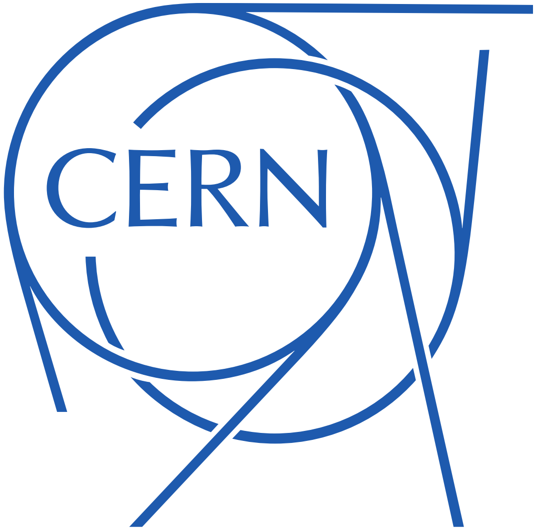
CERN

# Vacuum Systems
# Lecture 1

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# Vacuum?

## A transverse field across several engineering and scientific disciplines

Complementary information

# Outline

1. Introduction
2. Gas kinetic theory & gas flow
3. Measurement & production of vacuum

# 1. Introduction

# Vacuum

- “Perfect vacuum” does not exist on earth nor in space!
- Interstellar medium in a galaxy such as the Milky Way:
  - Composed of molecules, ions atoms, cosmic rays & dust (size 0.1 micron)
  - In molecular clouds, which are cold (>10 k) and dense region n ~ $10^4$ molecules/cm3
  - Atoms density:
    - 50 H/cm3 at 100 K (~$10^{-13}$ Pa)
    - 1 H/cm3 at 10 000 K (~$10^{-13}$ Pa)

Pilar of the creation

Nasa-ESA Hubble

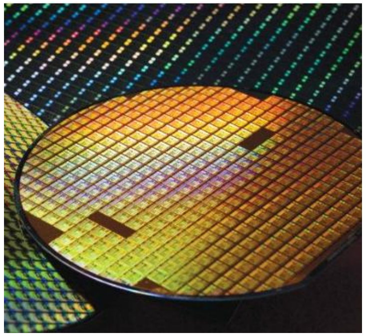
# Vacuum Systems on Earth

- Vacuum technology is present in many devices/ systems

Light bulb

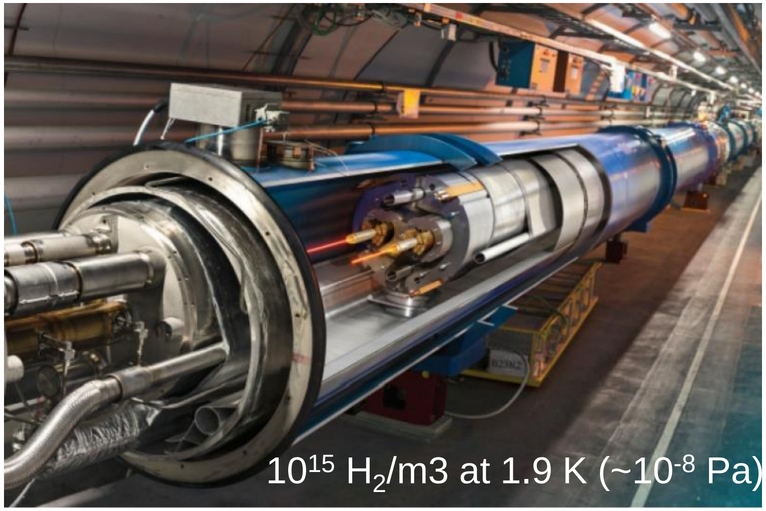
Vacuum pump
For wine

Electron beam welding machine



Semiconductor industry

Under vacuum brazing



$10^{15}$ $H_2$/m3 at 1.9 K (~$10^{-8}$ Pa)

Accelerator

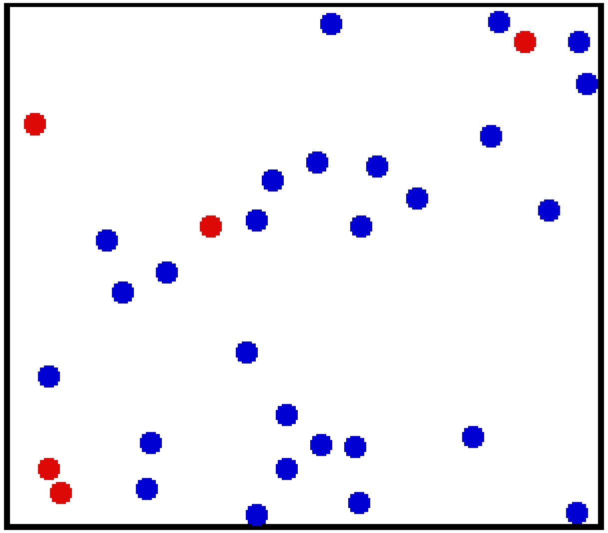
**The objective of Vacuum is to reduce the collision of molecules on the surrounding environment to preserve the quality of the process**

# 2. Gas kinetic theory & gas flow

# 2.1 Gas kinetic theory

# Introduction

- Assume a large number of molecules, always moving in a disordered manner
- The size of molecules is very small as compared to the intermolecular distance
- Molecules moves in a rectilinear uniform manner between successive collisions
- Collisions (elastic) are against molecules themselves or against the wall
- The molecular trajectories are broken lines



http://www.matierevolution.fr

# Maxwell Boltzmann Distribution

- Assume a pure gas, in thermal equilibrium and enclosed in an isothermal volume
- In this case:
    - The molecule density is constant in the volume and do not vary in time
    - The direction of the molecule's speed is uniform
    - The speed distribution is stationary

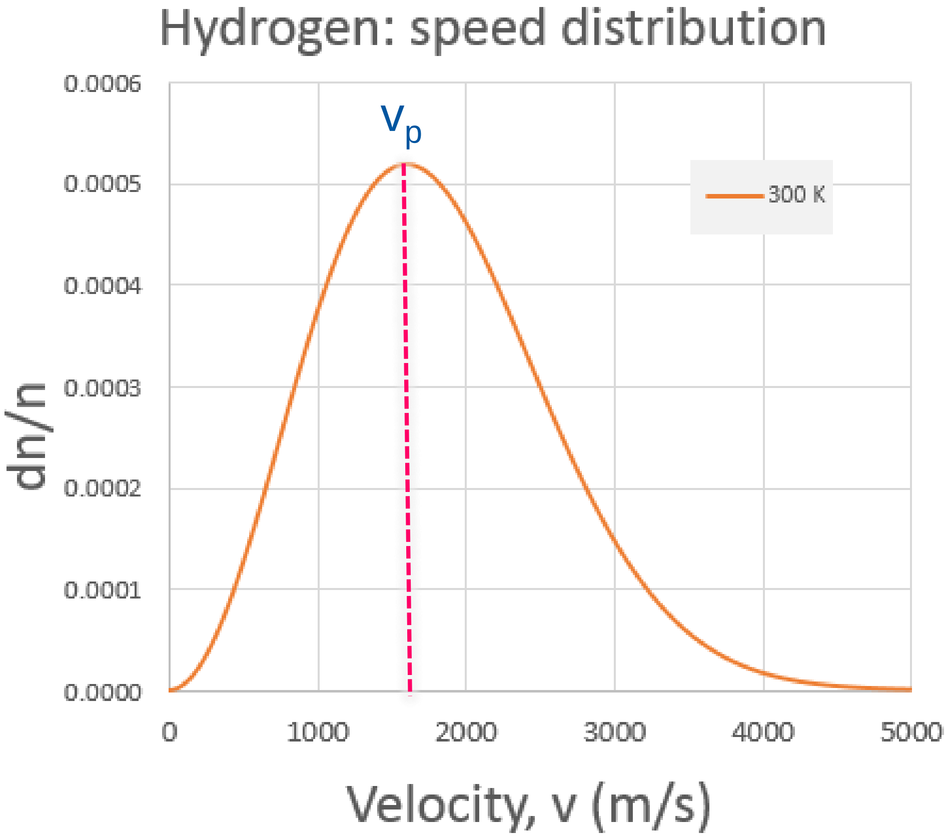
$$\boxed{\frac{dn}{n} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} v^2\, e^{-\frac{mv^2}{2kT}}\, dv}$$

- The speed of the molecules follows a Maxwell-Boltzmann distribution

- Most of the molecules have a speed around the maximum, $v_p$

- Less than 1/1000 of molecules have speed:

  $v<0.1\ v_p$ or $v>3\ v_p$



# Maxwell Boltzmann Distribution

- The most probable speed is given at the maximum of the distribution: d(dn/n)/dv =0. It equals

$$v_p = \sqrt{\frac{2kT}{m}}$$

- The mean thermal speed equals:

$$\bar{v} = \frac{1}{n}\int_0^\infty v\,\frac{dn}{dv}\,dv = \sqrt{\frac{8kT}{\pi\,m}}$$

- The average quadratic speed equals:

$${v_q}^2 = \overline{v^2} = \frac{1}{n}\int_0^\infty v^2\,\frac{dn}{dv}\,dv$$

$$v_q = \sqrt{\frac{3kT}{m}}$$

- The corresponding kinetic energy is:

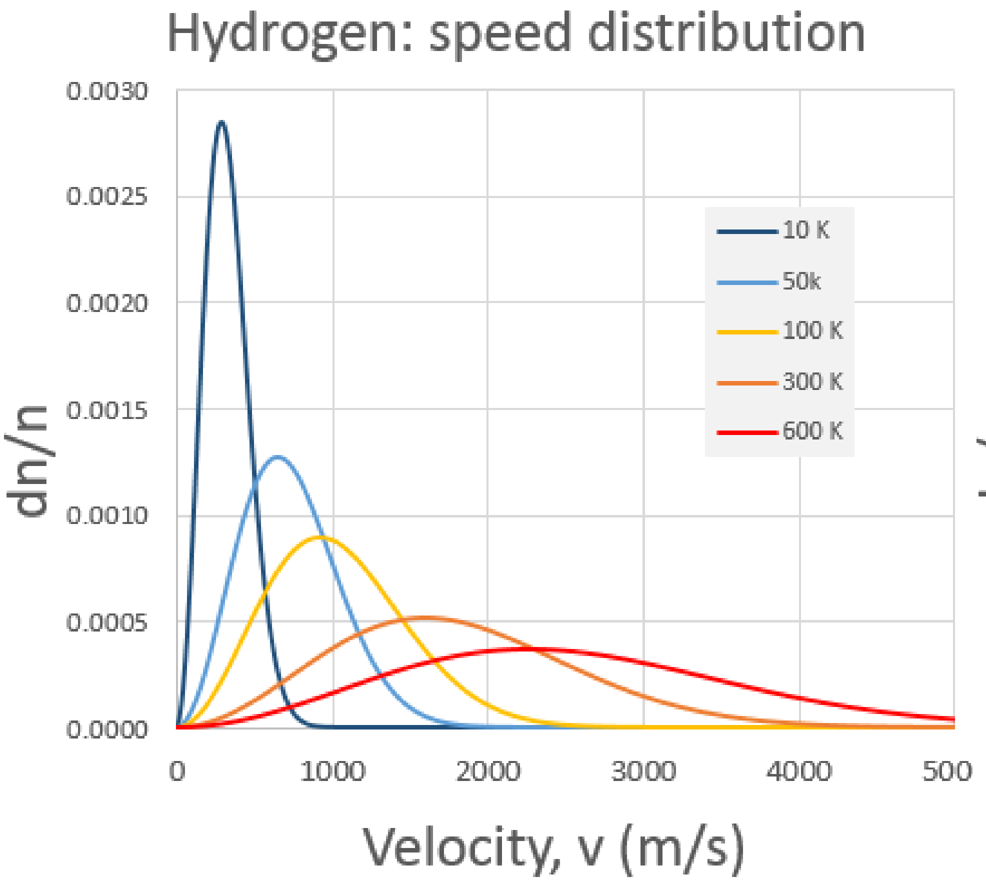
$$\frac{1}{2}m\,{v_q}^2 = \frac{3}{2}kT$$

**All the molecular speeds scales like ~ √*(T/m)***

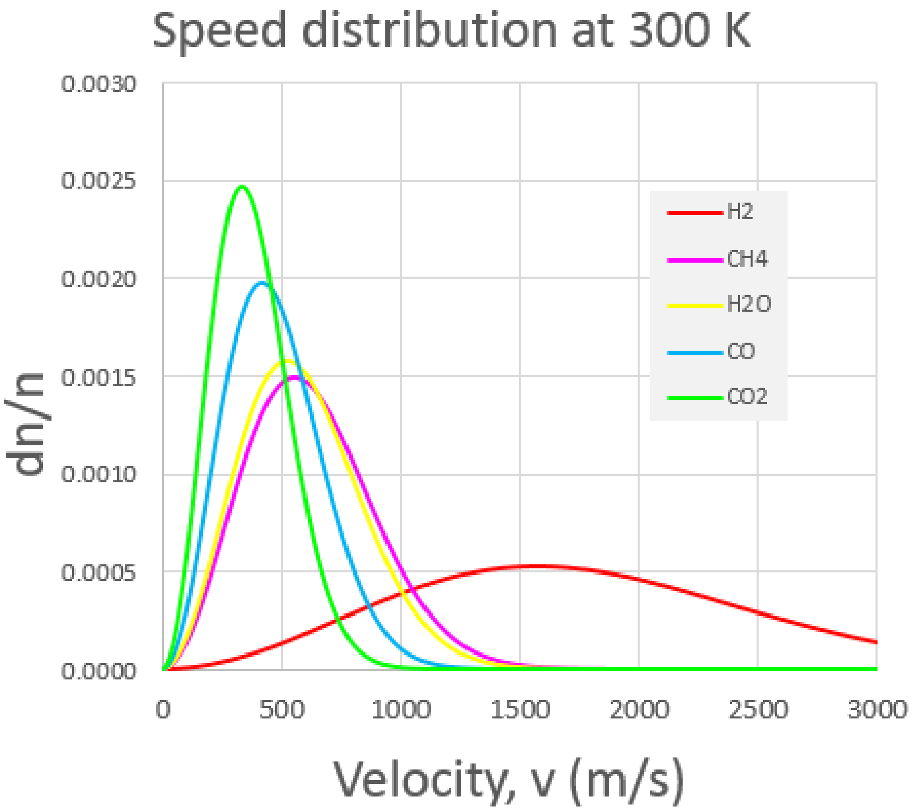
# Maxwell Boltzmann Distribution

- The gas velocity:
  - increase with increasing temperature
  - is the largest for light molecules

$\sim \sqrt{(T/m)}$



Hydrogen: speed distribution



Speed distribution at 300 K

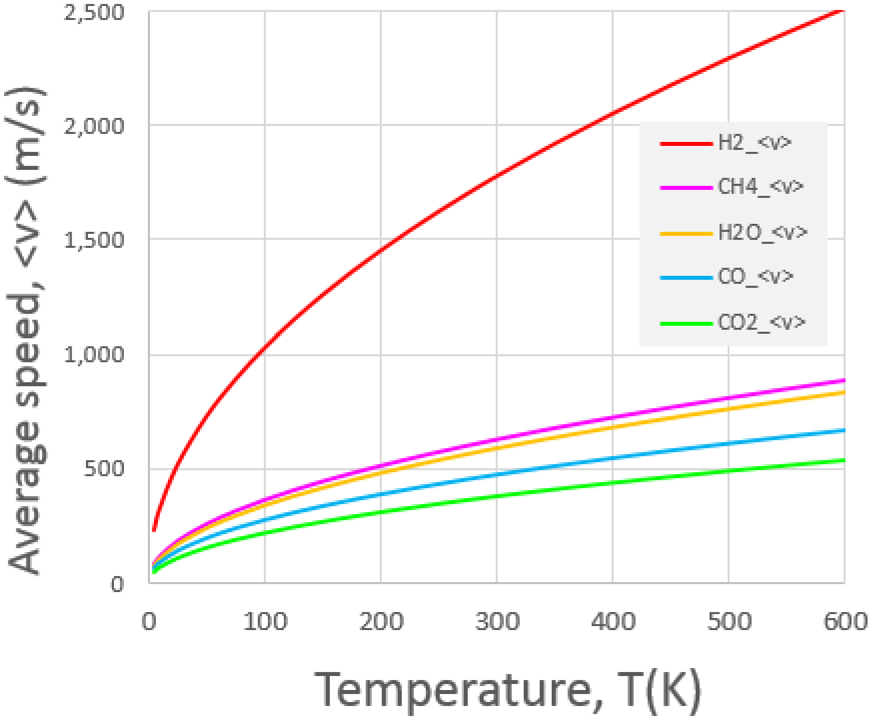
# Average velocity

- The mean thermal speed range from ~ 100 till 1000 m/s:
  This is much larger than the vacuum chamber dimensions!

$$\bar{v} = \sqrt{\frac{8kT}{\pi\, m}} = 145\sqrt{\frac{T}{M}}$$

| T (K) | He | Air | Ar |
|---|---|---|---|
| 4.2 | 150 | 55 | 50 |
| 300 | 1300 | 470 | 400 |
| 600 | 1800 | 660 | 560 |

$\sim \sqrt{(T/m)}$



# Collision on the wall

- The molecular collision rate on the wall (the incidence rate), ν, can be derived from the Maxwell Boltzmann distribution

$$\nu = \frac{number\ of\ collision\ with\ the\ wall}{area\ of\ wall\ x\ time} = \frac{1}{4}\, n\, \bar{v}$$

- Monolayer formation time

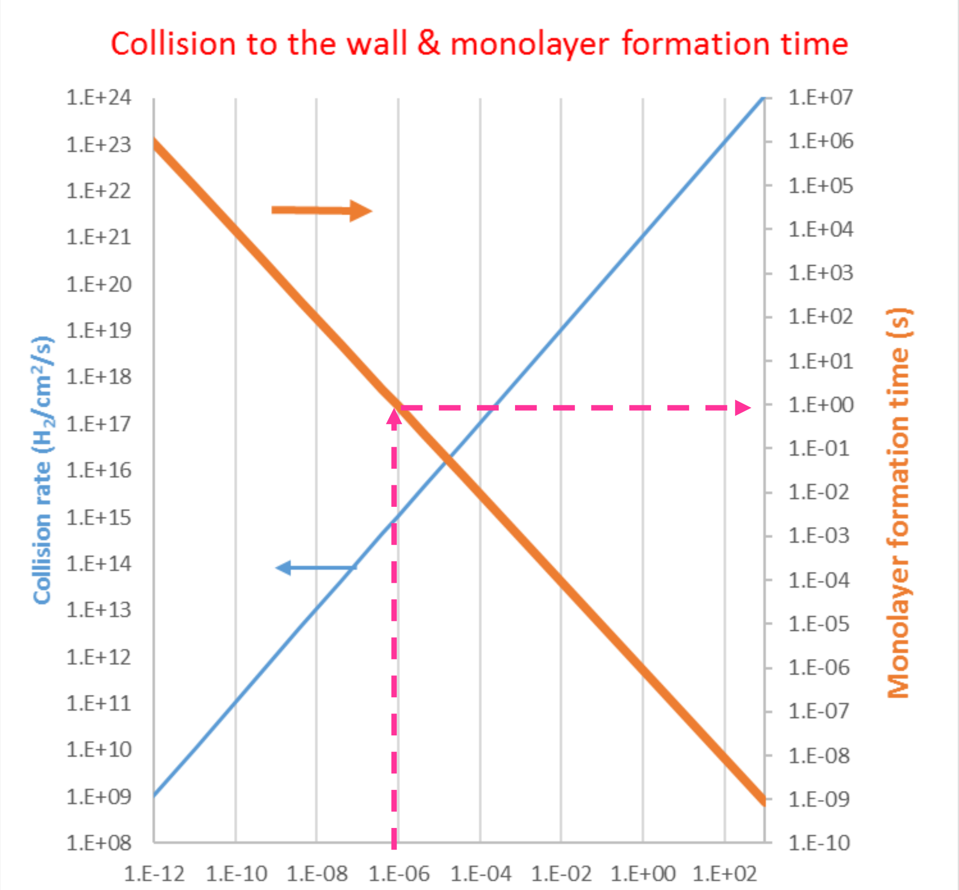
$10^{15}$ molecules/cm$^2$

- At room temperature, a monolayer is formed in 1 s at $10^{-6}$ Torr : Langmuir formation time

- 1 L = 1 monolayer.s

- Very low pressure is preferred to minimize surface contamination:

1 ns at 1 atm
1 s at $10^{-6}$ mbar
1 day at $10^{-11}$ mbar !!!



$H_2$ at 300 K

# Pressure & Ideal gas law

- Molecules which collide a wall of surface A, produce a force, F, onto it.
- The pressure P, exerted on the wall by the molecules is defined by the ratio of the force to the surface:

$$P = \frac{F}{A}$$

- It can be shown that, for any particle velocity distribution, the pressure is given by the mass density and the quadratic speed:

$$P = \frac{1}{3}\,\rho\,{v_q}^2$$

- In the special case the particle velocity distribution, follows a Maxwell Boltzman distribution, the pressure is given by the IDEAL GAS LAW:

$$P = n\,k\,T$$

- For such a gas, the pressure, P [Pa], is defined by the gas density, n [molecules.m$^{-3}$] , the temperature of the gas, T [K] and the Boltzman constant k , (1.38 10$^{-23}$ J/K)

- The pressure increases linearly with the gas temperature

# Ideal gas law: illustration

$$P = n\,k\,T$$

- Ultra-High Vacuum
  - $n = 10^{15}$ molecules/m$^3$
    - $k = 1.38\ 10^{-23}$ J/K
    - $T = 300$ K *i.e.* room temperature
    - ➔ $P = 10^{15} \times 1.38\ 10^{-23} \times 300 = 4\ 10^{-6}$ Pa

- This relation is another expression on the Avogadro's law:
  - The occupied volume by one mole in standard condition equals 22.4 l (*i.e.* $22.4\ 10^{-3}$ m$^3$)
    - ➔ $n = N / V = 6.02\ 10^{23} / 0.0224$ m$^3$ $= 2.7\ 10^{25}$ molecules/m$^3$
  - Atmospheric pressure at 0°C (standards conditions)
    - $P = 101\ 300$ Pa,
    - $k = 1.38\ 10^{-23}$ J/K
    - $T = 273$ K *i.e.* 0°C
    - ➔ $n = 101\ 300 / (1.38\ 10^{-23} \times 273) = 2.7\ 10^{25}$ molecules/m$^3$

# Units

- The pressure is the force exerted by the molecules per unit of surface : 1 Pa = 1 N/m$^2$

| → | **Pa** | **kg/cm$^2$** | **Torr** | **mbar** | **bar** | **atm** |
|---|---|---|---|---|---|---|
| **1 Pa** | 1 | $10.2\ 10^{-6}$ | $7.5\ 10^{-3}$ | $10^{-2}$ | $10^{-5}$ | $9.81\ 10^{-6}$ |
| **1 kg/cm$^2$** | $98.1\ 10^{3}$ | 1 | 735.5 | 980 | 0.98 | 0.96 |
| **1 Torr** | 133 | $1.35\ 10^{-3}$ | 1 | 1.33 | $1.33\ 10^{-3}$ | $1.31\ 10^{-3}$ |
| **1 mbar** | 101 | $1.02\ 10^{-3}$ | 0.75 | 1 | $10^{-3}$ | $0.98\ 10^{-3}$ |
| **1 bar** | $1.01\ 10^{5}$ | 1.02 | 750 | $10^{3}$ | 1 | 0.98 |
| **1 atm** | 101 300 | 1.03 | 760 | 1 013 | 1.01 | 1 |

- Examples:
  - $10^{-6}$ Torr is converted to 1.33 x $10^{-6}$ = 1.3 $10^{-6}$ mbar
  - $10^{-6}$ Torr is converted to 133 x $10^{-6}$ = 1.3 $10^{-4}$ Pa
  - 4 $10^{-6}$ Pa is converted to 4 $10^{-6}$ / 133 = 3 $10^{-8}$ Torr
  - 4 $10^{-6}$ Pa is converted to 4 $10^{-6}$ / 100 = 4 $10^{-8}$ mbar

# Force applied on a vacuum vessel

- When the vacuum vessel is evacuated, a force is exerts onto it
- It amounts to 1 kg/cm$^2$

- Example: force applied on a blank flange

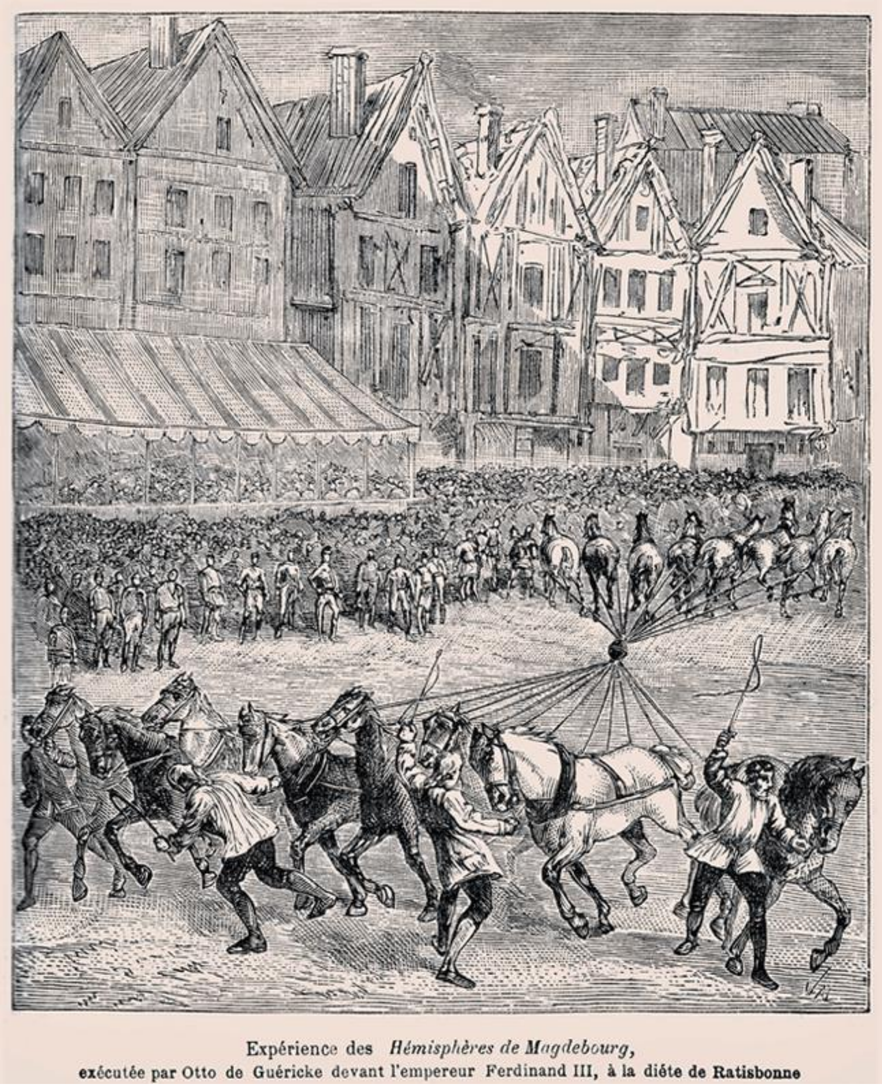
Picture Kurt J. Lesker

| **D (mm)** | **16** | **35** | **63** | **80** | **100** | **130** | **150** | **212** |
|---|---|---|---|---|---|---|---|---|
| **kg** | 2 | 10 | 32 | 52 | 81 | 137 | 182 | 363 |

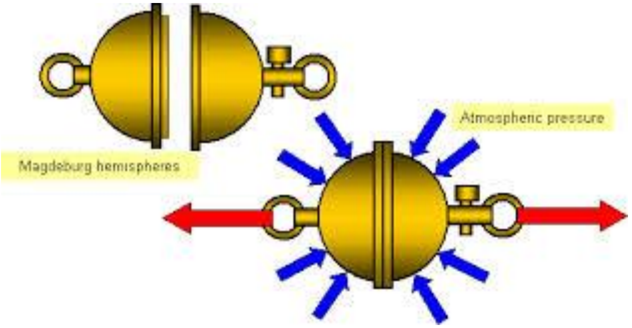
**As a consequence of the « vacuum force » …**

# “Vacuum force”: Magdeburg hemisphere

- 1654, Regensburg



Expérience des *Hémisphères de Magdebourg*,
exécutée par Otto de Guéricke devant l'empereur Ferdinand III, à la diète de Ratisbonne

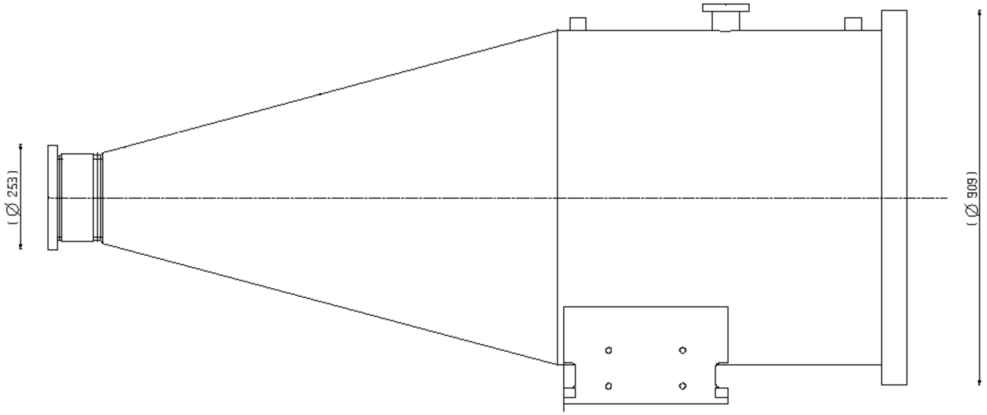


55 cm diameter ➔ 25 Tons

Otto von Guericke

# Work with the Mechanical Design Office !

0.5 ton →



← **6.6 tons**

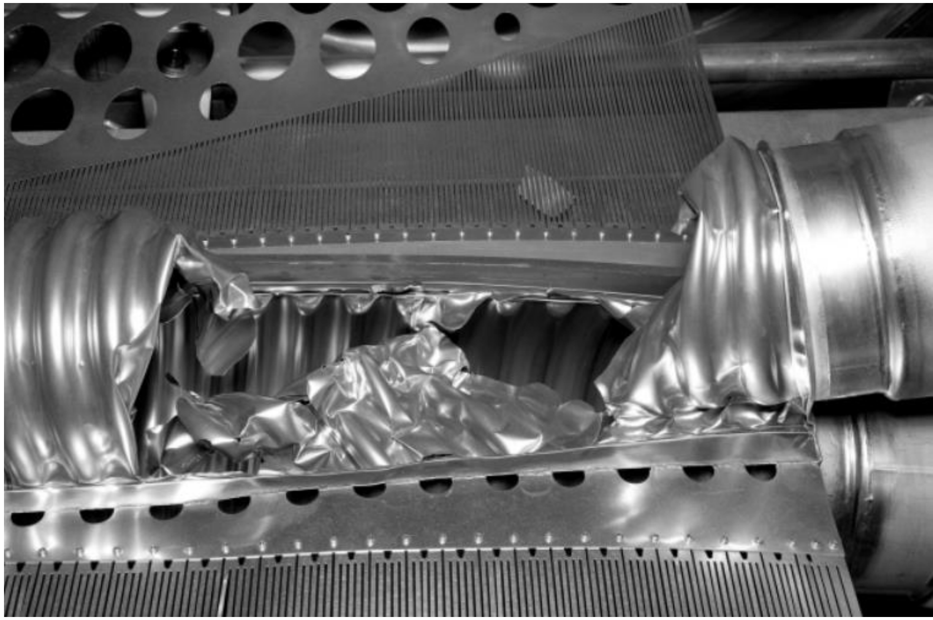
60

**Otherwise…**

# Typical accidents with UHV!

- Case of the CERN ISR in the 70's :

“spontaneous” breaking of the a bellow (due to a bad design or due to a fixed point not well attached ?)



Imploded “flat fish” at an ISR intersection

# Even in modern times …

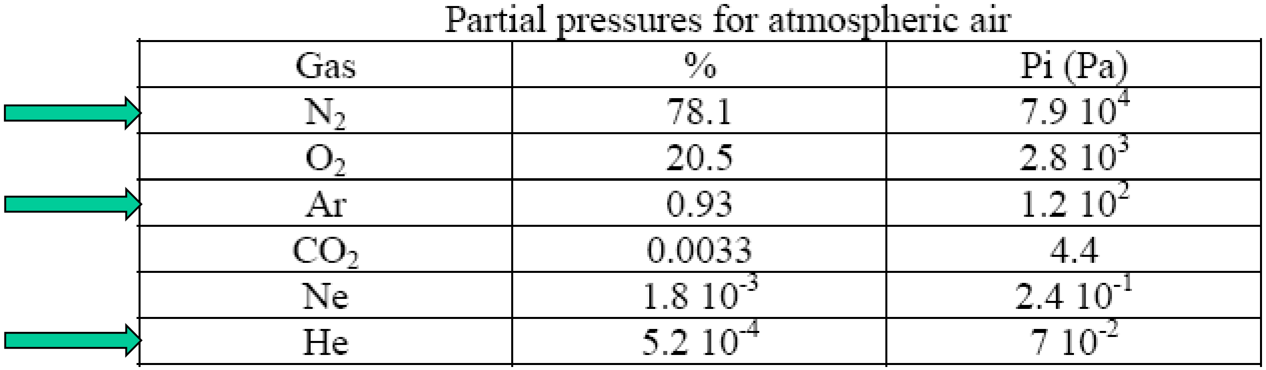
- Accident still possible nowadays even with modern computing tools …
- Case of the QRL's bellows in the LHC deformed during pump down,
- Origin attributed to a non-conform bellow with a too small corrugation high

# Total Pressure and Partial Pressure

- The gas is usually composed of several types of molecules (ex : air, residual gas in vacuum systems)

- The **total pressure,** $P_{Tot}$, is the sum of all the **partial pressure,** $P_i$ (Dalton law)

$$\boxed{P_{Tot} = \sum P_i = k\,T \sum n_i}$$



Partial pressures for atmospheric air

| Gas | % | Pi (Pa) |
|---|---|---|
| $N_2$ | 78.1 | $7.9\ 10^4$ |
| $O_2$ | 20.5 | $2.8\ 10^3$ |
| Ar | 0.93 | $1.2\ 10^2$ |
| $CO_2$ | 0.0033 | 4.4 |
| Ne | $1.8\ 10^{-3}$ | $2.4\ 10^{-1}$ |
| He | $5.2\ 10^{-4}$ | $7\ 10^{-2}$ |

# 2.2 Gas flow

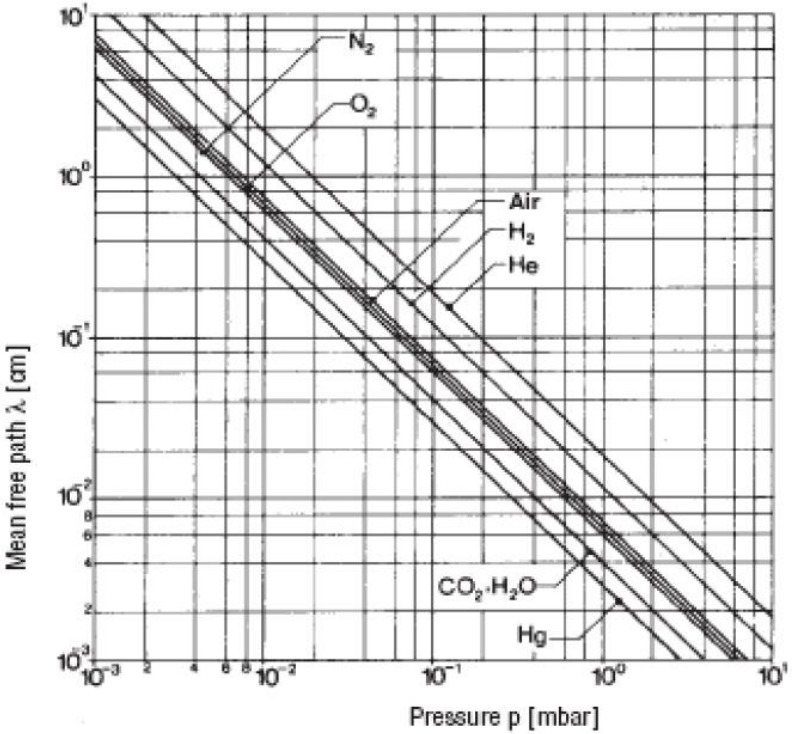
# Mean Free Path

- It is the path length that a molecules traverse between two successive impacts with other molecules. It was derived by Clausius.

- It is a function of the pressure, $P$, of the temperature, $T$, and of the molecular diameter, $\sigma$.

$$\lambda = \frac{1}{\sqrt{2}\pi n \sigma^2} = \frac{1}{\sqrt{2}\pi} \frac{kT}{P} \frac{1}{\sigma^2}$$

| Molecule | Diameter (Å) |
|---|---|
| $H_2$ | 2.8 |
| $H_2O$ | 2.9 |
| $O_2$ | 2.9 |
| $N_2$ | 3.7 |
| $CO_2$ | 3.2 |



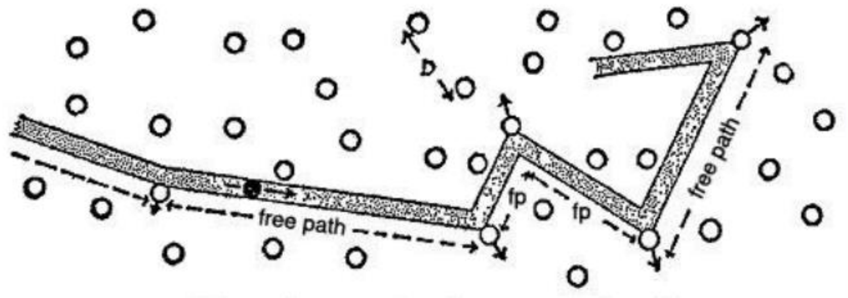
R. Clausius

# Mean Free Path: air at room temperature

- At atmospheric pressure, λ = 70 nm
- At 1 Torr, λ = 50 µm
- At $10^{-3}$ Torr, λ = 5 cm
- At $10^{-7}$ Torr, λ = 500 m
- At $10^{-10}$ Torr, λ = 500 km

$$\lambda_{air}[cm] = \frac{5\,10^{-3}}{P[Torr]}$$

Increasing mean free path when decreasing pressure



Mean free path of a gas molecule

# Classification of vacuum

- From atmospheric pressure to very low pressure, the mean free path varies over more than 10 orders of magnitude!

- Low or Rough vacuum
  - $10^5$ to $10^2$ Pa ; $10^3$ to 1 mbar

- Medium vacuum
  - $10^2$ to $10^{-1}$ Pa ; 1 to $10^{-3}$ mbar

- High vacuum (HV)
  - $10^{-1}$ to $10^{-5}$ Pa ; $10^{-3}$ to $10^{-7}$ mbar

- Ultra-high vacuum (UHV)
  - $10^{-5}$ to $10^{-10}$ Pa ; $10^{-7}$ to $10^{-12}$ mbar

- Extreme-high vacuum (XHV) (below actual limit of “standard” instrumentation)
  - $<10^{-12}$ Pa ; $<10^{-12}$ mbar

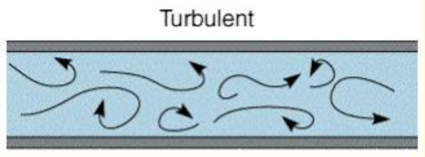
# Turbulent and Viscous Flows

- When pumping down from atmospheric pressure, the physics is characterised by different flow regimes. It is a function of the pressure, of the mean free path and of the components dimensions.

- Reynolds number, Re :
  - if Re > 2000 the flow is turbulent
  - it is viscous if Re < 1000

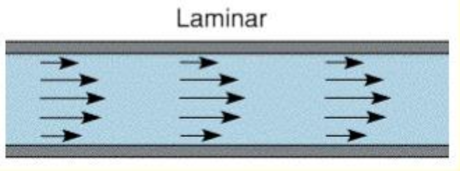
$$\mathrm{Re} = \frac{\mathrm{Q}[Torr.l/s]}{0.089\mathrm{D}[cm]}$$

- The turbulent flow is established around the atmospheric pressure



- In the low vacuum ($10^3$-1 mbar), the flow is viscous. The flow is determined by the interaction between the molecules themselves. The flow is laminar. The mean free path of the molecules is small compared to the diameter of the vacuum chamber

$$\text{Viscous flow} : \overline{\mathrm{P}}\,\mathrm{D} > 0.5\,[Torr.cm]$$



# Transition and Molecular Flows

- In the medium vacuum (1-$10^{-3}$ mbar), the flow is transitional. In every day work, this range is quickly crossed when pumping down vacuum chambers. In this regime, the calculation of the conductance is complex. A simple estimation is obtained by adding laminar and molecular conductances.

- In the high vacuum ($10^{-3}$ – $10^{-7}$ mbar) and ultra-high vacuum ($10^{-7}$–$10^{-12}$ mbar), the flow is molecular. The mean free path is much larger than the vacuum chamber diameter. The molecular interactions do not longer occurs. Molecules interact only with the vacuum chamber walls

$$\text{Molecular flow} : \overline{P}\, D < 1.5\, 10^{-2}\ [Torr.cm]$$

Molecular flow is the main regime of flow to be used in vacuum technology

In this regime, the vacuum vessel has been evacuated from its volume.
The pressure inside the vessel is dominated by the nature of **the surface.**

# Molecular Flow: application

$$\text{Molecular flow}: \bar{P}\,D < 1.5\,10^{-2}\ [Torr.cm]$$

- Assume an accelerator ring operating under UHV:
  - vacuum chamber diameter ~ 10 cm
  - average pressure $10^{-8}$ mbar (= 7.5 $10^{-9}$ Torr)
    - ➔ PxD = 7.5 $10^{-9}$ x 10 = 7.5 $10^{-8}$ Torr.cm ➔ molecular regime
  - mean free path:
    - ➔ $\lambda$ = 5 $10^{-5}$ / 7.5 $10^{-8}$ = 667 m

- Assume a large vacuum vessel, *e.g.* a large cryostat, operating under UV:
  - vacuum chamber diameter ~ 10 m (=1000 cm)
  - average pressure $10^{-5}$ mbar (= 7.5 $10^{-6}$ Torr)
    - ➔ PxD = 7.5 $10^{-6}$ x 1000 = 7.5 $10^{-3}$ Torr.cm ➔ molecular regime
  - mean free path:
    - ➔ $\lambda$ = 5 $10^{-5}$ / 7.5 $10^{-6}$ = 7 m

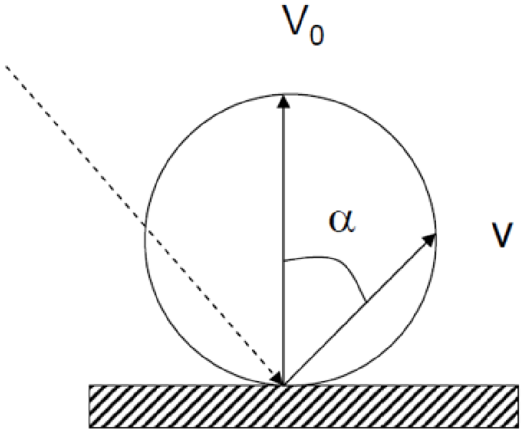
# Molecule interaction with the wall

- In the molecular regime, Knudsen observed that the speed of the molecules is reduced due to interactions with the pipe

- Following the collision on the wall, due to the roughness of the surface, the molecule is re-emitted into the vacuum system according to a Beer-Lambert law.

Knudsen number

$$K = \frac{\lambda}{d}$$



$$V = V_o \cos \alpha$$

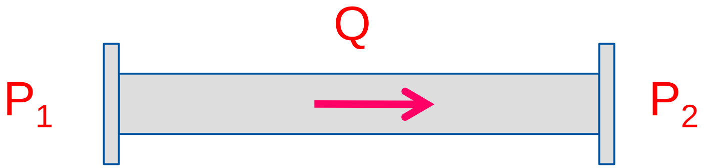
- This observation introduced the concept of conductance (Dushman)

Saul Dushman (1883–1954)

# Conductance

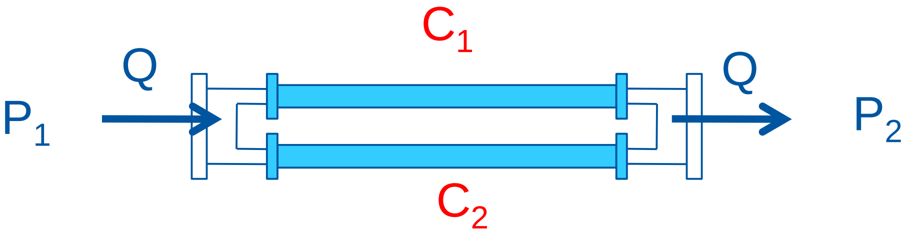
- It is defined by the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel. It is a function of the shape of the vessel, the nature of the gas and its temperature.

$$\boxed{C = \frac{Q}{(P_1 - P_2)}}$$



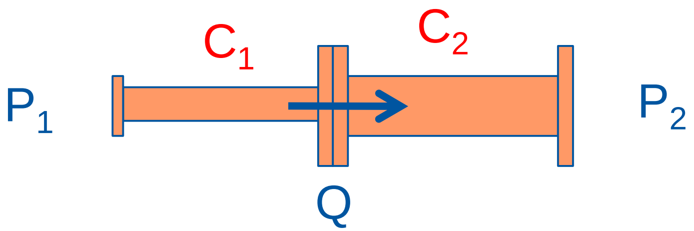
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$



# Conductance Calculus in Molecular Regime

- **For a (thin) orifice :**

$$C = \sqrt{\frac{kT}{2\pi\, m}}A; \quad C_{air,\,20^\circ}[l/s] = 11.6\, A[cm^2]$$

The conductance of an orifice of 10 cm diameter is 900 l/s

- **For a tube :**

$$C = \frac{1}{6}\sqrt{\frac{2\pi\, kT}{m}}\frac{D^3}{L}; \quad C_{air,\,20^\circ}[l/s] = 12.1\frac{D[cm]^3}{L[cm]}$$

The specific conductance of a tube of 10 cm diameter is 120 l/s.m

To increase the conductance of a vacuum system, it is better to have a vacuum chamber with large diameter and short lenght

# Scaling of conductances

- The conductance scales like:

$$\boxed{C \sim \sqrt{\frac{T}{M}}}$$

| Gas | M | C_orifice [l/s] | C_tube [l/s.m] |
|---|---|---|---|
| Air | 29 | 900 | 120 |
| $H_2$ | 2 | 3427 | 457 |
| $CH_4$ | 16 | 1212 | 162 |
| CO | 28 | 916 | 122 |
| $CO_2$ | 44 | 731 | 97 |

at room temperature

# Pumping Speed

- The pumping speed, S, is the ratio of the flux of molecules pumped to the pressure

mbar.l/s

l/s

$$\boxed{S = \frac{Q}{P}}$$

mbar

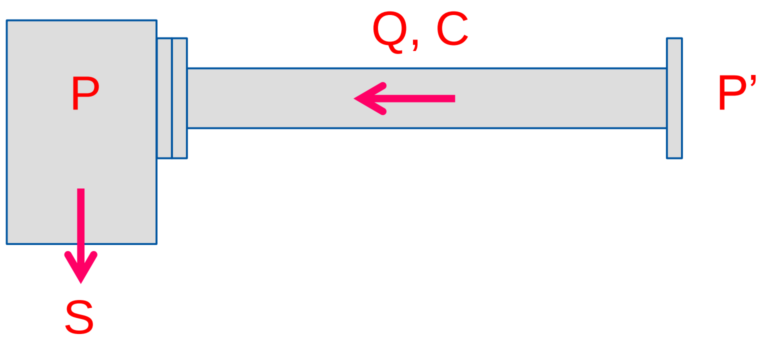
- S range from 10 to 20 000 l/s
- Q range from $10^{-14}$ mbar.l/s/cm$^{2}$ for metalic tubes to $10^{-5}$ – $10^{-4}$ mbar.l/s/cm$^{2}$ for plastics

3 orders of magnitude for pumping
vs
10 orders of magnitude for outgassing

**Outgassing MUST be optimised to achieve UHV**

# Effective pumping speed

- It is the pumping speed seen from P' trough the pipe of conductance, C



Pumping speed

$$\begin{cases} Q = P\,S \\ Q = C\,(P' - P) \end{cases} \Rightarrow Q = \frac{SC}{S+C} P' = S_{eff} P'$$

Conductance

$$S_{eff} = \frac{SC}{S+C}$$

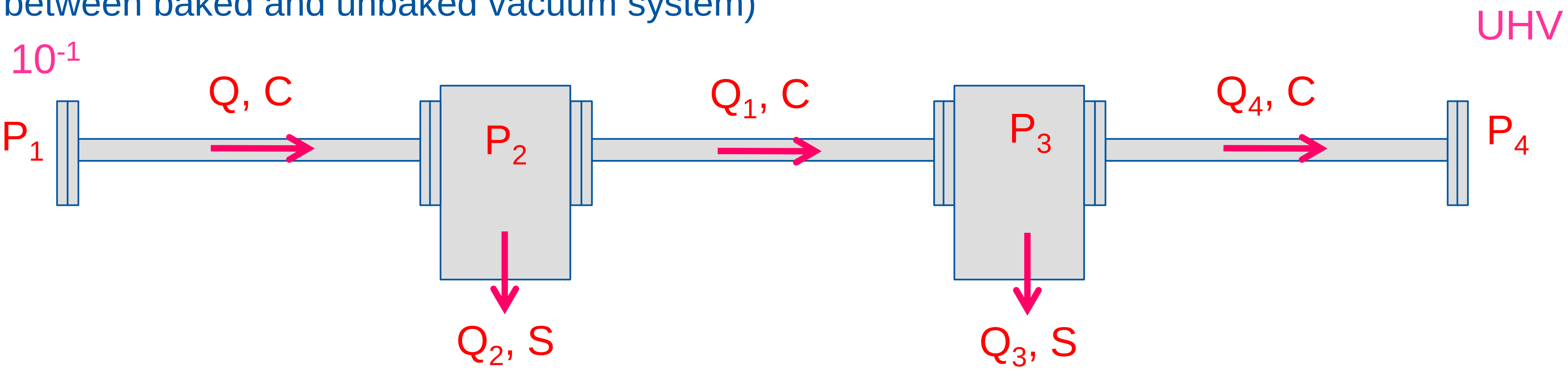
- This is the result of adding in series the conductance C with the pumping speed S

- If:
  1) C=S then $S_{eff}$ = S/2
  2) C>> S then $S_{eff}$ = S
  3) C<< S then $S_{eff}$ = C, the system is "conductance limited"

Large conductances preserve the efficiency of the pumping system

# Differential pumping system

- This system allows to decouple a vacuum system from another one (*e.g.* in Linac source, between baked and unbaked vacuum system)



$10^{-1}$

UHV

$P_1$

$Q, C$

$P_2$

$Q_1, C$

$P_3$

$Q_4, C$

$P_4$

$Q_2, S$

$Q_3, S$

- Commercial differential pumps

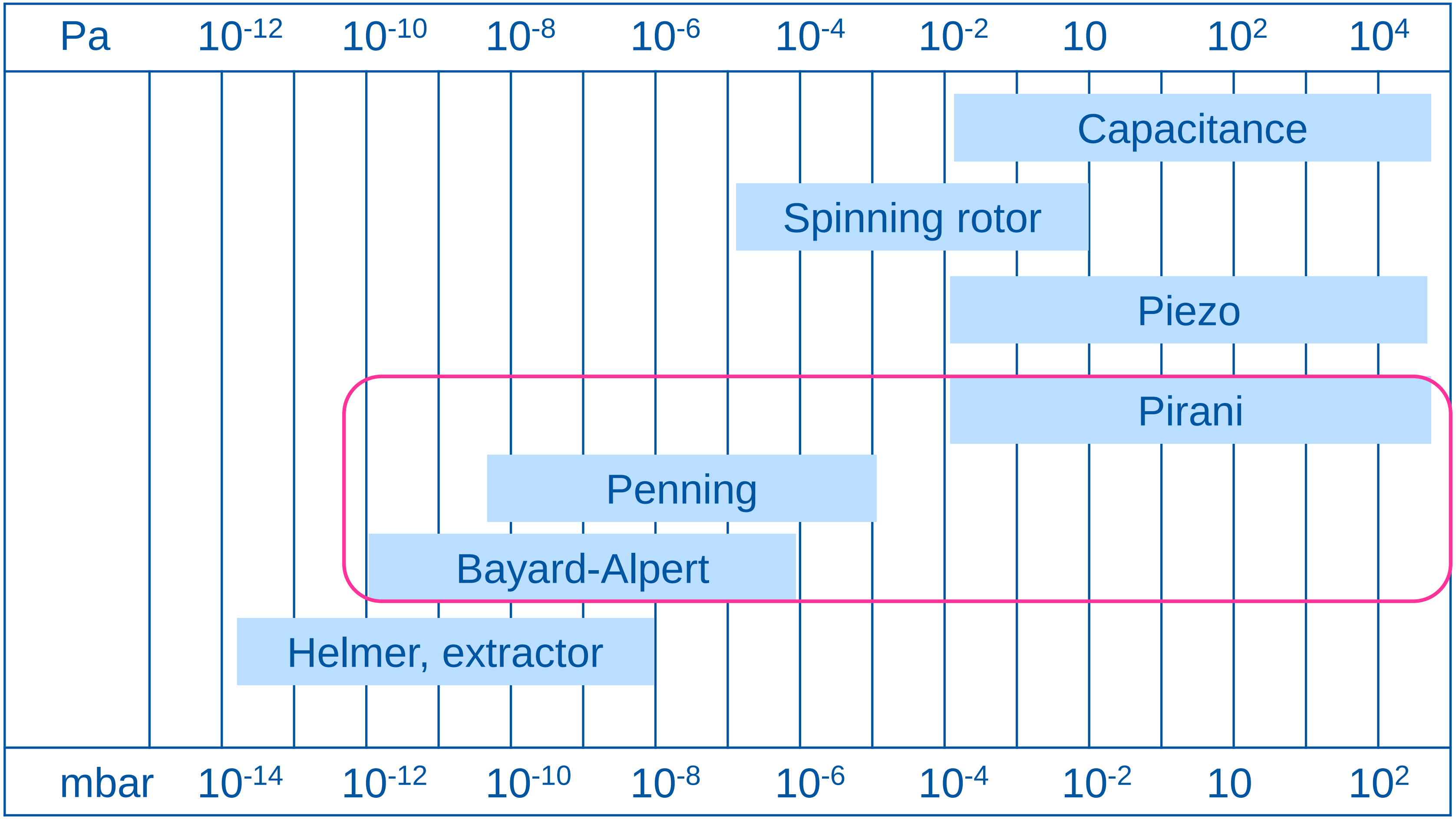
Pictures Edwards

# 3. Measurement & production of vacuum

# 3.1 Vacuum gauges

# Vacuum gauges pressure range

16 orders of magnitude !

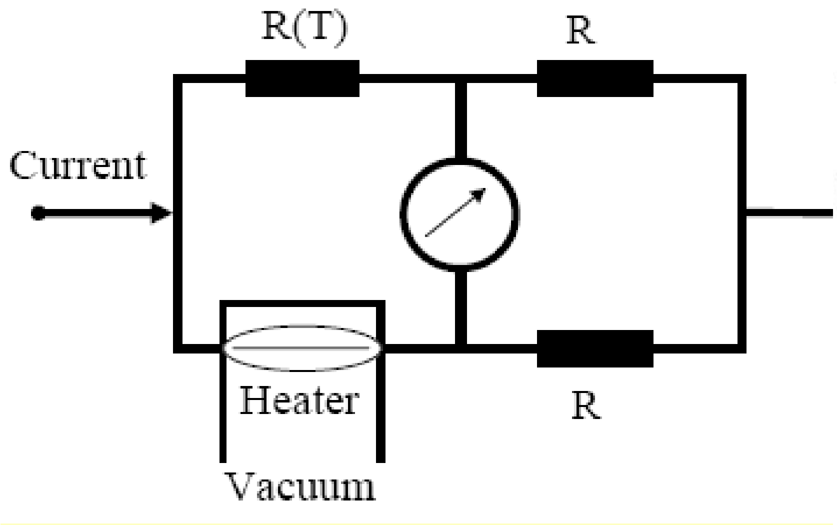


# Pirani Gauge

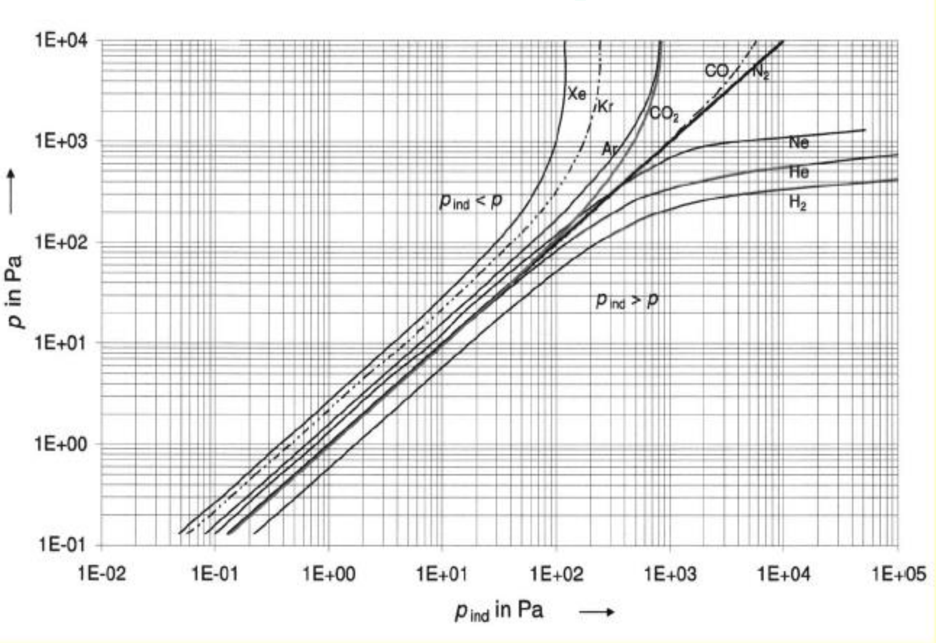
- Pirani gauges are commonly used in the range 1 atm -$10^{-4}$ mbar.

- The operating principle is based on the variation of the thermal conductivity of the gases as a function of pressure. A resistor under vacuum is heated at a constant temperature (~ 120°C). The heating current required to keep the temperature constant is a measure of the pressure.

- In the viscous regime, the thermal conductivity is independent of the pressure. Therefore pressure readings given above 1 mbar are wrong !



**True vs indicated pressure**



K. Jousten. J.Vac.Sci. Technol. 26(3), May/Jun 2008, 352-359

# Penning Gauge

- Penning gauges are commonly used in the range $10^{-5}$ -$10^{-10}$ mbar.  They are use for interlocking purposes

- It is a cold cathode ionisation gauge *i.e.* there are no hot filament

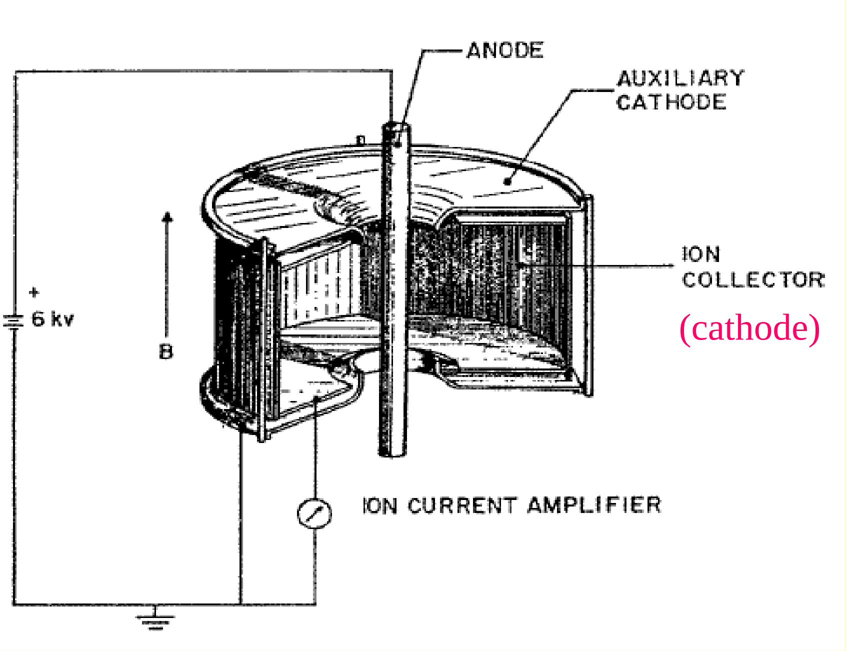
- The operating principle is based on the measurement of a discharge current in a Penning cell which is a function of pressure : $I^+ = P^n$, n is close to 1

- At high pressure the discharge is unstable due to arcing.
- At low pressure, the discharge extinguishes which means zero pressure reading …

- Electrons are produced by field emission and perform oscillations due to the magnetic field

- Along the path length, molecules are ionised and ions are collected onto the cathode

- WARNING :  leakage current on the HV cables simulates a higher pressure



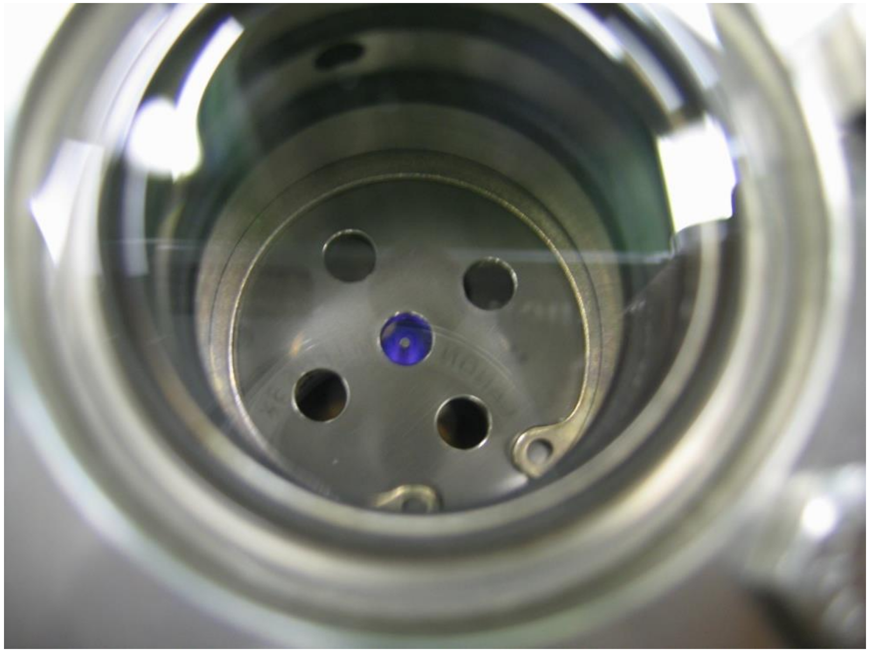
P. Redhead. J.Vac.Sci. 21(5), Sept/Oct 2003, S1-S5

# A discharge in a Penning gauge

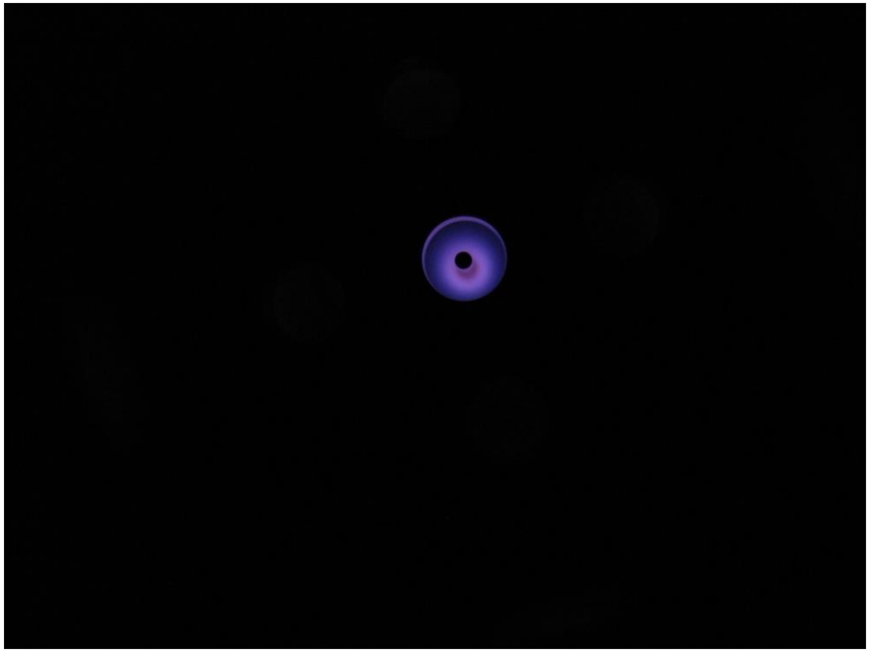
- a Penning gauge:

Courtesy Pfeiffer

Penning gauge ON behind a window



In the dark, the discharge is seen

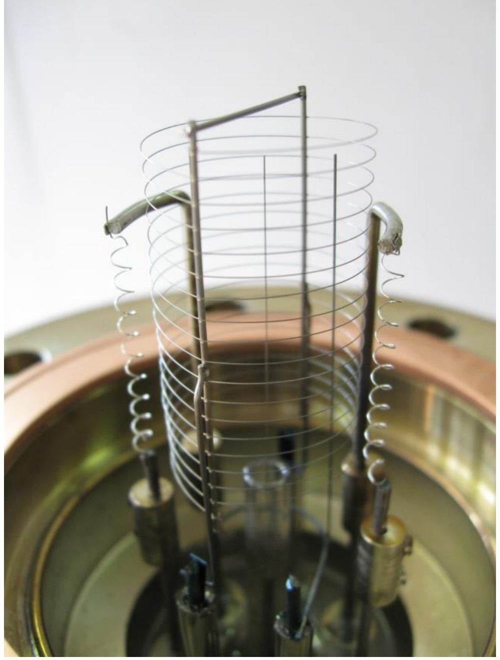


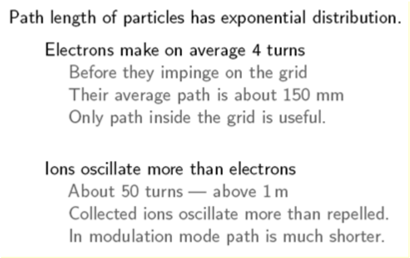
Pictures courtesy B. Henrist, TE-VSC

# Bayard-Alpert Gauge

- Bayard-Alpert gauges are used for vacuum measurement purposes in the range $10^{-6}$ -$10^{-12}$ mbar.

- It is a hot filament ionisation gauge. Electrons emitted by the filament perform a few oscillations inside the grid and ionise the molecules of the residual gas. Ions are then collected by an electrode.





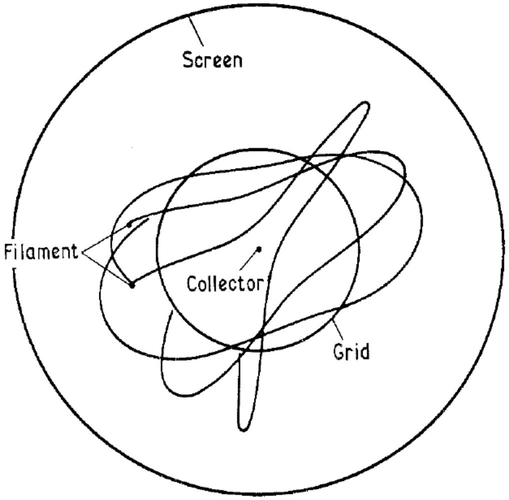
Path length of particles has exponential distribution.

Electrons make on average 4 turns
- Before they impinge on the grid
- Their average path is about 150 mm
- Only path inside the grid is useful.

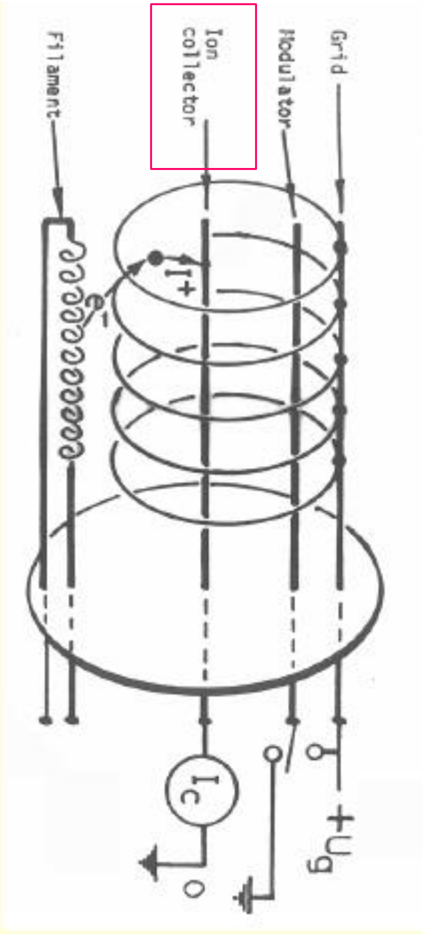
Ions oscillate more than electrons
- About 50 turns — above 1 m
- Collected ions oscillate more than repelled.
- In modulation mode path is much shorter.

Courtesy B. Jenninger

Ion collector = 0 V
Filament = + 50 V
Grid = + 150 V
Modulator = + 150 V



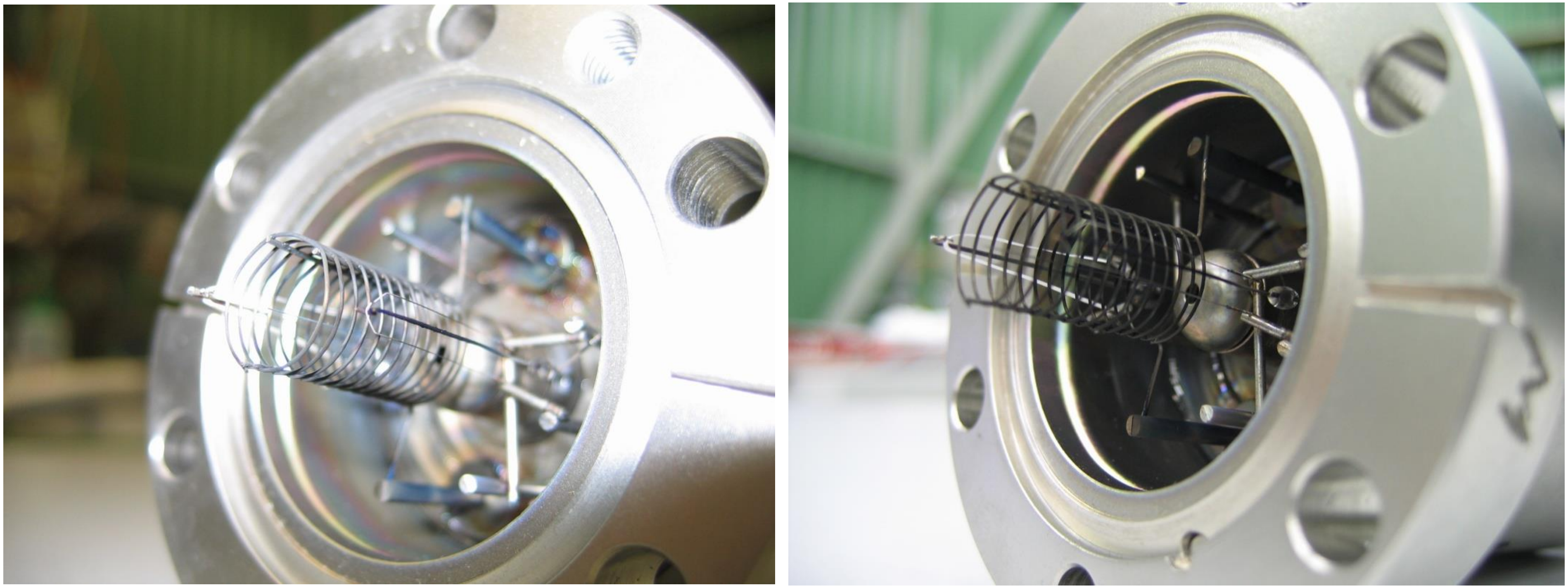
L.G. Pittaway. J. of Phys. D: Appl. Phys. 3, 1113-1121, 1970



# A burned filament

- Obviously, even is there are 2 filaments, the gauge is polluted therefore the pressure measurement will not be correct !

- It is wise to exchange the vacuum gauge



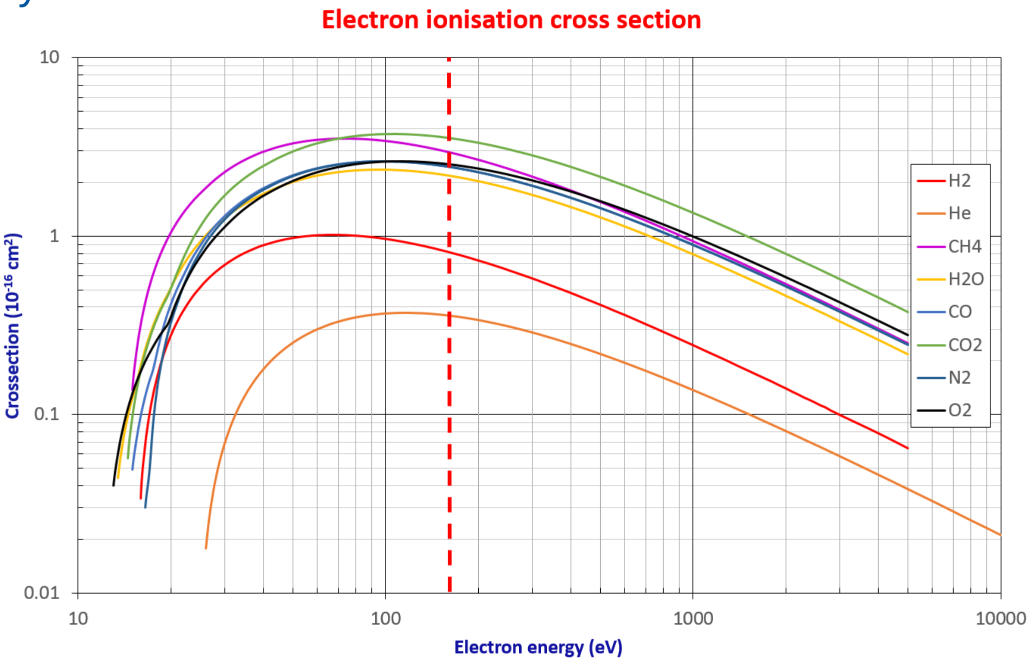
Pictures courtesy B. Henrist, TE-VSC

# Bayard-Alpert Gauge: Sensitivity

- The ion current collection can be described by:

$$I^+ = I_e \sigma\, n\, L$$

Where :
$I^+$ is the ion current
$I^-$ is the filament current
σ is the ionisation cross section
n the gas density
L the electron path length



- The vacuum gauge sensitivity, S in mbar$^{-1}$, is defined by:

$$I^+ = I_e\, S\, P \qquad S = \frac{\sigma\, L}{k\, T}$$

| $I_e$ (mA) | P (mbar) | $I^+$ (pA) |
|---|---|---|
| 4 | $10^{-10}$ | 16 |
| 4 | $10^{-12}$ | 0.16 |
| 0.1 | $10^{-10}$ | 0.4 |
| 0.1 | $10^{-12}$ | 0.004 |

- The gauge needs to be calibrated for several gases
- $S_{N2}$ ~ 40 mbar$^{-1}$
- The pressure reading is expressed in nitrogen equivalent
- In UHV, typical collected current are in the pA range

# Bayard-Alpert Gauge: Sensitivity

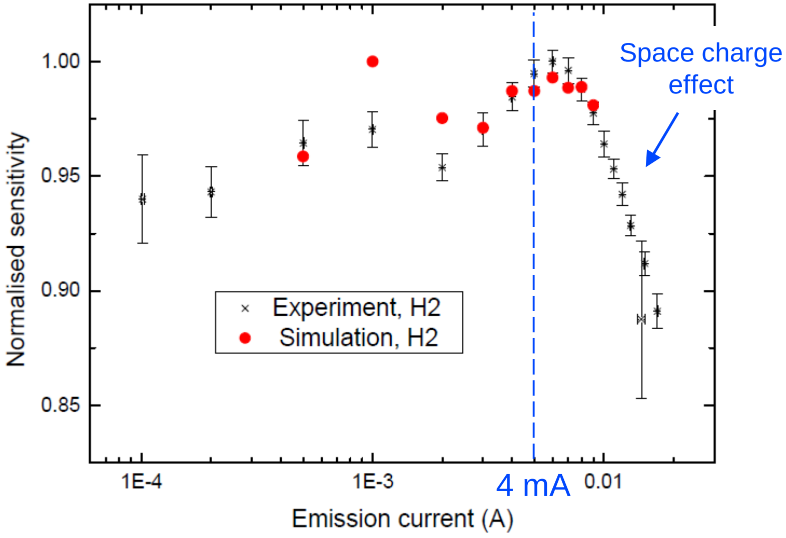
- The sensitivity can be measured and also computed from simulations

$$S_i = \frac{\sigma\, L}{k\, T}$$

- Relative sensitivity:

$$S_{rel,i} = \frac{S_{N2}}{S_i}$$

$$\boxed{P_i = S_{rel,i}\, P_{N2}}$$



B. Jenninger *et al*. Vacuum 138 (2017) 173-177

| | $H_2$ | He | $CH_4$ | Ne | $N_2$ | CO | $C_2H_6$ | Ar | $CO_2$ | Xe |
|---|---|---|---|---|---|---|---|---|---|---|
| $S_i$ ($mbar^{-1}$) | 19.06 | 7.46 | 60.62 | 10.48 | 41.84 | 42.30 | 114.71 | 53.19 | 54.48 | 7.50 |
| $S_{rel,i}$ ($mbar,i/mbar,N_2$) | 2.20 | 5.61 | 0.69 | 3.41 | 1.00 | 0.99 | 0.36 | 0.79 | 0.77 | 4.83 |

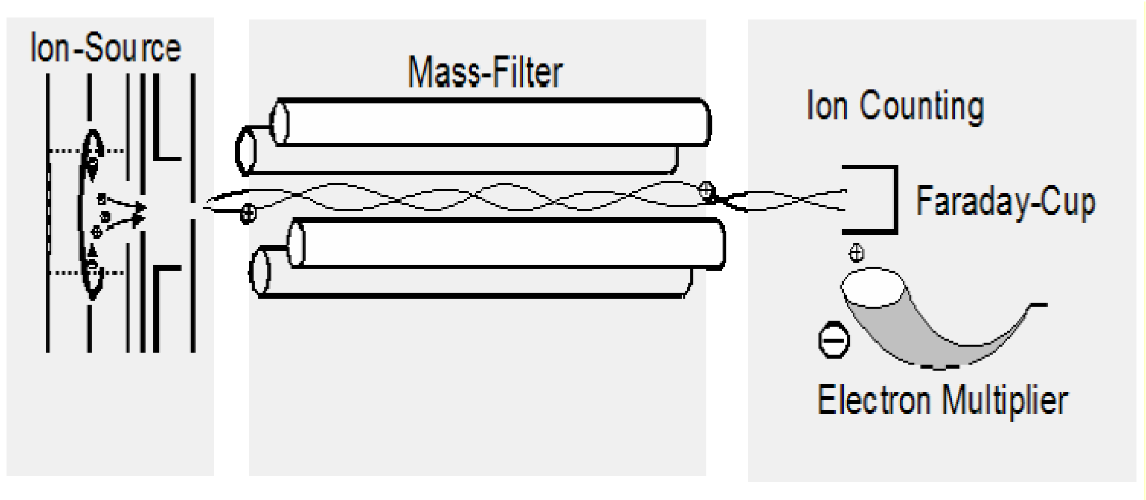
- The sensitivity relative error equals ~ 10 %
- A pressure reading in $N_2$ equivalent is: $P_{read}$ =2 $10^{-10}$ mbar, in the case the main molecular species is $H_2$, the real pressure is: $P = S_{rel,H2} \times P_{read}$ = 4.4 $10^{-10}$ mbar

# 3.2 Gas analysis

# Residual Gas Analysers

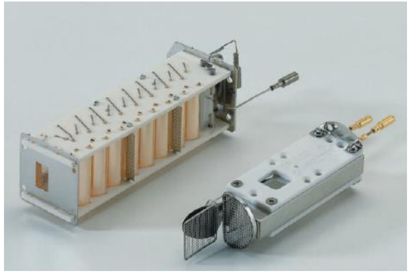
- Residual Gas Analysers are used in the range $10^{-4}$ -$10^{-13}$ mbar. Their purpose is to do gas analysis
- A filament produces electrons which ionise the residual gas inside a grid.
- A mass filter is introduced between the grid and the ion collector.
- The ion current can be measured in Faraday mode or in secondary electron multiplier mode.

G.J. Peter, N. Müller. CAS Vacuum in accelerators CERN 2007-003



1 mA
Q ~ 2 $10^{-9}$ mbar.l/s

ΔM at FHWM = 0.5 AMU



Range: $10^{-14}$ till $10^{-5}$ A
Gain ~ $10^{3}$ -$10^{4}$ electrons/ion

Picture Pfeiffer

# RGA: Cracking pattern

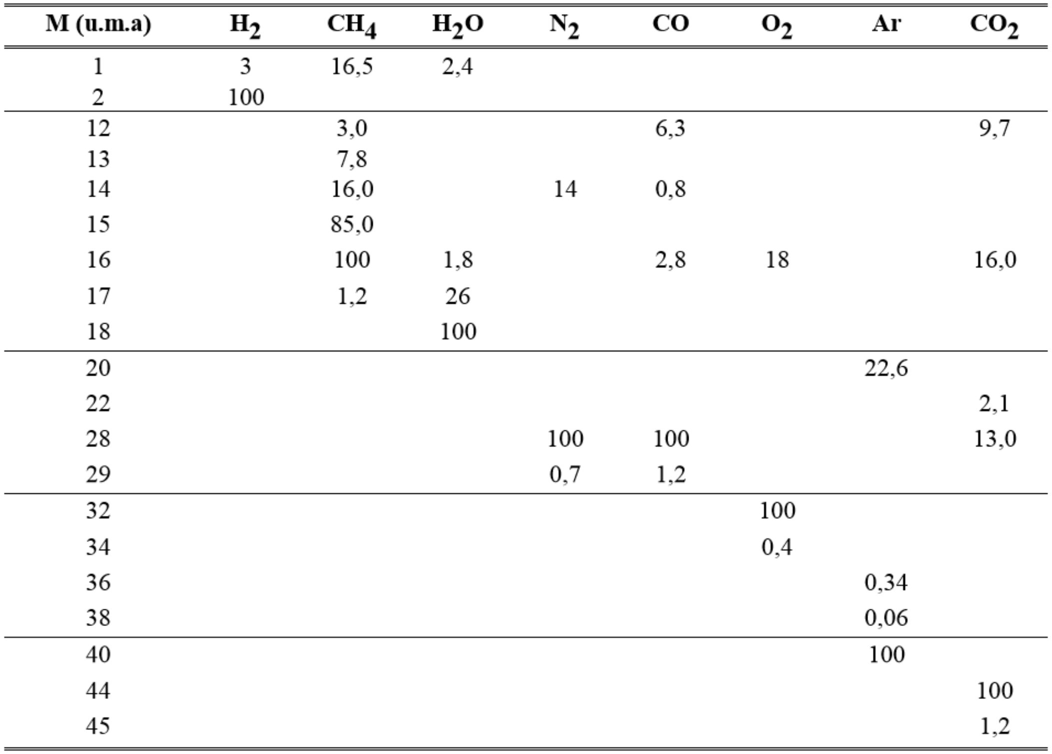
- Ions produced inside the grid can be fragmented into sub-species by the collisions with electrons
- The table gives the percentage of the fragments with respect to the main peak

- Example Mass 28

- Nitrogen is traced by mass:
  $28\ (N_2^+)$
  $14\ (N^+)$: $I_{14} = 0.14\ I_{28}$

- Carbon monoxide is traced by mass:
  $28\ (CO^+)$
  $12\ (C^+)$: $I_{12} = 0.06\ I_{28}$

- Carbon dioxide is traced by mass:
  $44\ (CO_2^+)$
  $28\ (CO^+)$: $I_{28} = 0.13\ I_{44}$
  $16\ (O^+)$: $I_{16} = 0.16\ I_{44}$
  $12\ (C^+)$: $I_{12} = 0.10\ I_{44}$

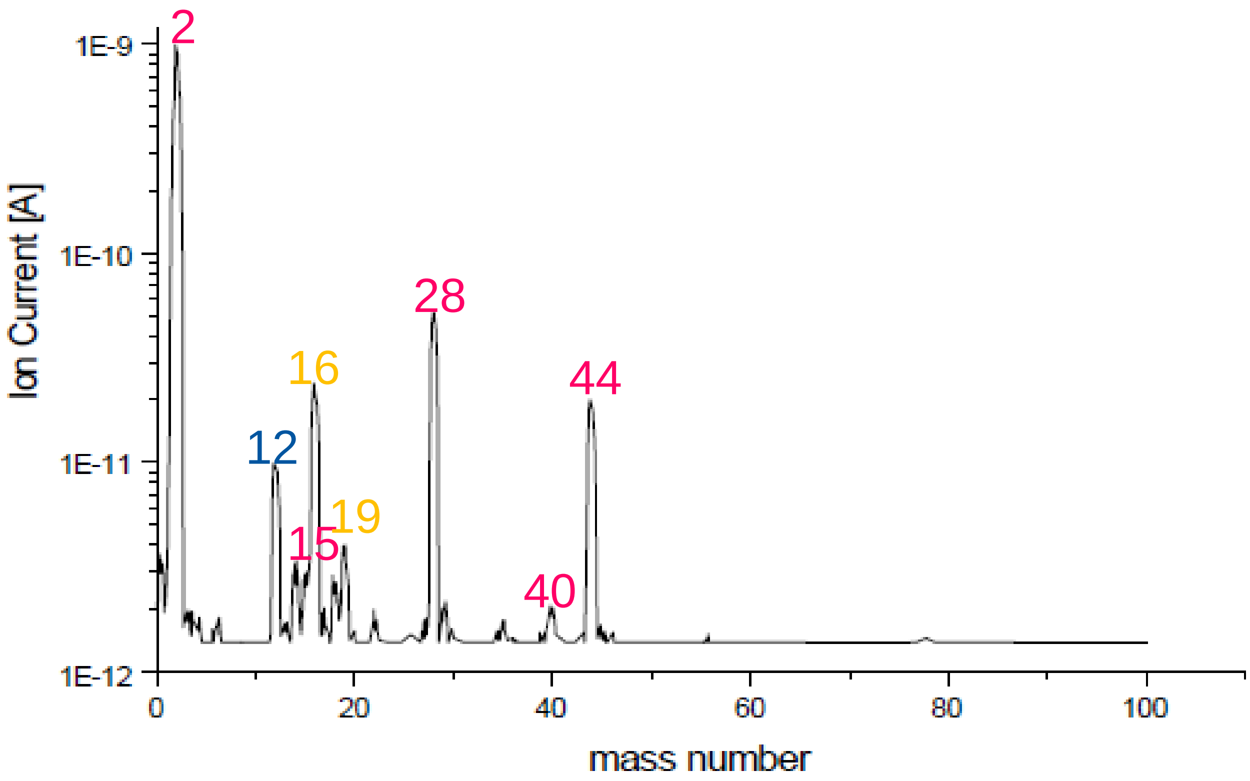


| M (u.m.a) | $H_2$ | $CH_4$ | $H_2O$ | $N_2$ | CO | $O_2$ | Ar | $CO_2$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 16,5 | 2,4 | | | | | |
| 2 | 100 | | | | | | | |
| 12 | | 3,0 | | | 6,3 | | | 9,7 |
| 13 | | 7,8 | | | | | | |
| 14 | | 16,0 | | 14 | 0,8 | | | |
| 15 | | 85,0 | | | | | | |
| 16 | | 100 | 1,8 | | 2,8 | 18 | | 16,0 |
| 17 | | 1,2 | 26 | | | | | |
| 18 | | | 100 | | | | | |
| 20 | | | | | | | 22,6 | |
| 22 | | | | | | | | 2,1 |
| 28 | | | | 100 | 100 | | | 13,0 |
| 29 | | | | 0,7 | 1,2 | | | |
| 32 | | | | | | 100 | | |
| 34 | | | | | | 0,4 | | |
| 36 | | | | | | | 0,34 | |
| 38 | | | | | | | 0,06 | |
| 40 | | | | | | | 100 | |
| 44 | | | | | | | | 100 |
| 45 | | | | | | | | 1,2 |

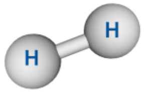
# RGA: Spectrum

- A typical spectrum of a baked vacuum system: P = $10^{-10}$ mbar

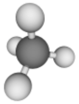
| M/e | Ion | Molecule |
|---|---|---|
| 2 | $H_2^+$ | $H_2$ |
| 15 | $CH_3^+$ | $CH_4$ |
| 28 | $CO^+$ | CO |
| 40 | $Ar^+$ | Ar |
| 44 | $CO_2^+$ | $CO_2$ |
| 12 | $C^+$ | $CO+CO_2$ |
| 16 | $O^+$ | Filament artefacts |
| 19 | $F^+$ | |



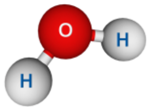
$H_2$
Di-Hydrogen
M/e=2;1



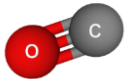
$CH_4$
Methane
M/e=15;(16)



$H_2O$
Water
M/e=18;17;16

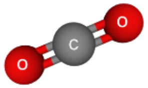


CO
Carbon monoxide
M/e=28;12

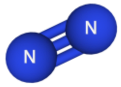


Ar
Argon
M/e=40;20

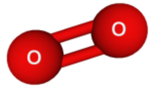
$CO_2$
Carbon dioxide
M/e=44;16;28;12



$N_2$
Nitrogen
M/e=28;14



$O_2$
Oxygen
M/e=32;16



# RGA: Partial Pressure

- The RGA needs to be calibrated against a total pressure gauge for standard gases.
- To take into account the RGA ageing, relatives sensitives are used and a normalization factor, K, is introduced

$$P_{i,N2} = K\, S_{abs,CO,RGA} \times S_{rel,i,RGA} \times I_i$$

- According to the Dalton's law, the reading given by the total pressure gauge shall equal the sum of the partial pressure, expressed in nitrogen equivalent:

$$P_{N2} = \sum_{j=1}^{n} P_{j,N2} = K\, S_{abs,CO,RGA} \sum_{j=1}^{n} \left(S_{rel,j,RGA} \times I_j\right)$$

- Therefore:

$$K = \frac{P_{N2}}{S_{abs,CO,RGA} \sum_{j=1}^{n} \left(S_{rel,j,RGA} \times I_j\right)}$$

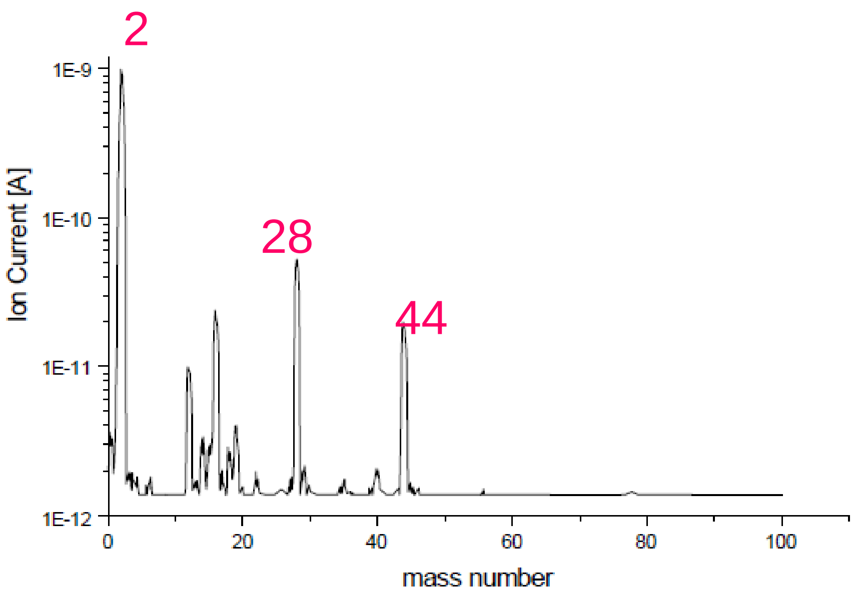
- So:

$$\boxed{P_i = S_{rel,i}\, P_{i,N2} = S_{rel,i} \frac{S_{rel,i,RGA}}{\sum_{j=1}^{n} S_{rel,j,RGA} \times I_j} P_{N2}\, I_i}$$

| | $H_2$ | $CH_4$ | $N_2$ | CO | Ar | $CO_2$ |
|---|---|---|---|---|---|---|
| $S_{rel,i,RGA}$ (Torr $N_2$/Torr) | 1.09 | 0.93 | 0.99 | 1 | 1.18 | 1.96 |

# RGA: Partial Pressure

- Example: a baked system with P= $10^{-10}$ mbar $N_2$ eq

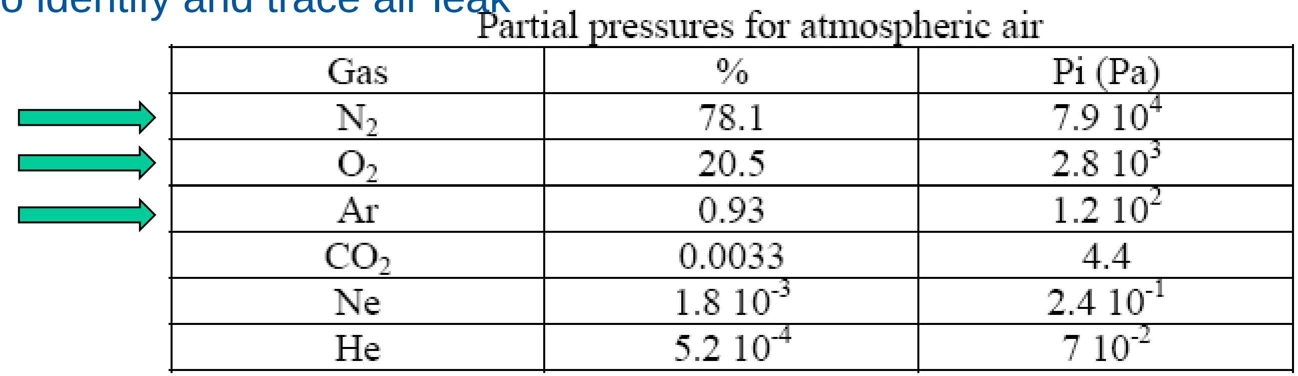


| | $H_2$ | $CH_4$ | CO | Ar | $CO_2$ |
|---|---|---|---|---|---|
| I (A) | $1\ 10^{-9}$ | $2\ 10^{-12}$ | $7\ 10^{-11}$ | $5\ 10^{-13}$ | $2\ 10^{-11}$ |
| P (mbar) | $2\ 10^{-10}$ | $1\ 10^{-13}$ | $6\ 10^{-12}$ | $4\ 10^{-14}$ | $3\ 10^{-12}$ |
| % Pi | 96 | 0 | 3 | 0 | 1 |

- Note: a simple estimation from the total pressure measurement would give P= 2.2 $10^{-10}$ mbar!

# RGA: Air Leak

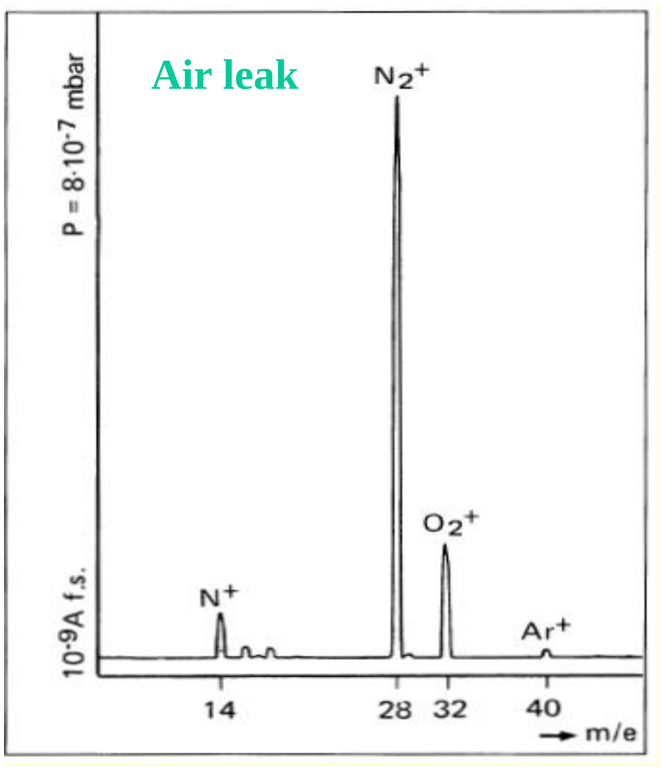
- RGA are useful to identify and trace air leak



Partial pressures for atmospheric air

| Gas | % | Pi (Pa) |
|---|---|---|
| $N_2$ | 78.1 | $7.9\ 10^4$ |
| $O_2$ | 20.5 | $2.8\ 10^3$ |
| Ar | 0.93 | $1.2\ 10^2$ |
| $CO_2$ | 0.0033 | 4.4 |
| Ne | $1.8\ 10^{-3}$ | $2.4\ 10^{-1}$ |
| He | $5.2\ 10^{-4}$ | $7\ 10^{-2}$ |

| M/e | Ion | Molecule |
|---|---|---|
| 14 | $N^+$ | $N_2$ |
| 28 | $N_2^+$ | $N_2$ |
| 32 | $O_2^+$ | $O_2$ |
| 40 | $Ar^+$ | Ar |



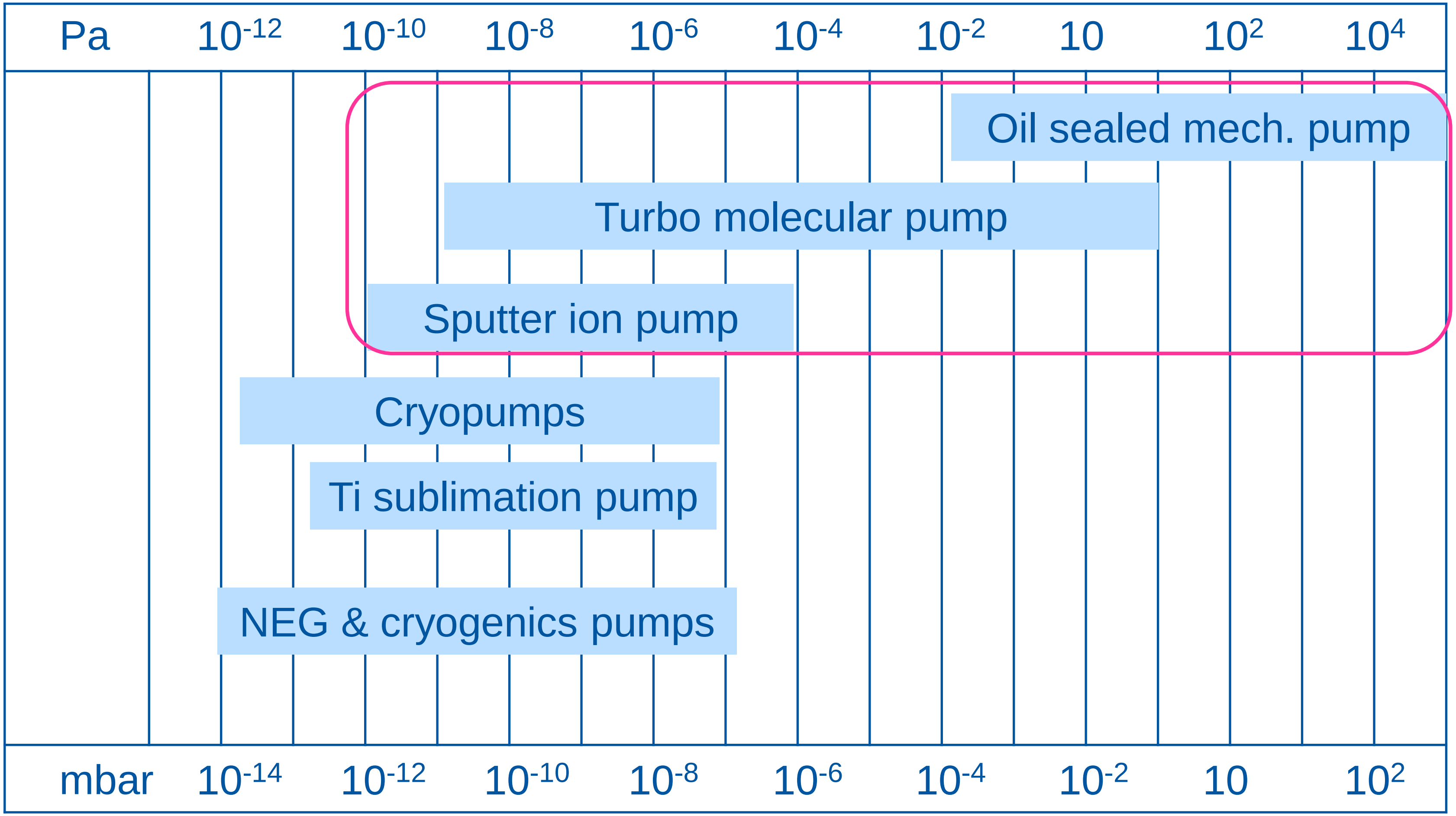
- Assume a 8 cm diam. tube with specific conductance ~ 60 l.s.m:
  - a leak located 10 m away from the gauge
  - a pumping speed of 6 l/s at the level of the leak would give a leak rate is $5\ 10^{-6}$ mbar.l/s (i.e. 6 x 8 $10^{-7}$)

- Oxygen being highly chemically reactive, its mass is not always present in the spectrum!

# 3.3 Vacuum pumps

# Vacuum pumps pressure range

16 orders of magnitude !



# Primary Pumps

- Are used to pump down from atmosphere down to $10^{-2}$ mbar with a speed of a few $m^3/h$

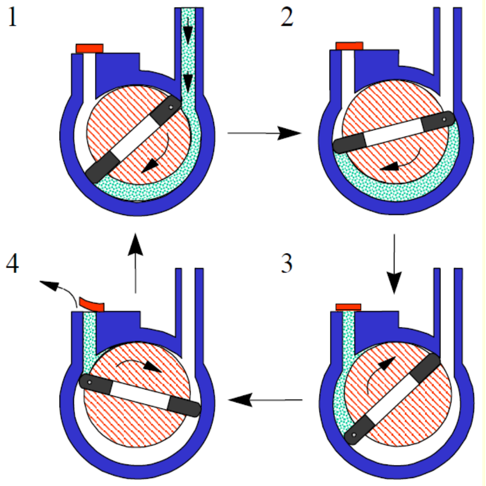
- They are usually used as a backing pump of turbomolecular pumps

- Two categories : dry and wet pumps.

- Dry pumps are expensive and need additional cooling (water)

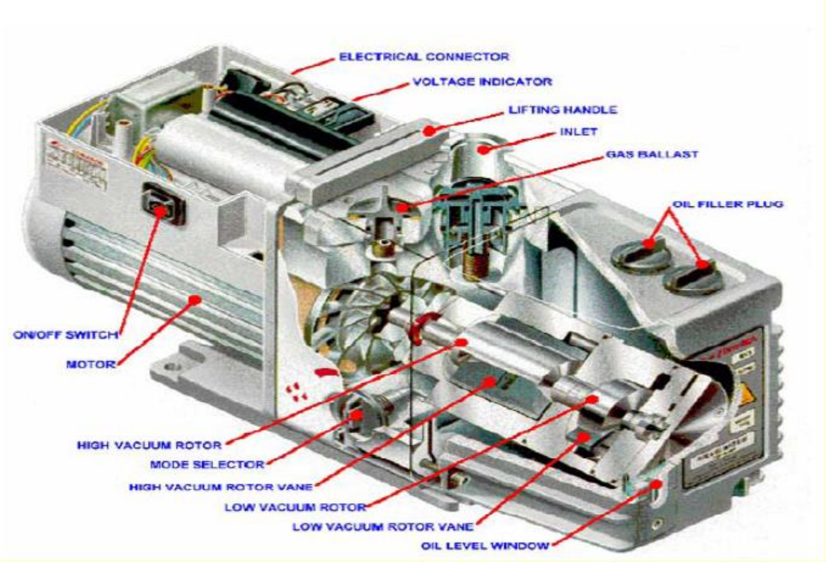
- Wet pumps are operating with oil which acts as a sealing, a lubricant, a heat exchanger and protects parts from rust and corrosion

**Oil Sealed Rotary Vane Pump**



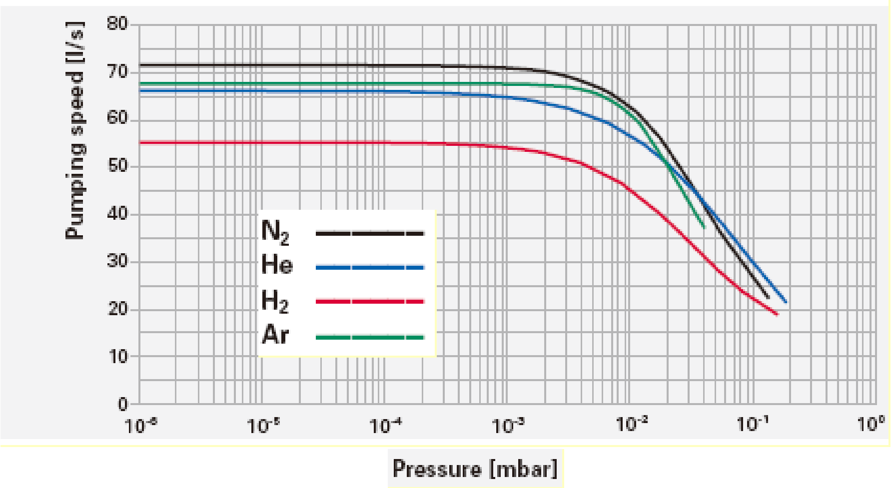
1 Inlet exposed
2 Trapped volume
3 Compression
4 Exhaust

A.D. Chew. CAS Vacuum in accelerators CERN 2007-003



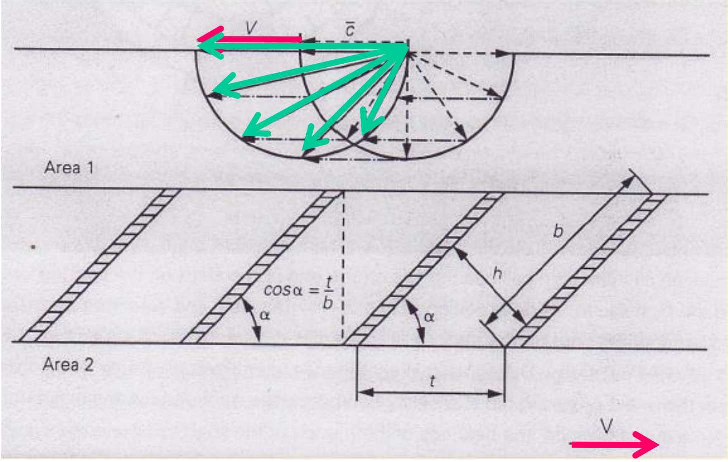
# Turbomolecular Pump

- This pump operates in the molecular regime and is used to pump down an accelerator vacuum system. Usually, it is installed with its primary pump on a mobile trolley : it can be removed after valving off
- Its ultimate pressure can be very low : $10^{-11}$ mbar
- Its pumping speed range from 10 to 3 000 l/s



Picture Pfeiffer

- The pumping mechanism is based on the transfer of impulse. When a molecule collide a blade, it is adsorbed for a certain lenght of time. After re-emission, the blade speed is added to the thermal speed of the molecules. To be significant, the blade speed must be comparable to the thermal speed hence it requires fast moving surfaces (~ 40 000 turns/min)

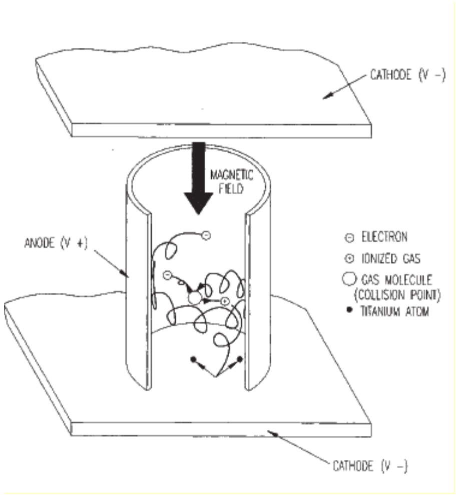


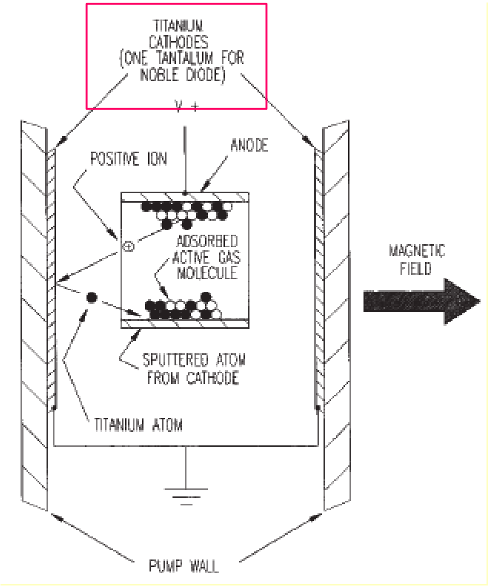
- The compression ratio ($P_{inlet}/P_{outlet}$) increase exponentially with $\sqrt{M}$ : "clean" vacuum without hydrocarbons. So, the oil contamination from the primary pump is avoided

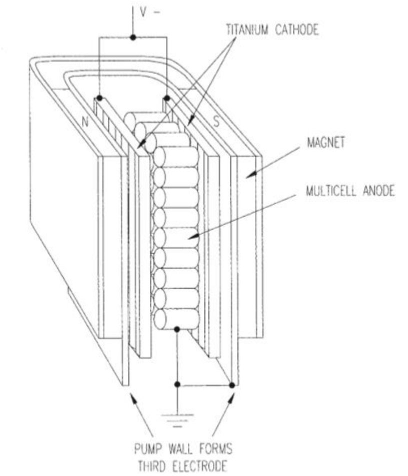
# Sputter Ion Pump

- This pump operate in the range $10^{-5}$ -$10^{-11}$ mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator.
- Their pumping speed range from 1 to 500 l/s.

- When electrons spiral in the Penning cell, they ionised molecules. Ions are accelerated towards the cathode (few kV) and sputter Ti. Ti, which is deposited onto the surfaces, forms a chemical bounding with molecules from the residual gas. Noble gases and hydrocarbons ,which does not react with Ti, are buried or implanted onto the cathode.
- Advantage : like for a Penning gauge, the collected current is proportional to the pressure. It is also used for interlock.







Triode
(noble gas)

Picture Agilent, Varian

# Lecture 1 summary

- The kinetics of gas molecules is described by a Maxwell-Boltzmann distribution.

- The pressure is defined by the ideal gas law.

- As a function of mean free path, several regime of flow exits.

- The molecular flow is the regime of vacuum systems: the molecules interact only with the vacuum chamber wall.

- The conductance characterise the pressure drop along a vacuum component

- The pressure in a vessel is defined by the ratio of the gas flow to the pumping speed

- Main instruments for vacuum measurement are: Pirani, Penning, Bayart-Alpert gauges and residual gas analysers

- Main devices for vacuum pumping are: primary, turbomolecular and ion pumps.

# Some References

- Cern Accelerator School, Vacuum technology, CERN 99-05
- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
- Cern Accelerator School, Vacuum for particle accelerators, Glumslov, June 2017

- The physical basis of ultra-high vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen. AVS.
- Scientific foundations of vacuum technique, S. Dushman, J.M Lafferty. J. Wiley & sons.
- Les calculs de la technique du vide, J. Delafosse, G. Mongodin, G.A. Boutry. Le vide.
- Vacuum Technology, A. Roth. Elsevier Science
- Foundations of vacuum science and technology, Ed by J.M. Lafferty. J. Wiley & sons.

# Some Journals Related to Vacuum Technology

- Journal of vacuum science and technology
- Vacuum

**Thank you for your attention !!!**


CERN

# Complementary informations

# 2.1 Gas kinetic theory

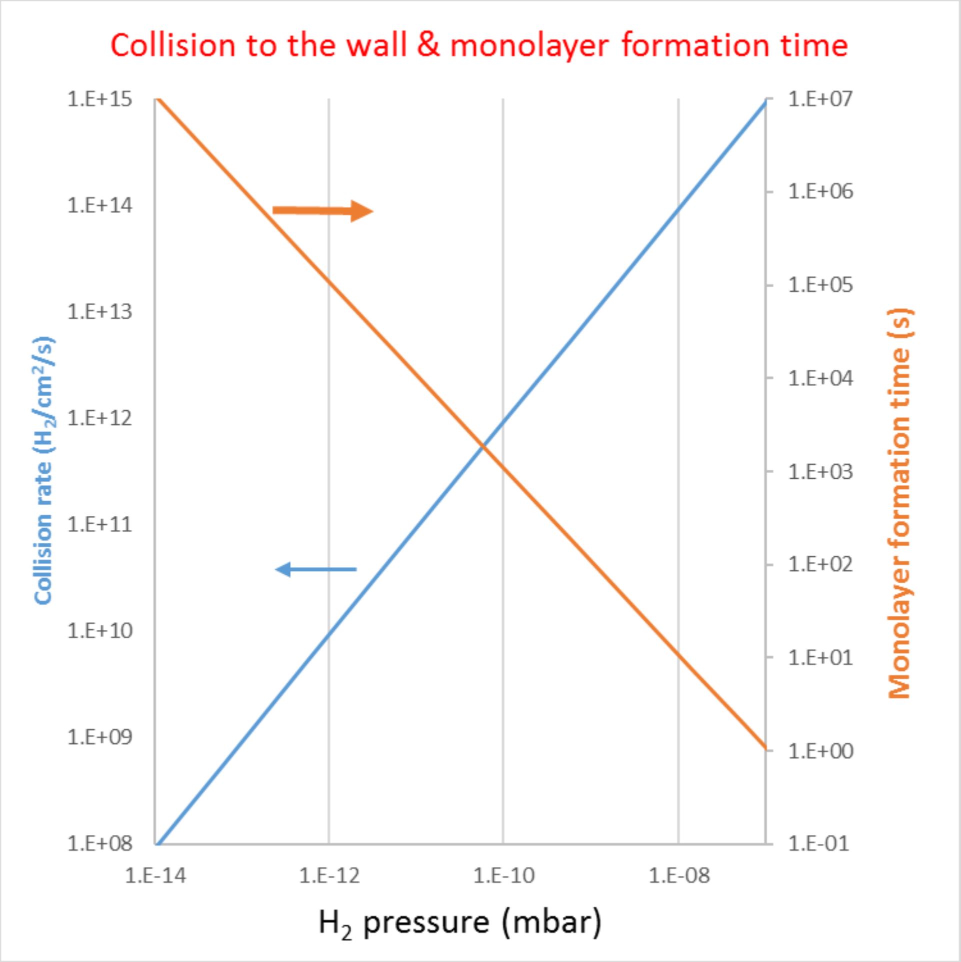
# Collision on the wall: cryogenic temperature

- The molecular collision rate on the wall (the incidence rate), ν, can be derived from the Maxwell Boltzmann distribution

Complementary information

| n<br>($H_2/m^3$) | V<br>($H_2/cm^2/s$) | Time |
|---|---|---|
| $10^{10}$ | $5\ 10^{7}$ | 220 d |
| $10^{11}$ | $5\ 10^{8}$ | 22 d |
| $10^{12}$ | $5\ 10^{9}$ | 2 |
| $10^{13}$ | $5\ 10^{10}$ | 5 h |
| $10^{14}$ | $510^{11}$ | 30 min |
| $10^{15}$ | $5\ 10^{12}$ | 3 min |

H2 at 4.2 K



# 2.2 Gas flow

# As a function of pressure

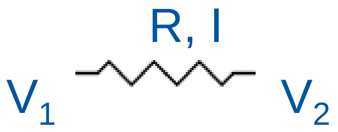
Complementary information

| P (mbar) | Force per unit surface | Density (molec.cm$^{-3}$) | Mean free path | Incidence rate (cm$^{-2}$.s$^{-1}$) | Monolayer formation time |
|---|---|---|---|---|---|
| 1013 | 1 kg/cm$^2$ | 2.5 $10^{19}$ | 0.1 μm | 2.9 $10^{23}$ | 3.4 ns |
| 1 | 1 g/cm$^2$ | 2.5 $10^{16}$ | 0.1 mm | 2.9 $10^{20}$ | 3.4 μs |
| $10^{-3}$ | 1 mg/cm$^2$ | 2.5 $10^{13}$ | 10 cm | 2.9 $10^{17}$ | 3.4 ms |
| $10^{-6}$ | 1 μg/cm$^2$ | 2.5 $10^{10}$ | 100 m | 2.9 $10^{14}$ | 3.4 |
| $10^{-9}$ | 10 μg/m$^2$ | 2.5 $10^{7}$ | 100 km | 2.9 $10^{11}$ | 1 h |
| $10^{-12}$ | 10 ng/m$^2$ | 2.5 $10^{4}$ | $10^5$ km | 2.9 $10^{9}$ | 40 days |

# Conductance: Analogy to electricity

Complementary information

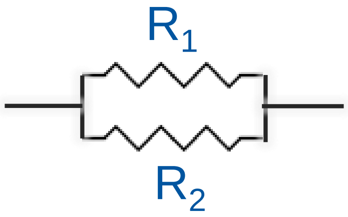
- The flux, Q, correspond to the current, I
- The pressure, P, corresponds to the voltage, V
- The inverse of the conductance, C, corresponds to the resistance, R



Ohm's law:

$$(V_1 - V_2) = R\,I \iff \frac{1}{R} = \frac{I}{(V_1 - V_2)} \longrightarrow \boxed{C = \frac{Q}{(P_1 - P_2)}}$$

- Adding resistances in parallel



$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \longrightarrow \boxed{C = C_1 + C_2}$$

- Adding resistances in series

$$R = R_1 + R_2 \longrightarrow \boxed{\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}}$$

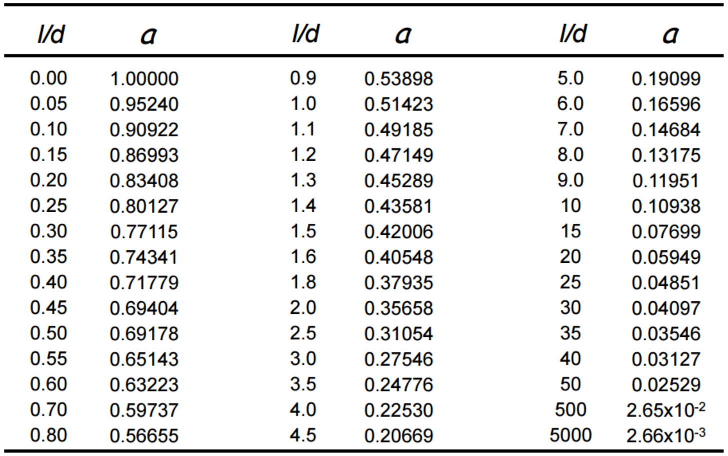
Vacuum systems can be computed using software developed for electrical engineering!

# More conductances

Complementary information

- Short tube: the conductance of an orifice multiplied by the Clausing factor *i.e.* the transmission probability trough the "short tube"

$$C = \alpha C_{Orifice} = \alpha \frac{v}{4} A$$



| l/d | a | l/d | a | l/d | a |
|---|---|---|---|---|---|
| 0.00 | 1.00000 | 0.9 | 0.53898 | 5.0 | 0.19099 |
| 0.05 | 0.95240 | 1.0 | 0.51423 | 6.0 | 0.16596 |
| 0.10 | 0.90922 | 1.1 | 0.49185 | 7.0 | 0.14684 |
| 0.15 | 0.86993 | 1.2 | 0.47149 | 8.0 | 0.13175 |
| 0.20 | 0.83408 | 1.3 | 0.45289 | 9.0 | 0.11951 |
| 0.25 | 0.80127 | 1.4 | 0.43581 | 10 | 0.10938 |
| 0.30 | 0.77115 | 1.5 | 0.42006 | 15 | 0.07699 |
| 0.35 | 0.74341 | 1.6 | 0.40548 | 20 | 0.05949 |
| 0.40 | 0.71779 | 1.8 | 0.37935 | 25 | 0.04851 |
| 0.45 | 0.69404 | 2.0 | 0.35658 | 30 | 0.04097 |
| 0.50 | 0.69178 | 2.5 | 0.31054 | 35 | 0.03546 |
| 0.55 | 0.65143 | 3.0 | 0.27546 | 40 | 0.03127 |
| 0.60 | 0.63223 | 3.5 | 0.24776 | 50 | 0.02529 |
| 0.70 | 0.59737 | 4.0 | 0.22530 | 500 | $2.65\times10^{-2}$ |
| 0.80 | 0.56655 | 4.5 | 0.20669 | 5000 | $2.66\times10^{-3}$ |

- For long circular tube, the transmission probability equals:

$$\alpha_{long\_tube} = {}^{4d}\!/_{3l}$$

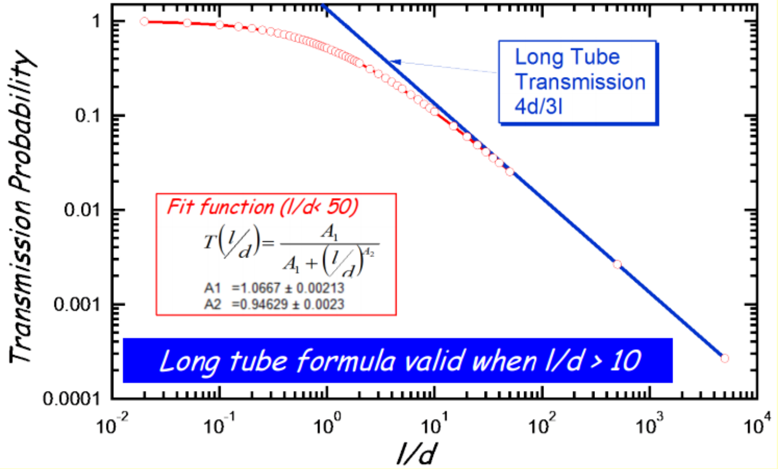
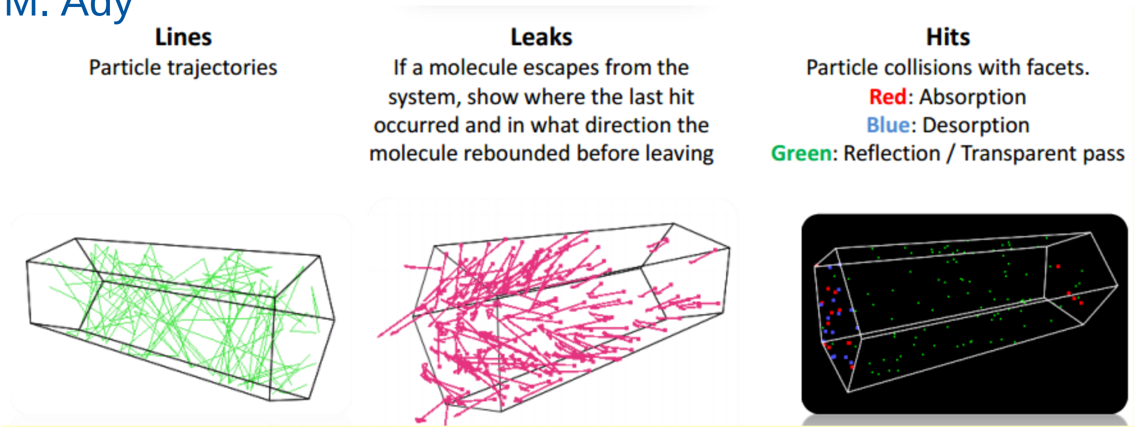


Table & plot courtesy of Y. Li and X. Liu
http://uspas.fnal.gov/materials/15ODU/Session1_Fundamentals.pdf

# Calculating conductances with Molflow+

Complementary information

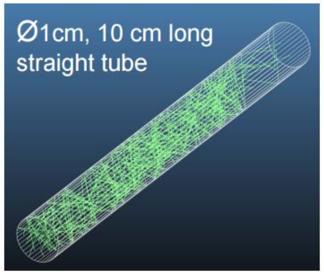
- A test particle Monte-Carlo code for molecular flow
- http://molflow.web.cern.ch/
- R. Kersevan – M. Ady

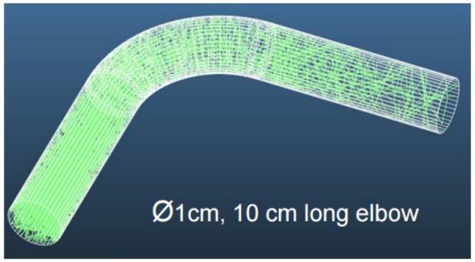


**Lines**
Particle trajectories

**Leaks**
If a molecule escapes from the system, show where the last hit occurred and in what direction the molecule rebounded before leaving

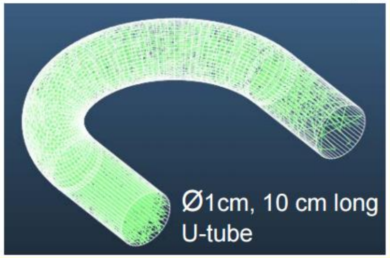
**Hits**
Particle collisions with facets.
**Red**: Absorption
**Blue**: Desorption
**Green**: Reflection / Transparent pass

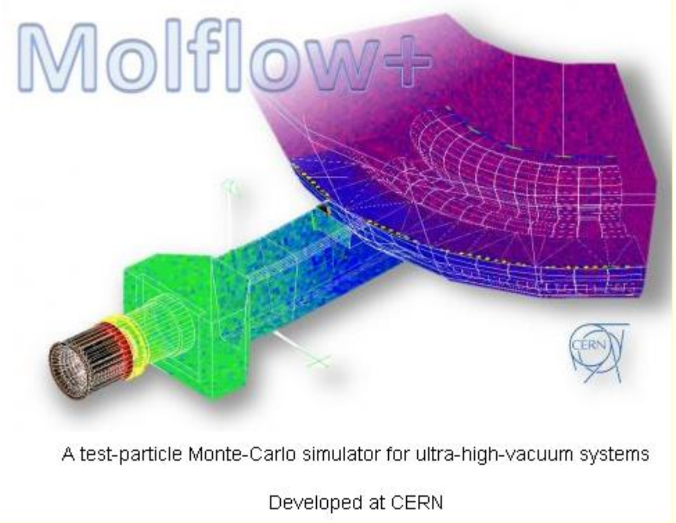




| Straight | $\alpha = 0.109$ |
|---|---|
| 90° Elbow | $\alpha = 0.105$ |
| 180° U | $\alpha = 0.093$ |

***These simple calculations took <1-minute***





A test-particle Monte-Carlo simulator for ultra-high-vacuum systems

Developed at CERN

courtesy of Y. Li and X. Liu

# 3.1 Vacuum gauges

# Spinning rotor gauge

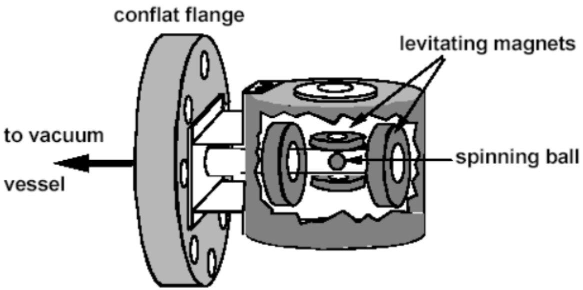
Complementary information

- It is a reference standard which allows an absolute measurement of the pressure
- It is fully bake able up to 450 deg (so low outgassing rate)
- SRG gauges are used in the range 5 $10^{-7}$ -$10^{-2}$ mbar, accuracy ~ 2 %, uncertainty ~0.5 %.

- A stainless steel ball is magnetically levitated and rotated by a drive assembly

- Collisions of the gas molecules with the surface of the ball decelerates the ball: the principle of measurement is mechanical

- The viscosity of the gas shall be entered into the power supply for pressure measurement



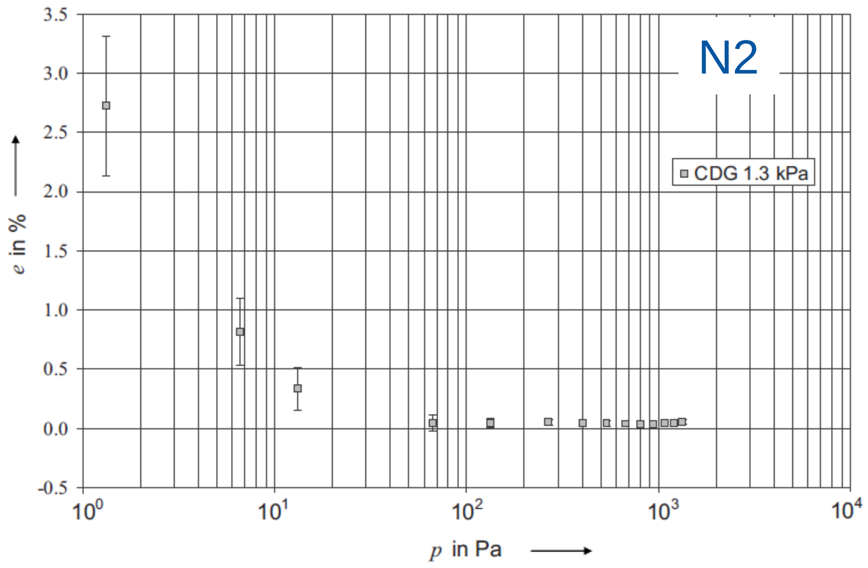
$$P = \frac{d_{Ball}}{10}\frac{\rho_{Ball}}{\sigma_{gaz}}\sqrt{\frac{2\pi RT}{M}}\frac{\left(T_{rev,n+1} - T_{rev,n}\right)}{\overline{T_{rev}}^{2}}$$

| Viscosity, $\sigma_{gaz}$ | $H_2$ | He | $CH_4$ | $H_2O$ | $N_2$ | CO | Ar | $CO_2$ | Xe |
|---|---|---|---|---|---|---|---|---|---|
| $10^{-6}$ Pa.s | 8.8 | 19.6 | 10.8 | 9 | 17.5 | 17.6 | 22.1 | 14.6 | 21.9 |

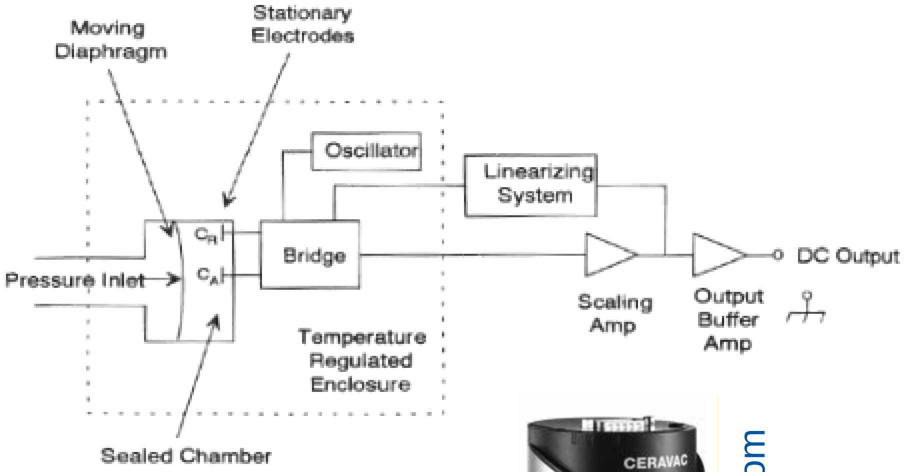
# Capacitance diaphragm gauge

Complementary information

- It allows an absolute direct measurement of the pressure: the reading is independent of the gas species!
- It operates in the range $10^{-5}$ – $10^{4}$ mbar
- Electrodes are placed in a vacuum of ~ $10^{-7}$ mbar maintained by a getter.
- The capacitance varies under the deflection of a 25 micron thick diaphragm due to the vacuum force (the pressure in the vacuum system)
- The sensitivity of the diaphragm deflection is 0.4 nm ($10^{-4}$ pF) !
- It is sensitive to thermal fluctuations: a thermostated housing is used (45 +/0.02 degres C)
- Uncertainty : 0.3 to 10 % - Accuracy: 0.15 %



K. Jousten, S. Nael, J.Vac. Sci.Technol. A 29(1), Jan/Feb 2011, 011011-1



Courtesy Vacom

# Strain gauge

Complementary information

- It allows a direct measurement of the pressure: the reading is independent of the gas species!

- A strain sensor is placed in a sealed volume

- The change of the pressure causes a diaphragm to move against the piezo sensitive plate of the strain sensor.

- This induce the change of the resistance of the piezoelectric transducer part of a bridge network

# Bayard-Alpert Gauge: CERN construction

Complementary information

- Large electron path length are needed to increase the vacuum gauge sensitivity: L ~ 7 cm
- The ionization volume (grid volume) must be large
- The gauge is mounted on a DN63 flange
- It is bake able to 400°C
- Low outgassing rate (~ 5 $10^{-10}$ mbar.l/s)

- Large sensitivity ~ 40 $\text{mbar}^{-1}$ for $N_2$

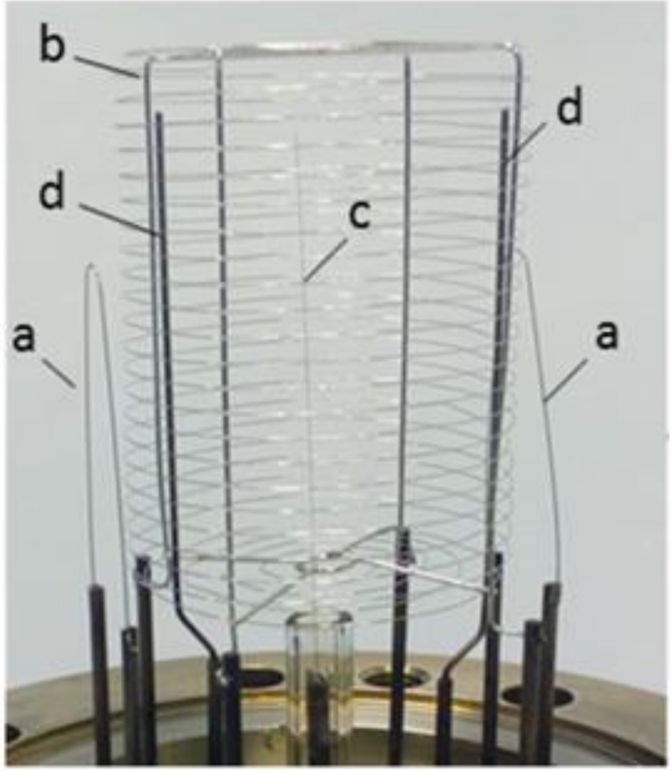
a. W Filament: Ø0.18, height 30

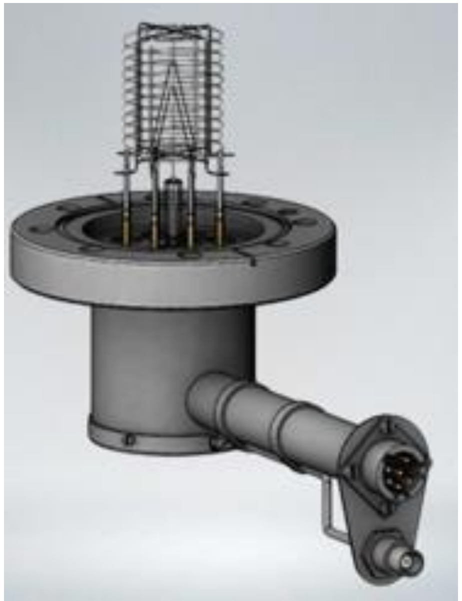
b. Closed grid: Ø35 x 45, pitch 2
Platinium-iridium wire: Ø0.13

c. W Collector: Ø0.05, length 42

d. Modulator: Ø0.7, length 42

$$V_{grid} = 50 \text{ cm}^3$$





# Bayard-Alpert Gauge: Filament

Complementary information

- Electron are produced at the W filament by thermo-electronic emission
- The emission is a function of the work function, Φ, of the material
- Filaments are made of Iridium/Ytrium, W/Thorium coated to reduce the work function, thereby reducing the operating temperature, T, (thus gas load into the system)

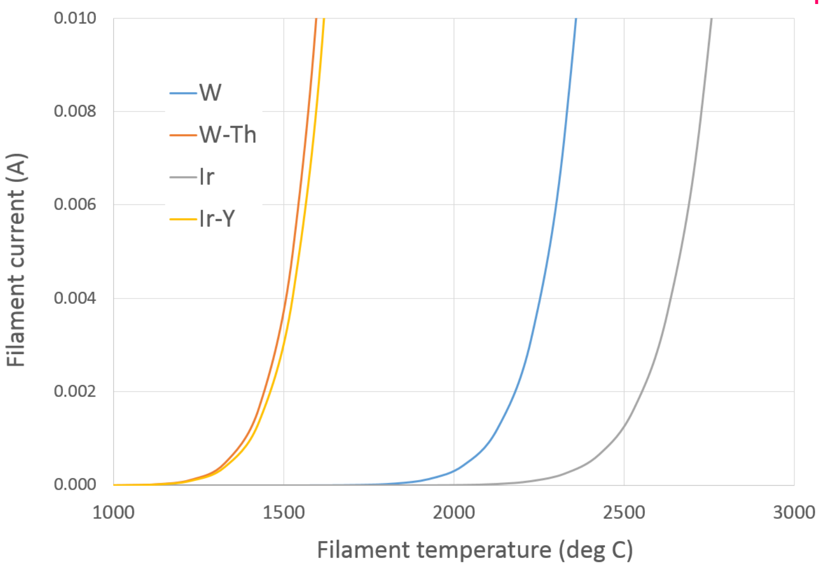
Richardson-Dushman equation

$$J = A\,T^2\,e^{-\left(\phi/kT\right)}$$

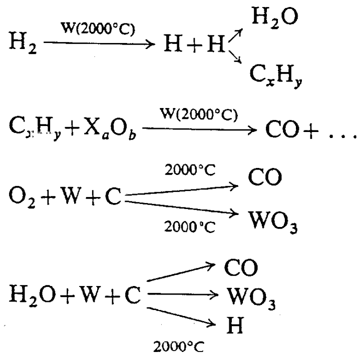
$A = (1-r)\,A_o$

$A_0 = 120\ \mathrm{A/(cm^2K^2)}$

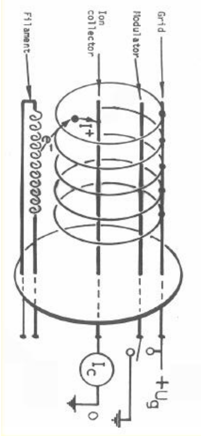
| Material | A | Φ (eV) |
|---|---|---|
| W | 60 | 4.54 |
| W-Th | 3 | 2.63 |
| Ir | 60 | 5.3 |
| Ir-Y | 2 | 2.6 |



Typical chemical reactions at the filament



D. Alpert, Le Vide 17 (1962),19



- Some electrons can bombard the grid with ~ 150 eV: they can desorb gas molecules and produce an artificial increase of the pressure.

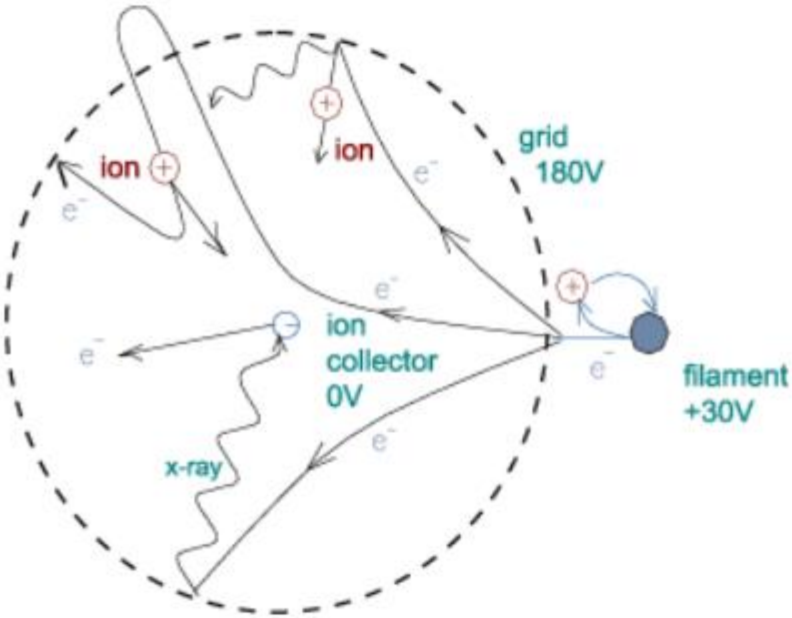
- The vacuum gauges are therefore “degassed” by electron bombardment at large current (~ 10 mA) and energy () of the grid and electrodes

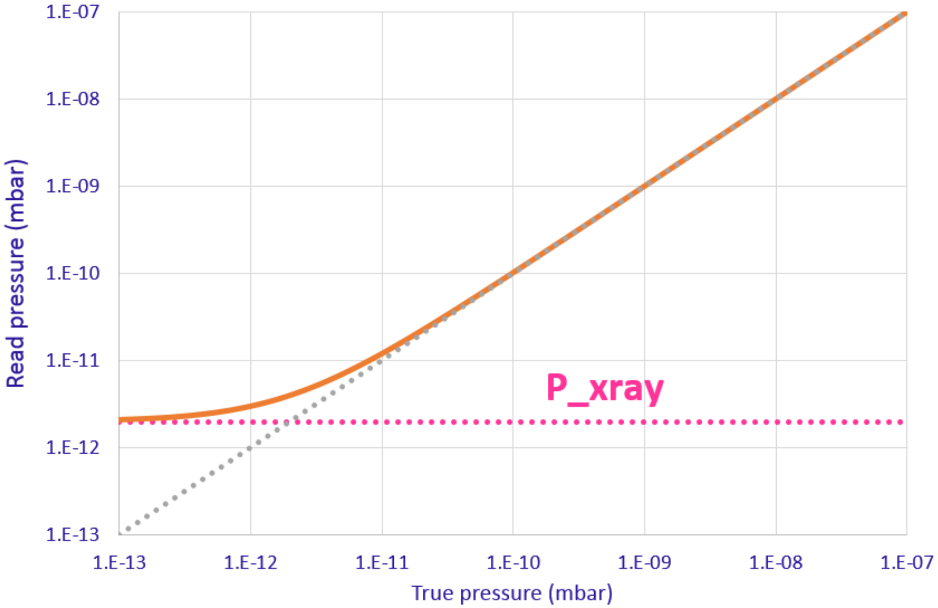
- Filaments have pumping speed: 0.1 – 1 l/s

# Bayard-Alpert Gauge: X-rays

Complementary information

- Electrons which are bombarding the grid, creates photons by bremsstrahlung
- A fraction of those photons irradiated the collector producing a photoelectron
- The photoelectron production is interpreted by the electronic system as a positive charge *i.e.* as a constant pressure, $P_{x\text{-}ray}$





- X-ray limit of $P_{xray}$ ~ 2 $10^{-12}$ mbar

# Bayard-Alpert Gauge: Modulation

Complementary information

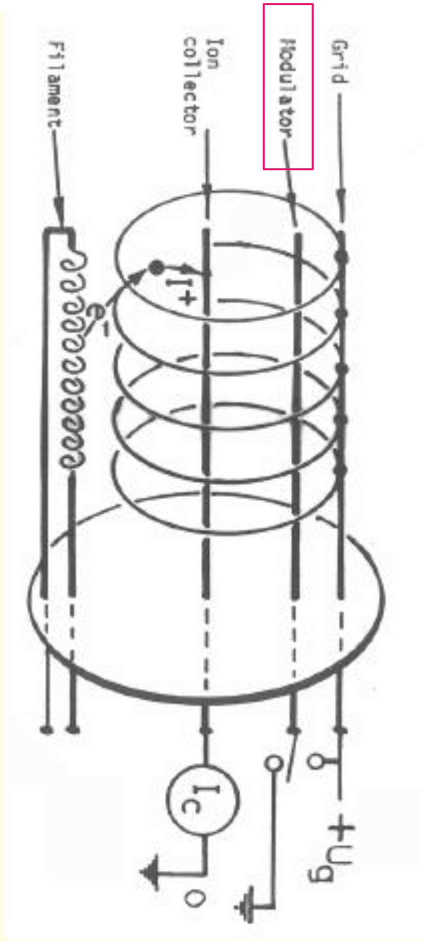
- A correction of the residual pressure due to the x-ray can by applied by the “modulation” technique

| Modulator | High Pres. | Low Pres. |
|---|---|---|
| 0 V | $I'_1 = I'^+$ | $I_1 = I^+ + I_x$ |
| + grid | $I'_2 = k\,I'^+$ | $I_2 = k\,I^+ + I_x$ |

$$k = \frac{I'_2}{I'_1} = \frac{P'_2}{P'_1}$$

$$\Rightarrow P = \frac{P_1 - P_2}{1 - k}$$

$$I^+ = \frac{I_1 - I_2}{1 - k}$$



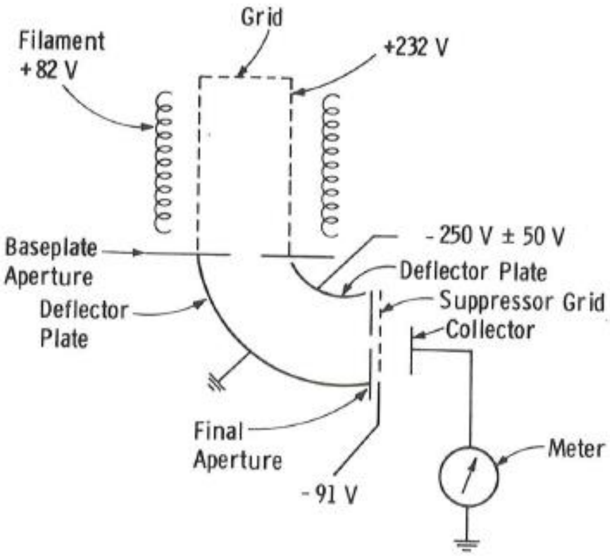
|  | $H_2$ | He | $CH_4$ | $N_2$ | CO | $C_2H_6$ | Ar | $CO_2$ |
|---|---|---|---|---|---|---|---|---|
| k | 0.86 | 0.91 | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 |

- X-ray limit of $P_{xray} \sim 2\ 10^{-12}$ mbar

# Helmer gauge

Complementary information

- Electrostatically-deflected ion beam with an electron suppressor grid
- Very low x-ray value ~ 5 $10^{-14}$ mbar
- $10^{-13}$ to $10^{-6}$ mbar with Ie ~ 10 mA
- $10^{-6}$ to $10^{-4}$ mbar with Ie ~ 0.18 mA
- Sensitivity: 20 $\text{mbar}^{-1}$ for $N_2$
- Bakeable to 450 deg C, degassing current at 100 mA with + 500 V on the grid



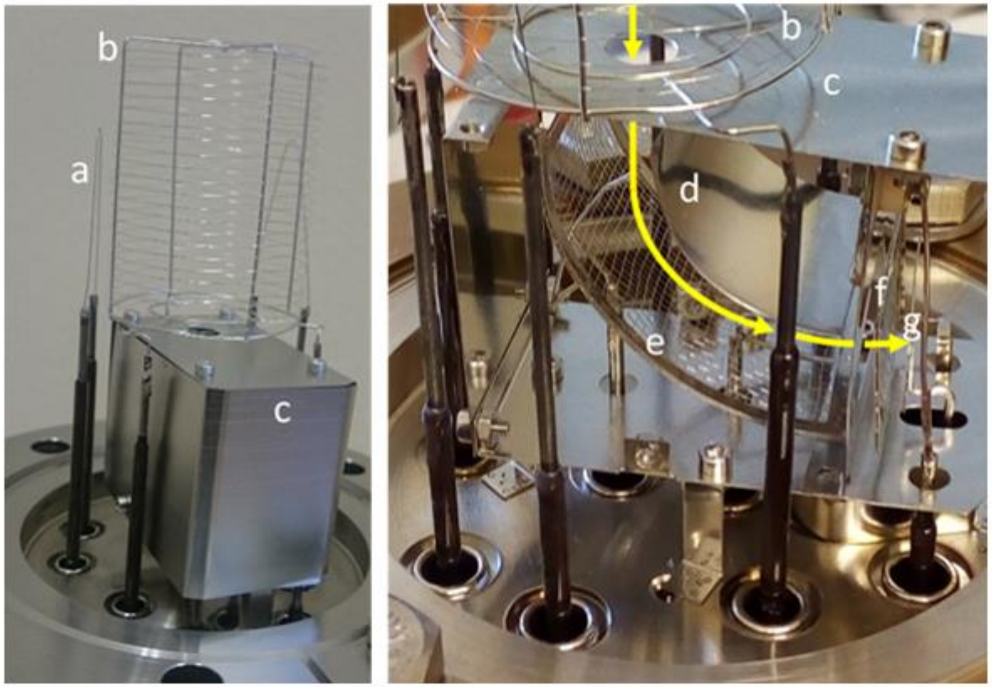
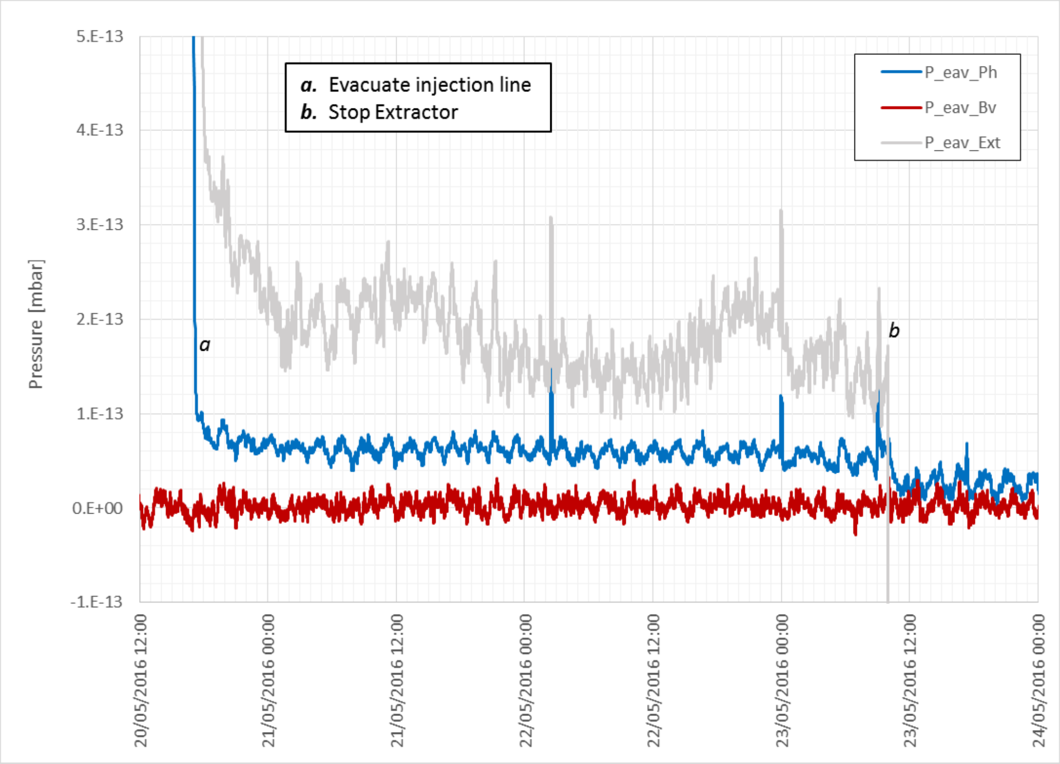


*Figure 8: Main components of the Helmer gauge; on the right with opened cage. (**a** filament, **b** grid, **c** cage, **d** inner deflector, **e** outer deflector (on ground potential), **f** suppressor, **g** collector). The yellow line indicates the ion trajectory from the grid volume towards the collector.*

# Helmer gauge and XHV

Complementary information

- Recently measured pressure is ~ 5  $10^{-14}$ mbar in a dedicated set up



Courtesy B. Jenninger

# Extractor gauge

Complementary information

- The ion collection (collector) is located outside the ionization region (grid)
- The reflector used to reflect the ions on the collector tip for sensitivy enhancement
- Low x-ray value ~ $10^{-12}$ mbar
- $10^{-12}$ to $10^{-4}$ mbar
- Operating current: 1.6 mA, filament in Iridium with yttric oxid coating
- Sensitivity: 5 $\text{mbar}^{-1}$ for $N_2$ (due to the small grid volume Ø12 x 25)
- Bakeable up to 350°C

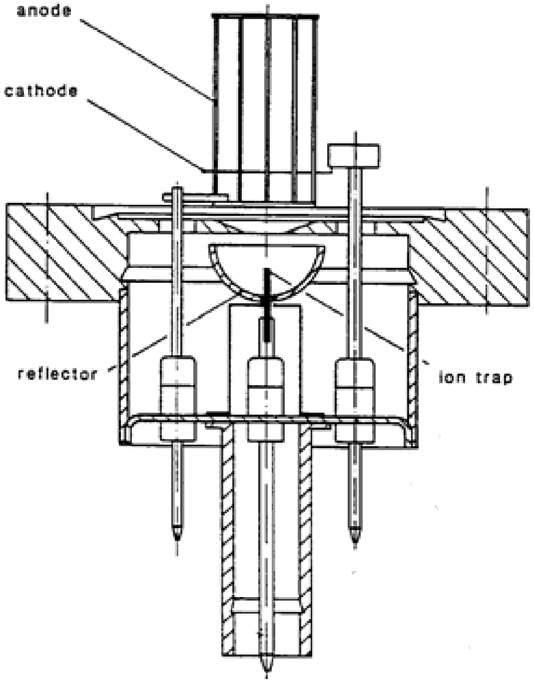
Anode: grid at 220 V

Cathode: filament at 100 V

Reflector at 205 V

Ion collector at 0 V

$V_{grid} = 10\ \text{cm}^3$



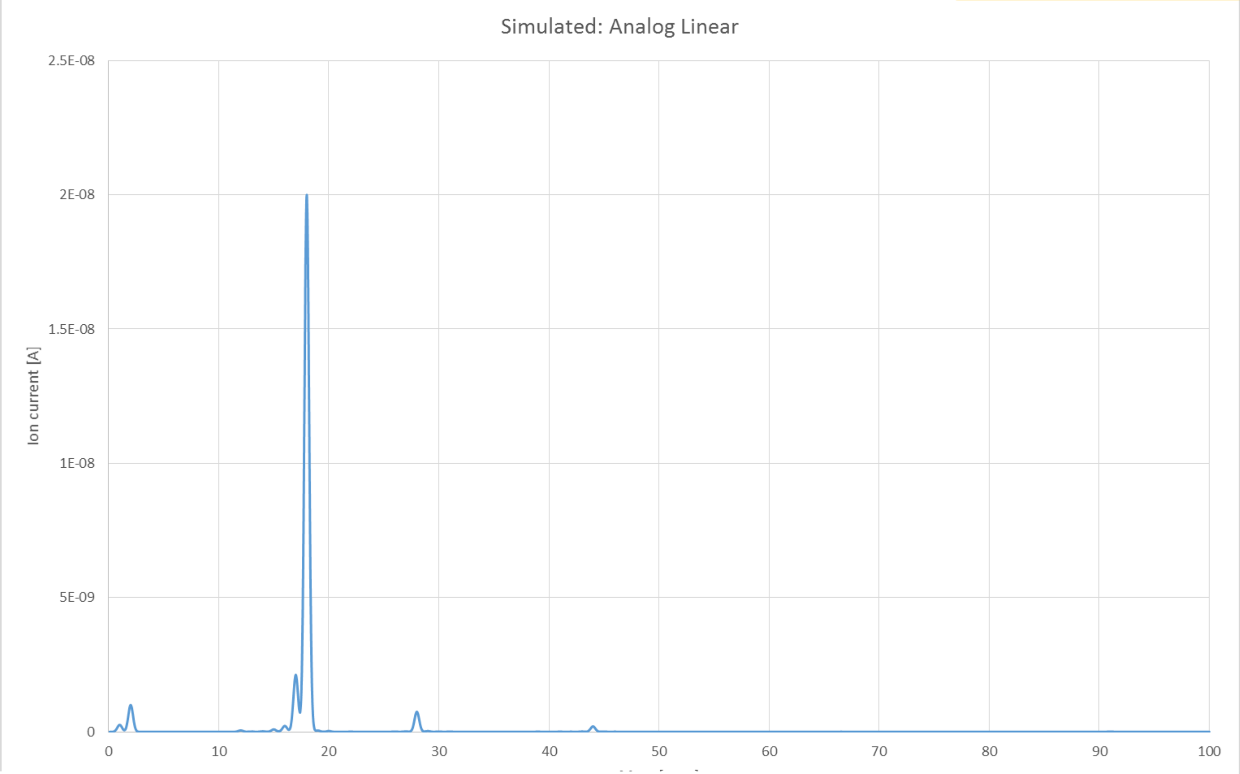
# 3.2 Gas analysis

# RGA: Unbaked system

Complementary information

- A typical spectrum of an unbaked vacuum system

| M/e | Ion | Molecule |
|---|---|---|
| 2 | $H_2^+$ | $H_2$ |
| 18 | $H_2O^+$ | $H_2O$ |

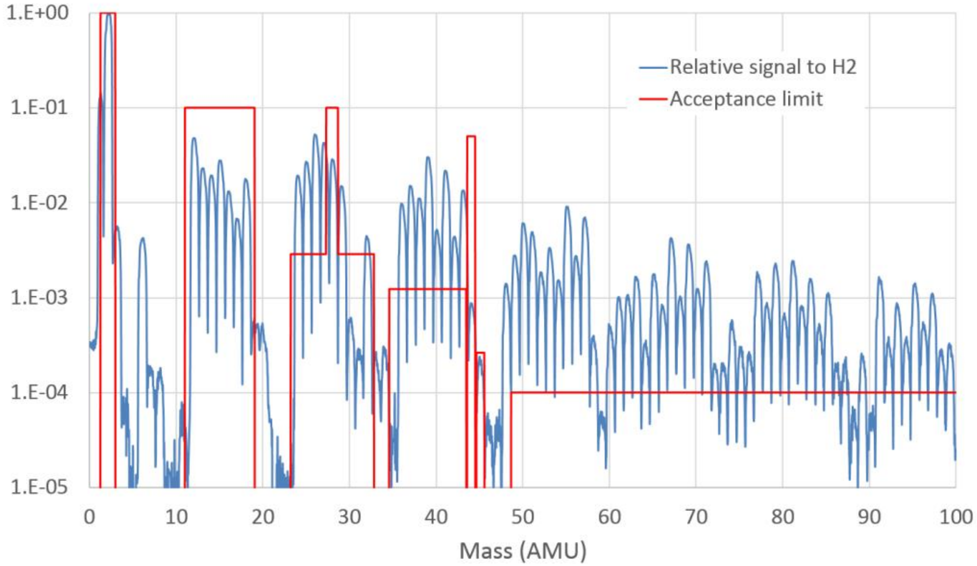


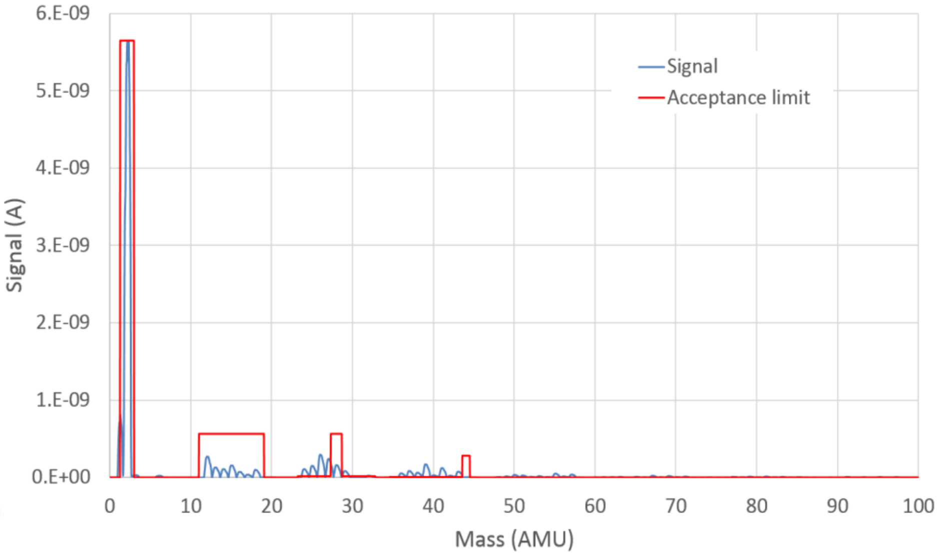
|  | $H_2$ | $CH_4$ | $H_2O$ | CO | $CO_2$ |
|---|---|---|---|---|---|
| I (A) | $1\ 10^{-9}$ | $1\ 10^{-10}$ | $2\ 10^{-8}$ | $7\ 10^{-10}$ | $2\ 10^{-10}$ |
| P (mbar) | $1\ 10^{-9}$ | $3\ 10^{-11}$ | $1\ 10^{-8}$ | $4\ 10^{-10}$ | $2\ 10^{-10}$ |
| % Pi | 10 | 0 | 85 | 3 | 1 |

# RGA: Contamination

Complementary information

- RGA spectra are used to qualify the cleanliness of a vacuum system
- A typical spectrum of a hydrocarbons contaminated system
- Peaks are separated by 14 units corresponding to one or more $CH_2$ groups ($C_nH_{2n+2}$)
- Acceptance limits are defined for validation tests





# 3.3 Vacuum pumps

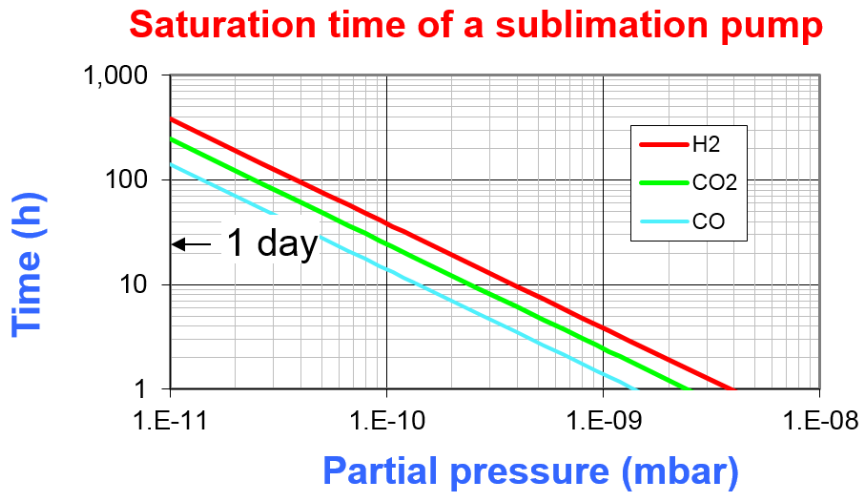
# Sublimation pump

Complementary information

- This pumps operates in the UHV regime in a range << $10^{-9}$ mbar
- It is used as a complementary pumping system to *e.g.* ion pumps.
- Their pumping speed is very large : ~5 000 l/s, typical surface ~ 1000 $cm^2$

- A Ti filament is sublimated by Joule effect. Ti is adsorbed on the vacuum chamber wall and provides molecular pumping by a “gettering” effect.
- Getterable gases are $H_2$, $H_2O$, $O_2$, CO, $O_2$ , $CO_2$ and,
- When assisted with liquid $N_2$ cooling $H_2$ pumping speed is boosted

- Sublimation at regular intervals is needed.


**Saturation time of a sublimation pump**

| l/s $cm^{-2}$ | $H_2$ | $D_2$ | $H_2O$ | CO | $N_2$ | $O_2$ | $CO_2$ |
|---|---|---|---|---|---|---|---|
| 300 K | 2.6 | 3.1 | 7.3 | 8.2 | 3.5 | 8.7 | 4.7 |
| 77 K | 17.0 | 6.2 | 14.6 | 11.0 | 8.2 | 11.0 | 9.3 |

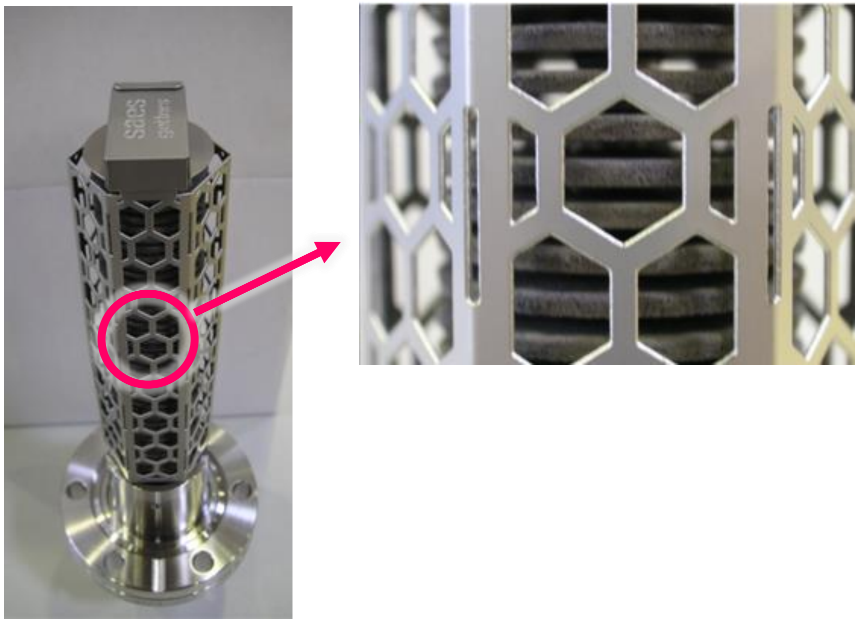
K. Welch, Capture pumping technology, Pergamon press, 1991

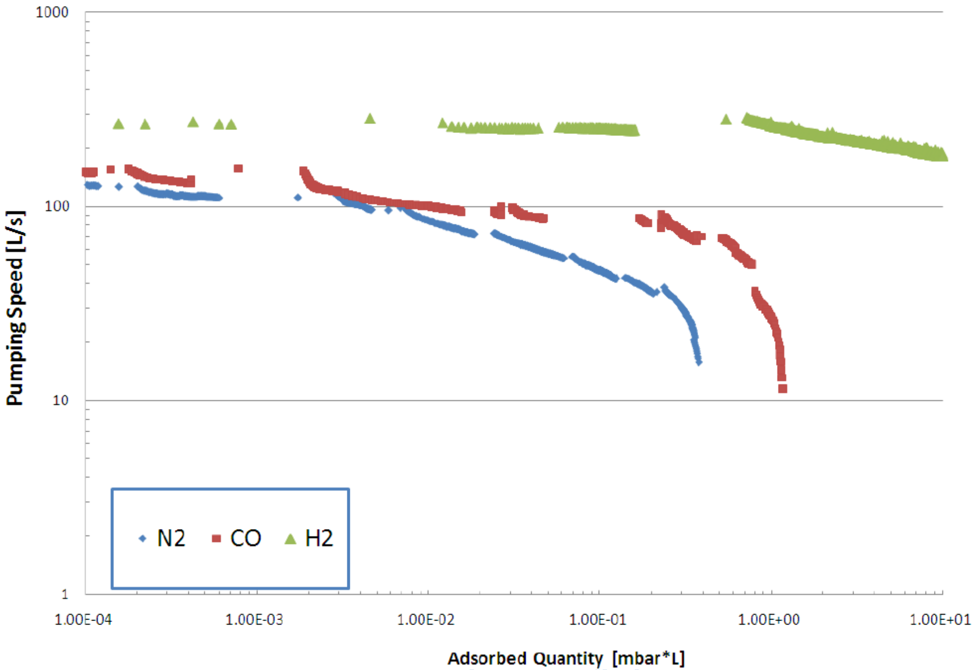
# NEG cartridge

Complementary information

- This pumps operates in the UHV regime in a range < $10^{-8}$ mbar
- It is used as a complementary pumping system to *e.g.* ion pumps.

- Zr based getter materials are sintered into porous disks.
- After activation at ~ 500ºC for 1h, the pumping speed can be large: 100 – 2 000 l/s
- Large sorption capacity: >0.1 – 10 mbar.l for $N_2$, CO and > 10 mbar.l for $H_2$!
- Reminder: 1 mbar.l = 4.3 $10^{19}$ molecules, ~ 1 monolayers of a 10m long,Ø10 tube
- $H_2$ diffuse into the bulk, CO is adsorbed in 1 active site whereas N2 requires 6.
- Gas mixture: CO adsorption inhibit $H_2$ and $N_2$ pumping



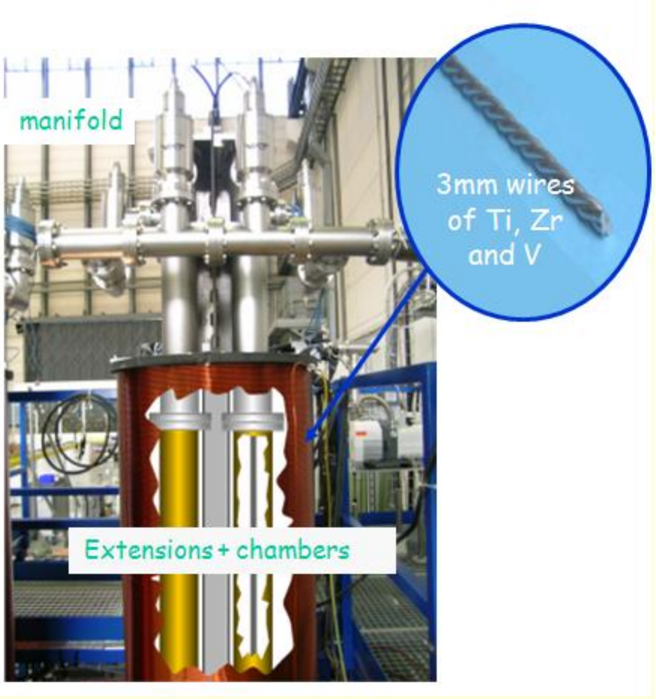


Courtesy G. Bregliozzi, J. Callagher, 2012

# NEG coated chamber

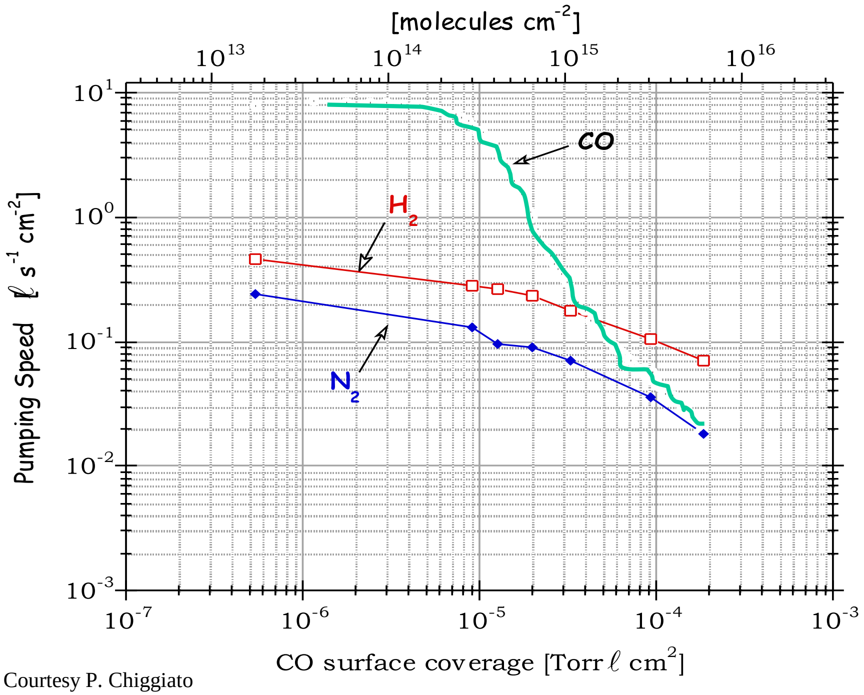
Complementary information

- A ~ 1 µm getter getter film made of TiZrVa is coated inside a vacuum chamber
- Ti-Zr-V is coated by magnetron sputtering with Kr gas



P. Costa Pinto, P. Chiggiato / Thin Solid Films 515 (2006) 382-388

Pumping Speed



Courtesy P. Chiggiato

- Very large pumping speed : ~ 250 l/s/m for $H_2$, 20 000 l/s.m for CO
- Very low outgassing rate

- But : limited capacity and fragile coating sensitive to pollutant (hydrocarbons, Fluor …)