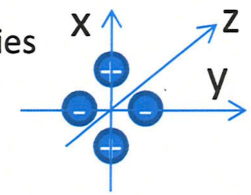
Heavier than selected



Lighter than selected

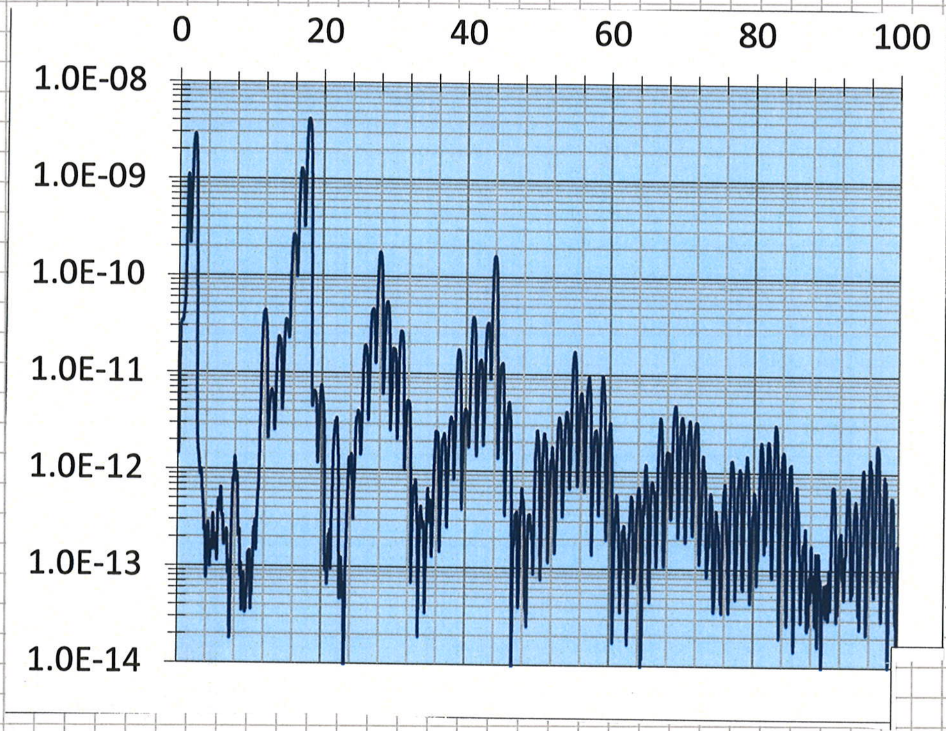


DC polarities

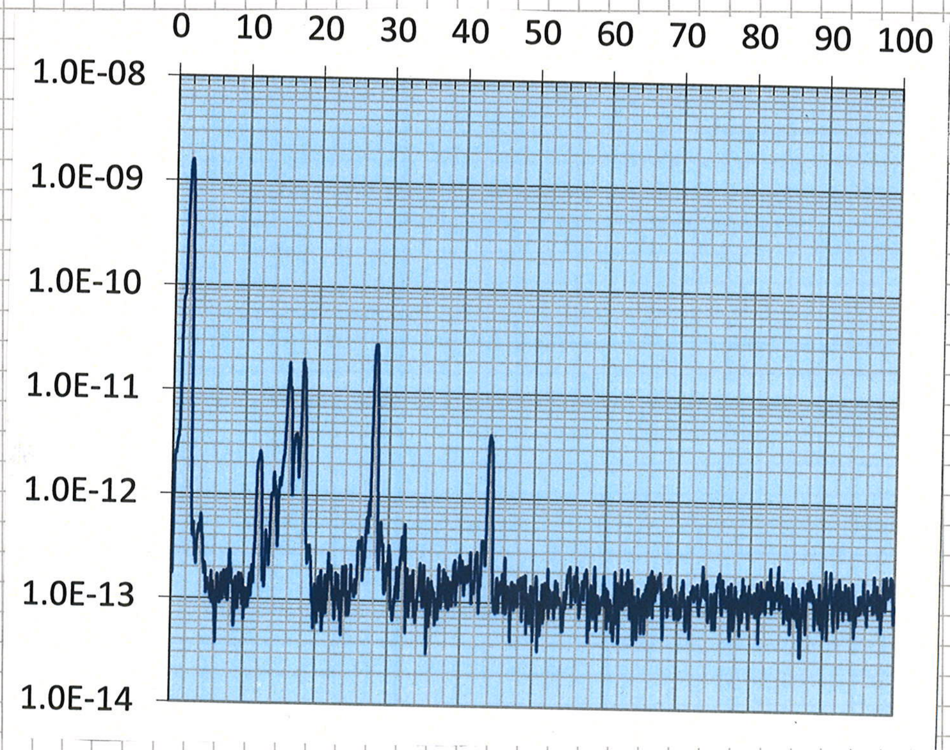


The ions escaped from the filter are detected by Faraday cup or secondary electron multipliers (SEM).

Typical spectra:



Unbaked system
(Faraday cup)



Baked system
(secondary electron multiplier)