CERN

Vacuum Systems
Lecture 1

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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

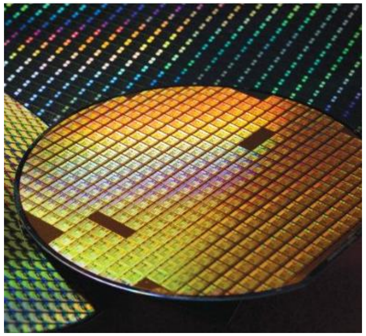
Vacuum Systems

- Vacuum technology is present in many devices/ systems

Light bulb

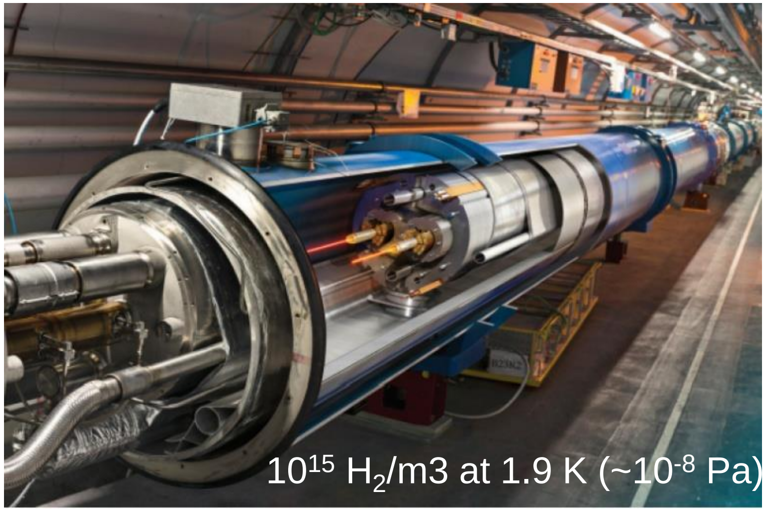
Vacuum pump
For wine

Electron beam welding machine



Semiconductor industry

Under vacuum brazing



Accelerator

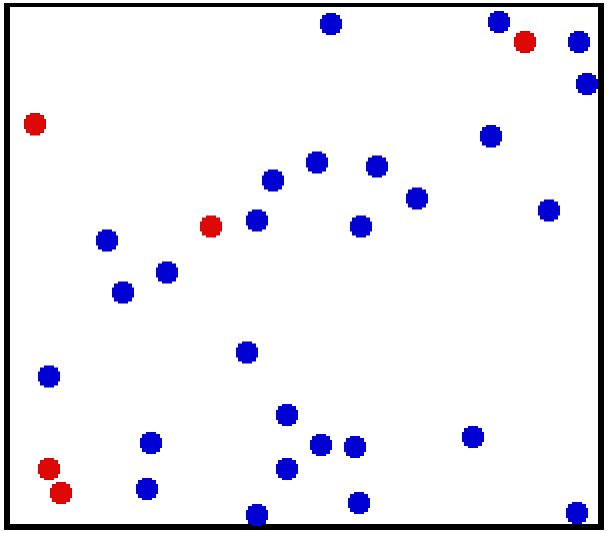
The objective is to reduce the collision of molecules on the surrounding to preserve the quality of the process

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

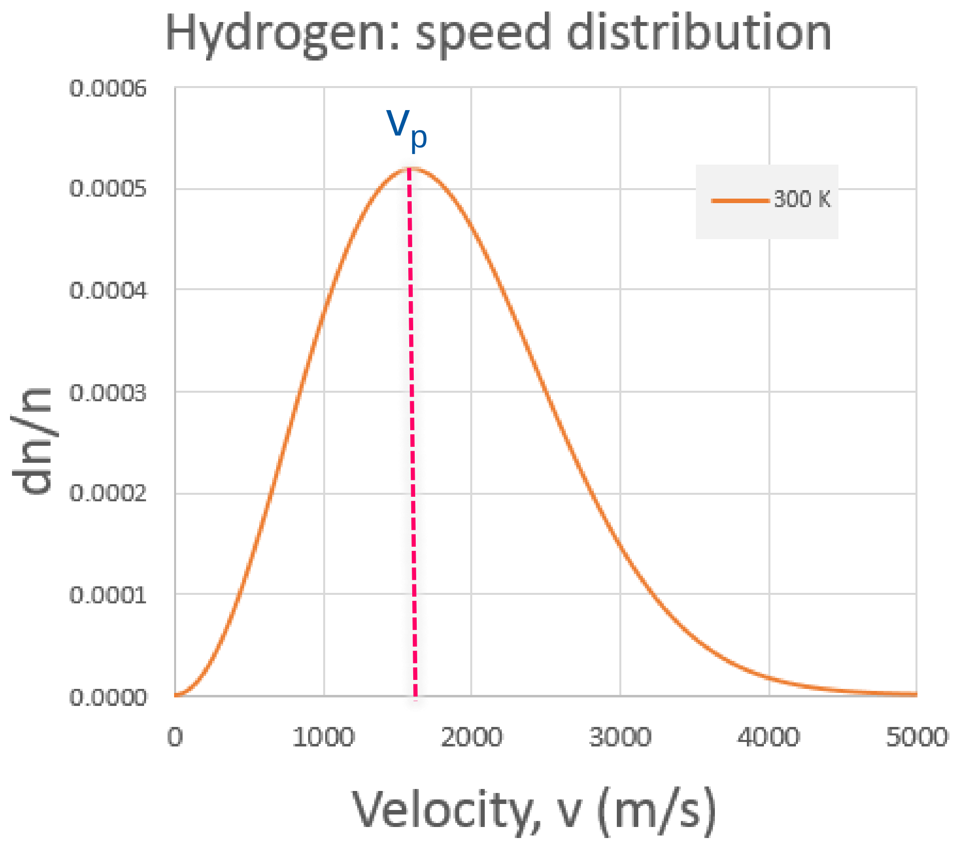
$$\frac{dn}{n} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} v^2\, e^{-\frac{mv^2}{2kT}}\, dv$$

- 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:

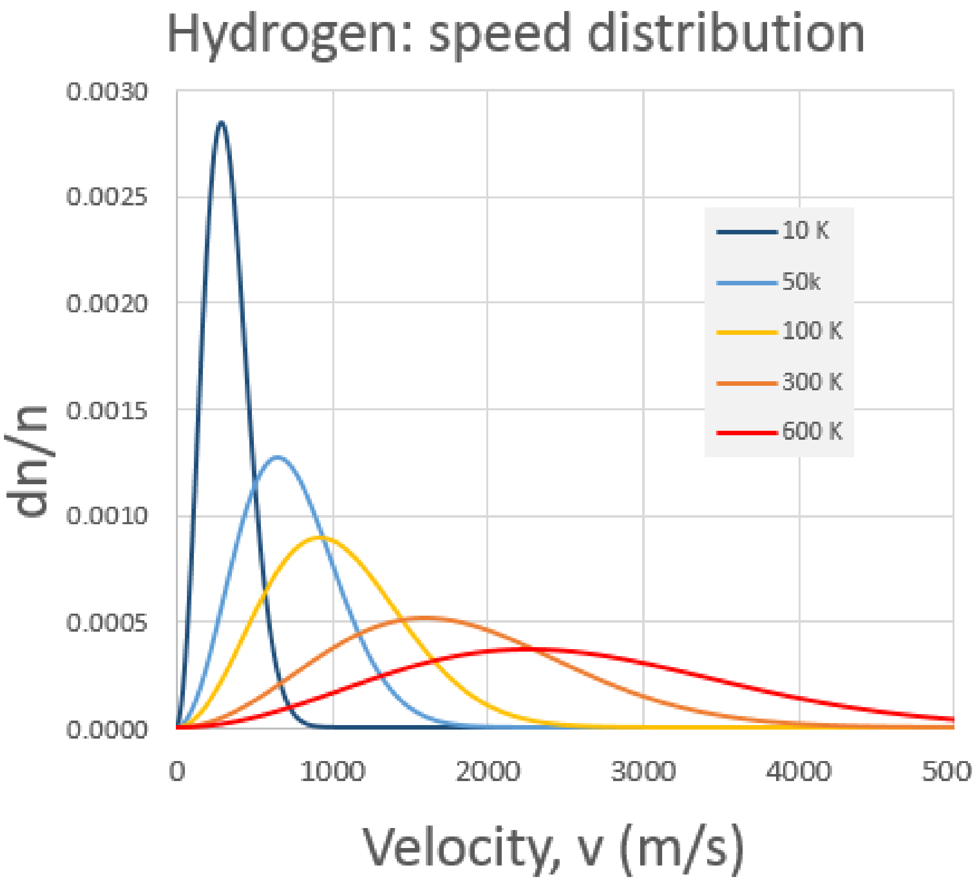
$$\frac{1}{2}m\,{v_q}^2 = \frac{3}{2}kT$$

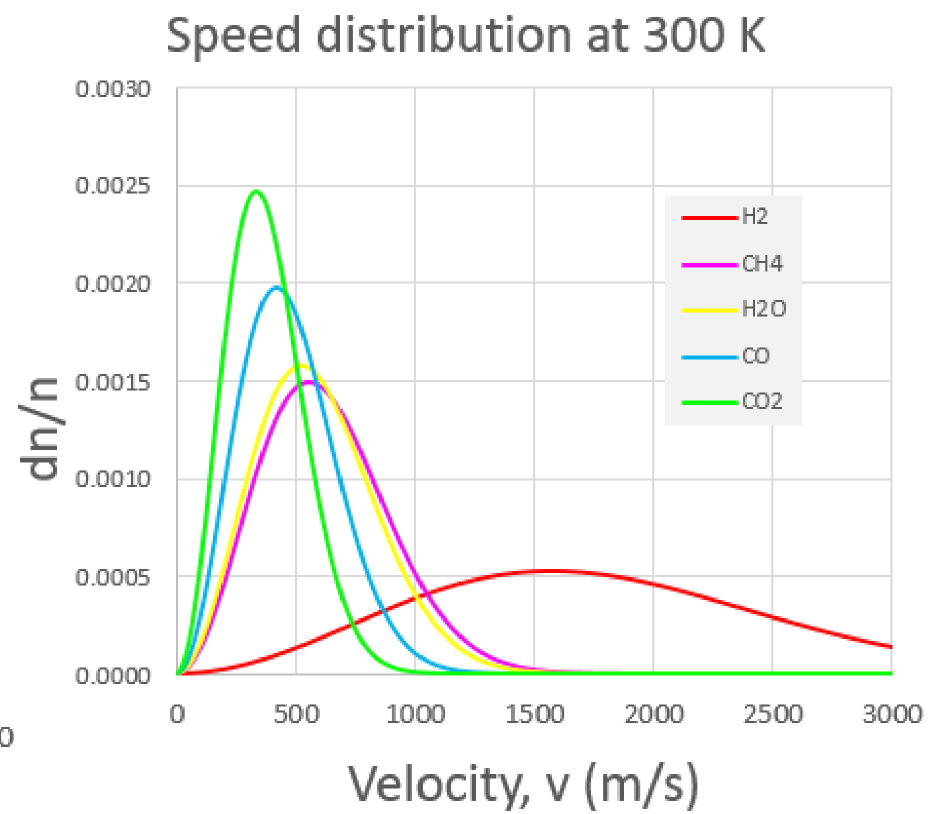
All the molecular speeds scales like ~ $\sqrt{(T/m)}$

Maxwell Boltzmann Distribution

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

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





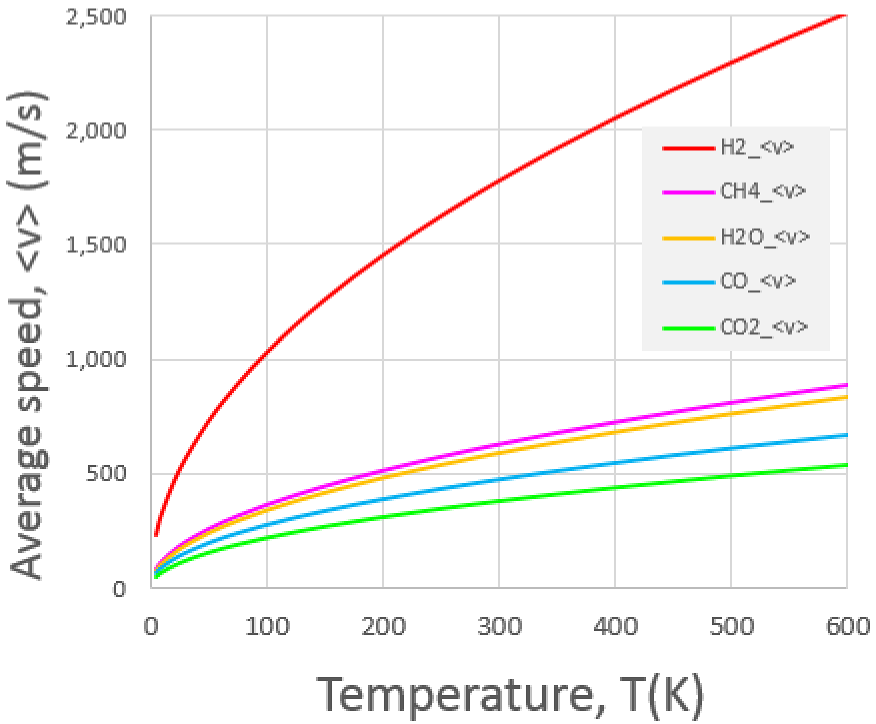
Average velocity

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

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

~ √(T/m)

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

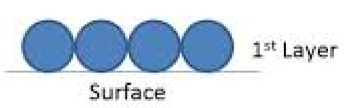


Collision on the wall

- 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



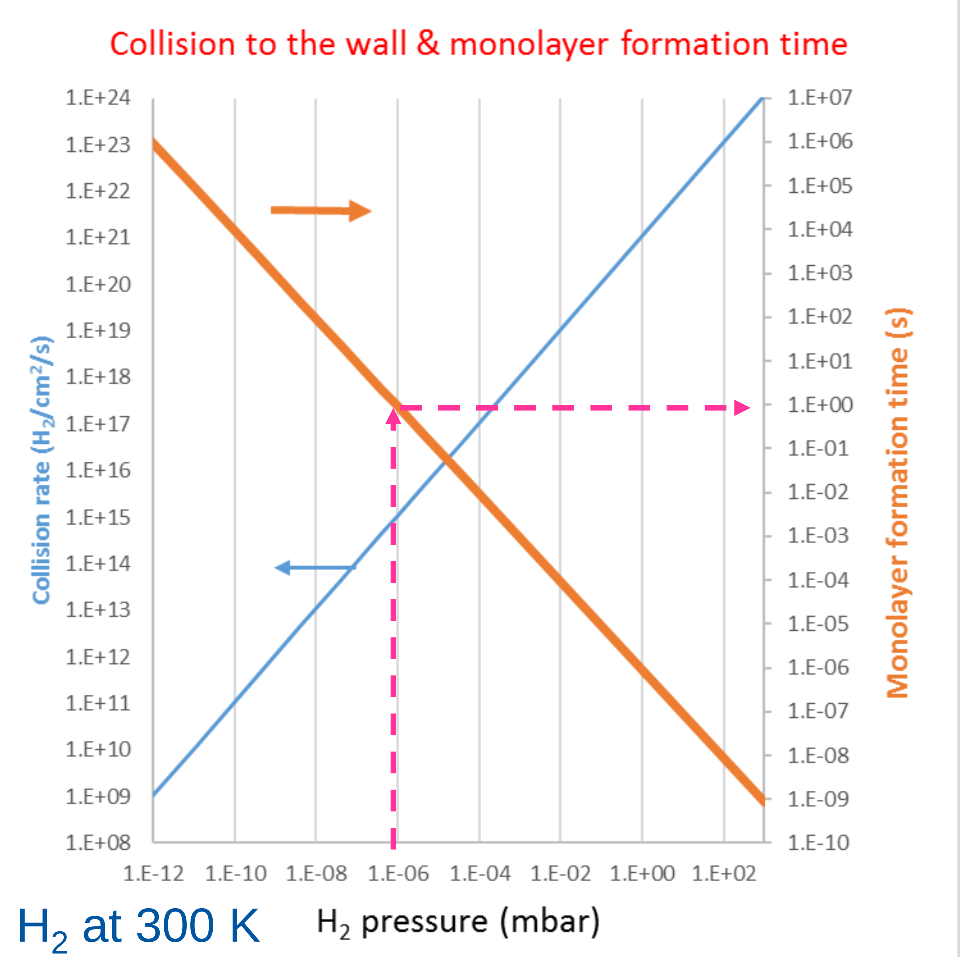
10^{15} molecules/cm^2

- 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 collides the 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 <u>any</u> 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 <u>special case</u> 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 increase 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} x 1.38 10^{-23} x 300 = 4 10^{-6} Pa

- This relation is an 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 m3 = 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} x 273) = 2.7 10^{25} molecules/m^3

Units

- The pressure is the force exerted by a molecule 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 equal to 1.33 x 10^{-6} = 1.3 10^{-6} mbar
  - 10^{-6} Torr is equal to 133 x 10^{-6} = 1.3 10^{-4} Pa
  - 4 10^{-6} Pa is equal to 4 10^{-6} / 133 = 3 10^{-8} Torr
  - 4 10^{-6} Pa is equal 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

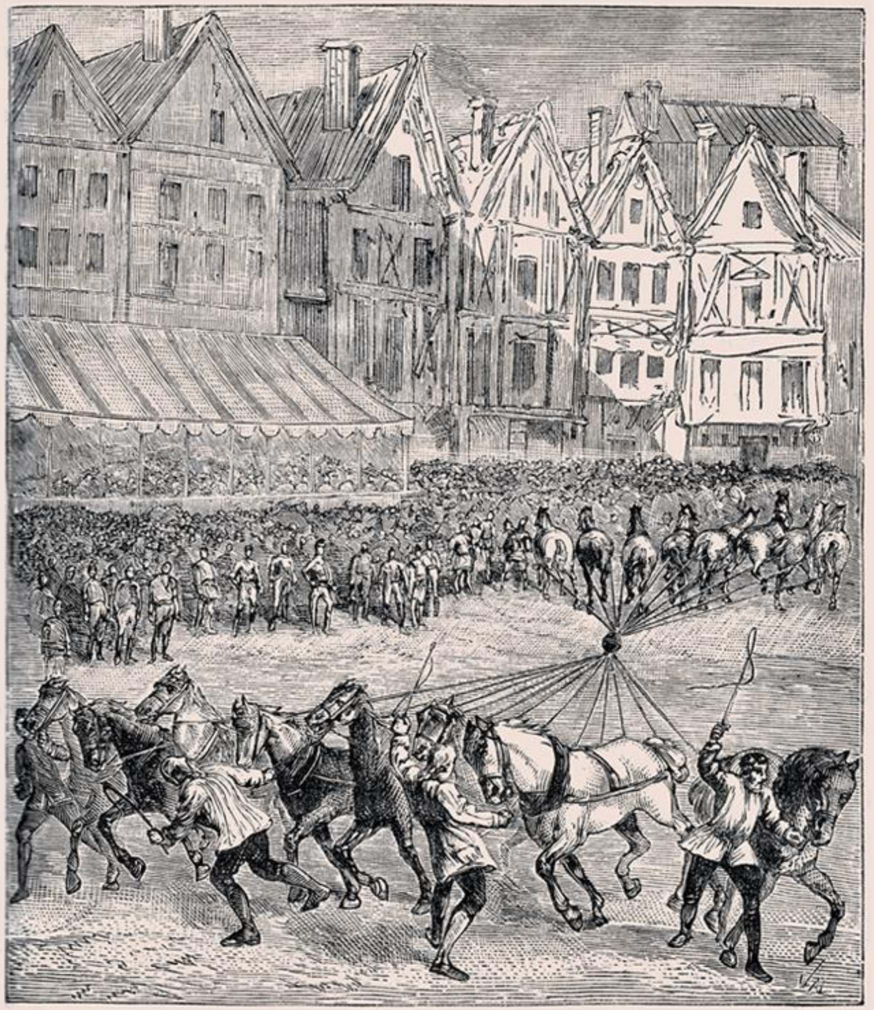
Picture Kurt J. Lesker

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

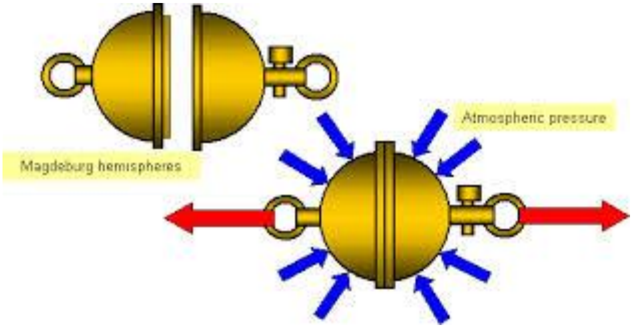
As a consequence of the « vacuum force » …

"Vacuum force": Magdeburg hemisphere

- 1654, Regensburg



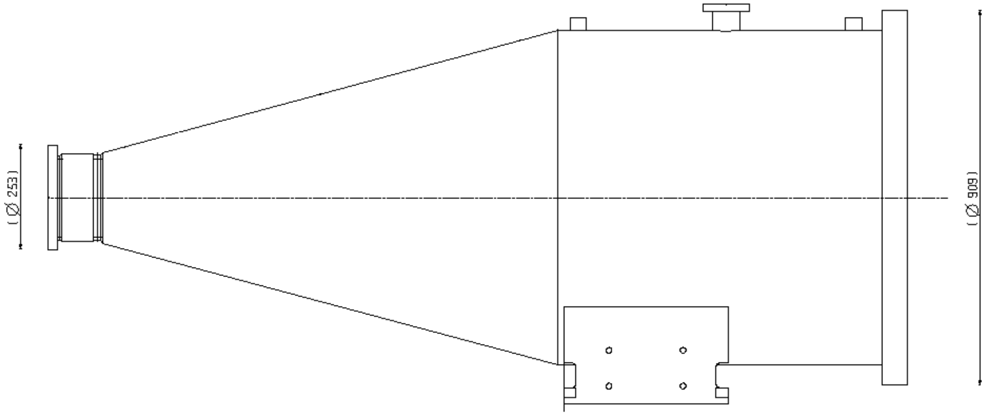
Expérience des *Hémisphères de Magdebourg*,
exécutée par Otto de Guéricke devant l'empereur Ferdinand III, à la diéte de Ratisbonne



55 cm diameter ➔ 25 Tons

Otto von Guericke

Work with the Mechanical Design Office !

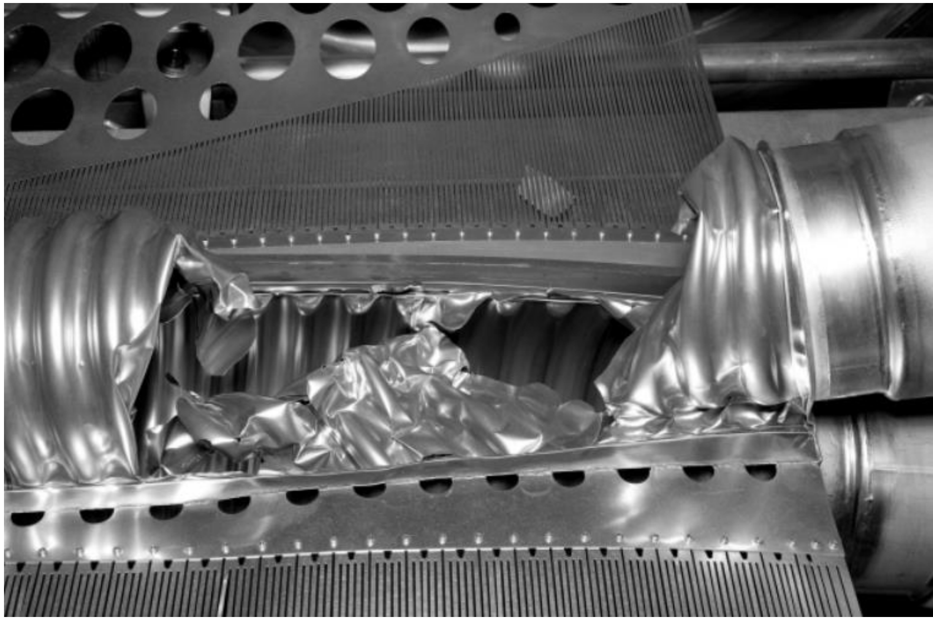
0.5 ton →  ← **6.6 tons**

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 <u>even</u> 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)

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

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

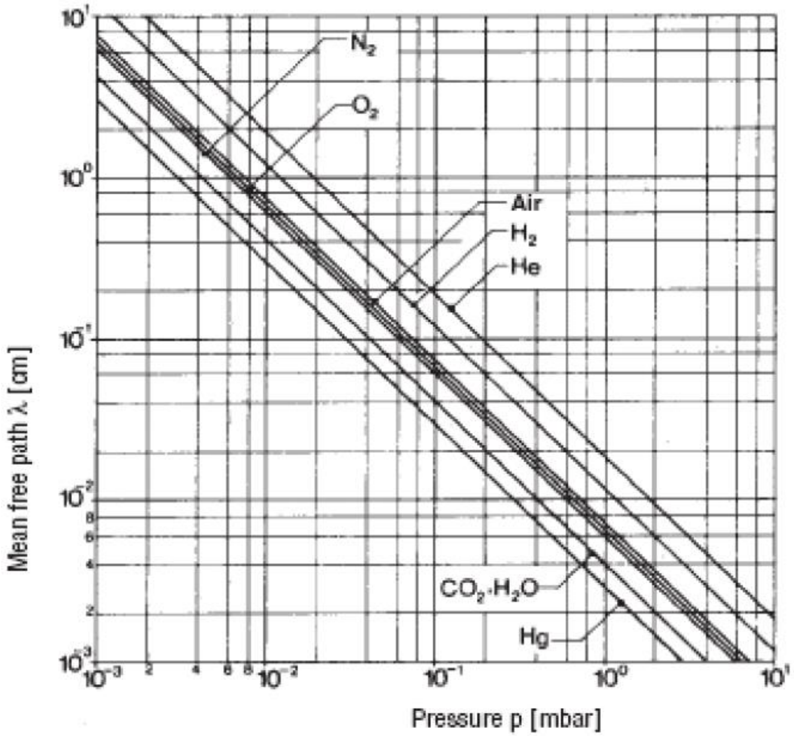
Mean Free Path

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

- It depends of the pressure, of the temperature and of the molecular diameter, σ.

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

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

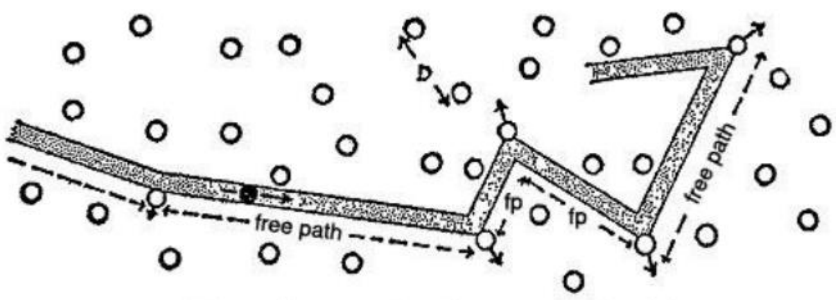


Mean Free Path: air at room temperature

- 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

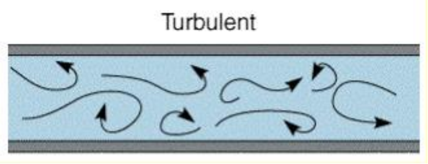
Turbulent and Viscous Flows

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

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

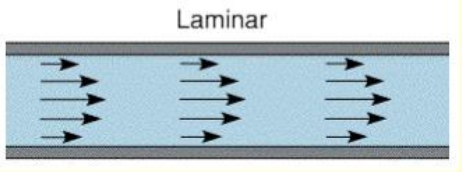
$$Re = \frac{Q[Torr.l/s]}{0.089D[cm]}$$

- 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

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



Transition and Molecular Flows

- In the medium vacuum (1-10^{-3} mbar), the flow is transitional. In every day work, this range is transited quickly 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

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

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
  - 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:
    - ➔ λ = 5 10^{-5} / 7.5 10^{-8} = 667 m

- Assume a large vacuum vessel operating under UV:
  - vacuum chamber diameter ~ 10 m (=1000 cm)
  - 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:
    - ➔ λ = 5 10^{-5} / 7.5 10^{-6} = 7 m

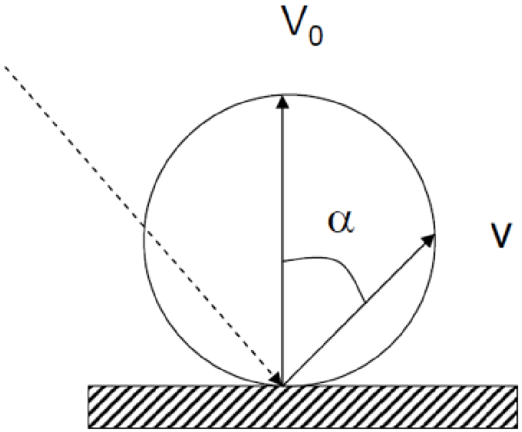
Molecule interaction with the wall

- 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

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



$$V = V_o \cos \alpha$$

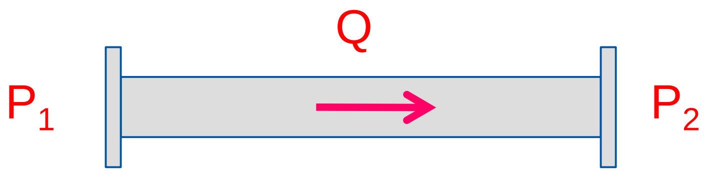
- This observation introduced the concept of conductance (Dushman)

Saul Dushman (1883–1954)

Conductance

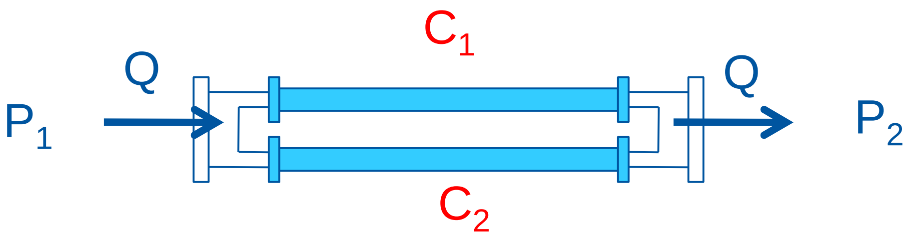
- It is defined by the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel. It is a function of the shape of the vessel, the nature of the gas and its temperature.

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



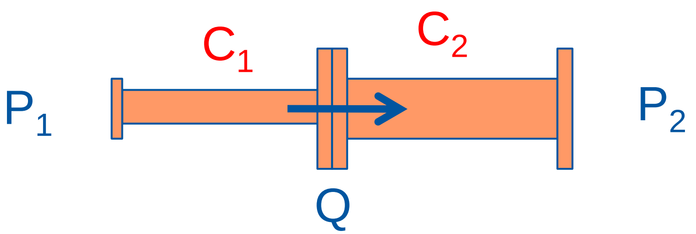
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

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



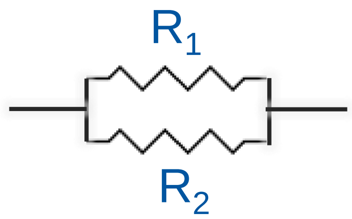
Analogy to electricity

- 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:

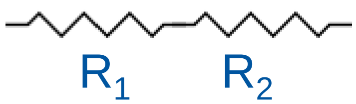
$$(V_1 - V_2) = R\,I \Leftrightarrow \frac{1}{R} = \frac{I}{(V_1 - V_2)} \longrightarrow \boxed{C = \frac{Q}{(P_1 - P_2)}}$$

- 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



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

Conductance Calculus in Molecular Regime

- **For an orifice :**

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

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

- **For a tube :**

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

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:

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

M	C_orifice [l/s]	C_tube [l/s.m]
29	900	120
2	3427	457
16	1212	162
28	916	122
44	731	97

Pumping Speed

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

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

l/s → S

Q ← mbar.l/s

P ← mbar

- S range from 10 to 20 000 l/s

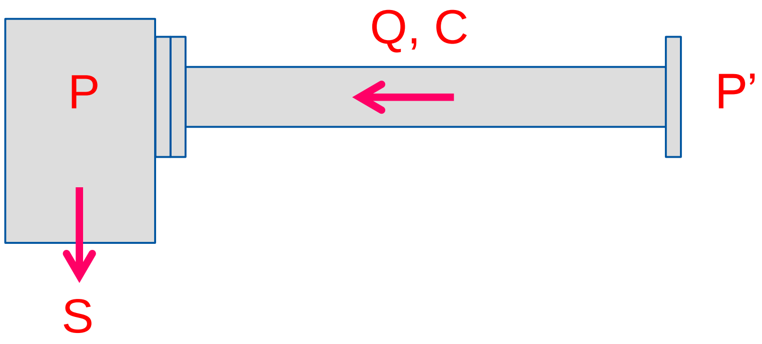
- Q range from 10^{-14} mbar.l/s/cm^2 for metalic tubes to 10^{-5} – 10^{-4} mbar.l/s/cm^2 for plastics

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

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

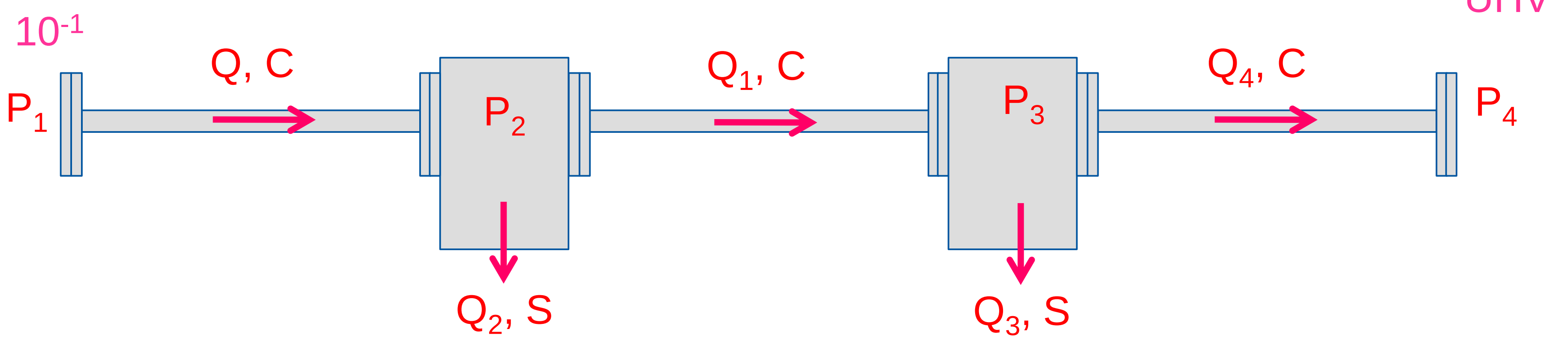
- This is the result of adding in series the conductance C with the pumping speed S

- 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"

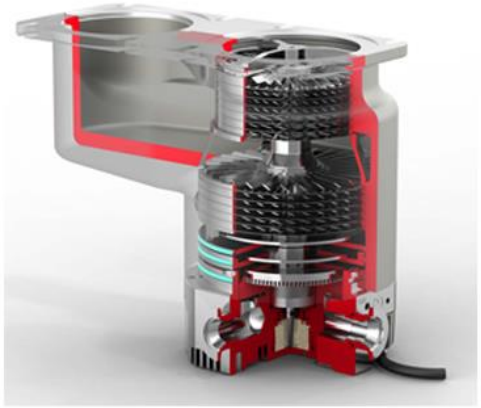
Large conductances preserve the efficiency of the pumping system

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)



- Commercial differential pumps



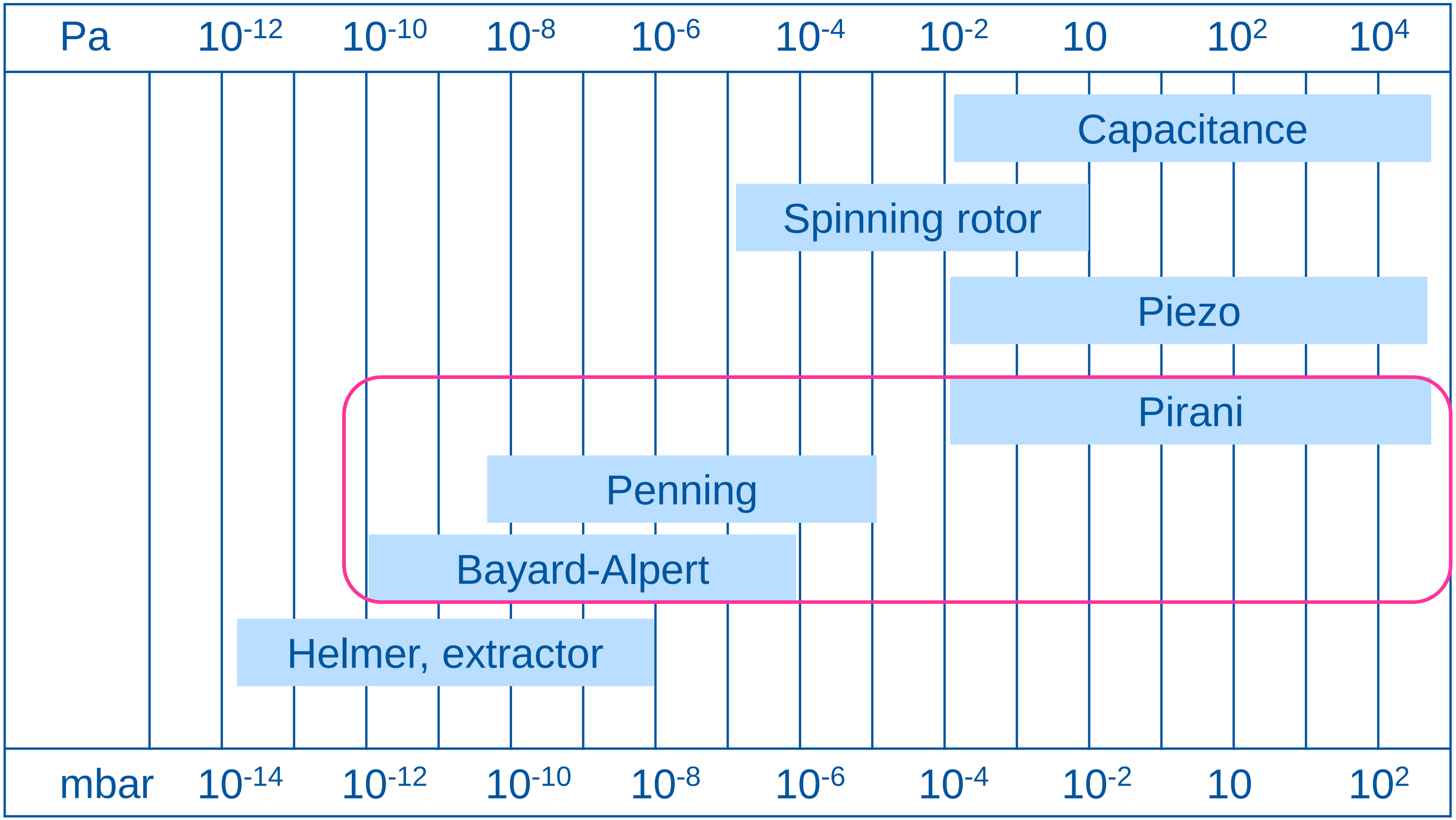
Pictures Edwards

3. Measurement & production of vacuum

3.1 Vacuum gauges

Vacuum gauges pressure range

16 orders of magnitude !

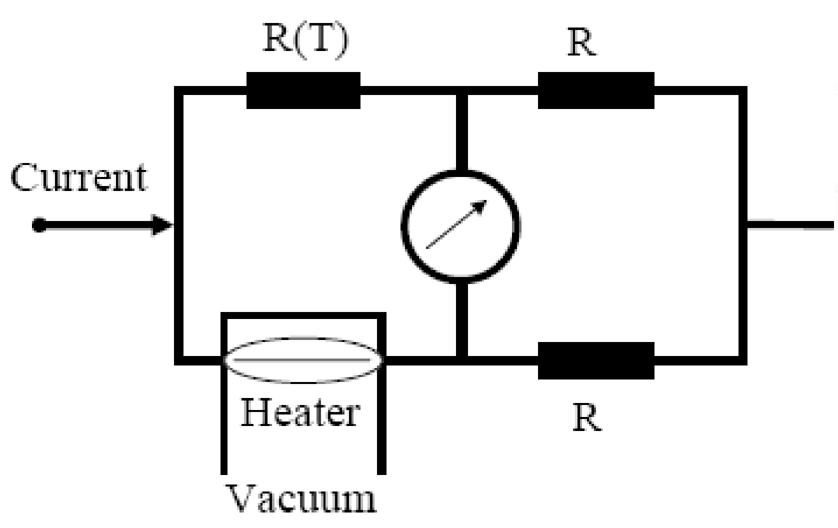


Pirani Gauge

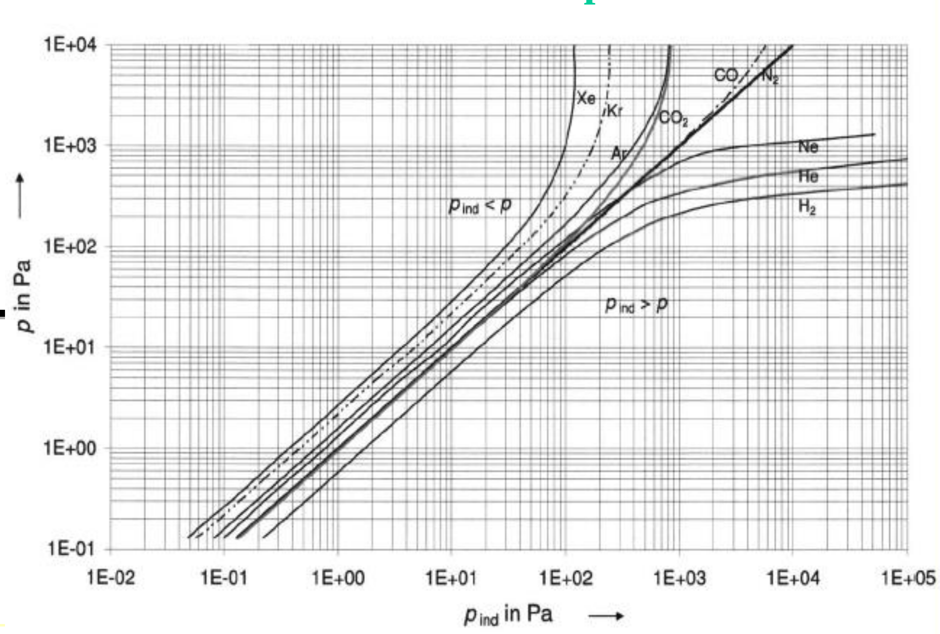
- Pirani gauges are commonly used in the range 1 atm -10^{-4} mbar.

- 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

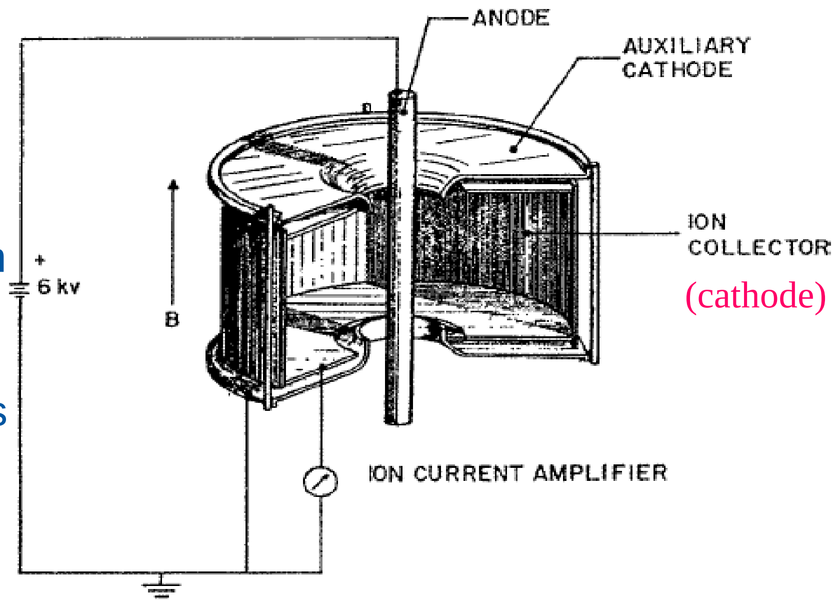
- The operating principle is based on the measurement of a discharge current in a Penning cell which is a function of pressure : $I^{+} = P^{n}$, n is close to 1

- 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



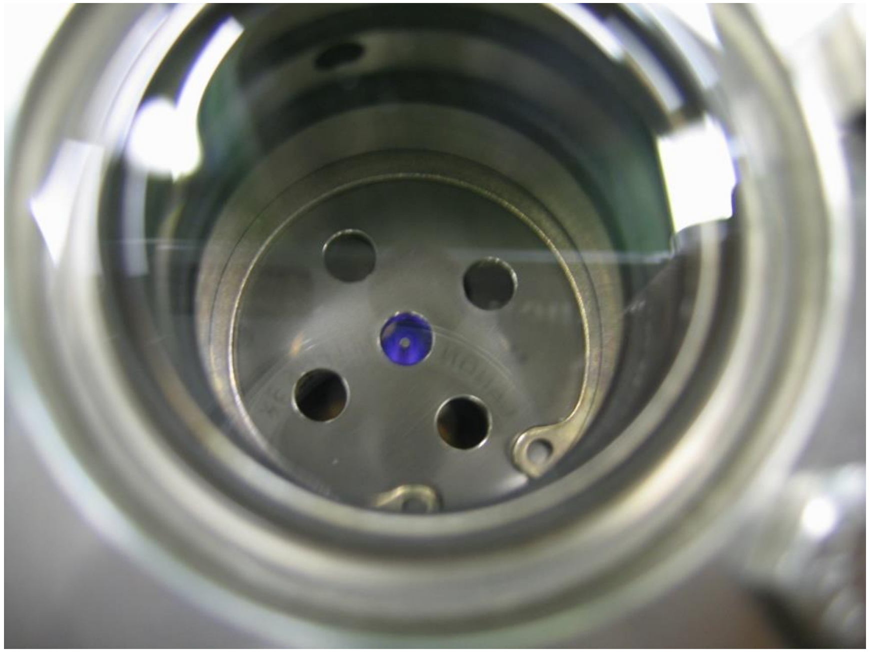
P. Redhead. J.Vac.Sci. 21(5), Sept/Oct 2003, S1-S5

A discharge in a Penning gauge

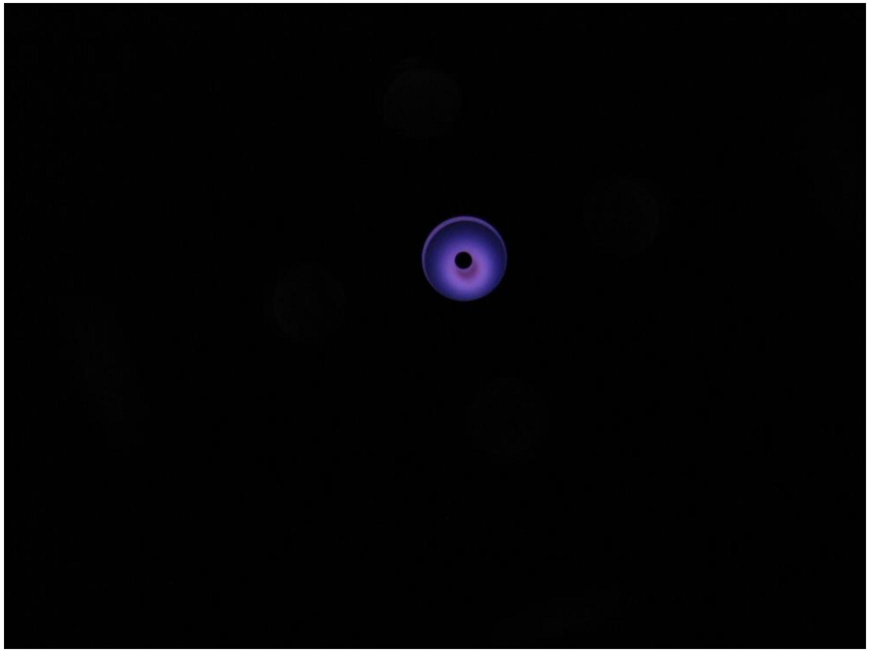
- a Penning gauge:

Courtesy Pfeiffer

Penning gauge ON behind a window



In the dark

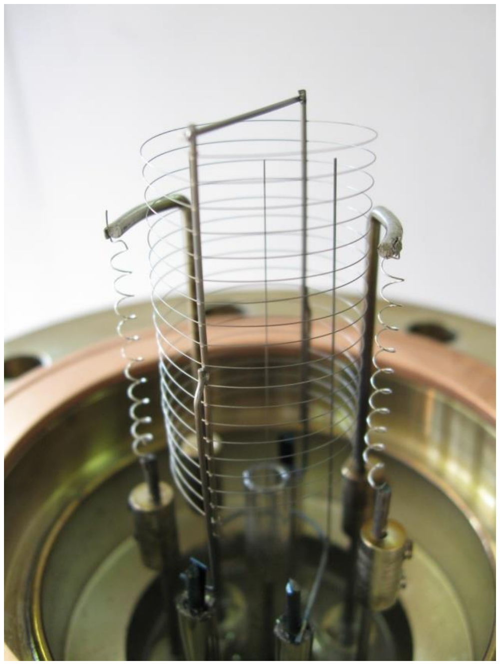


Pictures courtesy B. Henrist

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 oscillations inside the grid and ionise the molecules of the residual gas. Ions are then collected by an electrode.



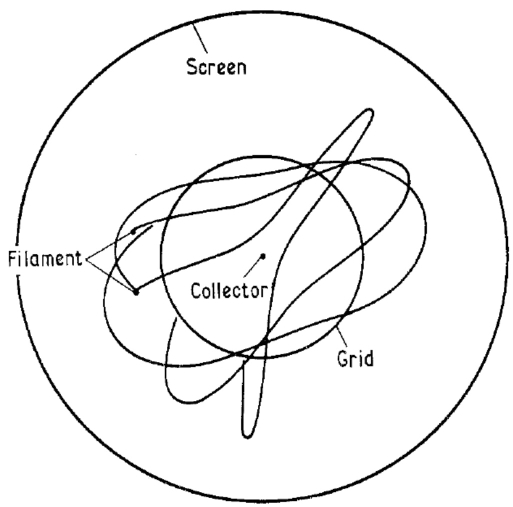
Path length of particles has exponential distribution.

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.

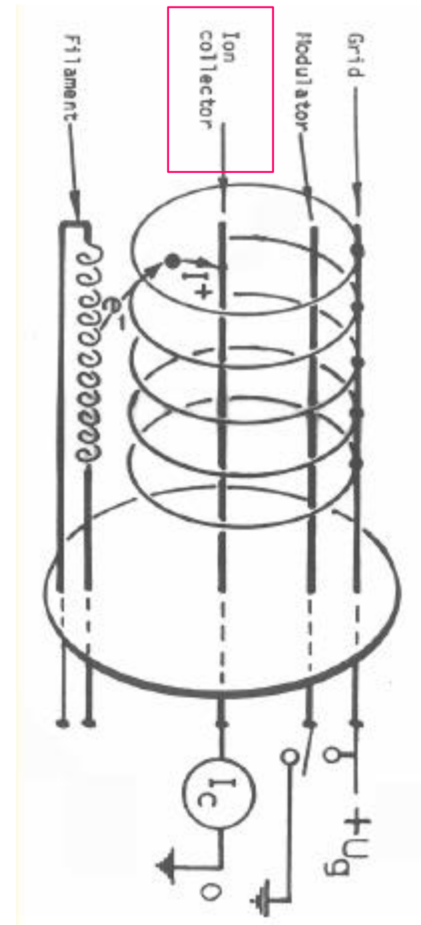
Ions oscillate more than electrons
- About 50 turns — above 1 m
- Collected ions oscillate more than repelled.
- In modulation mode path is much shorter.

Courtesy B. Jenninger

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



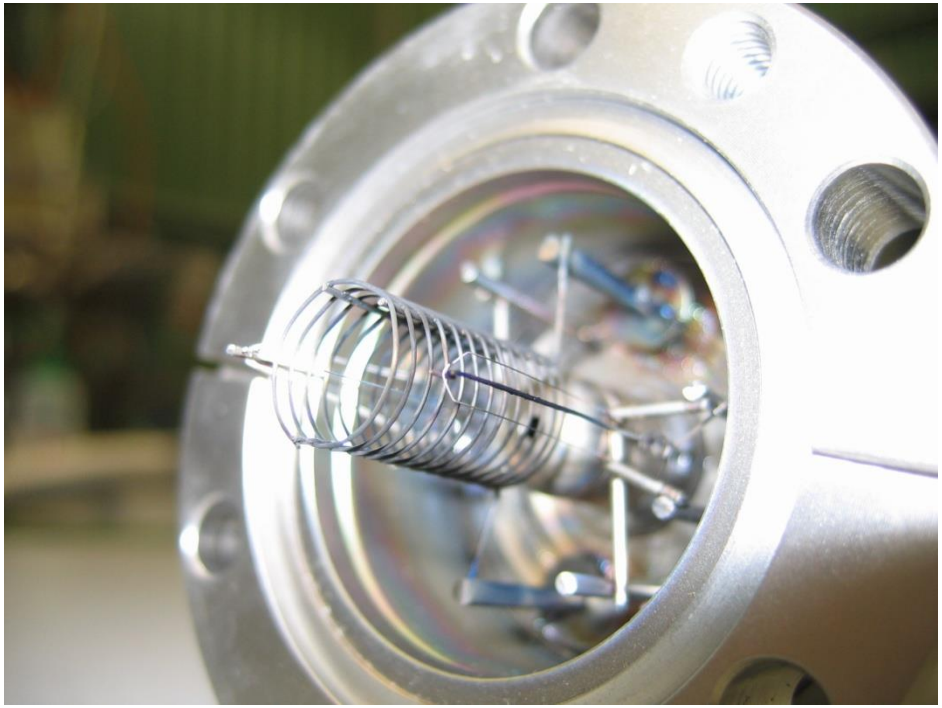
L.G. Pittaway. J. of Phys. D: Appl.Phys. 3, 1113-1121, 1970

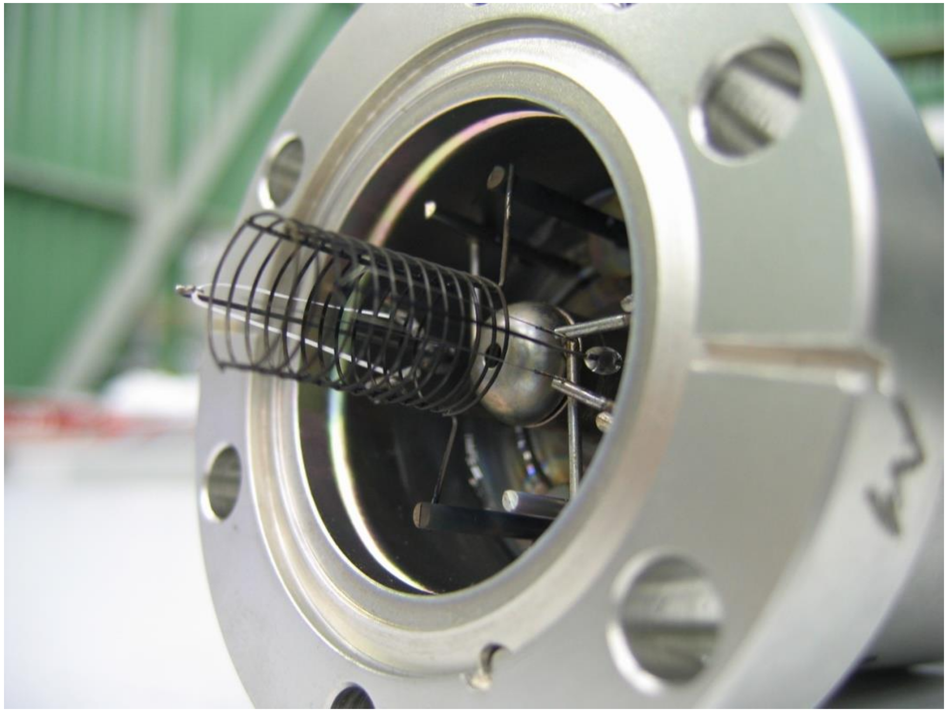


A burned filament

- 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





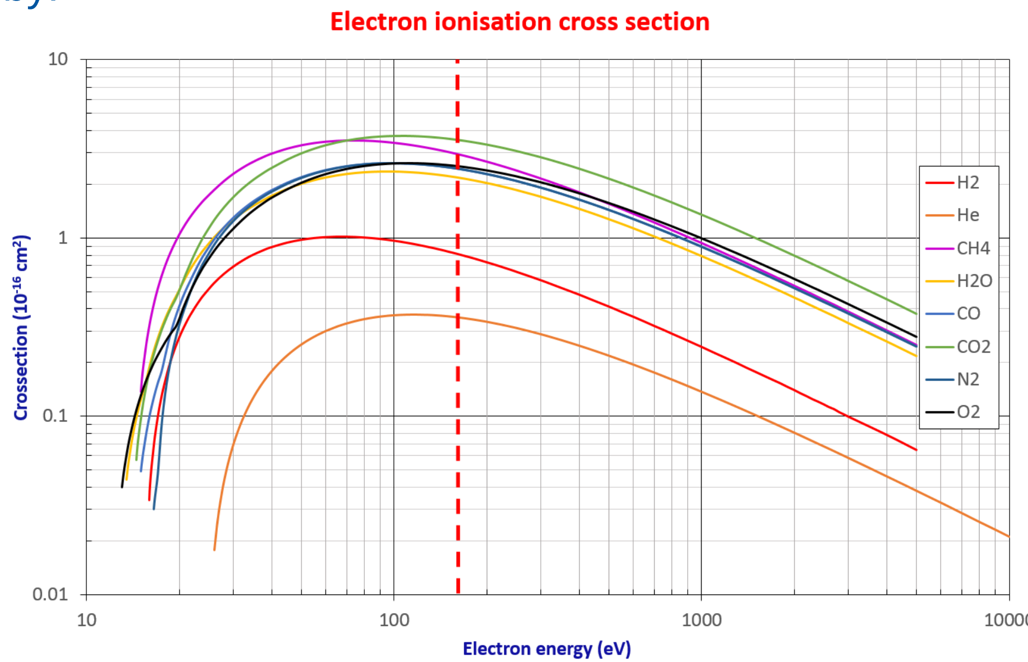
Pictures courtesy B. Henrist

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

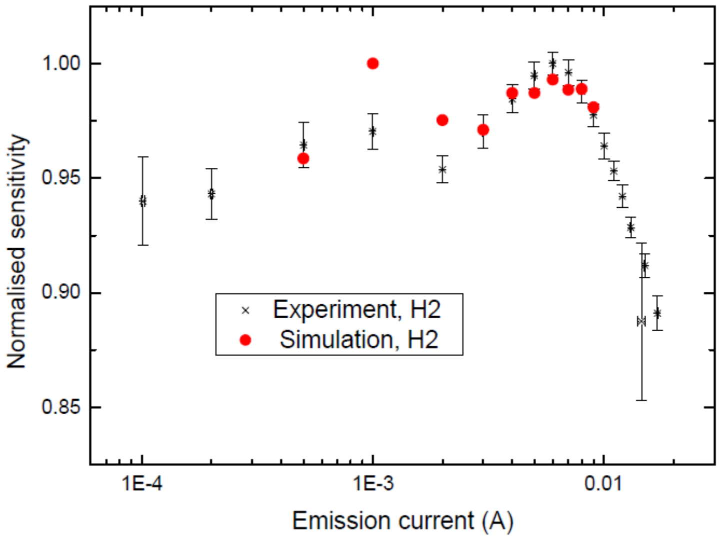
Bayard-Alpert Gauge: Sensitivity

- The sensitivity can be measured and also computed from simulations

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

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

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



B. Jenninger et al. Vacuum

	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

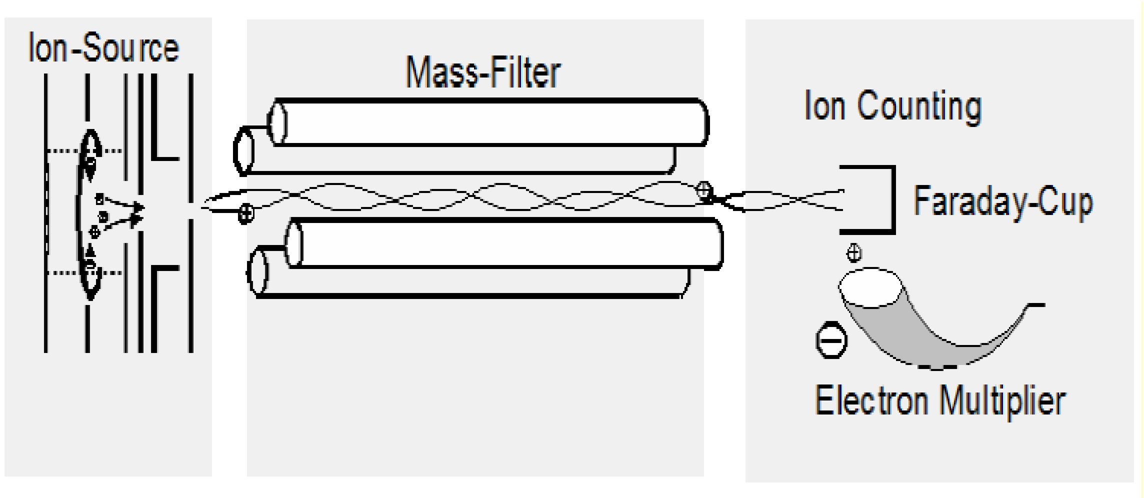
- The sensitivity relative error equals ~ 10 %
- A pressure reading in N_2 equivalent is: P_{read} =2 10^{-10} mbar, in the case the main molecular species is H_2, the real pressure is: P = $S_{rel,H2}$ x P_{read} = 4.4 10^{-10} mbar

3.2 Gas analysis

Residual Gas Analysers

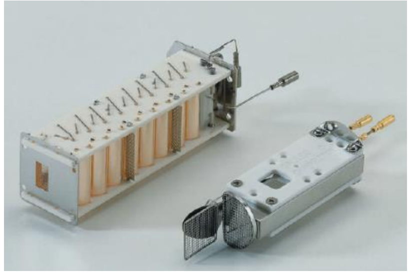
- Residual Gas Analysers are used in the range 10^{-4} -10^{-13} mbar. Their purpose is to do gas analysis
- A filament produces electrons which ionise the residual gas inside a grid.
- A mass filter is introduced between the grid and the ion collector.
- The ion current can be measured in Faraday mode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

- 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^+): $I_{12} = 0.06\ I_{28}$

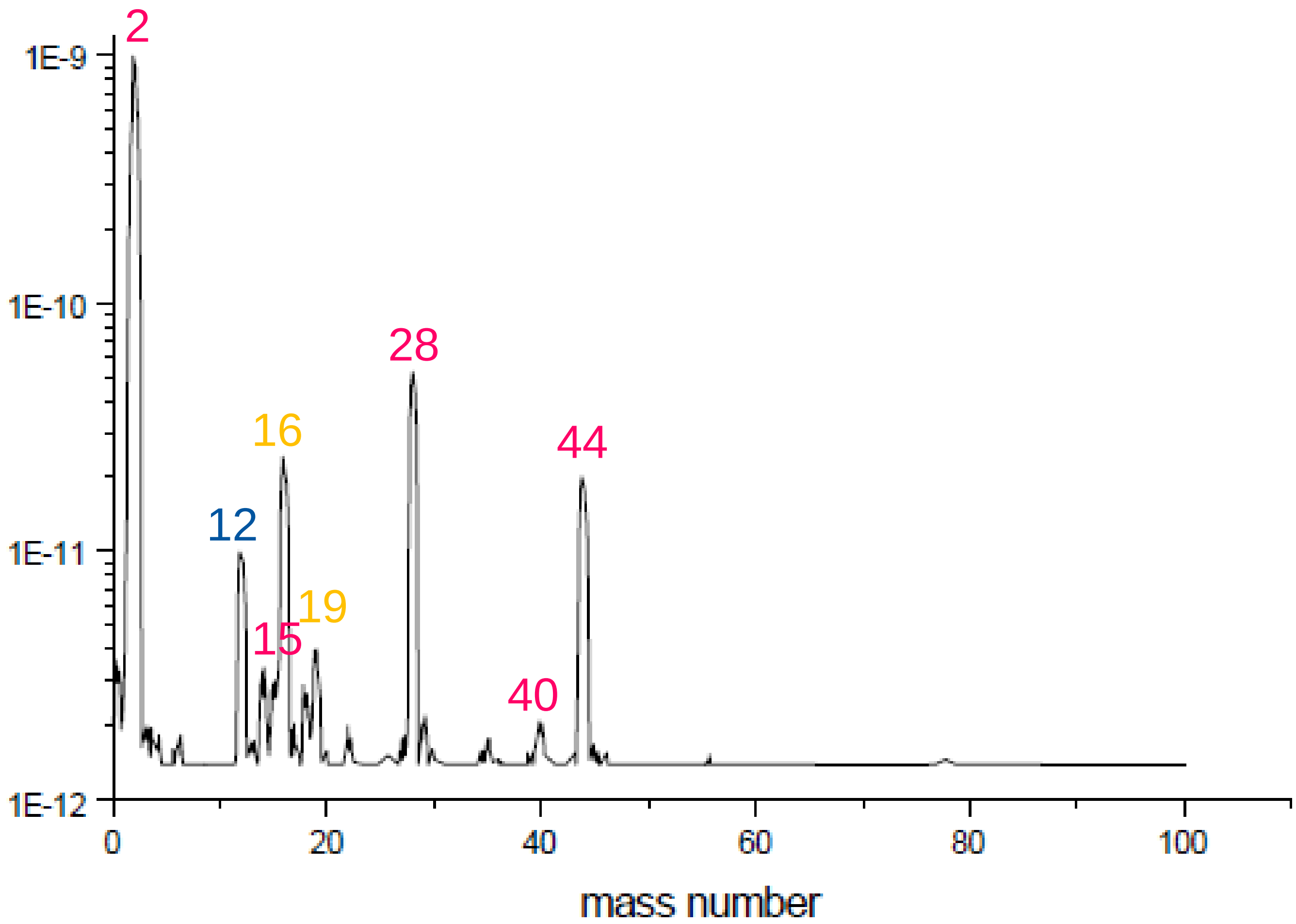
- Carbon dioxide is traced by mass:
  44 (CO_2^+)
  28 (CO^+): $I_{28} = 0.13\ I_{44}$
  16 (O^+): $I_{16} = 0.16\ I_{44}$
  12 (C^+): $I_{12} = 0.10\ I_{44}$

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	$H2^+$	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^+	



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:

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

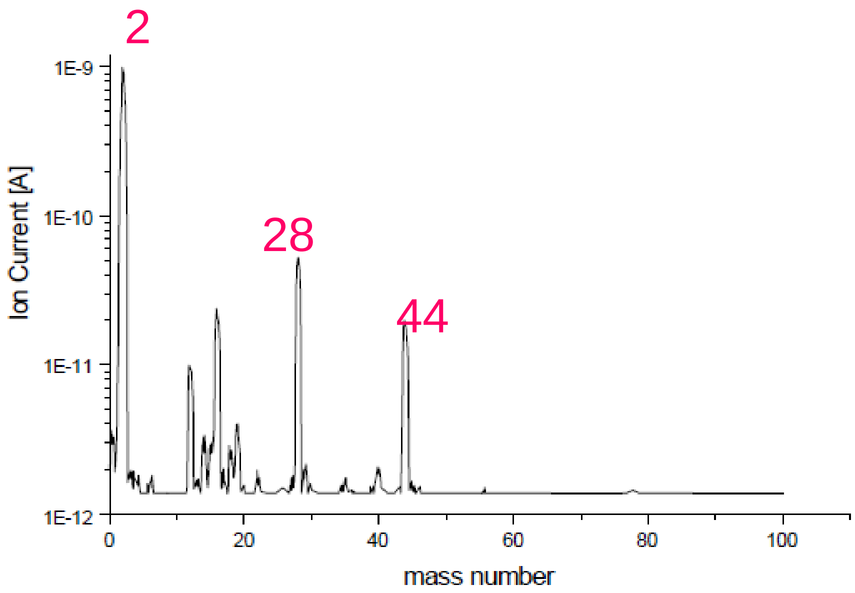
- So:

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

	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!

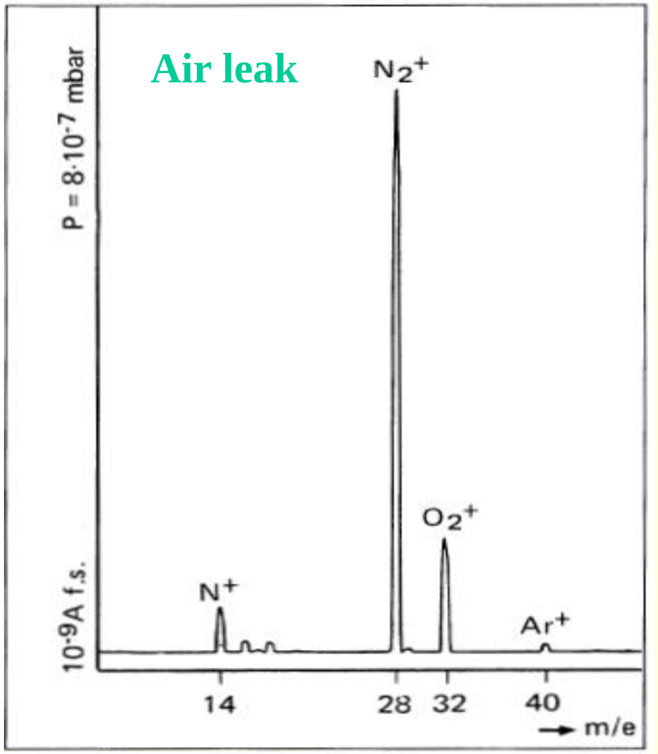
RGA: Air Leak

- 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

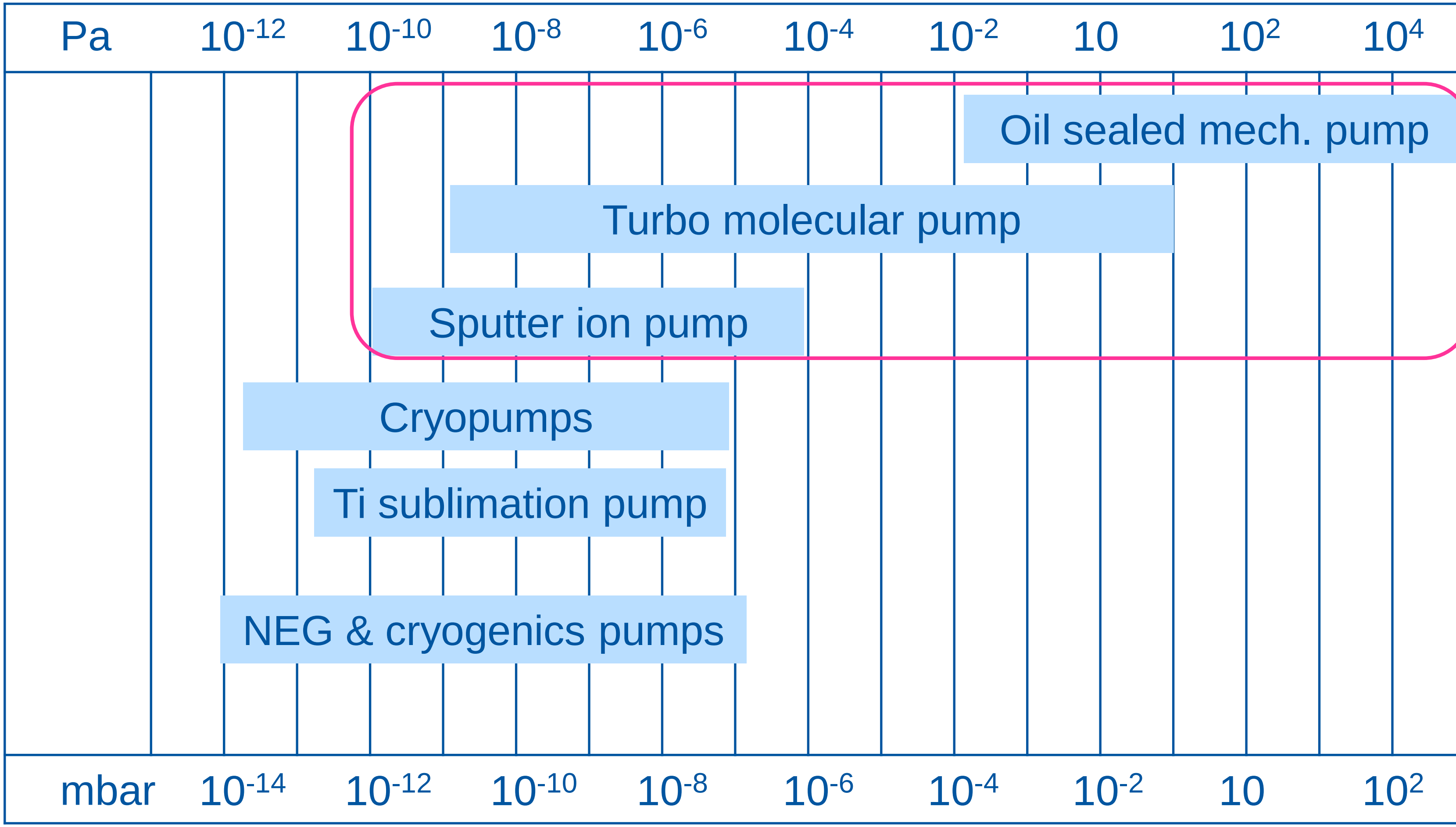


- Assuming a 10 m long, 8cm diam. tube of specific conductance ~ 60 l.s.m
- A pumping speed of 6 l/s at the level of the leak would give a leak rate is 5 10^{-6} mbar.l/s
- Oxygen being highly chemically reactive is not always present!

3.3 Vacuum pumps

Vacuum pumps pressure range

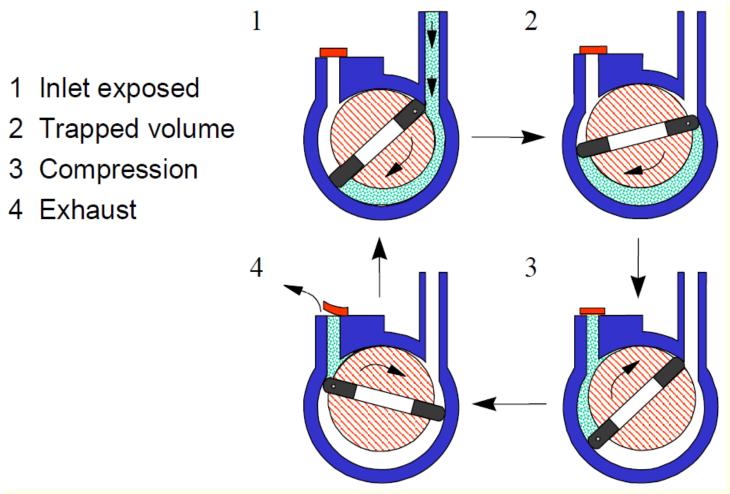
16 orders of magnitude !



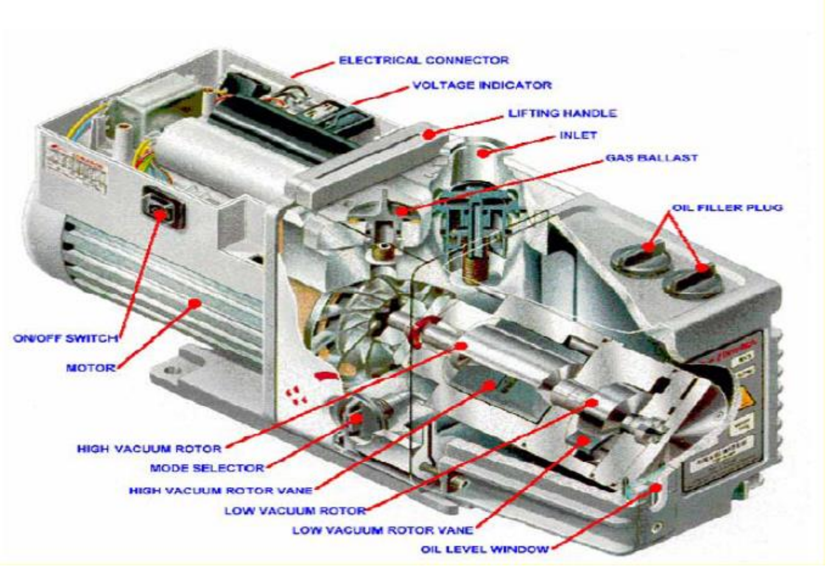
Primary Pumps

- 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

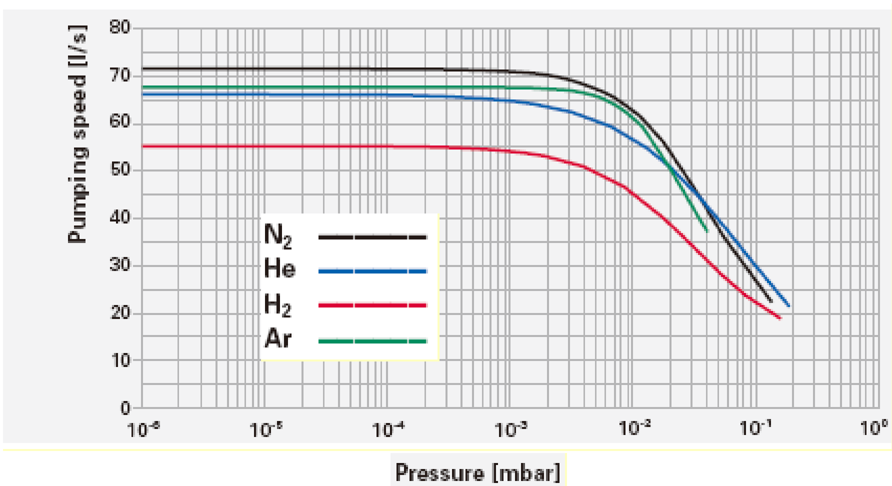


A.D. Chew. CAS Vacuum in accelerators CERN 2007-003



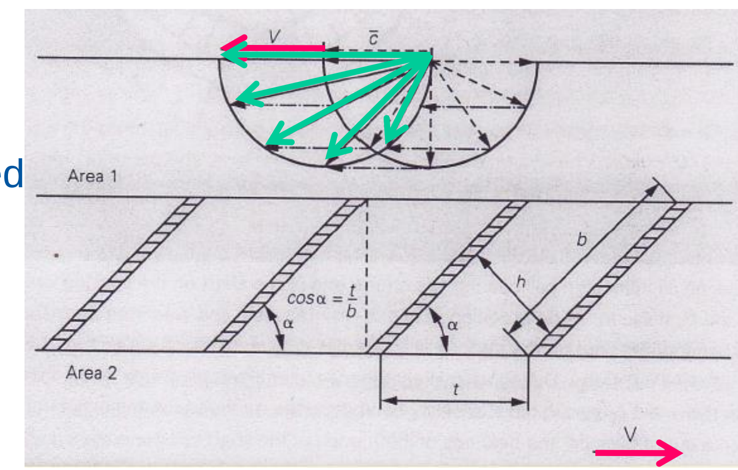
Turbomolecular Pump

- 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)

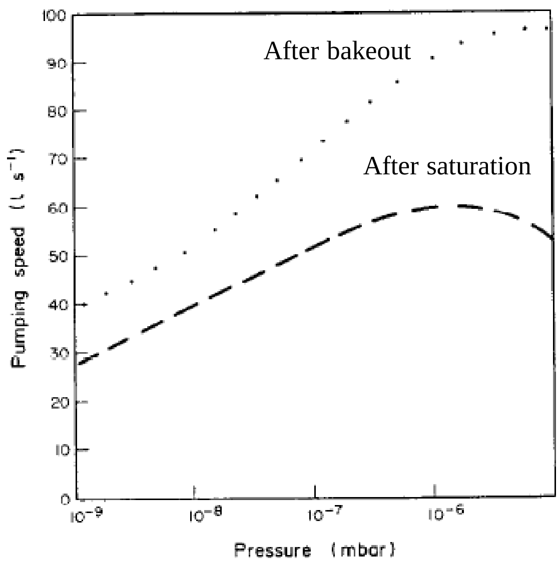


- The compression ratio (P_{inlet}/P_{outlet}) increase exponentially with $\sqrt{M}$: "clean" vacuum without hydrocarbons. So, the oil contamination from the primary pump is avoided

Sputter Ion Pump

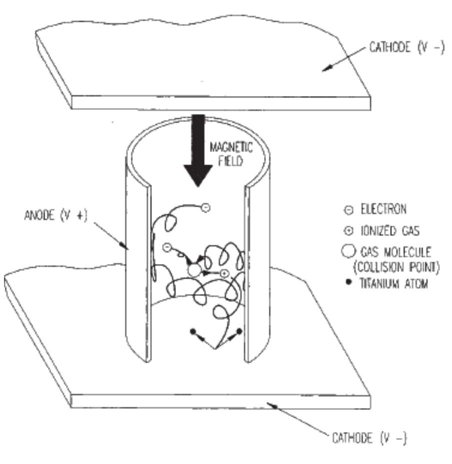
•This pump operate in the range 10^{-5} -10^{-11} mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator.
• Their pumping speed range from 1 to 500 l/s

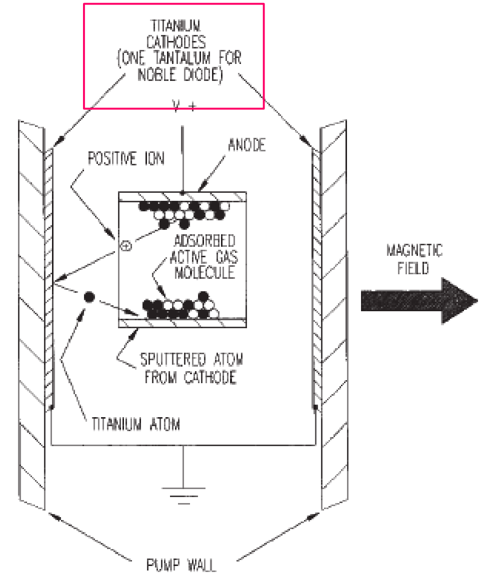
• When electrons spiral in the Penning cell, they ionised molecules. Ions are accelerated towards the cathode (few kV) and sputter Ti. Ti, which is deposited onto the surfaces, forms a chemical bounding with molecules from the residual gas. Noble gases and hydrocarbons ,which does not react with Ti, 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.



M. Audi. Vacuum 38 (1988) 669-671

Picture 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 Technolgy

- Journal of vacuum science and technology
- Vacuum

Thank you for your attention !!!

CERN

Complementary informations

2.1 Gas kinetic theory

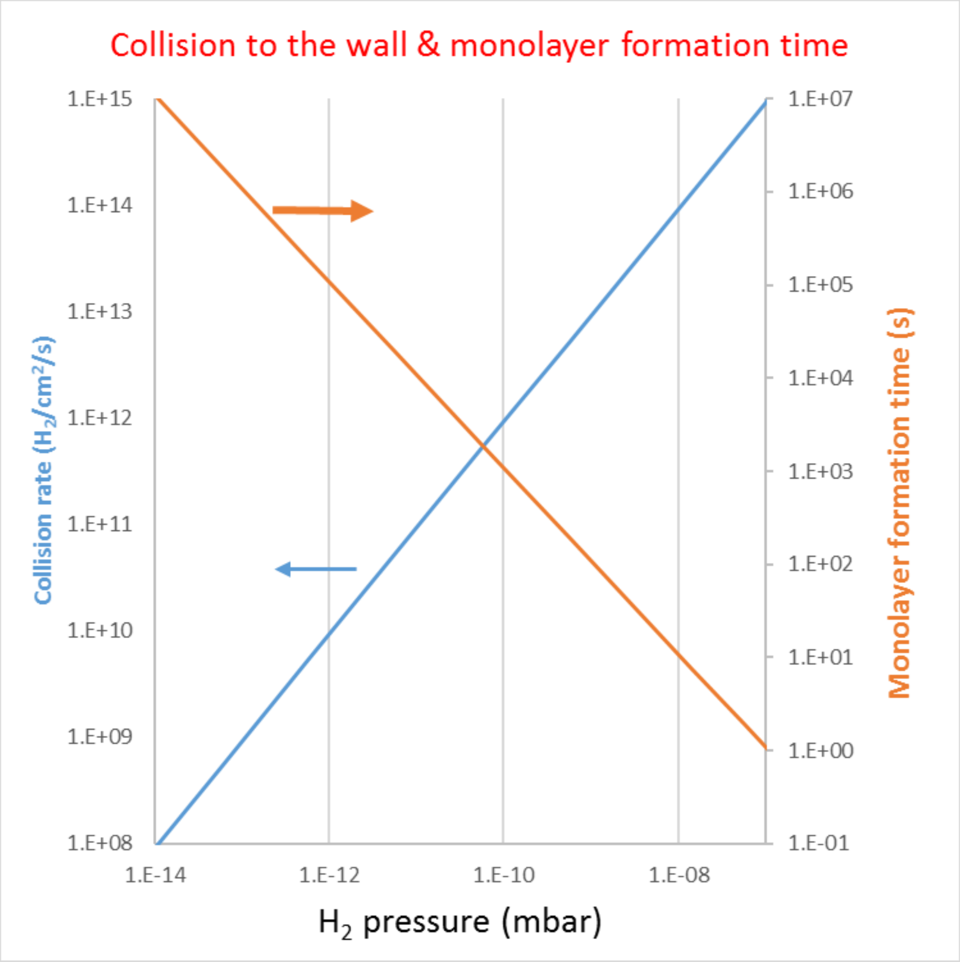
Collision on the wall: cryogenic temperature

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

Complementary information

n (H_2/m^3)	V ($H_2/cm^2/s$)	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

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	2.65×10^{-2}
0.80	0.56655	4.5	0.20669	5000	2.66×10^{-3}

- For long circular tube, the transmission probability equals:

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

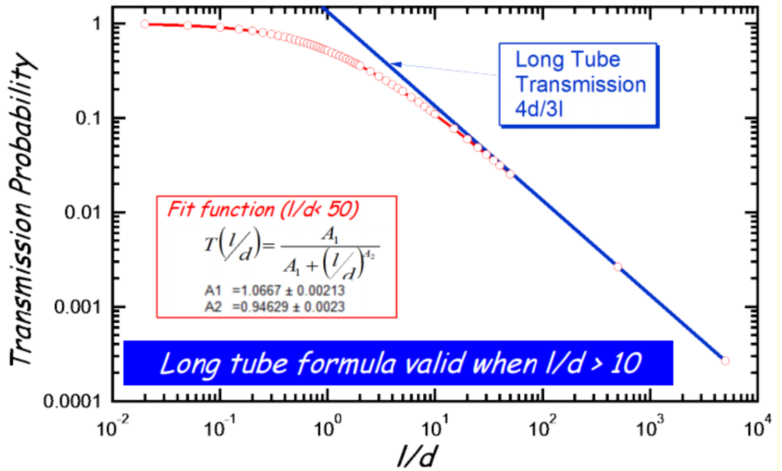


Table & plot courtesy of Y. Li and X. Liu
http://uspas.fnal.gov/materials/15ODU/Session1_Fundamentals.pdf

Calculating conductances with Molflow+

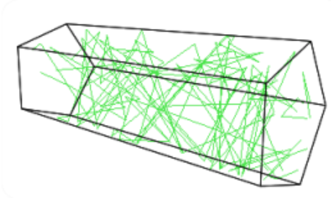
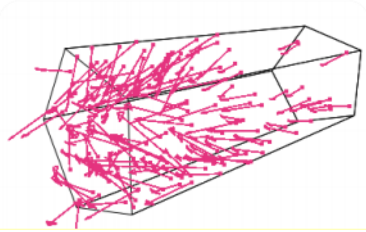
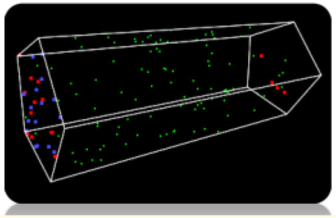
Complementary information

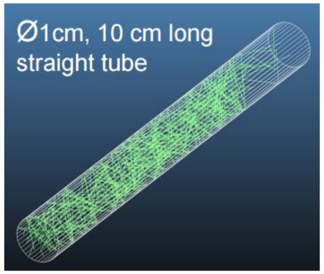
- A test particle Monte-Carlo code for molecular flow
- http://molflow.web.cern.ch/
- R. Kersevan – M. Ady

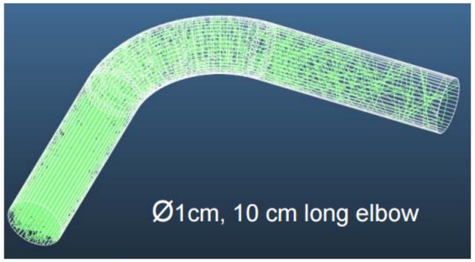
Lines
Particle trajectories

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

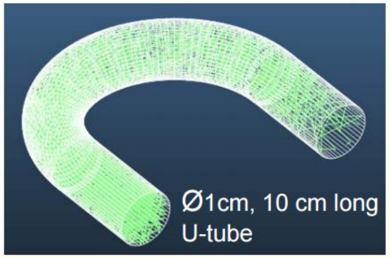




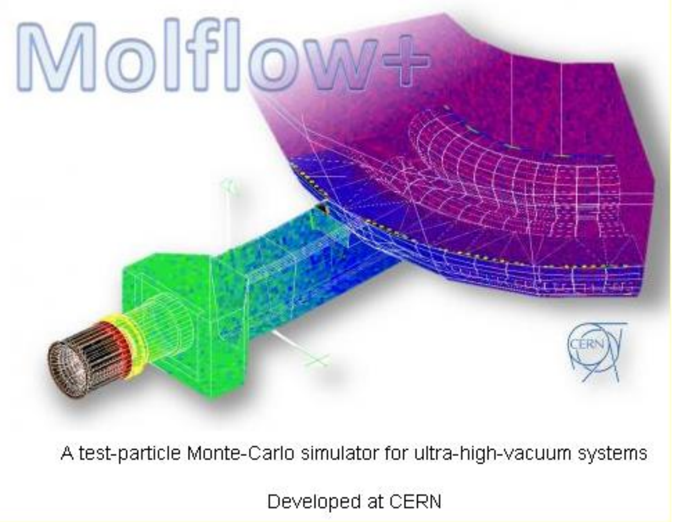




Straight	α = 0.109
90° Elbow	α = 0.105
180° U	α = 0.093

These simple calculations took <1-minute





courtesy of Y. Li and X. Liu

3.1 Vacuum gauges

Spinning rotor gauge

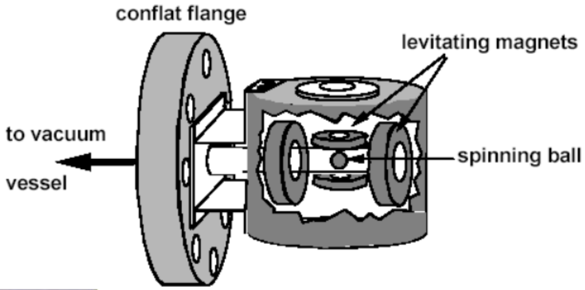
Complementary information

- 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



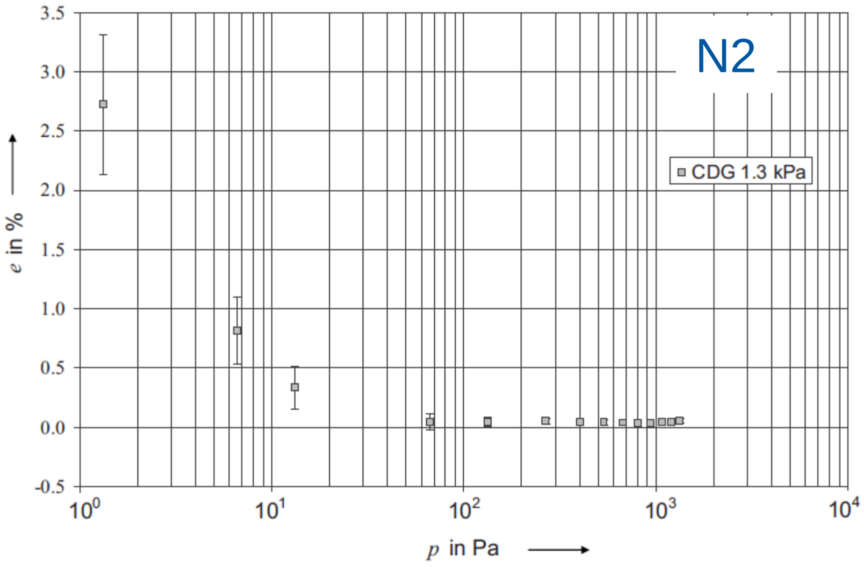
$$P = \frac{d_{Ball}}{10}\frac{\rho_{Ball}}{\sigma_{gaz}}\sqrt{\frac{2\pi RT}{M}}\frac{(T_{rev,n+1} - T_{rev,n})}{\overline{T_{rev}}^2}$$

Viscosity, σ_{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

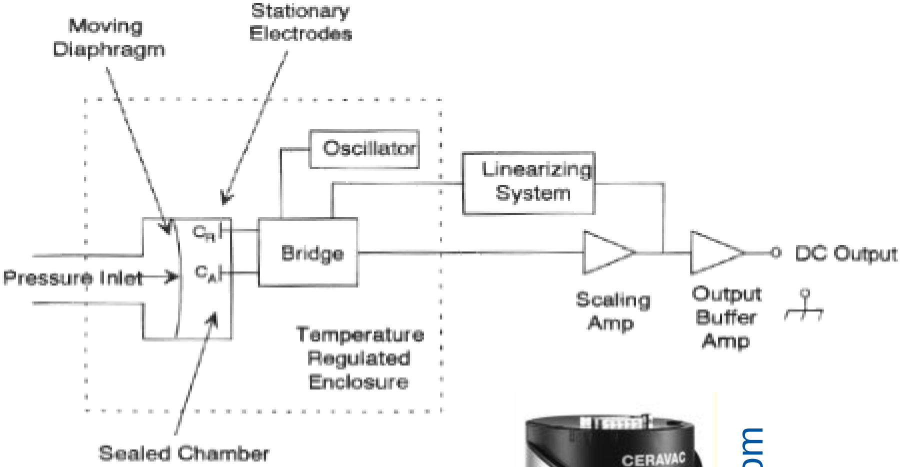
Capacitance diaphragm gauge

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 $mbar^{-1}$ for N_2

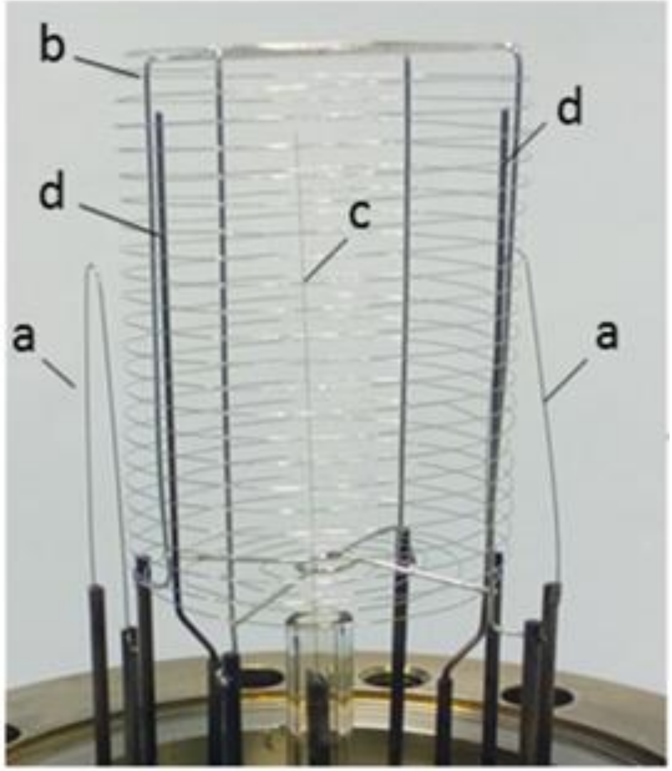
a. W Filament: Ø0.18, height 30

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

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



Bayard-Alpert Gauge: Filament

Complementary information

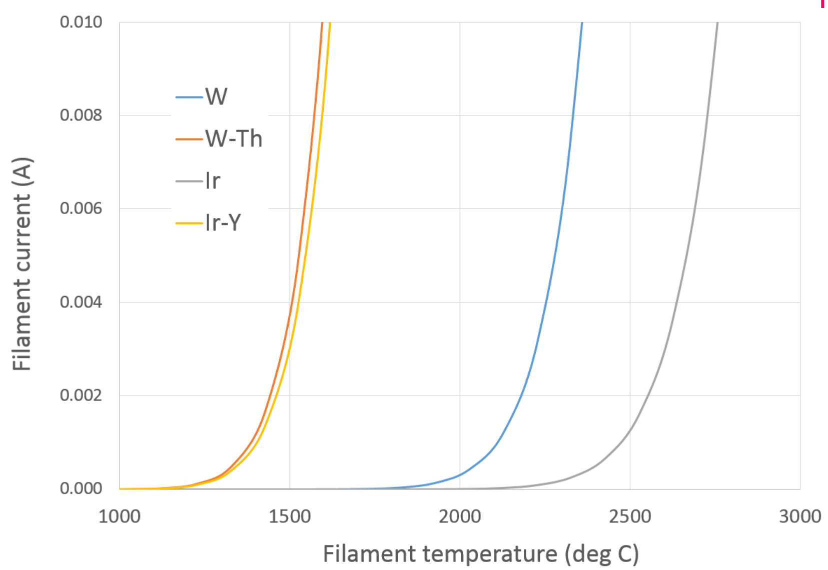
- Electron are produced at the W filament by thermo-electronic emission
- The emission is a function of the work function, Φ, of the material
- Filaments are made of Iridium/Ytrium, W/Thorium coated to reduce the work function, thereby reducing the operating temperature, T, (thus gas load into the system)

Richardson-Dushman equation

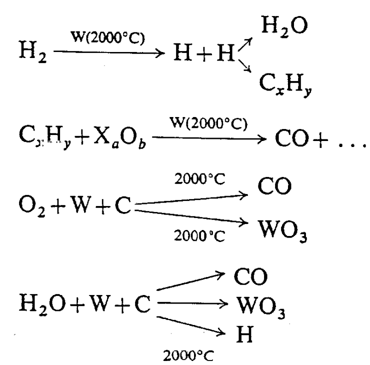
$$J = A\,T^2\,e^{-\left(\phi/_{kT}\right)}$$

A = (1-r) A_o
A_0 = 120 A/(cm^{2}K^2)

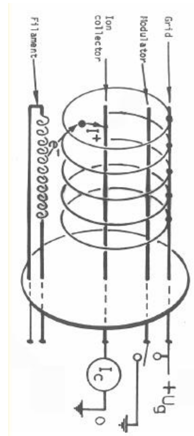
Material	A	Φ (eV)
W	60	4.54
W-Th	3	2.63
Ir	60	5.3
Ir-Y	2	2.6



Typical chemical reactions at the filament



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

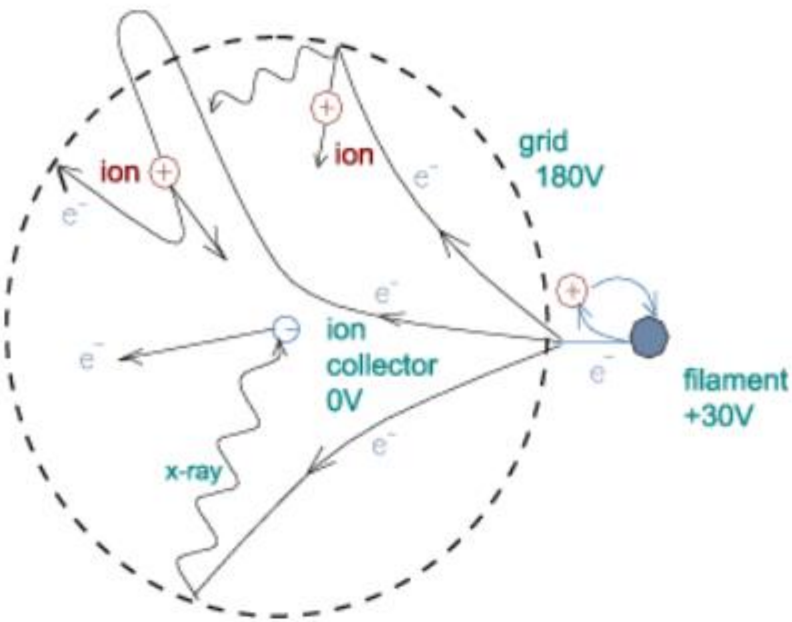


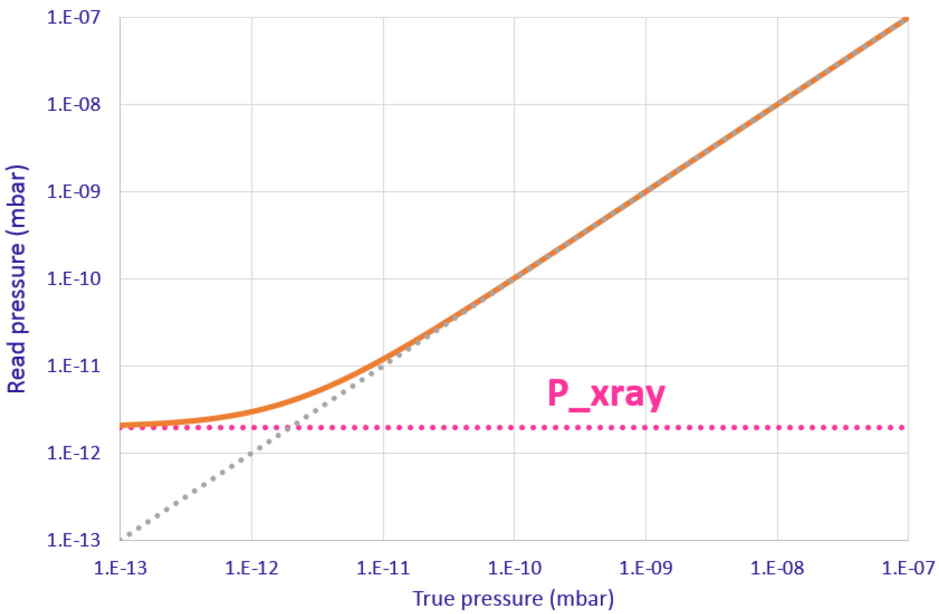
- Some electrons can bombard the grid with ~ 150 eV: they can desorb gas molecules and produce an artificial increase of the pressure.
- The vacuum gauges are therefore "degassed" by electron bombardment at large current (~ 10 mA) and energy () of the grid and electrodes
- Filaments have pumping speed: 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 $P_{xray} \sim 2\ 10^{-12}$ mbar

Bayard-Alpert Gauge: Modulation

Complementary information

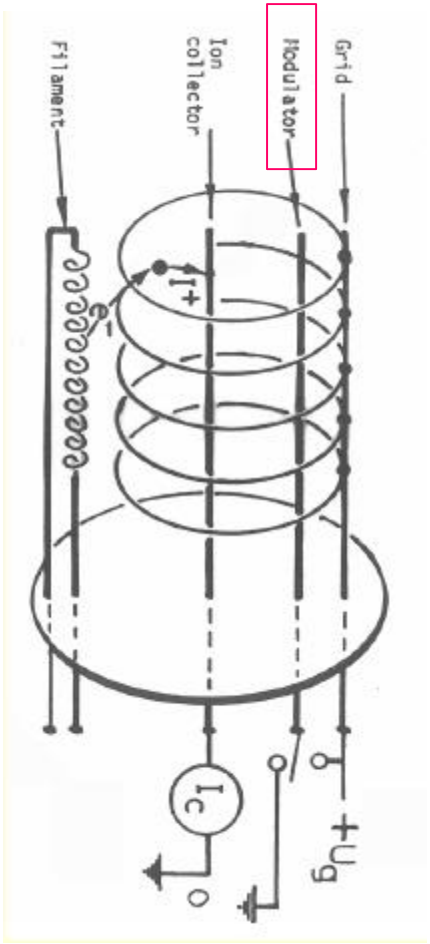
- A correction of the residual pressure due to the x-ray can by applied by the "modulation" technique

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

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

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

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



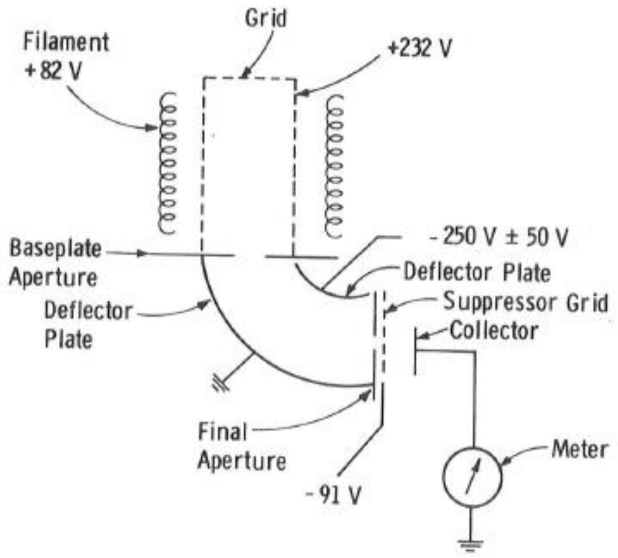
	H_2	He	CH_4	N_2	CO	C_2H_6	Ar	CO_2
k	0.86	0.91	0.89	0.89	0.89	0.89	0.89	0.89

- 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 $mbar^{-1}$ for N_2
- Bakeable to 450 deg C, degassing current at 100 mA with + 500 V on the grid



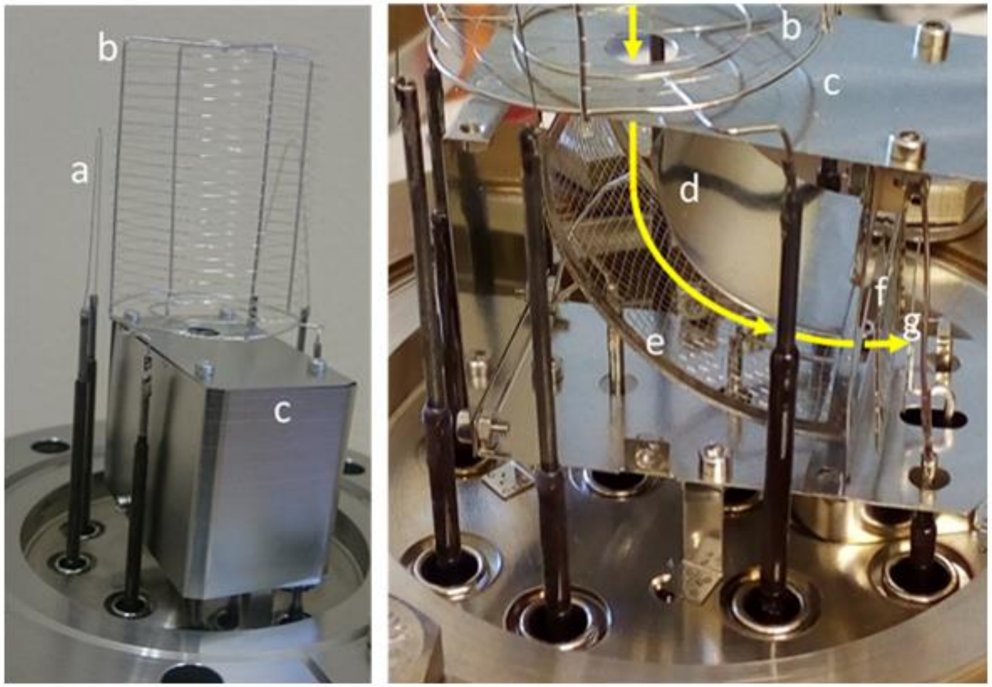
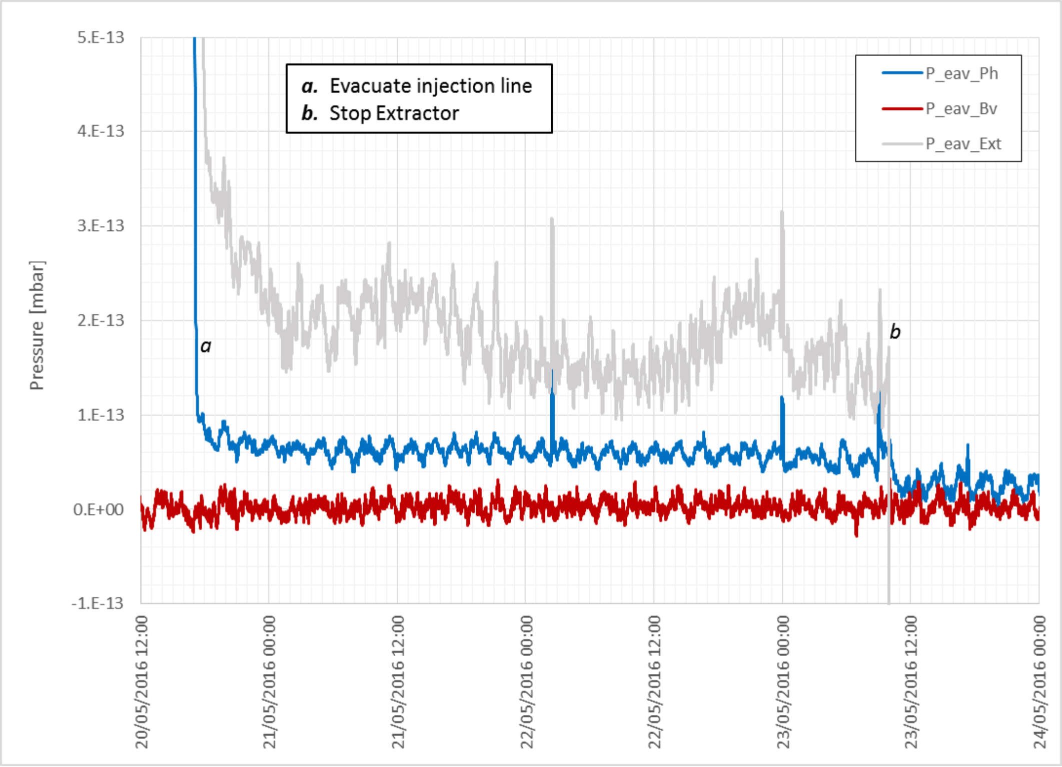


*Figure 8: Main components of the Helmer gauge; on the right with opened cage. (**a** filament, **b** grid, **c** cage, **d** inner deflector, **e** outer deflector (on ground potential), **f** suppressor, **g** collector). The yellow line indicates the ion trajectory from the grid volume towards the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

Helmer gauge and XHV

Complementary information

- Recently measured pressure are ~ 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 mbar^{-1} for N_2 (due to the small grid volume Ø12 x 25)
- Bakeable up to 350°C

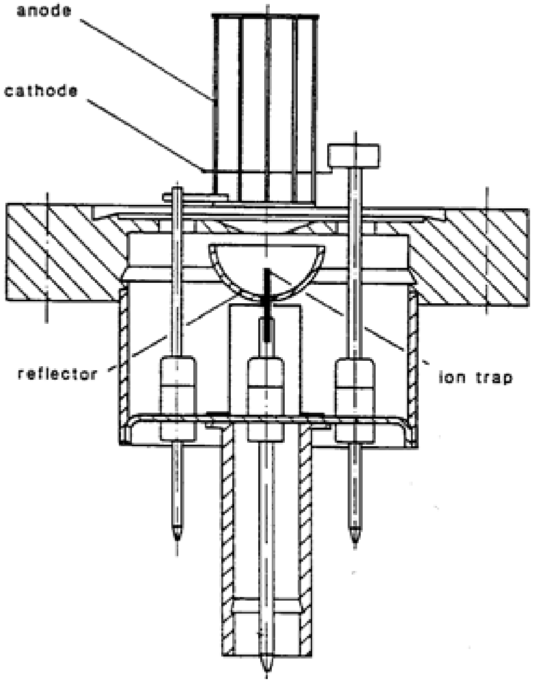
Anode: grid at 220 V

Cathode: filament at 100 V

Reflector at 205 V

Ion collector at 0 V

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



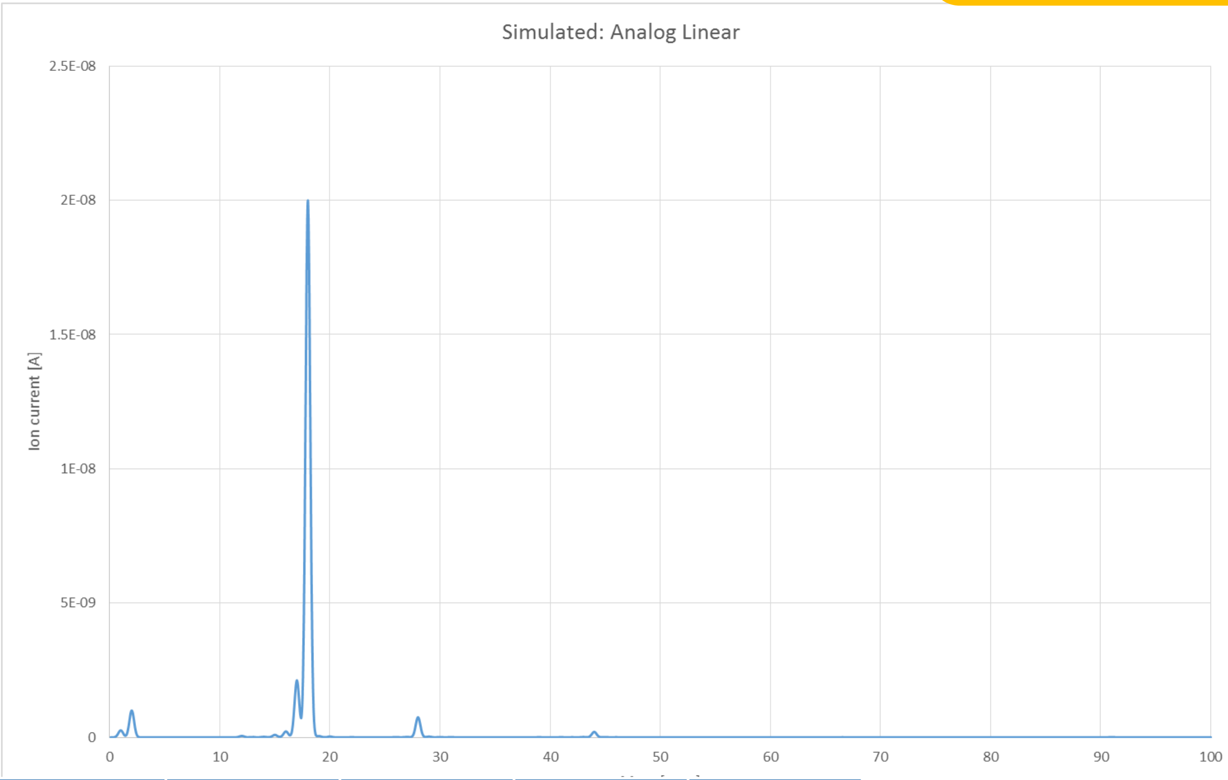
3.2 Gas analysis

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

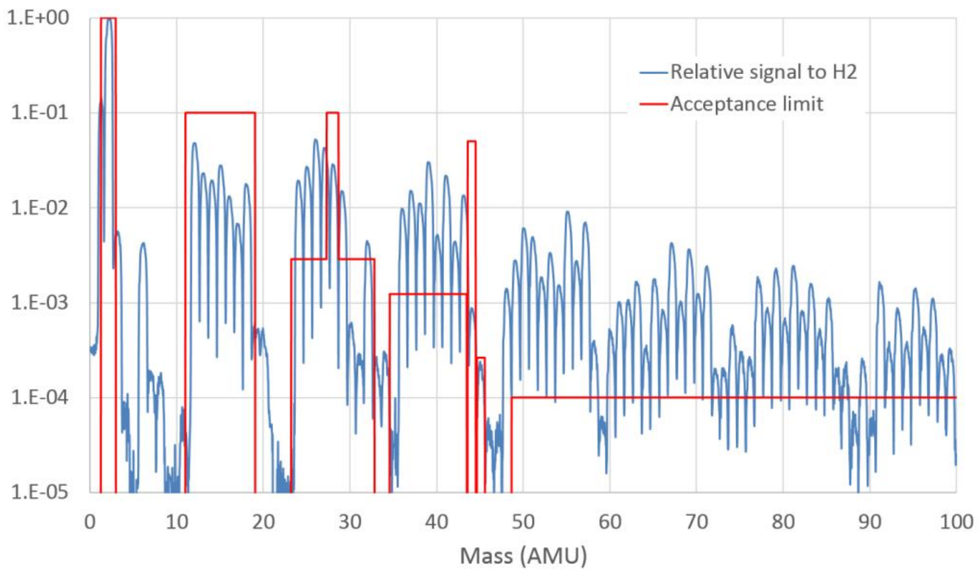


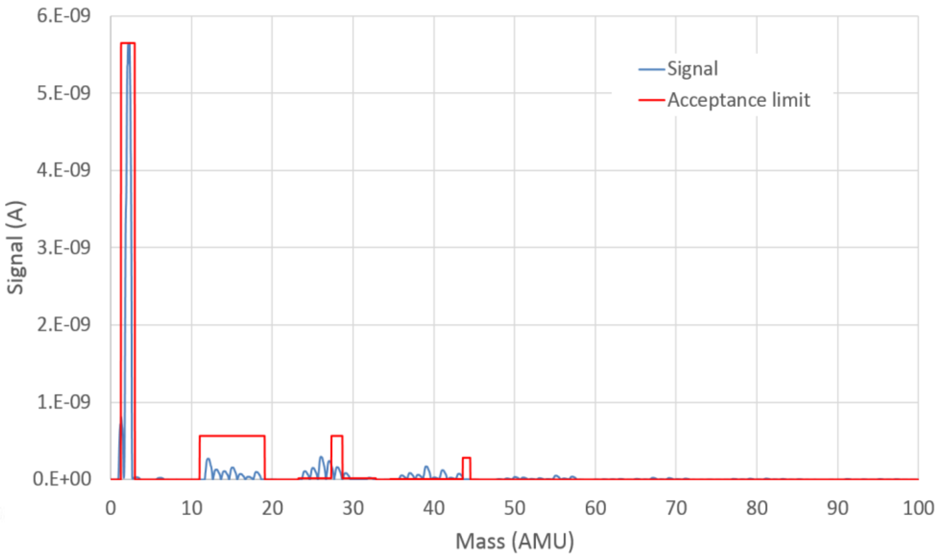
	H_2	CH_4	H_2O	CO	CO_2
I (A)	$1\ 10^{-9}$	$1\ 10^{-10}$	$2\ 10^{-8}$	$7\ 10^{-10}$	$2\ 10^{-10}$
P (mbar)	$1\ 10^{-9}$	$3\ 10^{-11}$	$1\ 10^{-8}$	$4\ 10^{-10}$	$2\ 10^{-10}$
% Pi	10	0	85	3	1

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

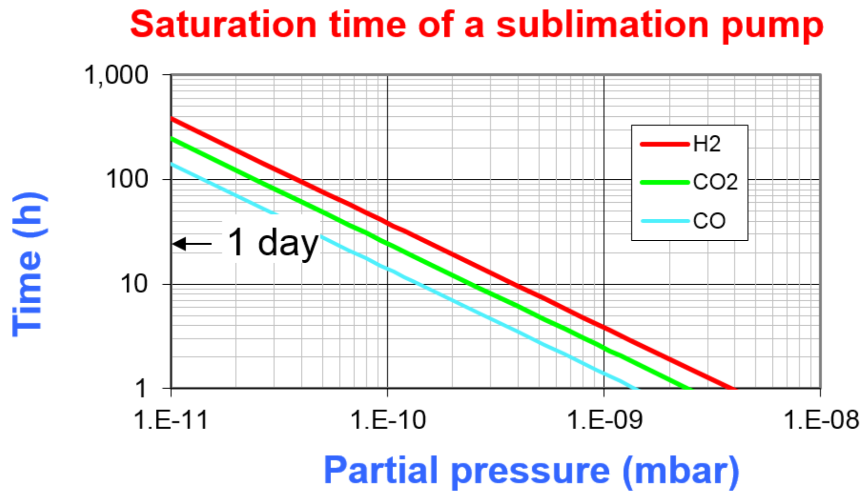
Sublimation pump

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.



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

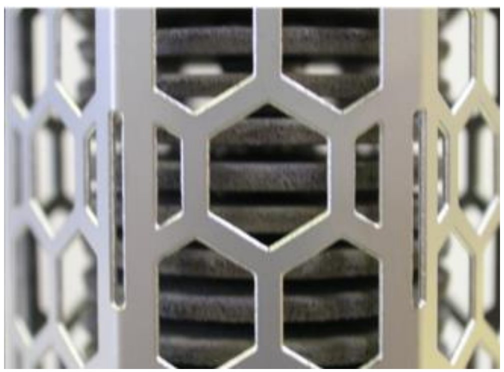
K. Welch, Capture pumping technology, Pergamon press, 1991

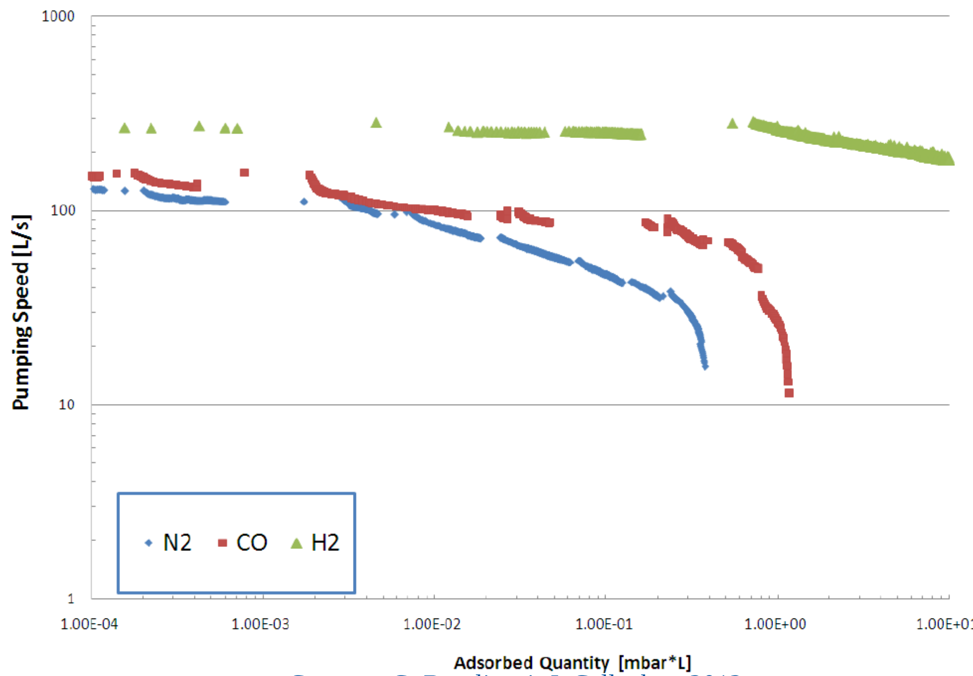
NEG cartridge

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



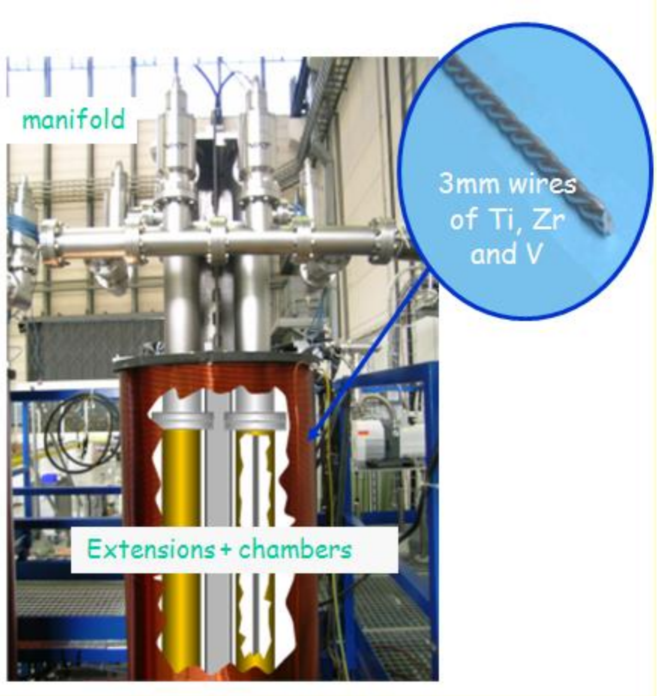


Courtesy G. Bregliozzi, J. Callagher, 2012

Neg coated chamber

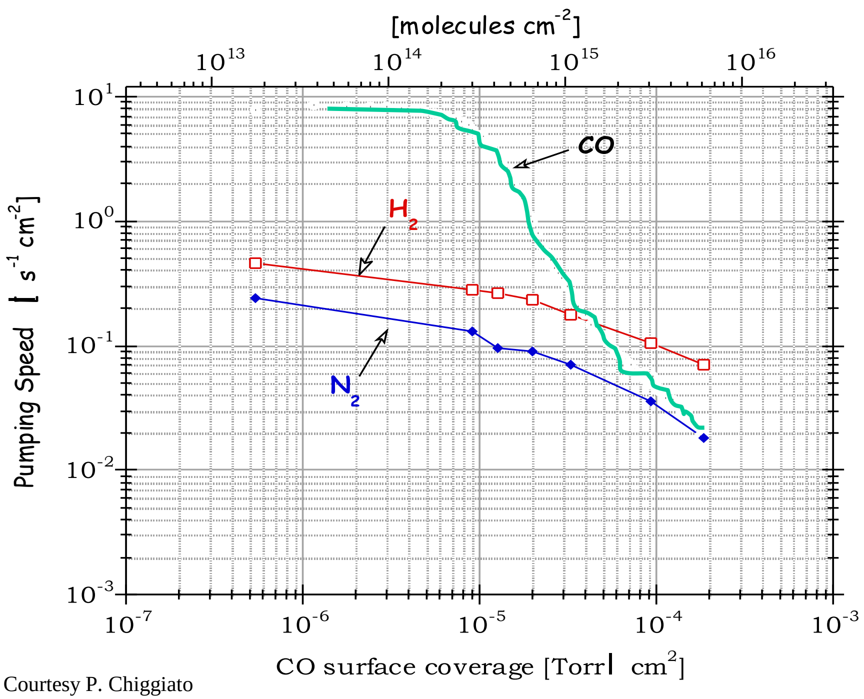
Complementary information

- 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 …)