
CERN

Vacuum Technology for Particle Accelerators
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1. **A quick view of vacuum technology**
2. **The basis of vacuum technology: pressure, conductance, pumping speed**
3. **Calculation of simple pressure profiles**
4. **Gas sources: thermal outgassing and beam-induced desorption**
5. **Gas pumping: momentum-transfer and capture pumps**
6. **Instruments**
7. **Seminar: Example of vacuum system design for particle accelerators (by Roberto Kersevan)**

Selected books

Karl Jousten (Ed.), *Handbook of Vacuum Technology Book* (Verlag-VCH, Weinheim, 2008)

James M. Lafferty (Ed.), *Foundations of Vacuum Science and Technology* (John Wiley and Sons, 1998)

A.Berman, *Vacuum Engineering calculation, Formulas, and Solved Exercises* (Academic Press, 1992)

P. A. Redhead, J. P. Hobson, E. V. Kornelsen, *The Physical Basis of Ultrahigh Vacuum*, (Chapman and Hall, 1968)

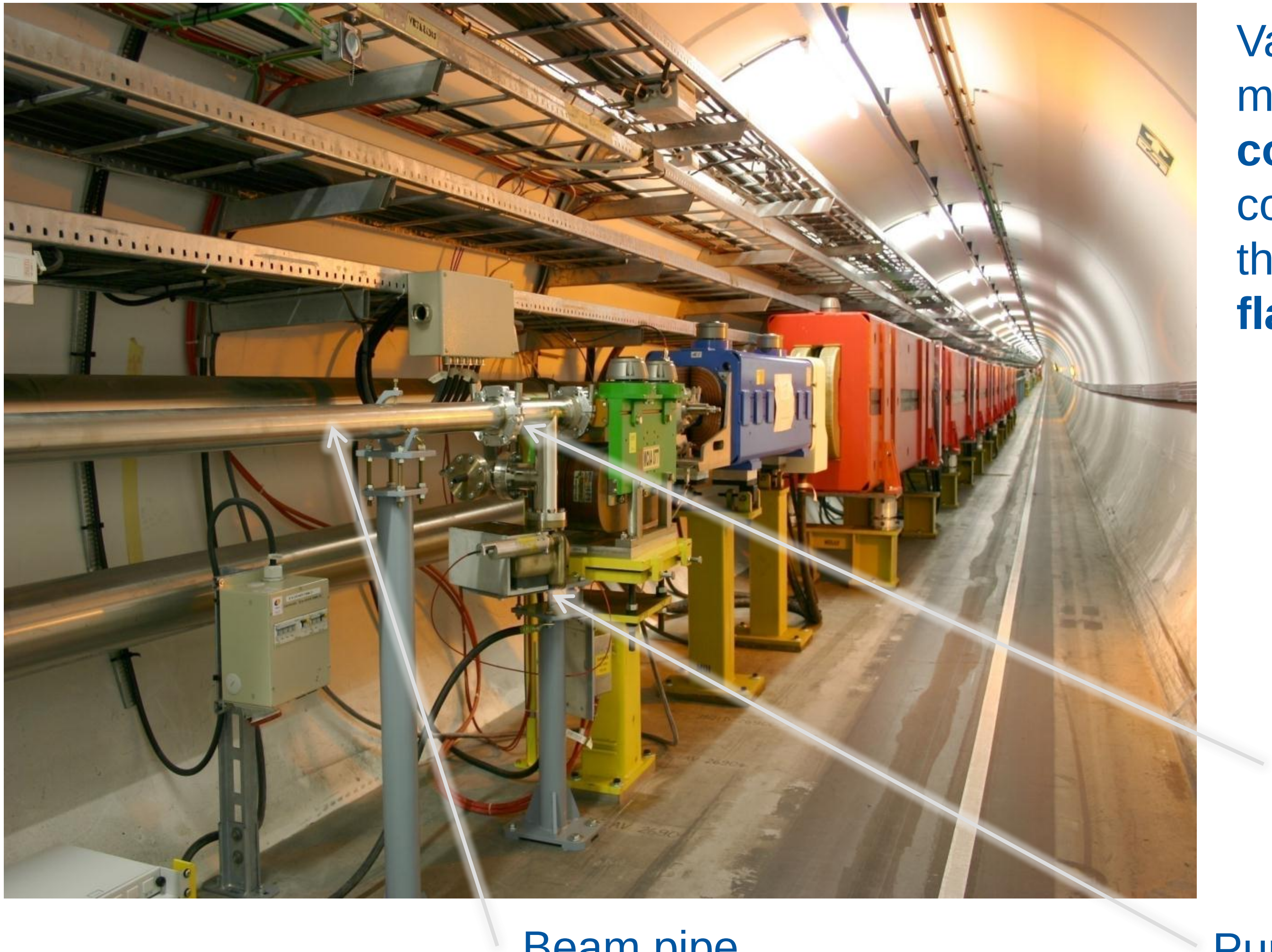
John F. O'Hanlon, *A User's Guide to Vacuum Technology*

Handbook of Materials and Techniques for Vacuum Devices (AVS Classics in Vacuum Science and Technology)

A. Berman, *Total pressure measurement in vacuum technology*, Academic Press, 1985

Part 1
A quick view of vacuum technology

A quick view of vacuum technology



Vacuum systems are made of **several components**. The connection between them is obtained by **flanges**.

A quick view of vacuum technology

Beam pipe & NEG coating

A vacuum sector is delimited by **gate valves**.

The pressure is monitored in each vacuum sector by **gauges**.

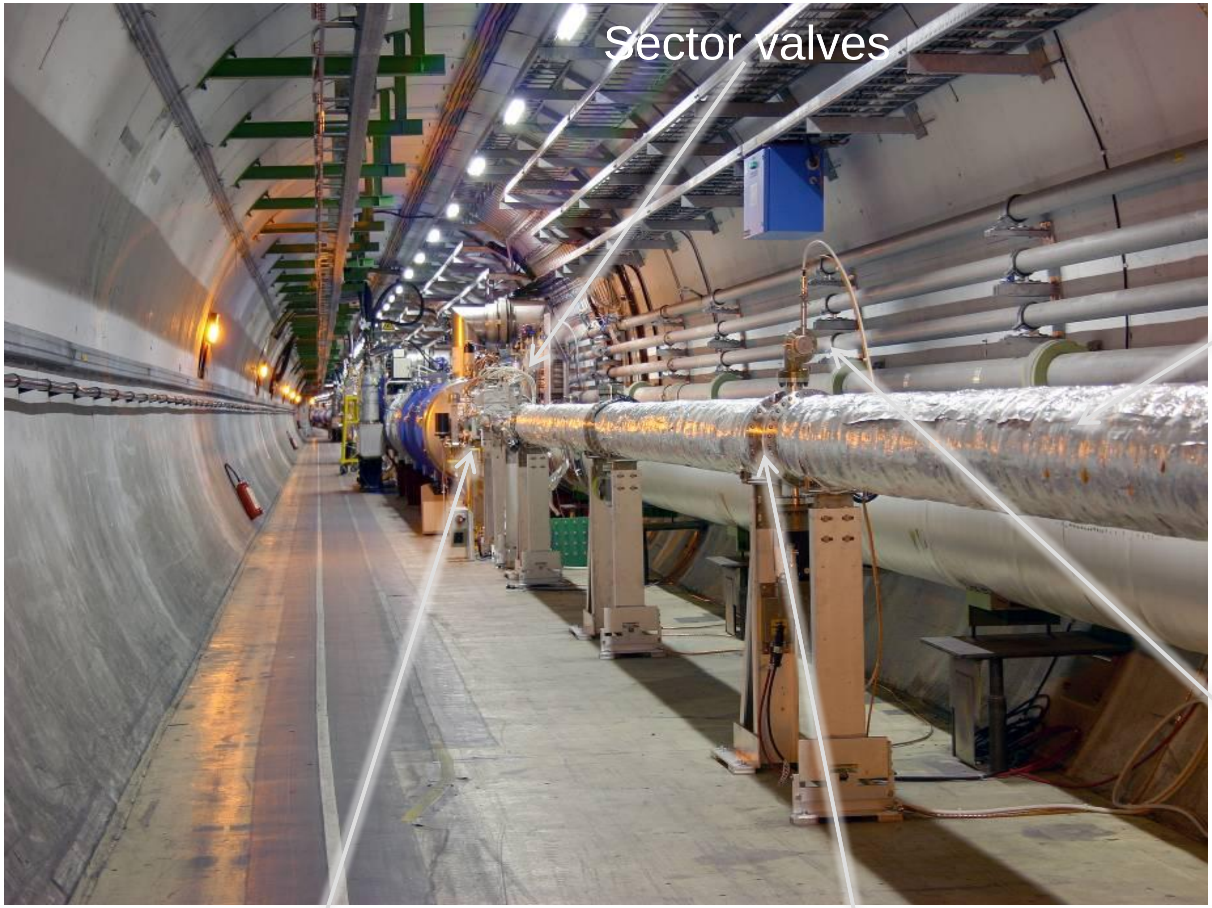
The beam pipes can be at different temperatures

Pressure measurement

Flange

Pump (sputter ion pump)

A quick view of vacuum technology



Sector valves

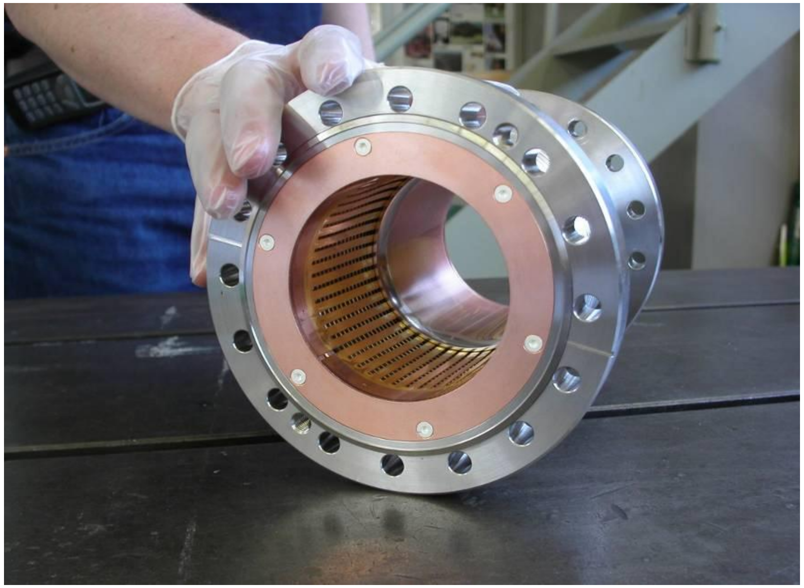
Beam pipe & NEG coating

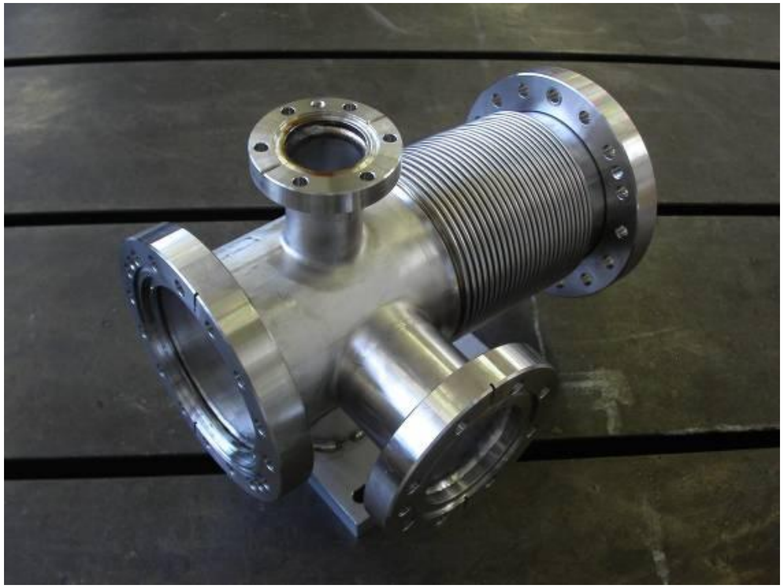
Gauge

Pump (sputter ion pump)

Flange

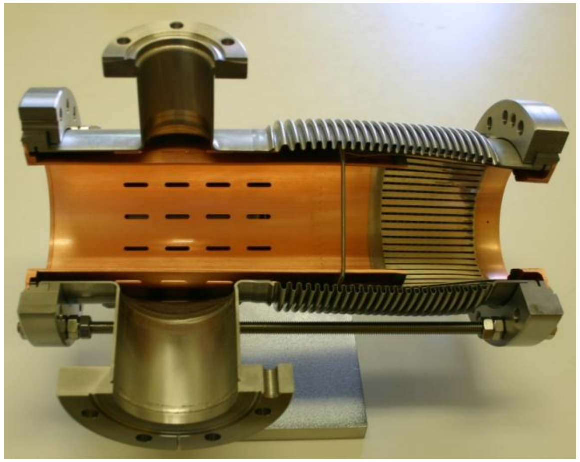
A quick view of vacuum technology





Example of vacuum components:

- pumping ports
- bellows
- RF shield
- flanges



A quick view of vacuum technology

Example of vacuum components:

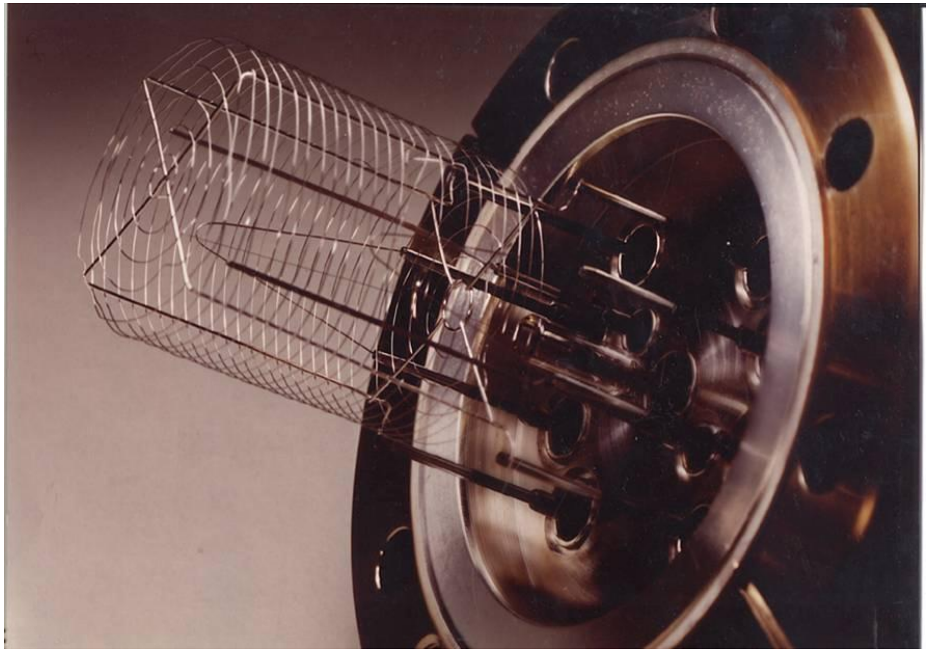
- Copper beam pipes with stainless steel flanges

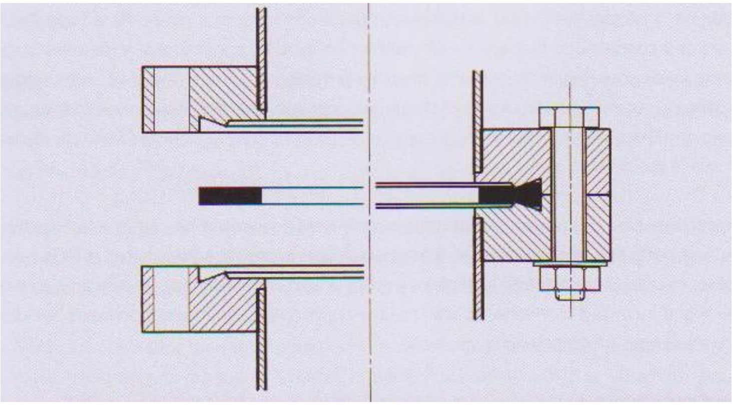
A quick view of vacuum technology

Example of vacuum components:

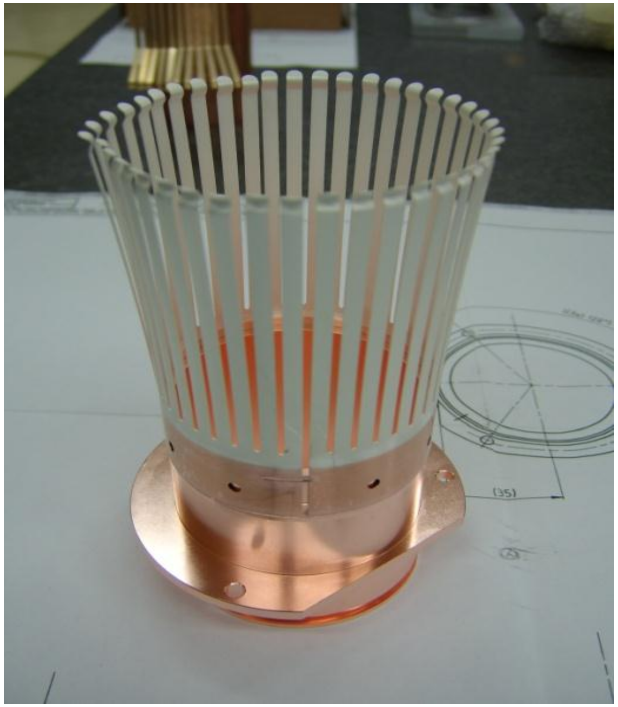
- Beryllium beam pipes in the collision area of the ATLAS experiment (CERN)

A quick view of vacuum technology





In general the leak-tight connection is made by copper gaskets that are squeezed between two stainless steel knives.



In general vacuum systems for particle accelerators are made of metals:

- Austenitic stainless steel
- Copper and its alloys
- Aluminum and its alloys
- Inconel (a Ni alloy)
- Beryllium

In several components the characteristics of the surface is modified by chemical treatment and coating.

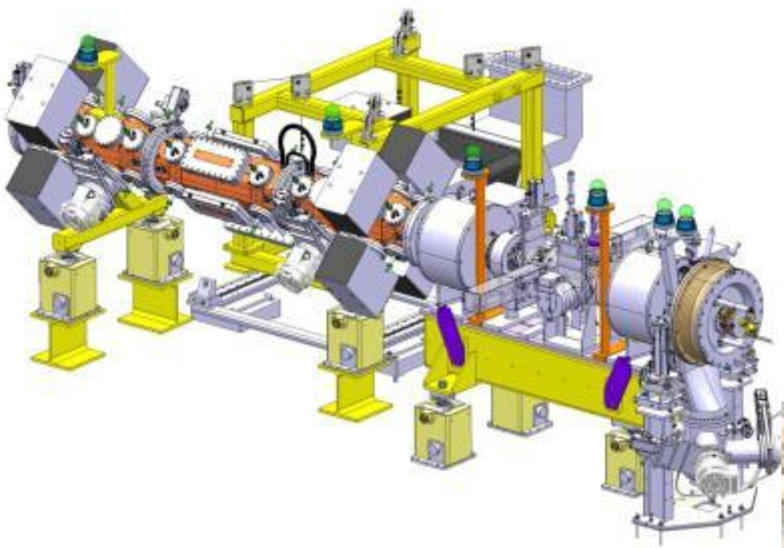
Some example of surface treatments:

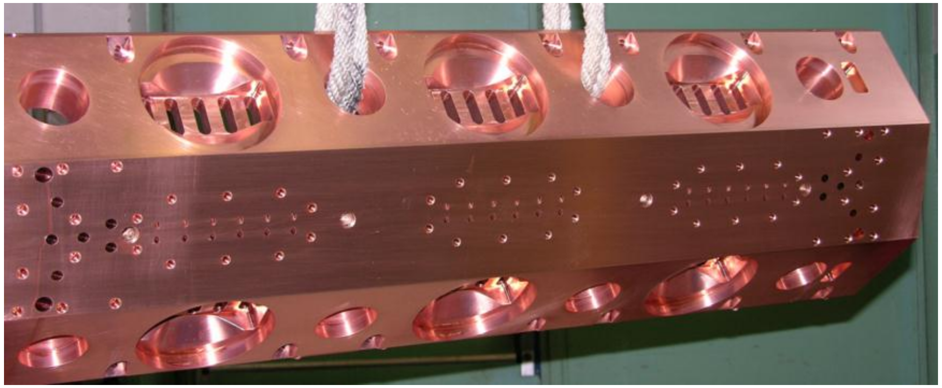
- Chemical cleaning (mandatory!)
- Electropolishing
- Passivation
- Elecroplating
- Thin-film coating by sputtering

A quick view of vacuum technology

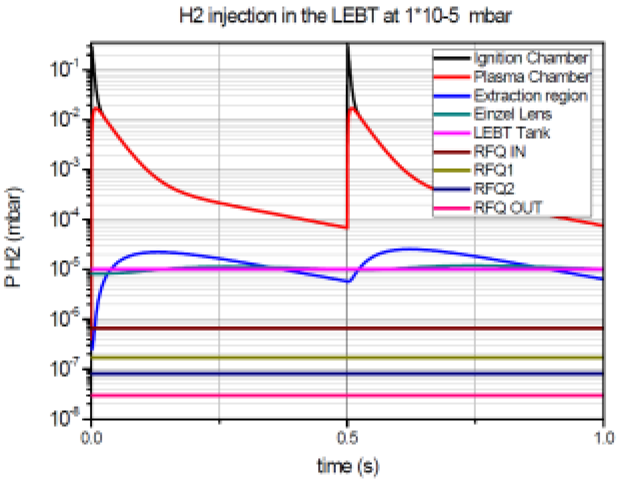
Steps in the production of vacuum systems:

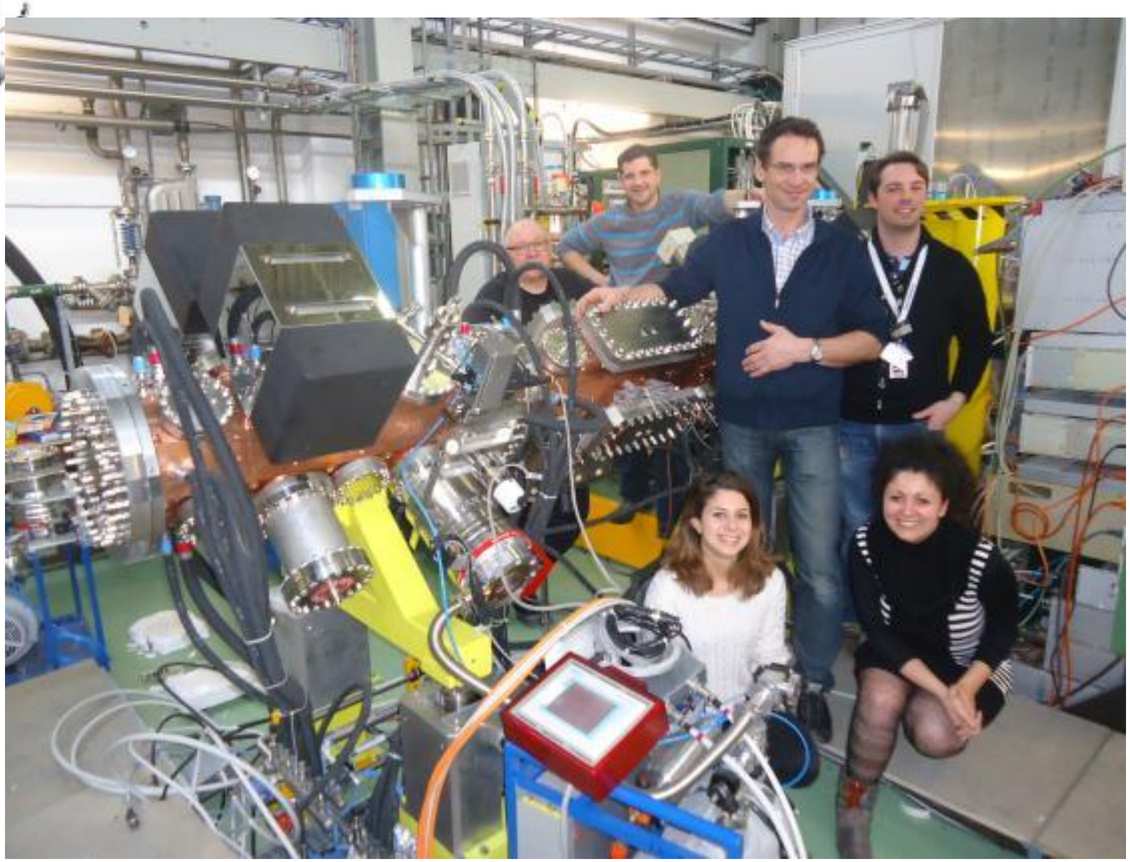
- Identification of requirements
- Choice of materials and treatments
- Design, mechanical evaluation and pressure profile calculation
- Machining & assembly (welding, brazing)
- Surface treatments
- Leak test and global assessment.
- Installation and in situ final check.





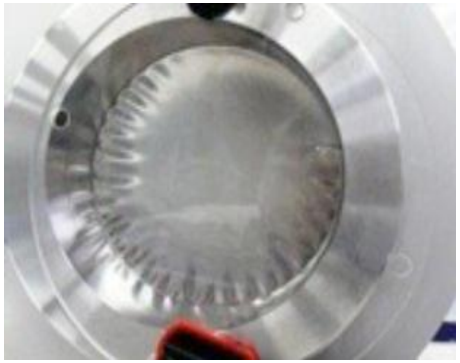
Example of vacuum system: The H$^-$ source of the Linac4

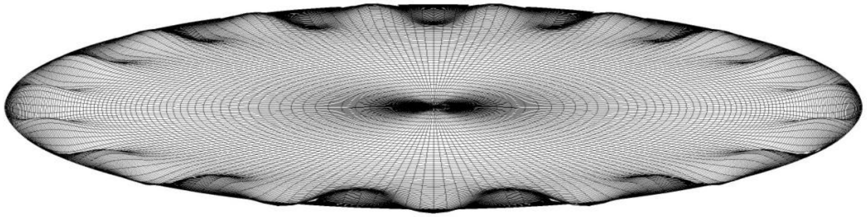

H2 injection in the LEBT at 1*10-5 mbar



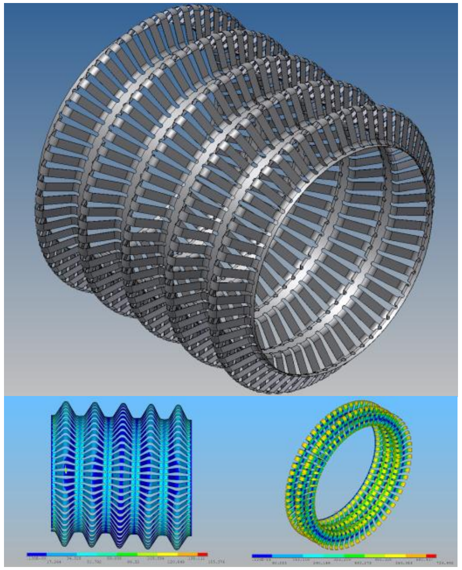
A quick view of vacuum technology

Mechanical engineering for vacuum technology

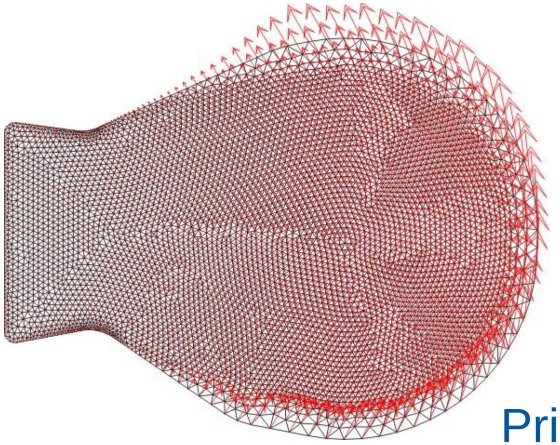


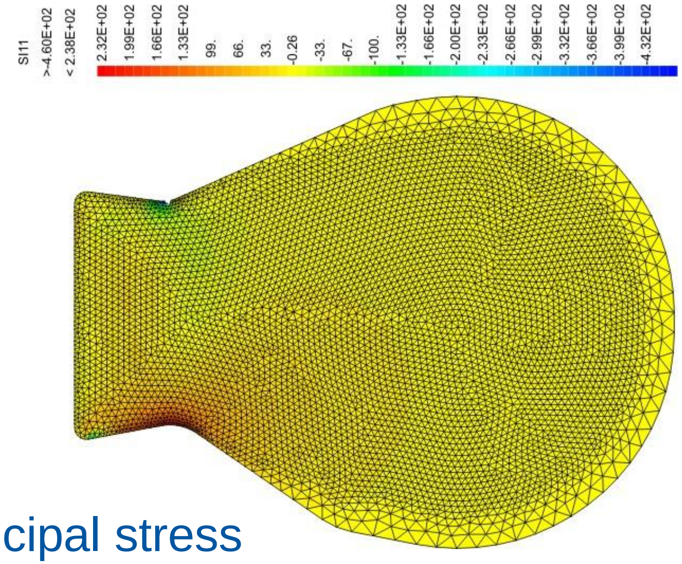


Buckling mode



Dynamic nodal forces



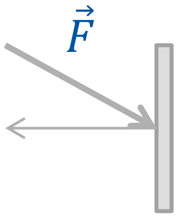


Principal stress

Part 2
The basis of vacuum technology

The basis of vacuum technology: pressure

Definition of pressure: $\dfrac{|Force\ component\ in\ normal\ direction|}{Surface\ area}$



Unit of measurement: $\dfrac{[Force]}{[Surface]} \rightarrow \dfrac{N}{m^2} = Pa \rightarrow 10^5 Pa = 1\ bar \rightarrow 1\ atm = 1.013\ bar$

In vacuum technology : $mbar\ or\ Pa$

Still used in vacuum technology:

$1\ Torr = pressure\ exerted\ by\ a\ column\ of\ 1\ mm\ of\ Hg; 1\ atm = 760\ Torr$

Conversion Table

	Pa	**bar**	**atm**	**Torr**
1 Pa	1	10^{-5}	$9.87\ 10^{-6}$	$7.5\ 10^{-3}$
1 bar	10^5	1	0.987	750.06
1 atm	$1.013\ 10^5$	1.013	1	760
1 Torr	133.32	$1.33\ 10^{-3}$	$1.32\ 10^{-3}$	1

The basis of vacuum technology: pressure

Degree of Vacuum

	Pressure boundaries [mbar]	Pressure boundaries [Pa]
Low Vacuum LV	1000-1	10^5-10^2
Medium Vacuum MV	1-10^{-3}	10^2-10^{-1}
High Vacuum HV	10^{-3}-10^{-9}	10^{-1}-10^{-7}
Ultra High vacuum UHV	10^{-9}-10^{-12}	10^{-7}-10^{-10}
Extreme Vacuum XHV	$<10^{-12}$	$<10^{-10}$

Pressures and gas quantities are correlated by the gas equation of state. In vacuum the ideal gas law is always fulfilled :

$$P\ V = n\ R\ T$$ (thermodynamic)

$$P\ V = N\ k_B \mathrm{T}$$ (statistical mechanics)

P pressure, **V** volume, **T** temperature, quantity of gas in moles (**n**) and number of molecules (**N**), **R** gas constant, $\mathbf{k_B}$ Boltzmann constant

The basis of vacuum technology: gas density

$$\frac{molecules}{cm^3}$$

	Pressure [Pa]	Gas Density 293 K	Gas Density 4.3K
Atmosphere	$1.013\ 10^{5}$	$2.5\ 10^{19}$	$1.7\ 10^{21}$
Plasma chambers	1	$2.5\ 10^{14}$	$1.7\ 10^{16}$
LINAC pressure upper limit	10^{-5}	$2.5\ 10^{9}$	$1.7\ 10^{11}$
Lowest pressure ever measured at room T	10^{-12}	250	$1.7\ 10^{4}$

$$P\ V = N k_B T \rightarrow P = \left(\frac{N}{V}\right) k_B T \quad k_B = 1.38\ 10^{-23}\ \frac{Pa\ m^3}{K} = 1.04\ 10^{-22}\ \frac{Torr\ l}{K}$$

The basis of vacuum technology: gas quantity

Gas quantities can be expressed in:

- Number of molecules: N
- Moles: $\frac{N}{N_A}\left(N_A = 6.022\ 10^{23}\left[\frac{molecules}{mole}\right]\right)$
- PV quantities if the temperature is known and constant : $P\,V = N(k_B T)$

Example: 1 Pa m^3 **at 293K** contains $N = \frac{1\,[Pa.m^3]}{1.38.10^{-23}\left[\frac{J}{K}\right]293\,[K]} = 2.47\ 10^{20}\text{molecules}$

1 Torr l = 3.3 10^{19} molecules

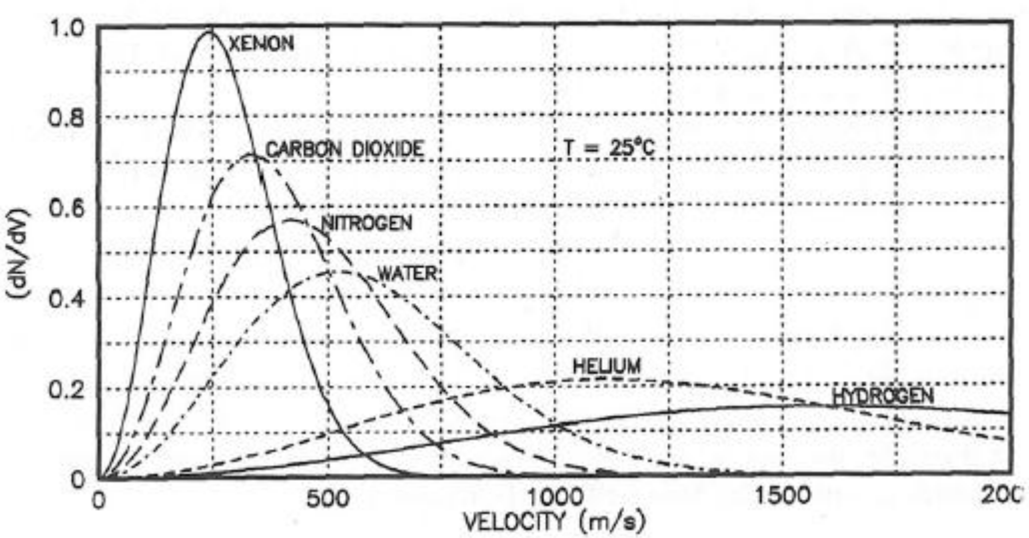
1 mbar l = 2.47 10^{19} molecules

The basis of vacuum technology: gas kinetics

In the kinetic theory of gas the mean speed of a molecule is the mathematical average of the speed distribution:

$$\langle v \rangle = \sqrt{\frac{8\,k_B T}{\pi\, m}} = \sqrt{\frac{8\,R\,T}{\pi\, M}}$$

m is the molecular mass [Kg]
M is the molar mass [Kg]



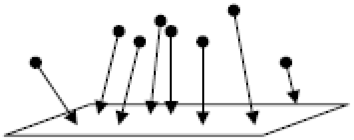
The basis of vacuum technology: gas kinetics

Gas	$\langle v\rangle$ at 293 K $\left[\frac{m}{s}\right]$	$\langle v\rangle$ at 4.3 K $\left[\frac{m}{s}\right]$
H_2	1761	213
He	1244	151
CH_4	622	75
N_2	470	57
Ar	394	48

The basis of vacuum technology: impingement rate

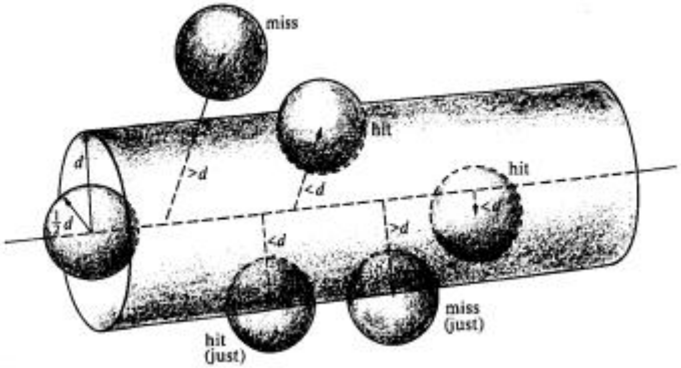
$$\varphi = \frac{1}{4} n \langle v \rangle = \frac{1}{4} n \sqrt{\frac{8\, k_B T}{\pi\, m}}$$

$$\varphi[cm^{-2}s^{-1}] = 2.635\ 10^{22} \frac{P\ [mbar]}{\sqrt{M[g]T[K]}}$$



Gas	**Pressure [mbar]**	**Impingement rate 293 K [$cm^{-2}s^{-1}$]**
H_2	10^{-3}	$1.1\ 10^{18}$
	10^{-8}	$1.1\ 10^{14}$
	10^{-14}	$1.1\ 10^{8}$
N_2	10^{-3}	$2.9\ 10^{17}$
	10^{-8}	$2.9\ 10^{13}$
Ar	10^{-3}	$2.4\ 10^{17}$
	10^{-8}	$2.4\ 10^{13}$

The basis of vacuum technology: mean free path



The molecular collision rate ω in a gas is:

$$\omega = \sqrt{2}\, n \, \langle v \rangle \, \sigma_c$$

where σ_c is the collision cross section.
For a single gas, in case of elastic collision of solid spheres:

$$\sigma_c = \pi \delta^2 \; \rightarrow \; \omega = \sqrt{2}\, \pi \, n \, \langle v \rangle \, \delta^2$$

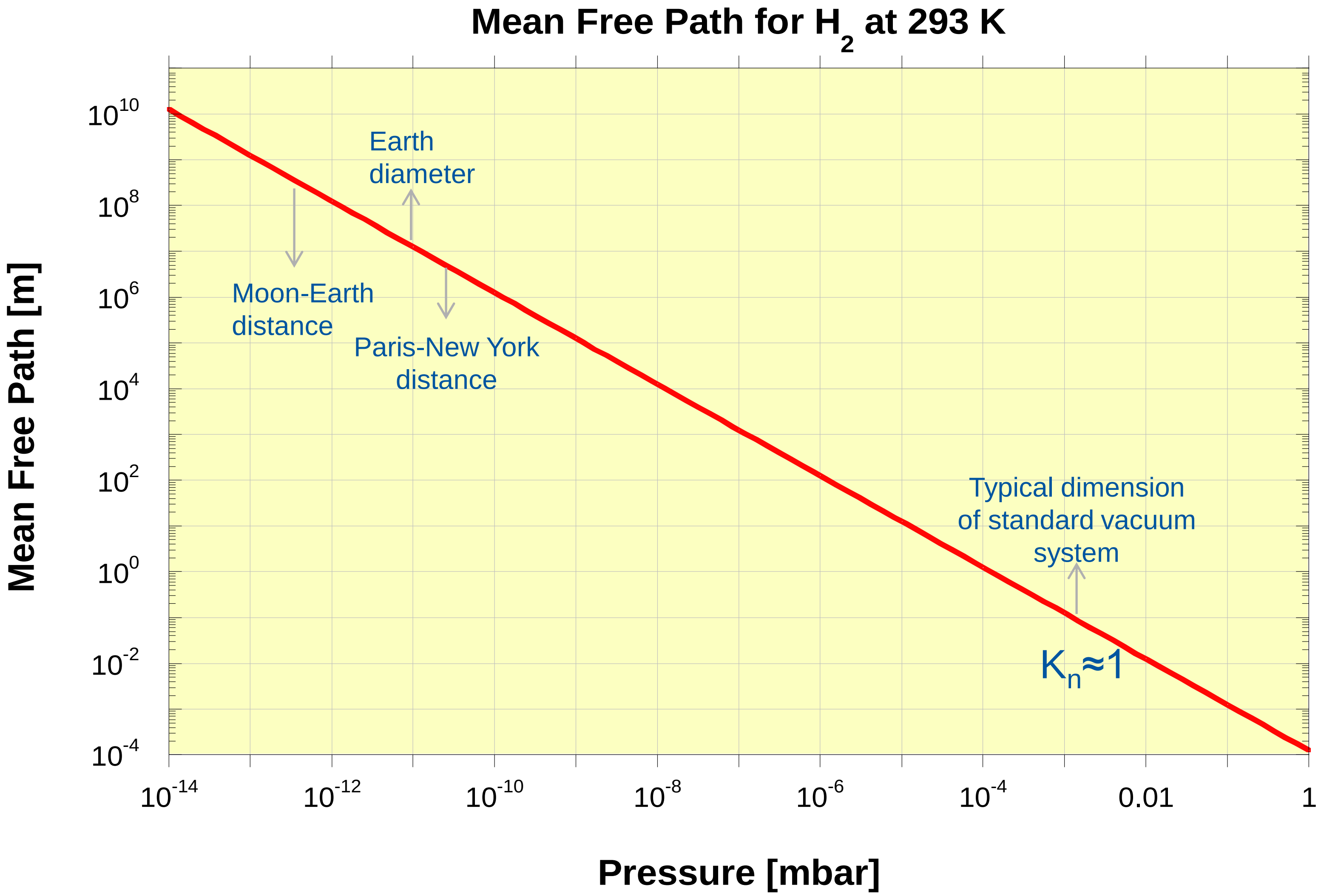
and δ is the molecular diameter.
The mean free path λ , i.e. the average distance travelled by a molecule between collisions, is given by:

$$\bar{\lambda} = \frac{\langle v \rangle}{\omega} = \frac{1}{\sqrt{2}\, \pi \, n \, \delta^2} = \frac{k_B T}{\sqrt{2}\, \pi \, P \, \delta^2}$$

$$\overline{\lambda_{H_2}}[m] = 4.3 \; 10^{-5} \frac{T[K]}{P[Pa]}$$

Gas	$\sigma_c \, [nm^2]$
H_2	0.27
He	0.21
N_2	0.43
O_2	0.40
CO_2	0.52

The basis of vacuum technology: mean free path



The basis of vacuum technology: mean free path

When **the mean free path** is of the order of typical dimensions of the vacuum vessel, for example the **diameter of cylindrical beam pipes**, molecular collisions with the wall of the vacuum envelope become preponderant.

For even longer $\bar{\lambda}$, the **gas dynamics is dominated by molecule-wall collisions**; intermolecular interactions lose any effect on the gas displacement.

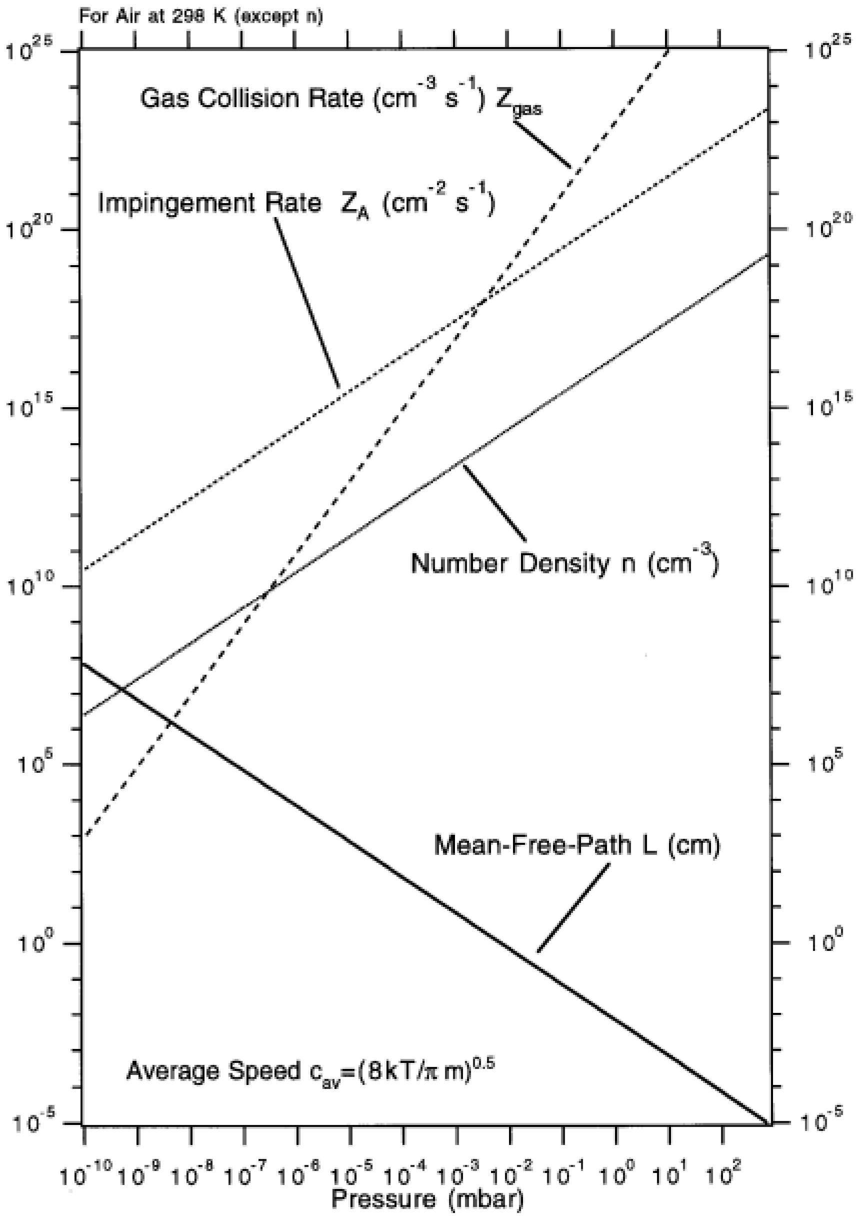
The basis of vacuum technology: Knudsen number

$$K_n = \frac{\bar{\lambda}}{D}$$

$\bar{\lambda}$ is the mean free path and **D** is a characteristic dimension of a vacuum system (p.ex. the diameter of a beam pipe).

K_n range	Regime	Description
$K_n > 0.5$	**Free molecular flow**	The gas dynamic is dominated by molecular collisions with the walls of the system
$K_n < 0.01$	Continuous (viscous) flow	The gas dynamic is dominated by intermolecular collisions
$0.5 < K_n < 0.01$	Transitional flow	Transition between molecular and viscous flow

Except for ion source's plasma chambers, vacuum systems of accelerators operate in free molecular regime; only this vacuum regime is considered in this lesson.


For Air at 298 K (except n)
Gas Collision Rate (cm^{-3} s^{-1}) Z_{gas}
Impingement Rate Z_A (cm^{-2} s^{-1})
Number Density n (cm^{-3})
Mean-Free-Path L (cm)
Average Speed $c_{av}=(8kT/\pi m)^{0.5}$
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Pressure (mbar)

The basis of vacuum technology: conductance

In molecular regime the net flux of molecules from one point (1) to another (2) is proportional to the pressure drop:

$$Q = C\ (P_1 - P_2)$$

C is called the gas conductance from the two points. It **does not depend on pressure**.

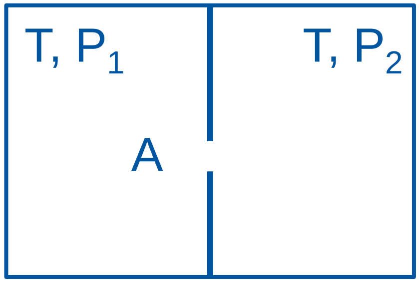
It depends only on the mean **molecular speed** and vacuum system **geometry**.

If the gas flow units are expressed in terms of pressure-volume, the conductance is reported as volume per unit time, i.e. **l $\mathbf{s^{-1}}$** or $m^3\ s^{-1}$.

The basis of vacuum technology: conductance

The simplest example is the gas flow through a small wall slot of area A and infinitesimal thickness

$$\varphi = \frac{1}{4} n\langle v\rangle = \frac{1}{4} n \sqrt{\frac{8\,k_B T}{\pi\, m}}$$



Gas flow 1 ⇒ 2 : $\varphi_{1\to 2} = \frac{1}{4} A\, n_1 \langle v\rangle$

Gas flow 2 ⇒ 1 : $\varphi_{2\to 1} = \frac{1}{4} A\, n_2 \langle v\rangle$

Net flow: $\frac{1}{4} A\,(n_1 - n_2)\langle v\rangle = \frac{1}{4} A \frac{\langle v\rangle}{k_B T} (P_1 - P_2)$

In PV units $(PV = N k_B T) \to Q = \frac{1}{4} A\langle v\rangle (P_1 - P_2) \to C = \frac{1}{4} A\langle v\rangle$

$$\boxed{C = \frac{1}{4} A\langle v\rangle \propto \sqrt{\frac{T}{m}}}$$

The basis of vacuum technology: conductance

The conductance of the wall slots is **inversely proportional to the square root of the molecular mass**.

Therefore, for equal pressure drop the gas flow of **H_2 is the highest**.

For gas molecules of different masses, the **conductance scales as the square root of the inverse mass ratio**:

$$\frac{C_1}{C_2} = \sqrt{\frac{m_2}{m_1}}$$

The basis of vacuum technology: conductance

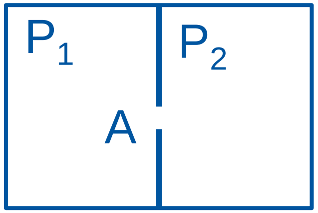
This table collects conductance values, for an orifice, **per unit surface area** (**C'**) at room temperature for common gas species.

Conductance of a wall aperture in PV units, per unit area: $C' = \frac{1}{4}\langle v \rangle$

T= 293 K

Gas	$\langle v \rangle$ at 293 K $\left[\frac{m}{s}\right]$	C' at 293 K $\left[\frac{m^3}{s\,m^2}\right]$	C' at 293 K $\left[\frac{l}{s\,cm^2}\right]$
H_2	1761	440.25	**44**
He	1244	311	31.1
CH_4	622	155.5	15.5
H_2O	587	146.7	14.7
N_2	470	11.75	11.75
Ar	394	98.5	9.85

The basis of vacuum technology: conductance



Example: $\boldsymbol{H_2}\ P_1 = 5\ 10^{-4} mbar, P_2 = 7\ 10^{-5} mbar, A = 0.8\ cm^2$

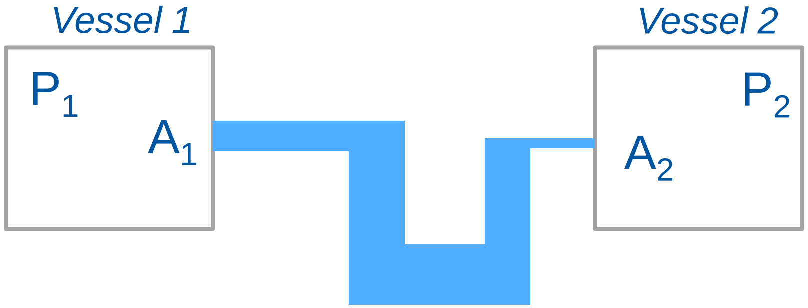
$$\rightarrow Q = \mathbf{44} \times 0.8 \times (5\ 10^{-4} - 7\ 10^{-5}) = 1.5 \times 10^{-2} \frac{mbar\ l}{s}$$

$$\rightarrow Q = 1.5 \times 10^{-2} \frac{mbar\ l}{s} \times 2.47\ 10^{19} \frac{molecules}{mbar\ l} = 3.74\ 10^{17} \frac{molecules}{s}$$

If the gas was **N_2**, the flow would have been $\sqrt{\frac{28}{2}} = 3.7$ times **smaller**

The basis of vacuum technology: conductance

For more complex gas flow restrictions, the transmission probability τ is introduced.



Gas flow 1 ⟹ 2 :

$$\varphi_{1\rightarrow 2} = \frac{1}{4} A_1 n_1 \langle v \rangle \, \tau_{1\rightarrow 2}$$

Gas flow 2 ⟹ 1:

$$\varphi_{2\rightarrow 1} = \frac{1}{4} A_2 \, n_2 \langle v \rangle \, \tau_{2\rightarrow 1}$$

In absence of net flow: $\varphi_{1\rightarrow 2} = \varphi_{2\rightarrow 1}$ and $P_1 = P_2 \rightarrow A_1 \tau_{1\rightarrow 2} = A_2 \tau_{2\rightarrow 1}$

$$Q = \frac{1}{4} A_1 n_1 \langle v \rangle \, \tau_{1\rightarrow 2} - \frac{1}{4} A_2 \, n_2 \langle v \rangle \, \tau_{2\rightarrow 1} = \frac{1}{4} A_1 \langle v \rangle \, \tau_{1\rightarrow 2} \frac{(P_1 - P_2)}{k_B T}$$

In PV units:

$$Q = \frac{1}{4} A_1 \langle v \rangle \, \tau_{1\rightarrow 2} (P_1 - P_2) = \mathrm{C} \, (P_1 - P_2)$$

$$C = C' A_1 \, \tau_{1\rightarrow 2}$$

$$\boldsymbol{C = \, [conductance\ of\ the\ aperture] \times [molecular\ transmission\ probability]}$$

The basis of vacuum technology: conductance

$$\boldsymbol{C} = [\boldsymbol{conductance\ of\ the\ aperture}] \times [\boldsymbol{molecular\ transmission\ probability}]$$

The molecular transmission probabilities:

- Depend only on the **geometry** of the vacuum system;
- They are accurately obtained by Monte Carlo methods.
- They can be calculated analytically only for simple geometry;

The basis of vacuum technology: conductance

Example:

- **Tubes** of uniform circular cross section (L length, R radius); **Santeler formula** (max error 0.7%):

$$\tau = \tau_{1\rightarrow 2} = \tau_{2\rightarrow 1} = \frac{1}{1 + \frac{3L}{8R}\left(1 + \frac{1}{3\left(1 + \frac{L}{7R}\right)}\right)}$$

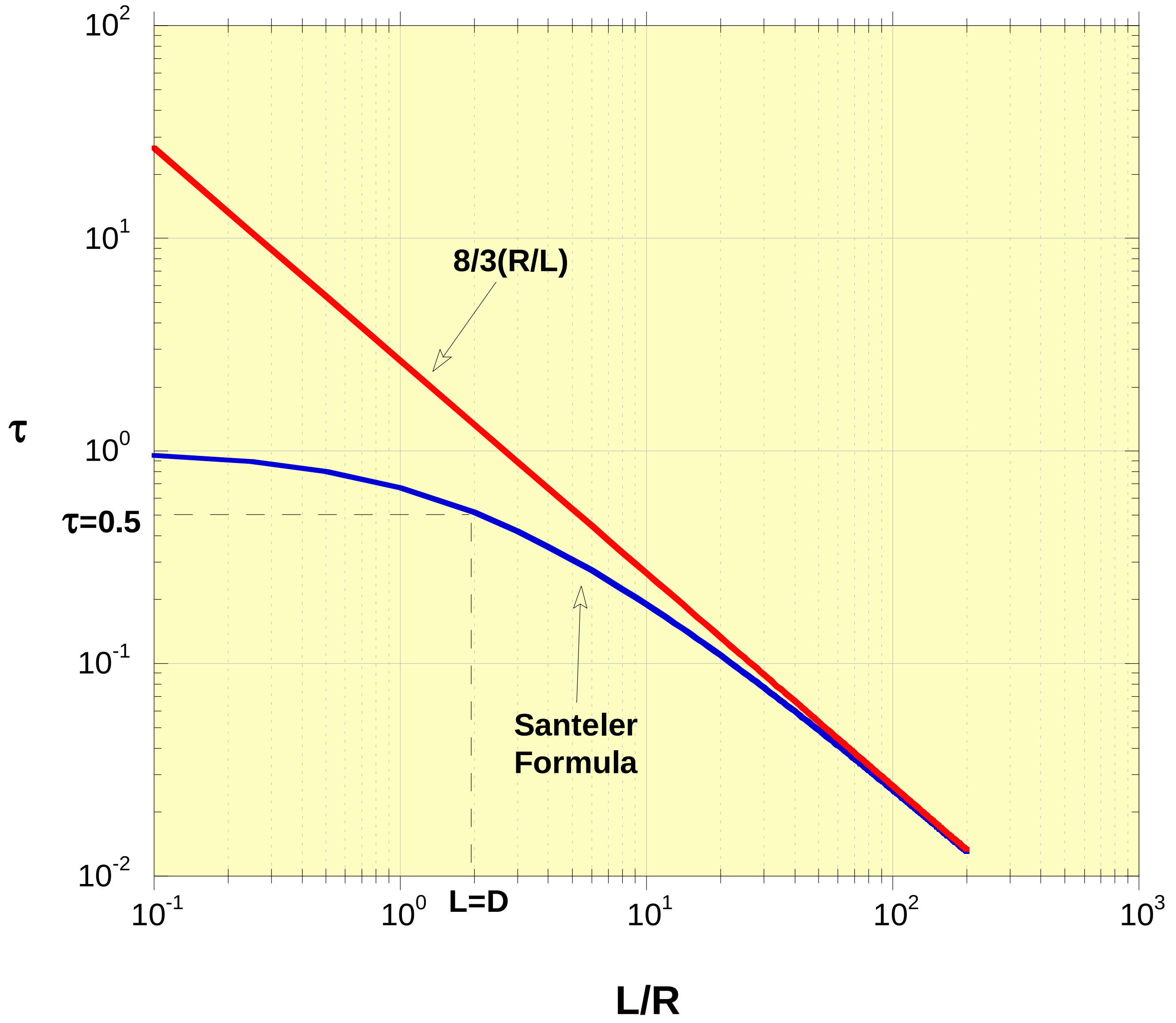
For long tubes ($\frac{L}{R} \gg 1$): $\tau \approx \frac{1}{1+\frac{3L}{8R}} \approx \frac{8}{3}\frac{R}{L}$

For N$_2$ and $\frac{L}{R} \gg 1 \rightarrow$

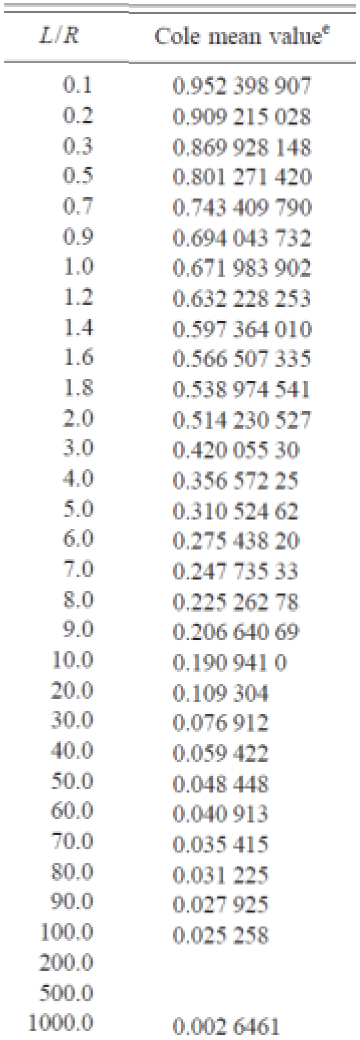
$$C = C'A\,\tau \approx 11.75 \times \frac{\pi D^2}{4} \times \frac{4D}{3L} = 12.3\,\frac{D^3}{L}\left[\frac{l}{s}\right]$$

$$([D]\ and\ [l]\ in\ cm\ \ )$$

The basis of vacuum technology: conductance



Monte Carlo

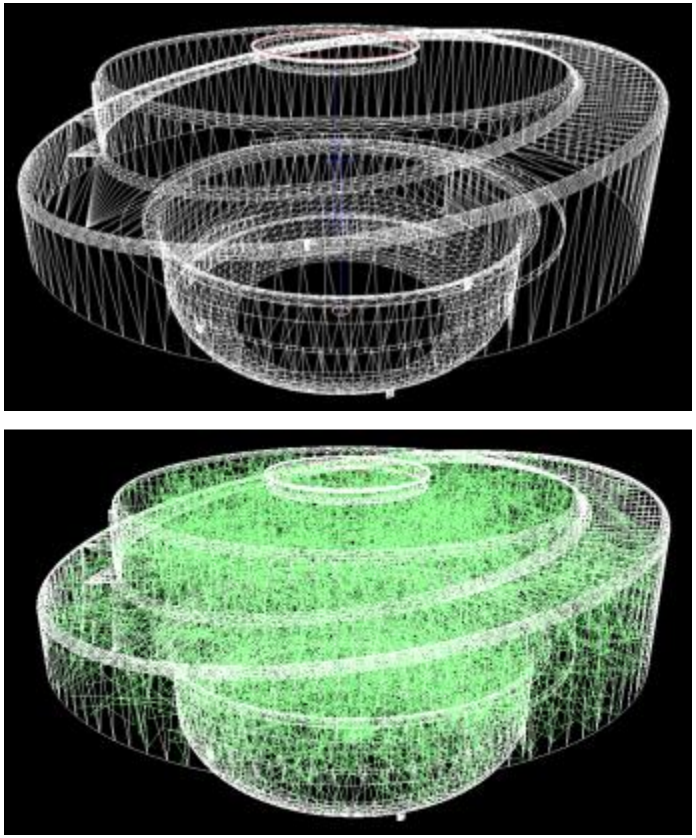


L/R	Cole mean value[e]
0.1	0.952 398 907
0.2	0.909 215 028
0.3	0.869 928 148
0.5	0.801 271 420
0.7	0.743 409 790
0.9	0.694 043 732
1.0	0.671 983 902
1.2	0.632 228 253
1.4	0.597 364 010
1.6	0.566 507 335
1.8	0.538 974 541
2.0	0.514 230 527
3.0	0.420 055 30
4.0	0.356 572 25
5.0	0.310 524 62
6.0	0.275 438 20
7.0	0.247 735 33
8.0	0.225 262 78
9.0	0.206 640 69
10.0	0.190 941 0
20.0	0.109 304
30.0	0.076 912
40.0	0.059 422
50.0	0.048 448
60.0	0.040 913
70.0	0.035 415
80.0	0.031 225
90.0	0.027 925
100.0	0.025 258
200.0	
500.0	
1000.0	0.002 6461

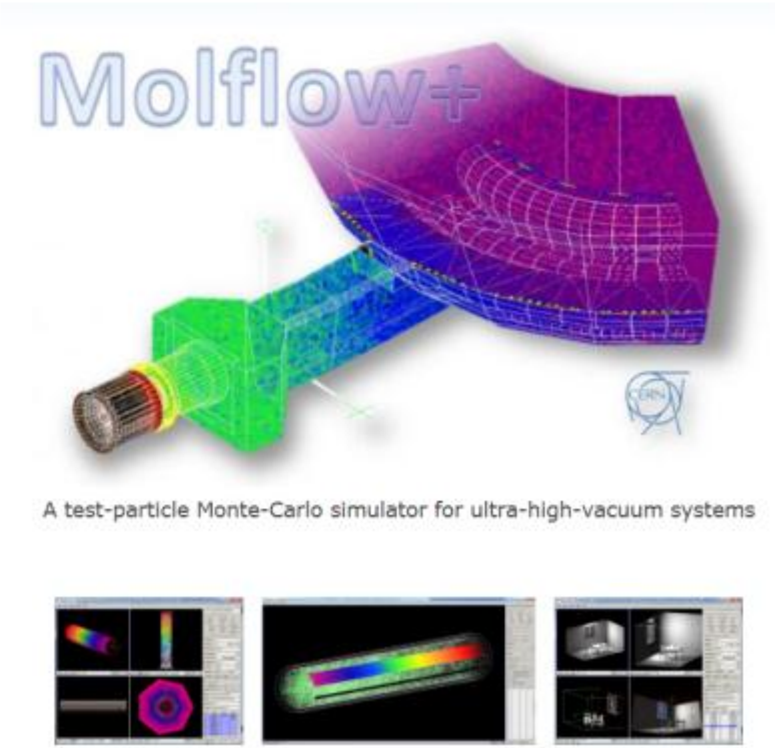
The basis of vacuum technology: conductance

Other analytical expressions for the transmission probability can be found for ducts of circular, rectangular and elliptical cross section (see for example J. M. Lafferty, Foundation of Vacuum Science and Technology, Wiley Interscience).

For more complicated geometry, **Test-Particle Monte Carlo methods** (TPMC) are used.



roberto.kersevan@cern.ch



The basis of vacuum technology: conductance

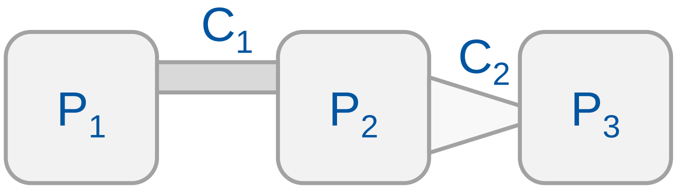
The TPMC:

- generates “random” molecules according to the cosine distribution at the entrance of the tube;
- then follows their traces until they reach the exit of the tube
- each collision with the walls is followed by a random emission
- many simulated molecules are needed in order to reduce the statistical scattering

The software used at CERN is Molflow+, written and maintained by **Roberto Kersevan** and Marton Szakacs (CERN, TE-VSC)

The basis of vacuum technology: conductance

Conductance of components connected in series:



$$Q_1 = C_1(P_1 - P_2)$$
$$Q_2 = C_2(P_2 - P_3)$$
$$Q_{TOT} = C_{TOT}(P_1 - P_3)$$

In stable conditions, there is no gas accumulation in the whole system: $Q_1 = Q_2 = Q_{TOT}$

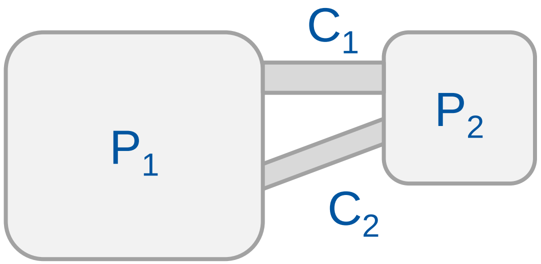
It can be easily verified that: $C_{TOT} = \frac{C_1 C_2}{C_1 + C_2}$ and $\frac{1}{C_{TOT}} = \frac{1}{C_1} + \frac{1}{C_2}$:

In general for N vacuum components traversed by the same gas flux, i.e. placed **in series** :

$$\frac{1}{C_{TOT}} = \sum_{1}^{N} \frac{1}{C_i}$$

The basis of vacuum technology: conductance

For components connected in **parallel** (same pressures at the extremities):



$$Q_1 = C_1(P_1 - P_2)$$
$$Q_2 = C_2(P_1 - P_2)$$
$$Q_{TOT} = C_{TOT}(P_1 - P_2)$$

$$Q_{TOT}=Q_1+Q_2 \rightarrow C_{TOT} = C_1 + C_2$$

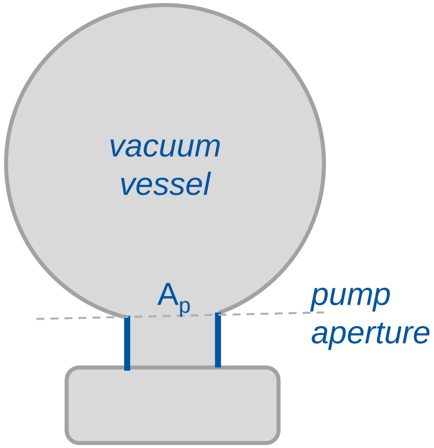
$$C_{TOT} = \sum_{1}^{N} C_i$$

The basis of vacuum technology: pumping speed

In vacuum technology a pump is any ‘object’ that remove gas molecules from the gas phase.

The pumping speed **S** of a pump is defined as the **ratio** between the **pump throughput Q_P** (flow of gas definitively removed) and the **pressure P at the entrance** of the pump:

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



$$[S] = \frac{[Volume]}{[Time]} = [conductance]$$

The basis of vacuum technology: pumping speed

The gas removal rate can be written as:

$$Q_P = \frac{1}{4} A_P\, n\langle v\rangle\, \sigma = A_P\, C' n\, \sigma$$

A_P: is the area of the pump aperture
C': is the conductance of the unit surface area
n: the gas density
σ : the capture probability, i.e. the probability that a molecule entering the pump is definitively captured

As usual, in term of pressure and PV units:

$$Q_P = \; A_P C' n\, \sigma(k_B T) = A_P C' \sigma\, P$$

From the definition of pumping speed:

$$\boldsymbol{S = A_P C' \sigma}$$

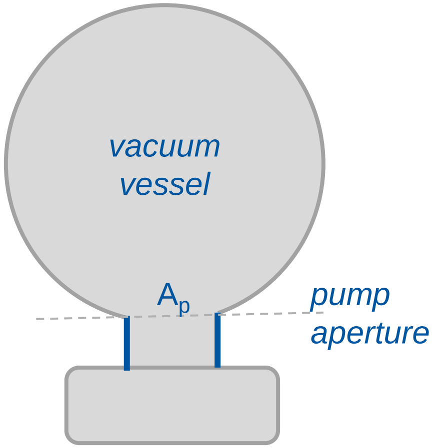
The basis of vacuum technology: pumping speed

S depends on the conductance of the pump aperture $A_P C'$ and the capture probability σ.

σ is <u>in general</u> not a constant; it may depend on many parameters including pressure, kind of gas and quantity of gas already pumped.

$$\boldsymbol{S = A_P C' \sigma}$$

The **maximum pumping speed** is obtained for $\boldsymbol{\sigma = 1}$ and is equal to the conductance of the pump aperture.



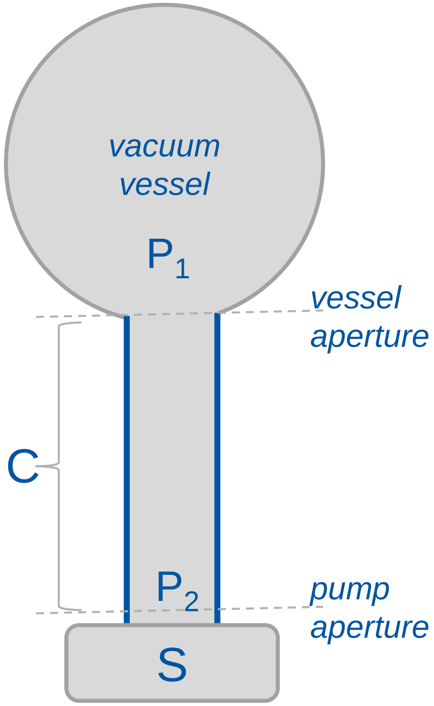
Maximum pumping speed [l s^{-1}]for different circular pump apertures

ID [mm]	H_2	N_2	Ar
36	448	120	100
63	1371	367	307
100	3456	924	773
150	7775	2079	1739

The basis of vacuum technology: pumping speed

A gas flow restriction interposed between a pump and a vacuum vessel reduces the 'useful' pumping speed.

The effective pumping speed S_{eff} seen by the vacuum vessel is easily calculated:



$$Q = C_1(P_1 - P_2) = SP_2 = S_{eff}P_1$$

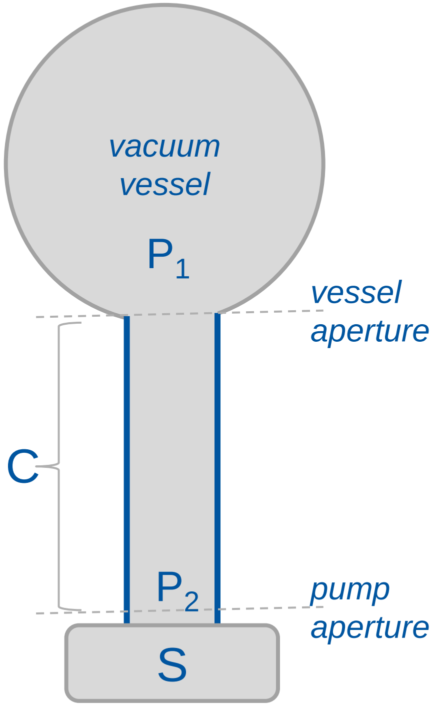
$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$

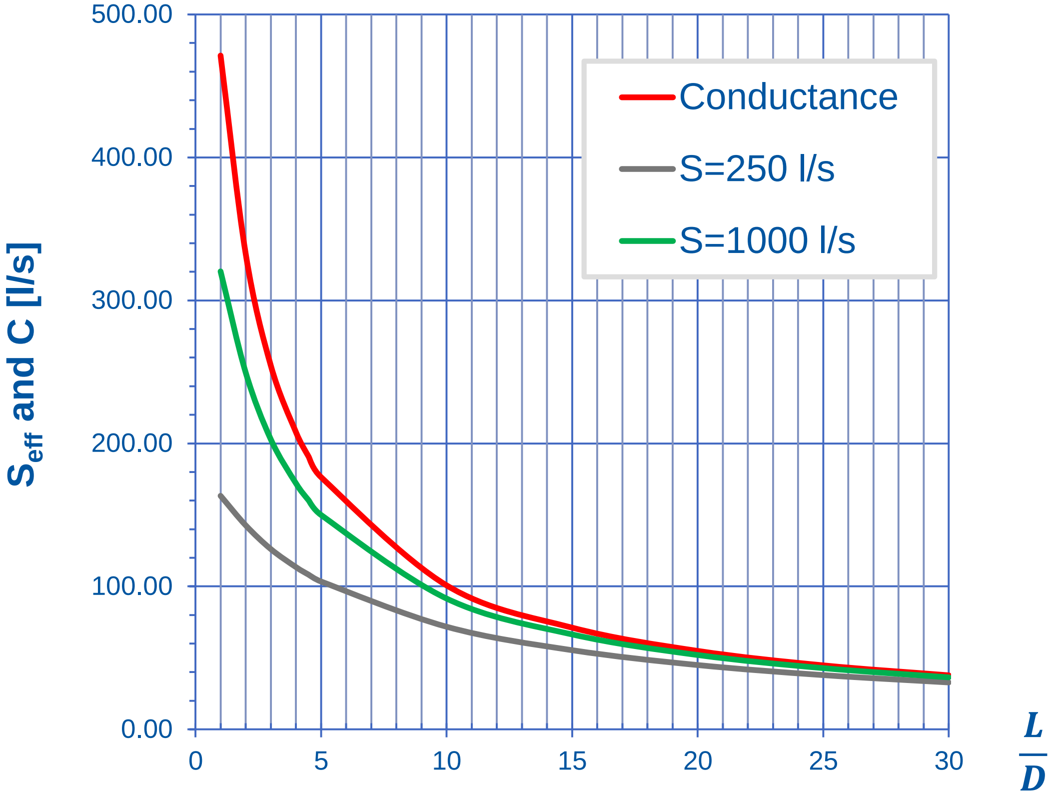
For C<<S: $S_{eff} \approx C$

The basis of vacuum technology: pumping speed

Example:

Vessel and pump connected by a **10 cm diameter** tube; N_2, S=250 l/s and 1000 l/s.



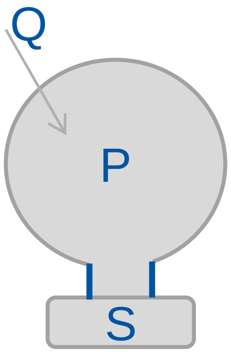


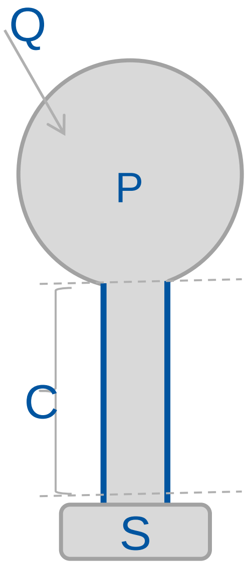
Efficient pumping?

Part 3

Calculation of simple pressure profiles

Simple pressure profiles: stationary values



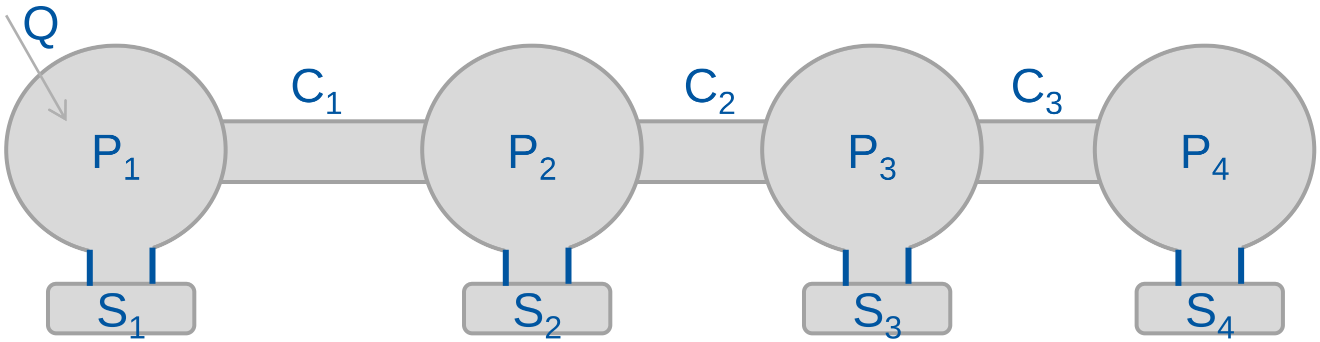


$$P=\frac{Q}{S}+P_0$$

$$P=\frac{Q}{S_{eff}}+P_0=\frac{Q(C+S)}{C\times S}+P_0$$

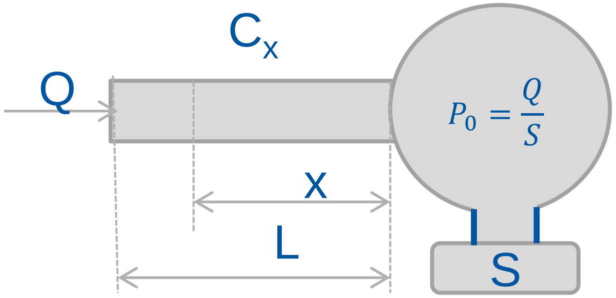
P_0 is the pressure attained in the vacuum system without any gas load. It is an intrinsic limitation of the pump.

Simple pressure profiles: stationary values



Flux balance at the connexions (node analysis):

$$\begin{cases} Q = P_1 S_1 + C_1(P_1 - P_2) \\ C_1(P_1 - P_2) = C_2(P_2 - P_3) + P_2 S_2 \\ C_2(P_2 - P_3) = C_3(P_3 - P_4) + P_3 S_3 \\ C_3(P_3 - P_4) = P_4 S_4 \end{cases}$$

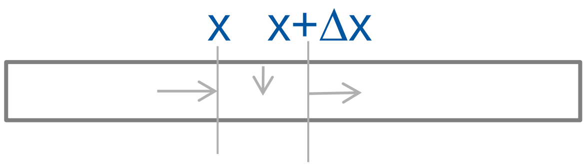


$$P_x = P_0 + \frac{Q}{C(x)}$$

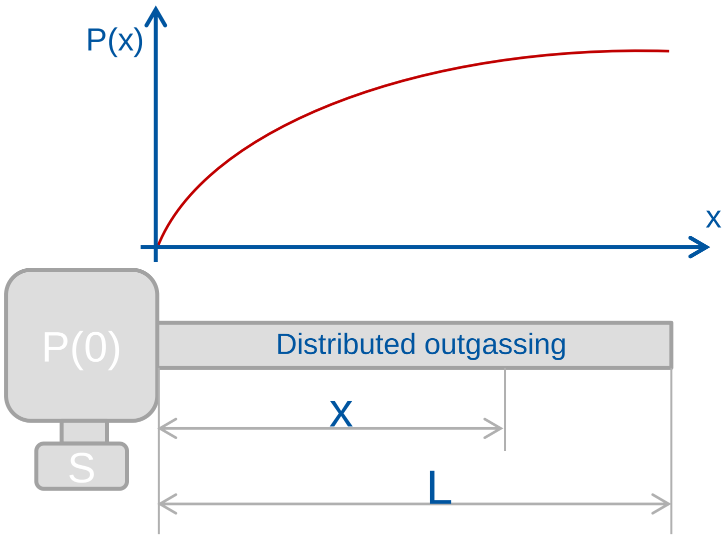
$$C(x) = C(L)\frac{L}{x}$$

Simple pressure profiles: stationary values

Pressure profiles with **distributed gas load** can be calculated analytically (for simple geometry), by electrical analogy or by Monte Carlo simulation.



Distributed gas load, one pump at one extremity only



$$Q(x+\Delta x)-Q(x)=2\pi R\Delta x\cdot q \rightarrow \frac{dQ}{dx}=2\pi R\cdot q$$

$$Q(x+\Delta x)=-C\frac{L}{\Delta x}\big(P(x+\Delta x)-P(x)\big)=-CL\frac{dP}{dx}$$

$$\rightarrow CL\frac{d^2P}{dx^2}=-2\pi R\cdot q$$

$$P(0)=\frac{2\pi RL\cdot q}{S}=\frac{Q_{TOT}}{S}$$

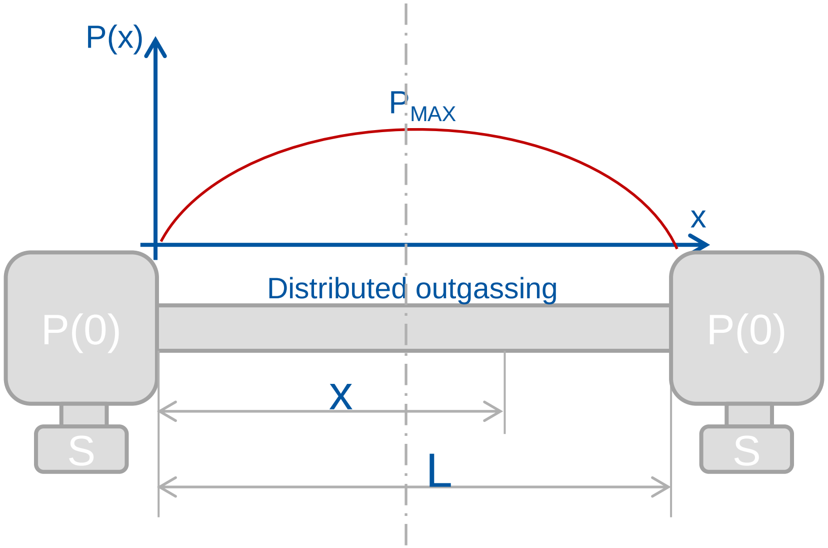
$$\left(\frac{dP}{dx}\right)_{x=L}=0$$

$$P(x)-P(0)=-\frac{Q_{TOT}}{C}\left[\left(\frac{x}{L}\right)-\frac{1}{2}\left(\frac{x}{L}\right)^2\right]$$

$$P(L)-P(0)=\frac{Q_{TOT}}{2C}$$

Simple pressure profiles: stationary values

Distributed gas load, one pumps at each extremity



$$CL\frac{d^2P}{dx^2} = -2\pi R \cdot q$$

$$P(0) = \frac{2\pi RL \cdot q}{2S} = \frac{Q_{TOT}}{2S}$$

$$\left(\frac{dP}{dx}\right)_{x=L/2} = 0$$

$$P(x) - P(0) = -\frac{Q_{TOT}}{2C}\left[\left(\frac{x}{L}\right) - \left(\frac{x}{L}\right)^2\right]$$

$$P(\frac{L}{2}) - P(0) = \frac{Q_{TOT}}{8C}$$

Simple pressure profiles: time dependent values

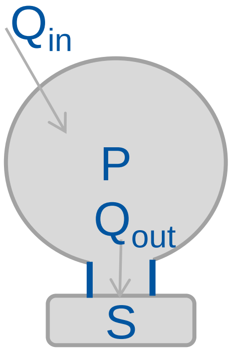
In time dependent condition:

$$Q_{in} \neq Q_{out}$$

Therefore, the variation of the gas density in the system has to be taken into account.

From the ideal gas equation: $PV = Nk_BT \rightarrow V\frac{dP}{dt} = k_BT\frac{dN}{dt}$

A gas balance equation can be written as: $\frac{dN}{dt} = Q_{in} - Q_{out}$



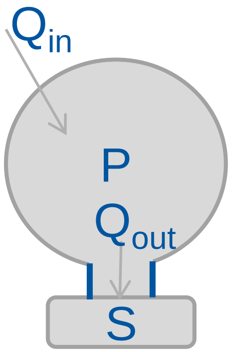
$$V\frac{dP}{dt} = k_BT(Q_{in} - Q_{out});$$

in PV units: $V\frac{dP}{dt} = (Q_{in} - Q_{out})$

The pumped gas rate is: $Q_{out} = SP \rightarrow \boldsymbol{V\frac{dP}{dt} = Q_{in} - SP}$

t

Simple pressure profiles: time dependent values

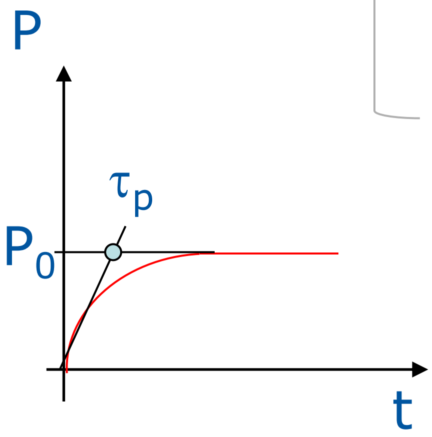


$$\boldsymbol{V\frac{dP}{dt} = Q_{in} - SP}$$

$$P(t) = Ae^{-\frac{t}{\tau_p}} + \frac{Q_{in}}{S}$$

A = integration constant

$$\left\{\begin{array}{l} P(0) = P_0 \rightarrow P(t) = \left(P_0 - \dfrac{Q_{in}}{S}\right)e^{-\frac{t}{\tau_p}} + \dfrac{Q_{in}}{S} \\[2em] P(0) = 0 \rightarrow P(t) = \dfrac{Q_{in}}{S}\left(1 - e^{-\frac{t}{\tau_p}}\right) \end{array}\right.$$



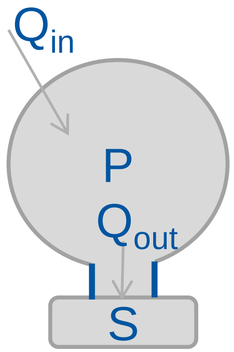
$$\boldsymbol{\tau_p = \frac{V}{S}}$$ characteristic time of pumping

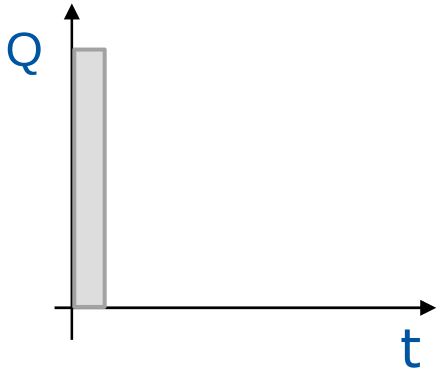
$\boldsymbol{\tau_p}$ characterizes all pressure transients in a vacuum system

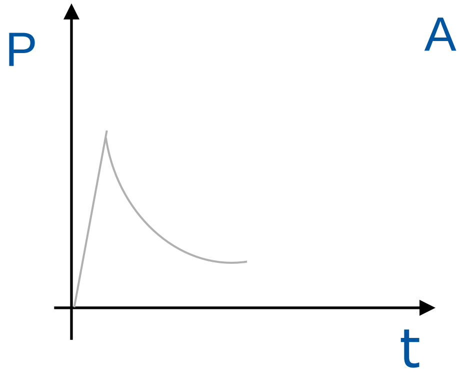
Simple pressure profiles: time dependent values

When Q_{in} is a function of time:

$$P(t) = \frac{\int e^{\frac{t}{\tau_p}} \frac{Q_{in}(t)}{V} dt + A}{e^{\frac{t}{\tau_p}}} = \frac{\int Q_{in}(t)dt}{V} - \frac{e^{-\frac{t}{\tau_p}}}{V\tau_p} \int e^{\frac{t}{\tau_p}} \left[\int Q_{in}(t)dt \right] dt + Ae^{-\frac{t}{\tau_p}}$$





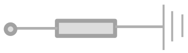
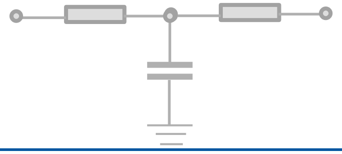


A = integration constant

For a network of vacuum chambers, systems of coupled differential equations for each chamber have to be solved.

However, a simpler method exists. It is based on the **analogy between vacuum systems and electrical networks**. Very powerful software is available for the time dependent analysis of electrical networks.

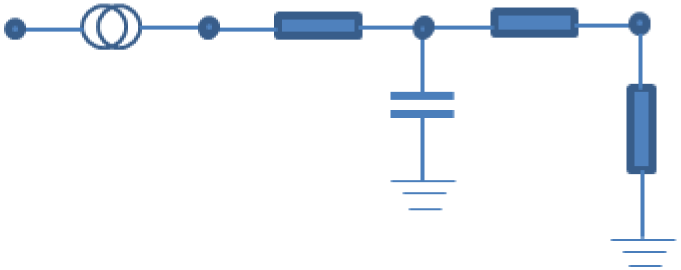
Simple pressure profiles: time dependent values

Vacuum element	Electrical elements
Conductance C	Conductance 1/R 
Gas Flow Q	Current I
Pressure P	Voltage V
Volume V	Capacitance C 
Pump	Conductance to ground 
Gas source	Current generator 
Constant pressure source	Voltage supply 
Vacuum chamber with conductance and volume	

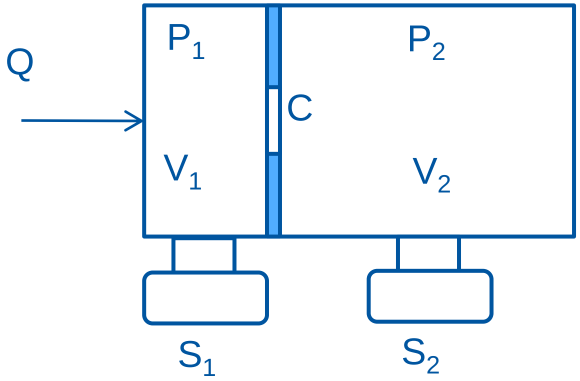
- The ground potential is equivalent to zero pressure.
- Long tubes are subdivided in smaller units and considered as single vacuum chambers (conductance + volume) in series.
- The conductance of a single small unit is equal to the conductance of the entire vacuum chamber times the number of units
- Non-linear electric characteristics can be used to simulate pressure and time dependent conductance and pumping speed.

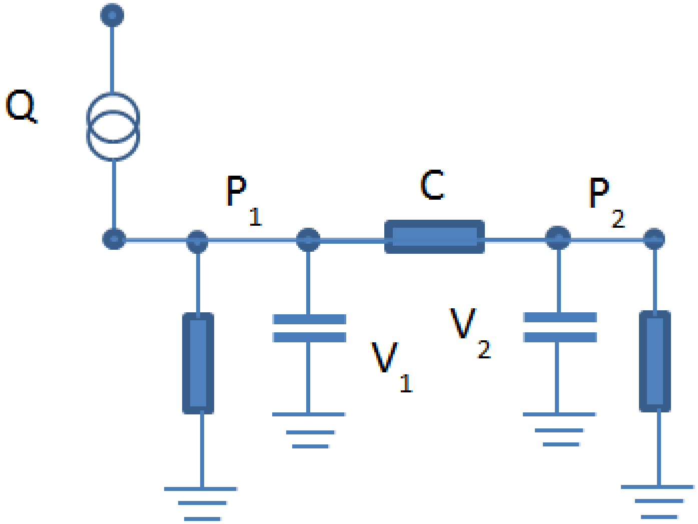
Simple pressure profiles: time dependent values

Electrical analogy of a **vacuum chamber** with gas injection and pumping



Electrical analogy of a vacuum system with **differential pumping**

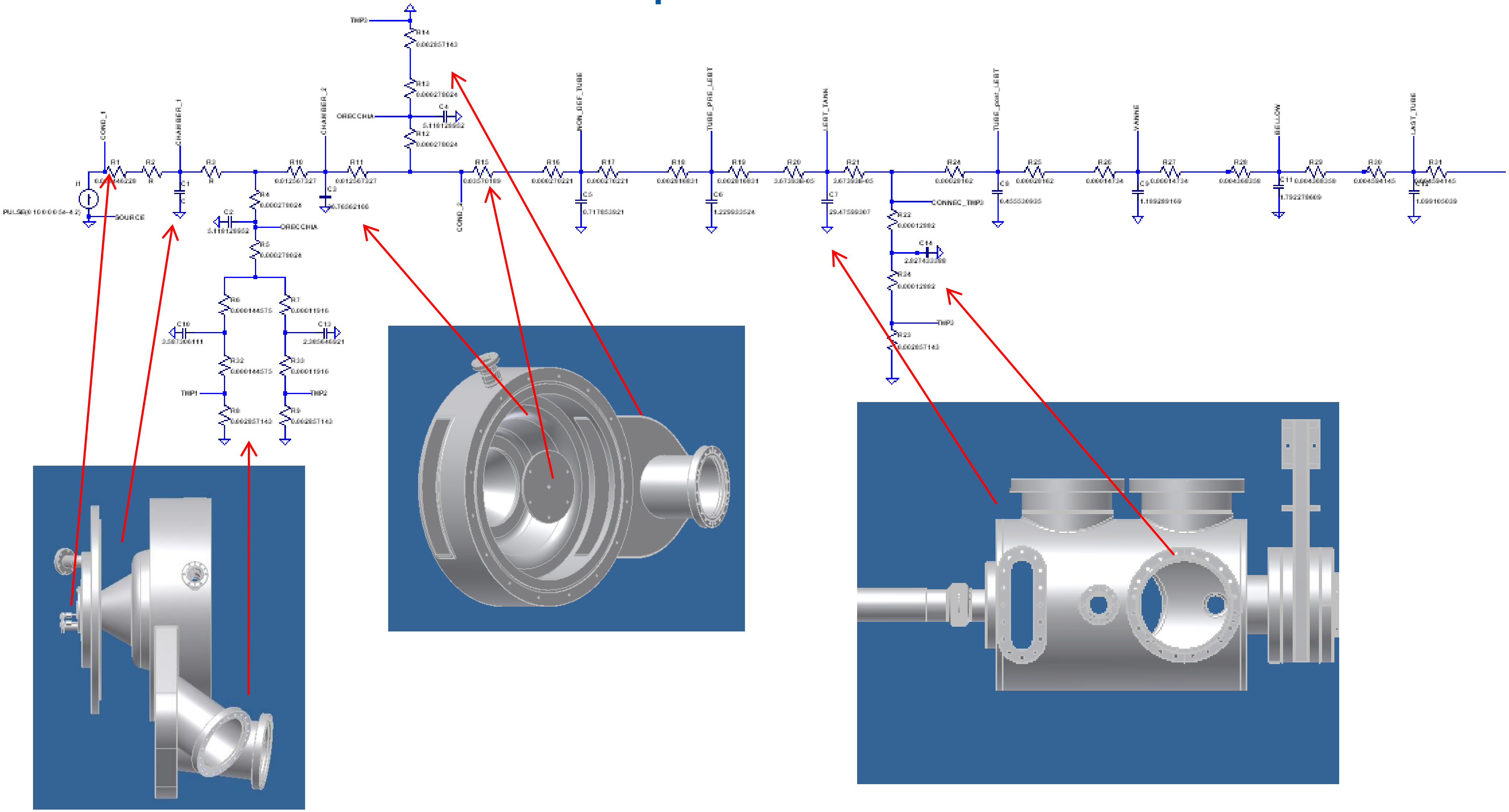




The electrical network is solved by dedicated software, for example LTSpice

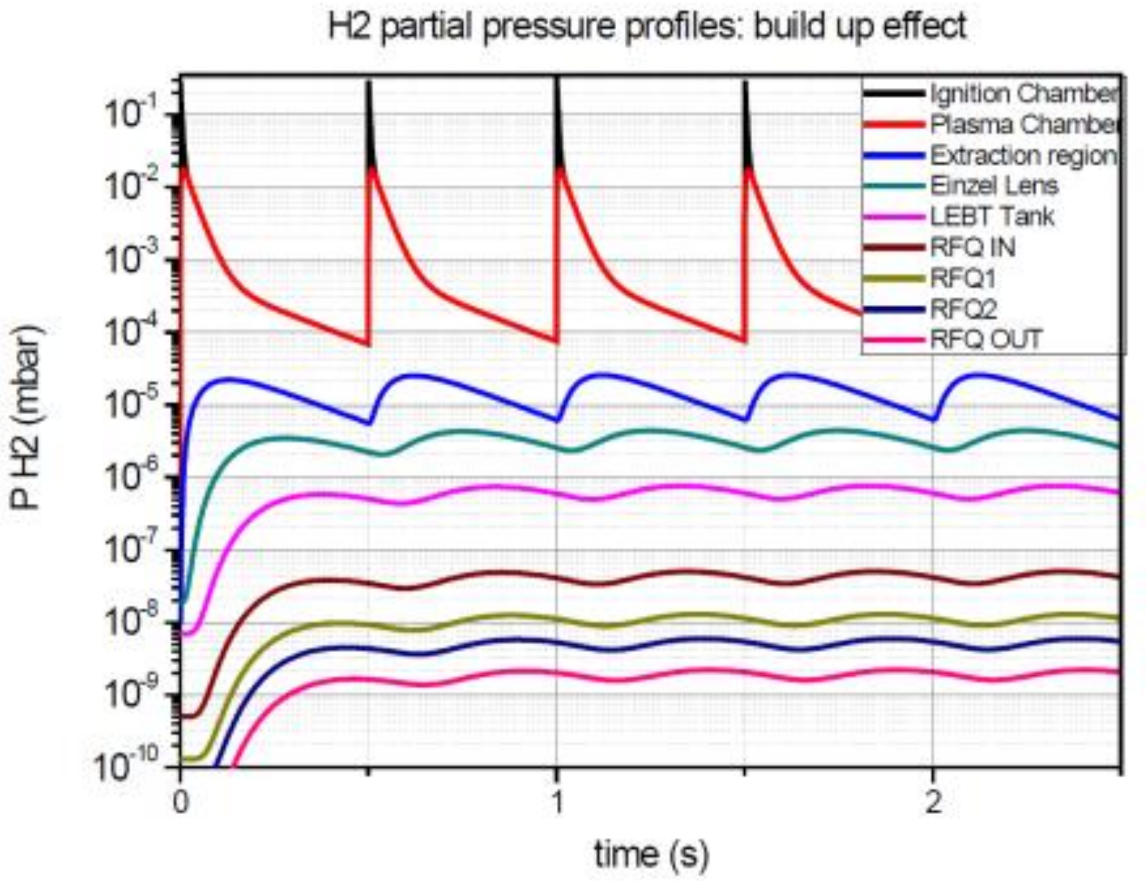
Simple pressure profiles: time dependent values

Example 1: the Linac4 ion source



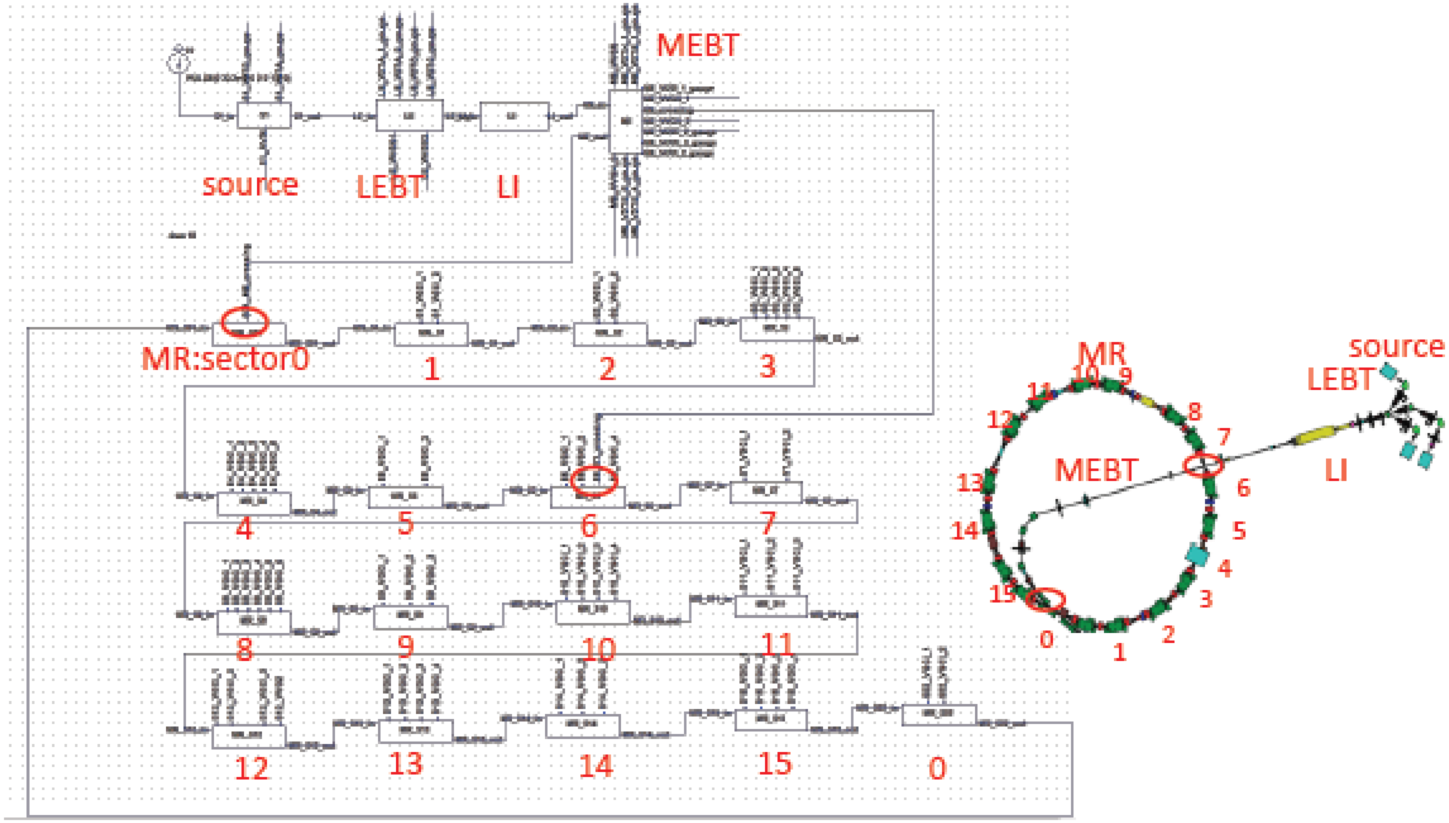
Simple pressure profiles: time dependent values

Example 1: the Linac4 ion source



Simple pressure profiles: time dependent values

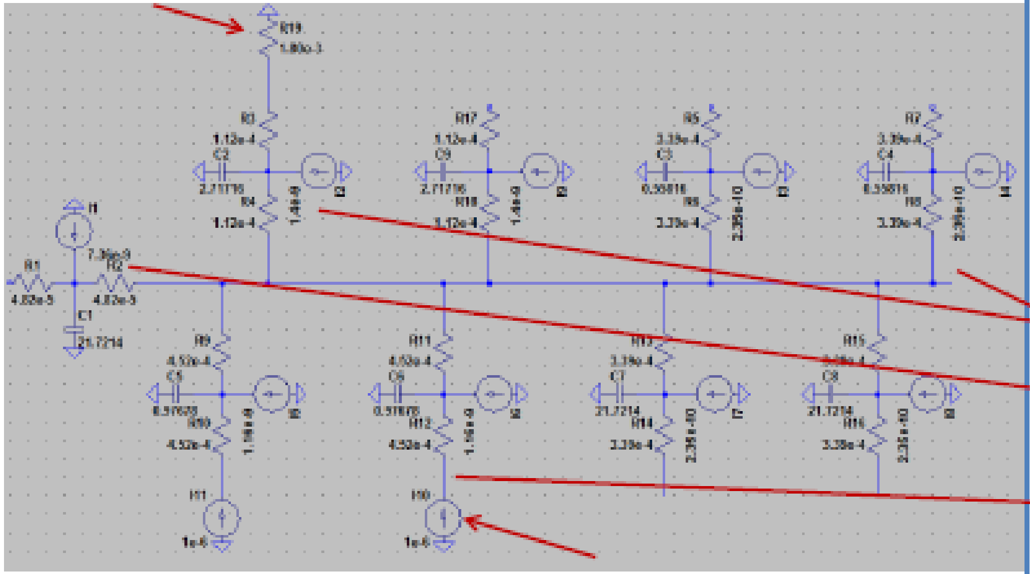
Example 2: the MedAustron facility



Simple pressure profiles: time dependent values

Example 2: the MedAustron facility

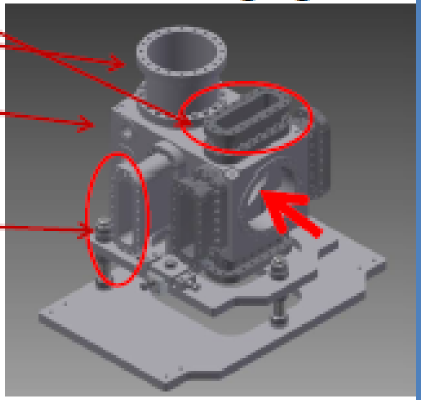
TMP: HiPace 700l/s



Degassing rate (H2O) of profile grid monitor after 100h pumping (the number is just an example)

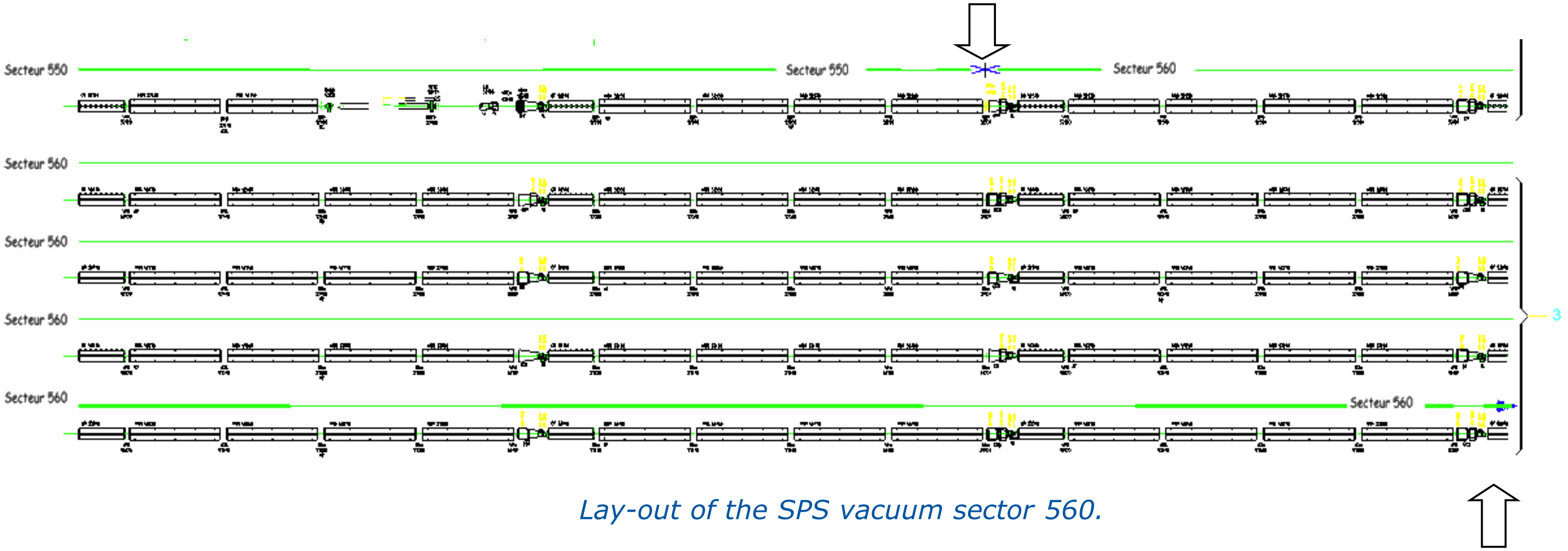
Vacuum Diagnostics Tank:

1. Main tank
2. 1xDN160 for TMP HiPace 700l/s
3. 1xDN160 for Beam Diagnostics (BD)
4. 6x rectangular for BD
5. 3xDN40 for gauges

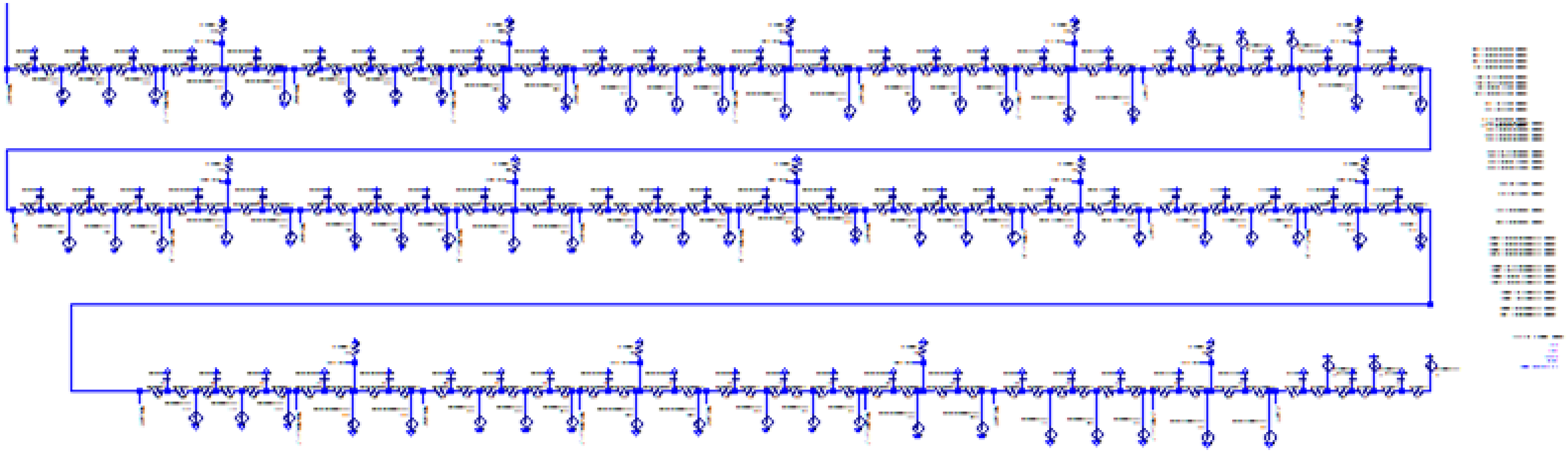


Simple pressure profiles: time dependent values

Example 3: pumpdown of one vacuum sector of the SPS



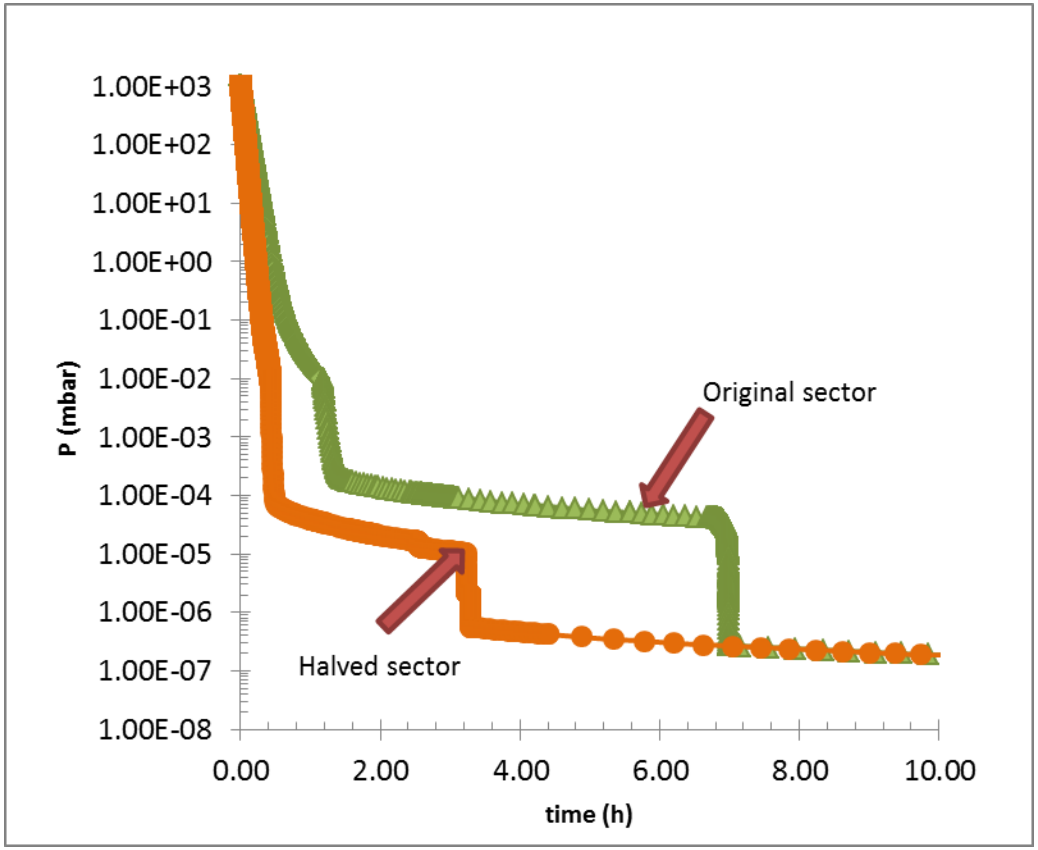
Lay-out of the SPS vacuum sector 560.



Equivalent electrical network for sector 560.

Simple pressure profiles: time dependent values

Example 3: pumpdown of one vacuum sector of the SPS



Current dependent resistances simulate conductance variations in the whole pressure range, even in viscous regime.

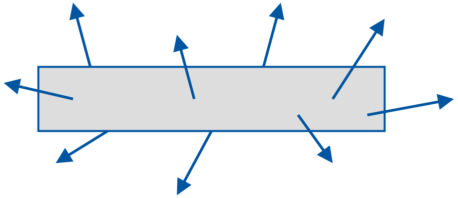
Comparison between calculated pumpdown curves for original (green) and halved (orange) longest SPS vacuum sector.

Part 4

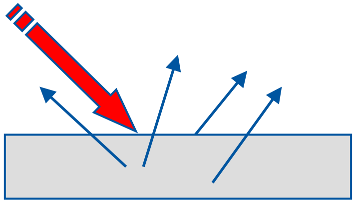
Gas sources in particle accelerators

Gas sources

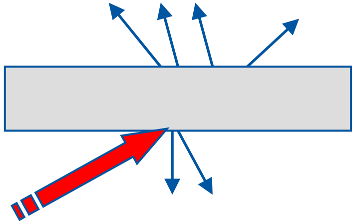
- Outgassing is the spontaneous evolution of gas from solid or liquid.



- Degassing is the deliberate removal of gas from a solid or a liquid.

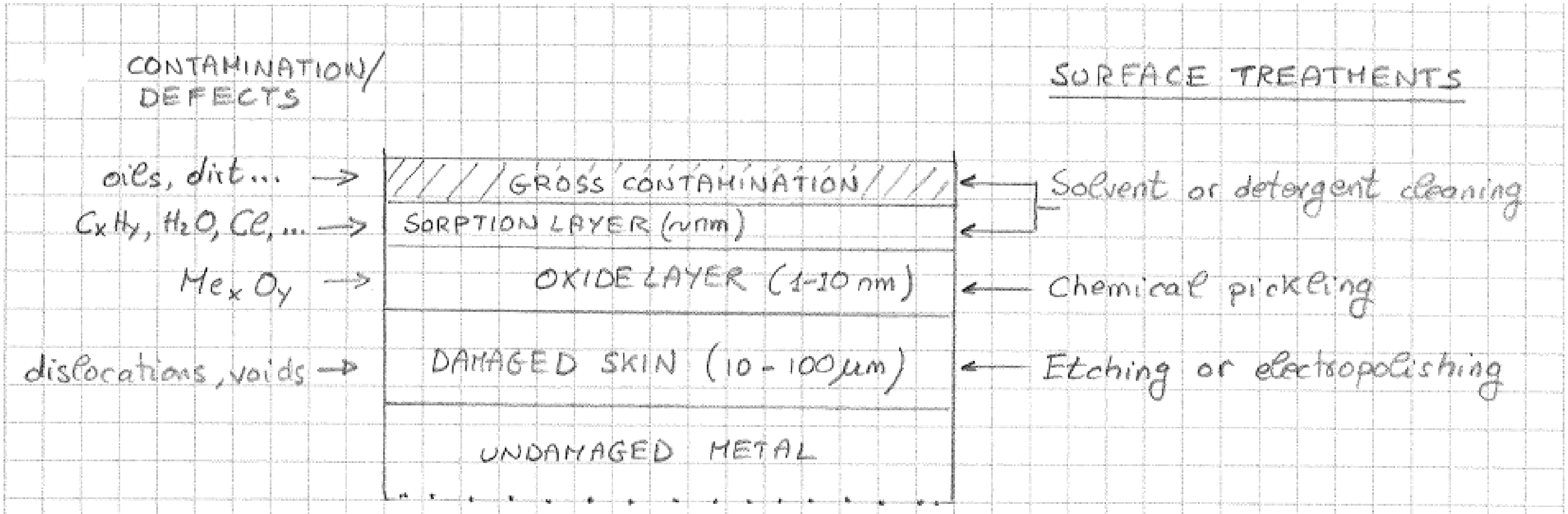


- Desorption is the release of adsorbed chemical species from the surface of a solid or liquid.



Gas sources

After production, the **surface** of vacuum components is **always contaminated**. They must be **thoroughly cleaned** before installation.



Solvents: their molecules interact and transport contaminants away by diffusion (dilution) -> quite selective! (C_2Cl_4, wide spectrum; HFC, more restricted action)

Detergents in water: allows organics and water to combine by forming micelle (surfactant: **surf**ace **act**ing **agent**). Based on molecule with hydrophilic heads and lipophilic tail: less selective than solvents

Gas sources: outgassing

The **bulk of materials** is also a source of gas.

Gas molecules dissolved in the materials diffuse towards the surfaces and are then released

Polymers dissolve **huge quantity** of molecules in the voids between the molecular chains.

Metals can dissolve only **limited quantities** of small atoms that are immobile in the lattice at room temperature, except for hydrogen.

In one day, H atoms travel in average 4 μm in austenitic stainless steels, while O atoms travel the same distance in 1000 years.

Therefore, amongst the dissolved elements in the bulk of metals, **only H_2 is released at room temperature**.

For comparison, in one day, H_2O molecules move along about 20 μm in PEEK, a high performance polymer.

Gas sources: outgassing

Materials	**Characteristics that determine outgassing rates**
Polymers	Dissolve entire molecules, for example H_2O, O_2, CO_2, solvents, etc.
	The solubility in the bulk can be very high in particular for H_2O (up to a few weight percentage)
	The dissolved molecules have a relatively high mobility
Metals	Only single atoms are dissolved (H, O, C, S, etc.)
	The atom solubility is in general very low at room temperature (typically up to 10^3 at. ppm)
	Only H has a significant mobility at room temperature

Gas sources: outgassing

Metals

After state-of-art surface cleaning

- If not heated in situ: mainly $\mathbf{H_2O}$ for the first months in vacuum, then also H_2.

$$q_{H_2O} \approx \frac{3 \times 10^{-9}}{t[h]} \left[\frac{mbar\ l}{s\ cm^2}\right]$$

  The source of H_2O is recharged after each venting to air.

- If heated in situ (baked-out): mainly $\mathbf{H_2}$. The outgassing rate can be assumed as constant; it depends on the accumulated effect of the previous thermal treatments

Organics (Polymers)

- High solubility of gas in the bulk, in particular $\mathbf{H_2O}$.
- In general, the outgassing process is dominated by H_2O release.
- In the initial phase of pumping:

$$q_{H_2O} \propto \frac{1}{\sqrt{t}}$$

- Heavier gas molecules can be outgassed (remnant of polymerisation, fraction of polymeric chains)
- The permeation of light molecules is not negligible, in particular He.

Gas sources: outgassing

Some examples of outgassing rates

Neoprene (10 h pumping):

$q_{H2O} \approx 10^{-5}$ Torr l s^{-1} cm^{-2}

$q_{H2O}=3.3x10^{14}$ molecules cm^{-2}

Unbaked stainless steel (10 h pumping):

$q_{H2O}=2x10^{-10}$ Torr l s^{-1} cm^{-2}

$q_{H2O}=6.6x10^{9}$ molecules cm^{-2}

Baked stainless steel (150º C x 24 h):

$q_{H2}=2x10^{-12}$ Torr l s^{-1} cm^{-2}

$q_{H2}=6.6x10^{7}$ molecules s^{-1} cm^{-2}

Baked OFS Copper (200º C x 24 h):

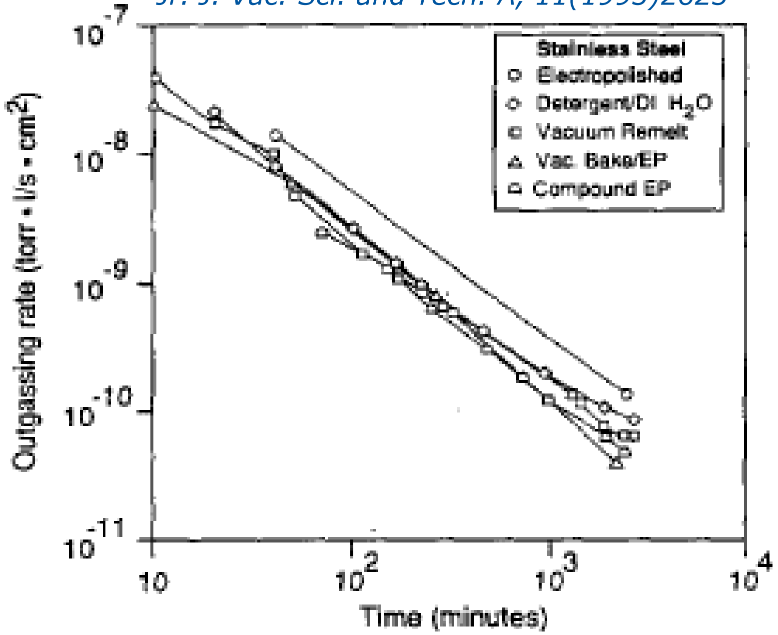
$q_{H2}=2x10^{-14}$ Torr l s^{-1} cm^{-2}

$q_{H2}=6.6x10^{5}$ molecules s^{-1} cm^{-2}

Gas sources: outgassing of metals

Outgassing rate of water vapour for unbaked metals

H.F. Dylla, D. M. Manos, P.H. LaMarche Jr. J. Vac. Sci. and Tech. A, 11(1993)2623



$$q_{H_2O} \approx \frac{3\times10^{-9}}{t[h]}\left[\frac{mbar\ l}{s\ cm^2}\right]$$

The most effective way to accelerate the water vapour outgassing rate is by in situ bakeout.

At least 120°C for 12 hours

Water vapour outgassing rate of stainless steel that underwent four different surface treatments

Gas sources: outgassing of metals

When water vapour outgassing is strongly reduced, by either long pumping or bakeout, the **outgassing process is led by H_2**.

This gas is dissolved in metals as single H atoms. Its **diffusion is relatively fast** and, after recombination on the surface, it can be released as molecular hydrogen

Most of the **H atoms are dissolved in metals at the liquid state**, during the production process.

H atoms mobility and solubility in the liquid are higher than in the solid.

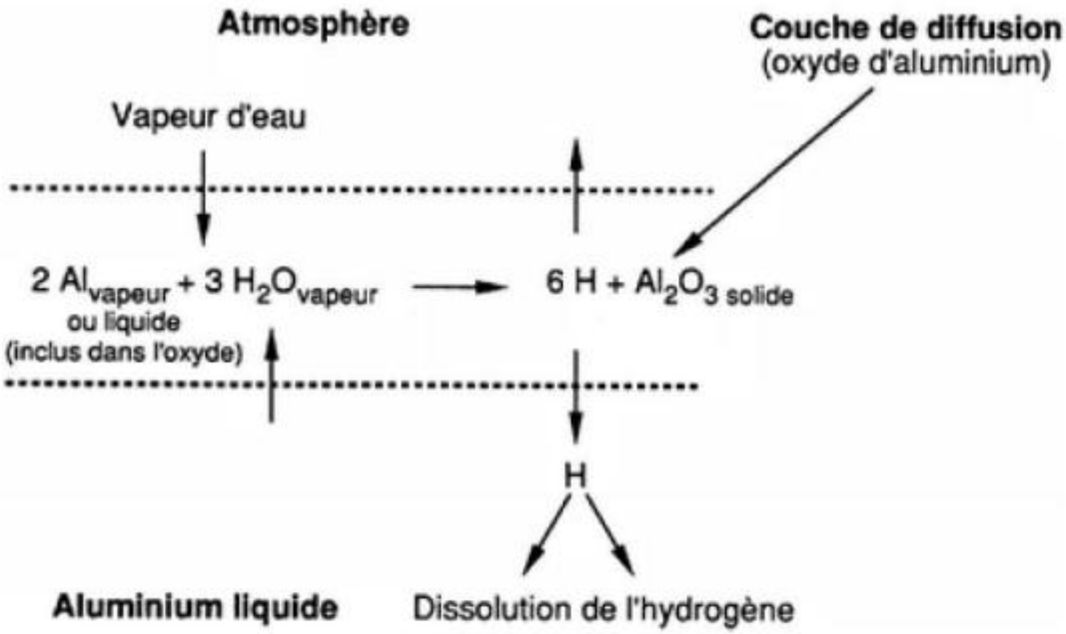
Typical sources of H are:

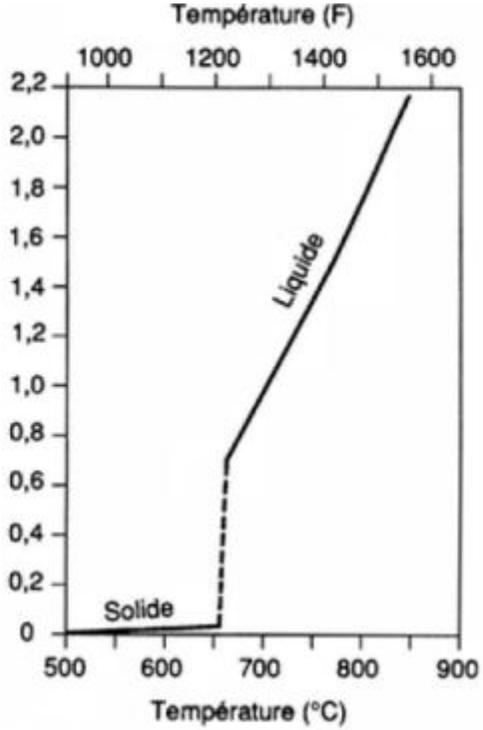
- metals ores;
- tools needed for fusion;
- refractory materials of furnaces;
- combustion and treatment gas;
- water vapour and fluids used for quenching (for example the hyperquench of austenitic stainless steels is carried out from 1100°C in water, air, or oil).

Gas sources: outgassing of metals

Example of a process of H_2 dissolution in liquid Al

If the solidification is fast, **the gas is trapped in the solid** far form the equilibrium





1 Ncm^3 correspond à 1 cm^3 de gaz mesuré dans les conditions normales de température (°C) et de pression (10^5 Pa).

Typical H_2 contents are about **1 wt. ppm** for copper, aluminum, and austenitic stainless steel

Gas sources: outgassing of metals

As for water vapour, hydrogen-outgassing rate is **reduced by heating**.

The high temperatures **increase the H atoms mobility** and, as a result, accelerate the depletion of the residual hydrogen content.

However, there is a **crucial difference between water vapour and hydrogen**.

Each time the vacuum system is exposed to air, water molecules re-adsorb on the surface, while **hydrogen is not recharged** in the bulk of the metal.

For most of the materials used for the manufacturing of vacuum chambers, the H **solubility is very low** in the solid state.

For example, to recharge **1 wt. ppm** of hydrogen at room temperature in stainless steel, the material has to be in equilibrium with the gas at **7 bar**. The hydrogen pressure in air is roughly 10^{-4} mbar, which gives a maximum recharging of about 2.10^{-4} wt. ppm.

Gas sources: outgassing of metals

For **copper and aluminium alloys**, a few bakeout at 150-200°C for 24 hours are sufficient to reduce the hydrogen-outgassing rate to less than 10^{-13} mbar l s^{-1} cm^{-2}.

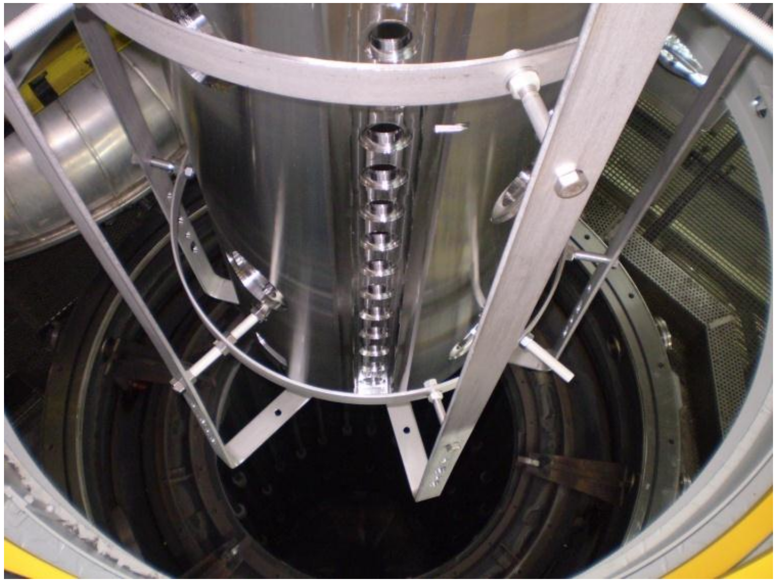
For **austenitic stainless steel**, higher temperatures are needed to have a similar effect for a few mm thick vacuum chambers. Repeated bakeout at temperature higher than 200°C may have a significant influence.

Materials	**Bakeout T[°C] x 24 h**	**q [mbar l s^{-1} cm^{-2}]**
Austenitic st. steel	150	$3\ 10^{-12}$
Austenitic st. steel	200	$2\ 10^{-12}$
Austenitic st. steel	300	$5\ 10^{-13}$
Copper Silver added (OFS)	150	$3\ 10^{-12}$
Copper Silver added (OFS)	200	$\approx 10^{-14}$
Beryllium	150	$< 10^{-14}$
Al alloys	150	$< 10^{-13}$

Gas sources: outgassing of metals

For austenitic stainless steels, a radical effect is obtained by heating in a vacuum furnace to temperature up to about 1000°C.

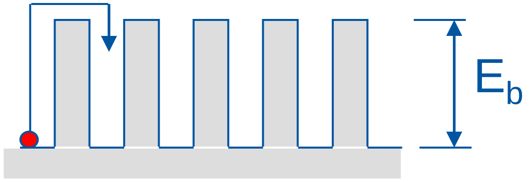
Such a treatment is called '**vacuum firing**'. At CERN it is carried out at **950°C for 2 h** in a vacuum better than 10^{-5} mbar at the highest temperature.



The **CERN's large furnace**: useful height and diameter: 6 m and 1 m, respectively. Maximum charge weight: 1000 Kg. Ultimate pressure: about 10^{-7} mbar; pressure at the end of the 950°Cx2h treatments: 10^{-5}mbar.

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing



$$D(T) = D_0 \cdot e^{-\frac{E_b}{k_B T}}$$

Diffusion, in most of the cases of interest, is described by the **Fick's equations**:

$$\left.\begin{aligned} -D\frac{\partial c(x,t)}{\partial x} &= \Gamma(x,t) \\ D\frac{\partial^2 c(x,t)}{\partial x^2} &= \frac{\partial c(x,t)}{\partial t} \end{aligned}\right\}$$

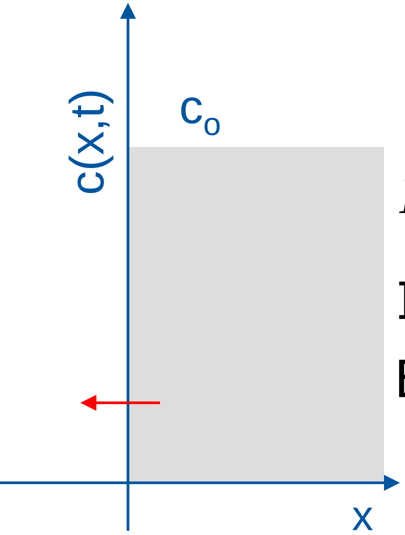
where c(x,t) is the concentration in the solid and Γ is the flow of molecules per cm^2

In the limit of this model, the outgassing rate is equal to a half of the flux of atoms arriving at the surface by diffusion (2 H atoms = 1 H_2 molecule):

$$\boxed{q(t) = -\frac{1}{2}D\left.\frac{\partial c(x,t)}{\partial x}\right|_{x=SURF.}}$$

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: semi-infinite solid approximation



$$\left.\begin{array}{l} D\dfrac{\partial c(x,t)}{\partial x^2}=\dfrac{\partial c(x,t)}{\partial t} \\ \text{I.C.}\quad c(x,0)=c_o \\ \text{B.C.}\quad c(0,t)=0 \end{array}\right\}\quad \boxed{c(x,t)=c_o\cdot erf\frac{x}{2\sqrt{Dt}}}$$

diffusion length

$$erf(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-\eta^2}\,d\eta$$

$$\boxed{q(t)=-D\left.\frac{\partial c(x,t)}{\partial x}\right|_0=\frac{D\cdot c_o}{\sqrt{\pi\cdot D\cdot t}}\propto t^{-0.5}}$$

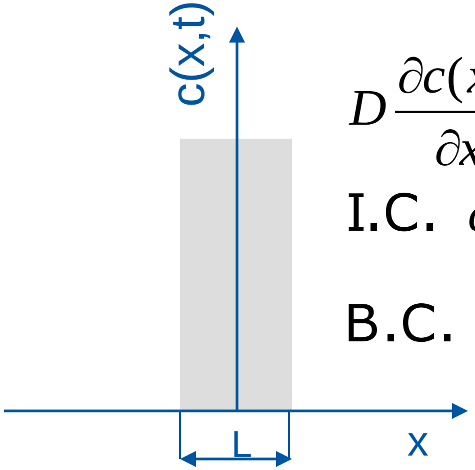
The $t^{-0.5}$ evolution holds also for solid of finite dimension L (slab) when $L \gg (Dt)^{0.5}$

The total amount of substance M(t) which has left the solid is:

$$\boxed{M(t)=\frac{2c_o}{\sqrt{\pi}}\cdot\sqrt{D\cdot t}}$$

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: slab approximation



$$D\frac{\partial c(x,t)}{\partial x^2}=\frac{\partial c(x,t)}{\partial t}$$

$$\text{I.C.}\quad c(x,0)=c_o$$

$$\text{B.C.}\quad c(\pm\frac{L}{2},t)=c_w$$

$$\boxed{\frac{c(x,t)-c_o}{c_w-c_o}=1-\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n-1}\cos\frac{(2n+1)\pi\cdot x}{L}\,e^{\frac{-D\cdot(2n+1)^2\pi^2 t}{L^2}}}$$

$$\boxed{q(t)=\frac{4\cdot\left(c_0-c_w\right)\cdot D}{L}\sum_{n=0}^{\infty}e^{-(2n+1)^2\pi^2\cdot\frac{D\cdot t}{L^2}}}$$

For Dt>0.05 L^2 only the first term of the series is relevant :

$$\boxed{q(t)\approx\frac{4\cdot\left(c_0-c_w\right)\cdot D}{L}e^{-\pi^2\cdot\frac{D\cdot t}{L^2}}}$$

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: Sievert's law

If hydrogen in the gas phase and on the surface are in equilibrium, the surface concentration c_w may be calculated by the Sievert's law:

$$c_w = K_s(T)\sqrt{P_{H_2}}$$

$$K_s(T) = K_0 e^{\frac{-E_s}{2k_B T}}$$

P_{H2} is the pressure of hydrogen in the gas phase

$K_s(T)$ is the hydrogen solubility in the metal

E_s is the H_2 solubility energy

K_0 a constant.

For stainless steel, E_s is positive; therefore, the solubility increases with temperature. At **room temperature** and for typical hydrogen pressure, **c_w is negligible** with respect to the residual hydrogen content. This is not true at higher temperature; for example during a vacuum firing treatment.

$$c_H[at.ppm] = 71.8 \cdot \sqrt{P_{H_2}[Torr]} \cdot e^{-\frac{0.114[eV]}{k_B \cdot T}}$$

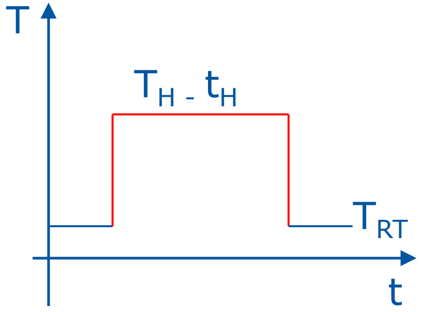
$$c\left[\frac{Torr\ l\ (H_2)}{cm^3}\right] = 8.21 \cdot 10^{-2}\sqrt{P_{H_2}[Torr]} \cdot e^{-\frac{2650}{1.99 \cdot T[K]}}$$

Sievert's law for austenitic stainless steel

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: Fourier number

If the slab is heated to a temperature T_H for a time t_H, the outgassing rate, when back at room temperature is:



$$q \approx \frac{4 \cdot (c_0 - c_w) \cdot D}{L} \exp\left[-\pi^2 \cdot \frac{D(T_H) \cdot t_H}{L^2} \right]$$

For an arbitrary thermal cycle T=T(t), it can be show that:

$$q \approx \frac{4 \cdot (c_0 - c_w) \cdot D}{L} \exp\left[-\pi^2 \cdot \frac{\int_0^{t_H} D(T) \cdot dt}{L^2} \right] = \frac{4 \cdot (c_0 - c_w) \cdot D}{L} \exp\left[-\pi^2 \cdot F_0 \right]$$

The dimensionless number: $F_o = \frac{\int_0^{t_H} D(T) \cdot dt}{L^2}$ is called the Fourier number

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: consecutive bakeouts

F_o 'records' the thermal history of the material and determines how much of the initial concentration is depleted.

When thermal treatment of **$F_o \approx 3$** are applied, the solid is actually emptied or in equilibrium with the surrounding gas phase.

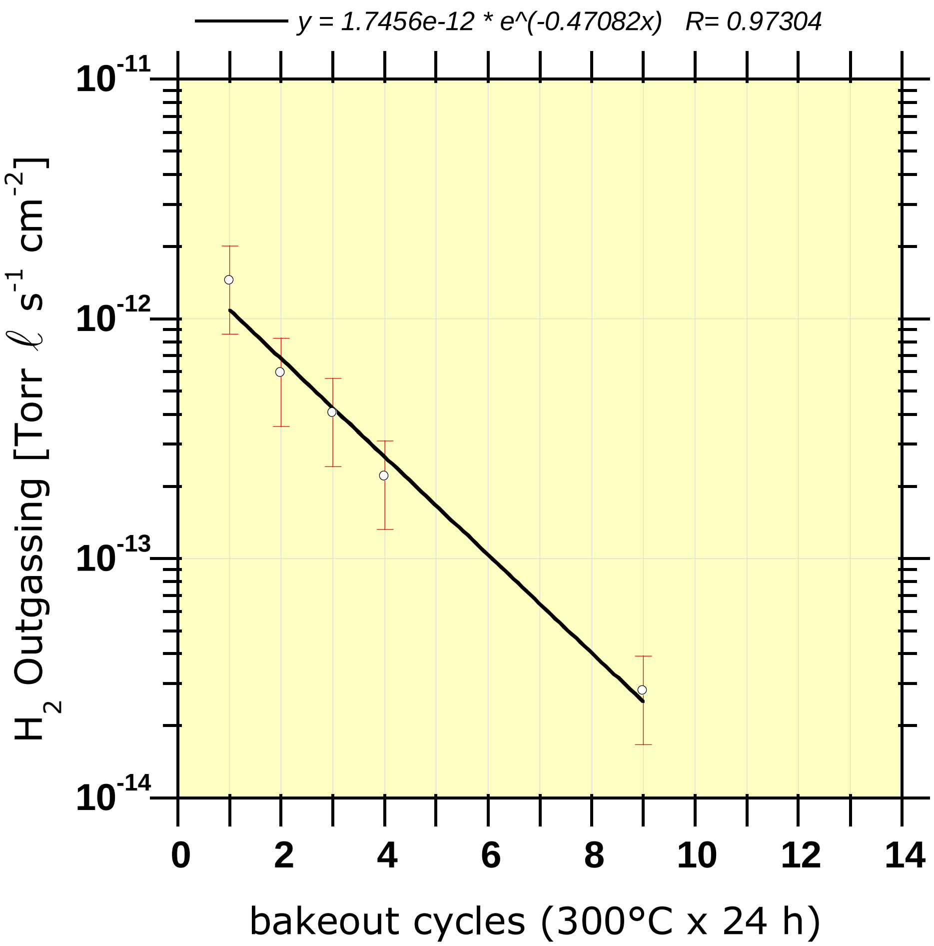
In case of **multiple identical thermal treatments** (for example bakeouts) with a given constant F_0, the calculated ratio of the outgassing rate at room temperature after two successive thermal cycles is:

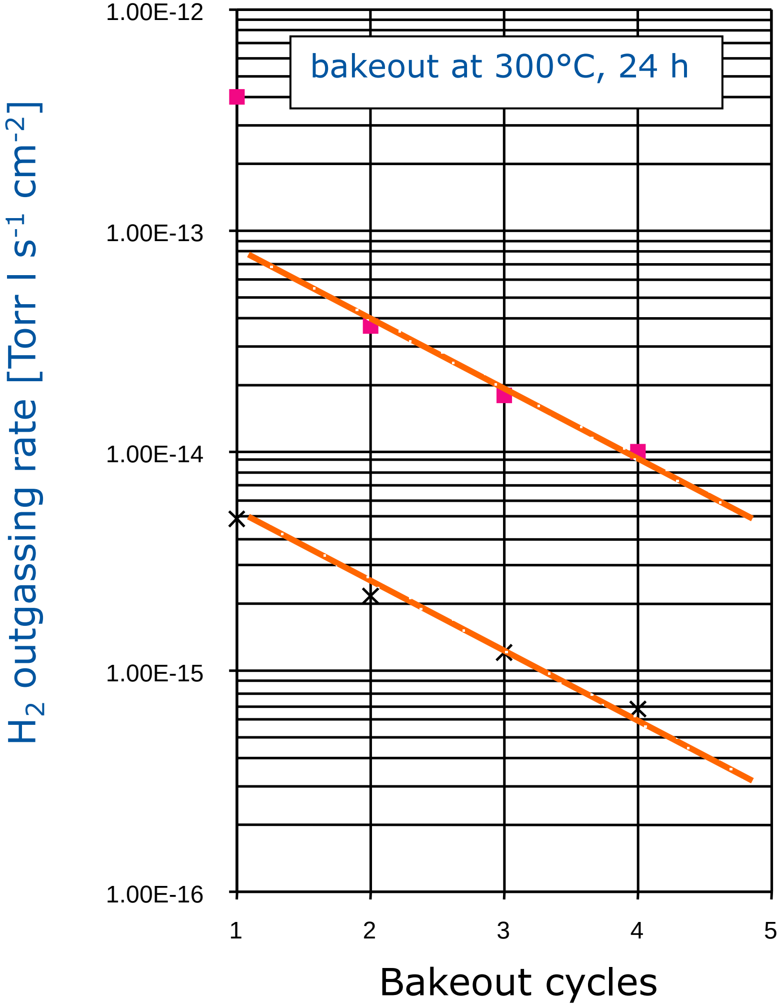
$$\frac{q_{n+1}}{q_n} = exp[-\pi^2 F_0]$$

That is to say that each bakeout reduces the outgassing rete of hydrogen by the same constant factor. This is in line with the experimental results.

Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: consecutive bakeouts

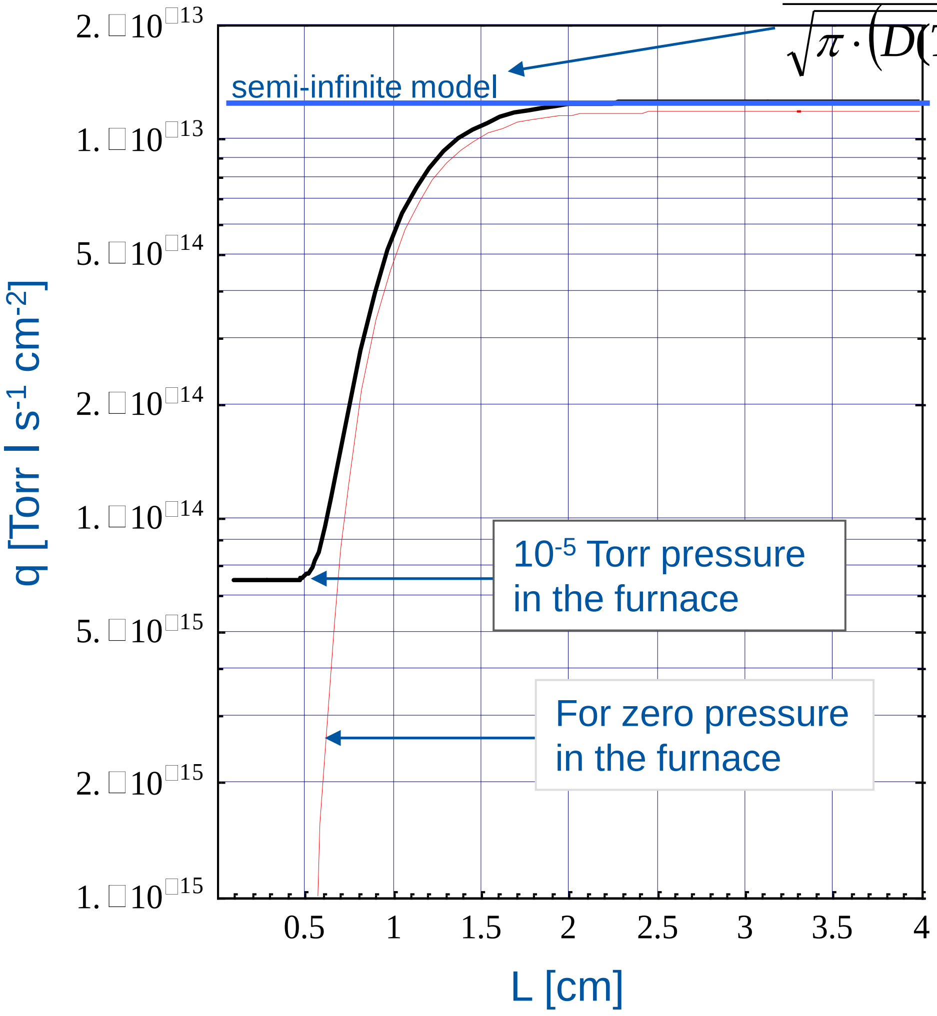




Gas sources: outgassing of metals

Diffusion model of H_2 outgassing: vacuum firing

$$\frac{D(T)\cdot c_0}{\sqrt{\pi\cdot\left(D(T_f)t_f + D(T_{bo})t_{bo}\right)}}$$



semi-infinite model

10^{-5} Torr pressure in the furnace

For zero pressure in the furnace

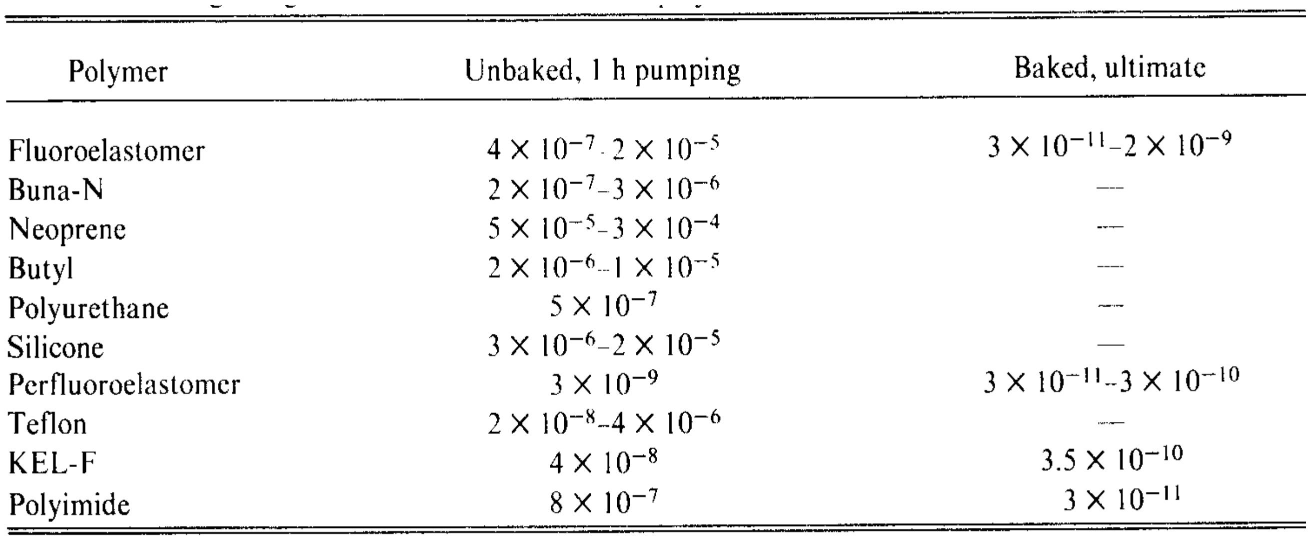
Parameters	Symbol	Values
Temperature of the firing treatment	T_f	950°C
Duration of the firing treatment	t_f	2 hours
In situ bakeout temperature	T_{bo}	150°C
Duration of the in situ bakeout	t_{bo}	24 hours
Initial content of residual hydrogen	c_o	1 ppm wt (≈50 ppm at.)
Hydrogen equilibrium concentration on slab surfaces during firing	c_w	0.06 ppm wt. Equivalent to P_{H2}=1.3x10^{-5} mbar

Gas sources: outgassing of polymers

Polymers, in particular their amorphous structures, can **dissolve huge quantities of gas**.

The water vapour solubility is very high; for example for common materials like Viton, PEEK, and Vespel the content of water in equilibrium with 50% humidity air at 20°C is 0.21, 0.2, and 1 wt. %, respectively.

The huge quantity of dissolved gas and the relatively high mobility through the polymeric chains result in much higher outgassing rates than the ones for metals. This is particularly marked for **water vapour**.



Polymer	Unbaked, 1 h pumping	Baked, ultimate
Fluoroelastomer	4×10^{-7}-2×10^{-5}	3×10^{-11}-2×10^{-9}
Buna-N	2×10^{-7}-3×10^{-6}	—
Neoprene	5×10^{-5}-3×10^{-4}	—
Butyl	2×10^{-6}-1×10^{-5}	—
Polyurethane	5×10^{-7}	—
Silicone	3×10^{-6}-2×10^{-5}	—
Perfluoroelastomer	3×10^{-9}	3×10^{-11}-3×10^{-10}
Teflon	2×10^{-8}-4×10^{-6}	—
KEL-F	4×10^{-8}	3.5×10^{-10}
Polyimide	8×10^{-7}	3×10^{-11}

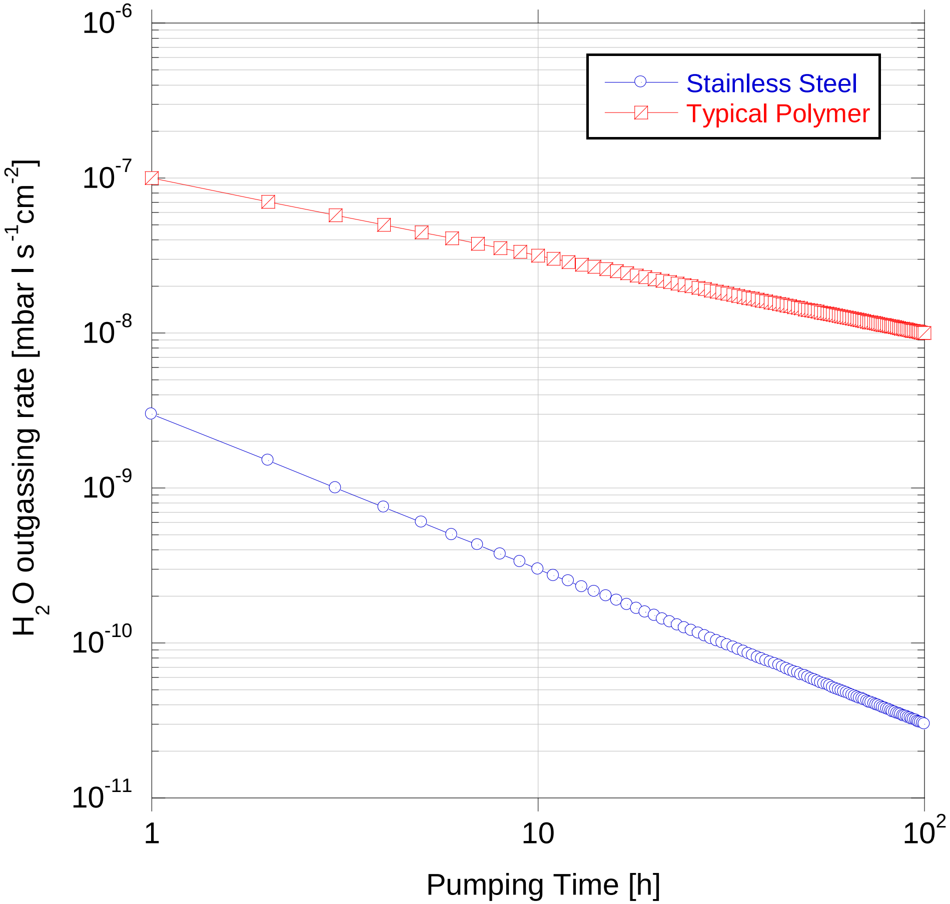
The maximum bakeout temperature depend on the type of polymer; it is limited to about 200 °C for Viton®.

Gas sources: outgassing of polymers

The outgassing rates of thick (L>Dt) slab of polymers, as expected by the diffusion model, decrease with the inverse of the square root of the pumping time t:

$$q_{H_2O} \propto \frac{1}{\sqrt{t}}$$

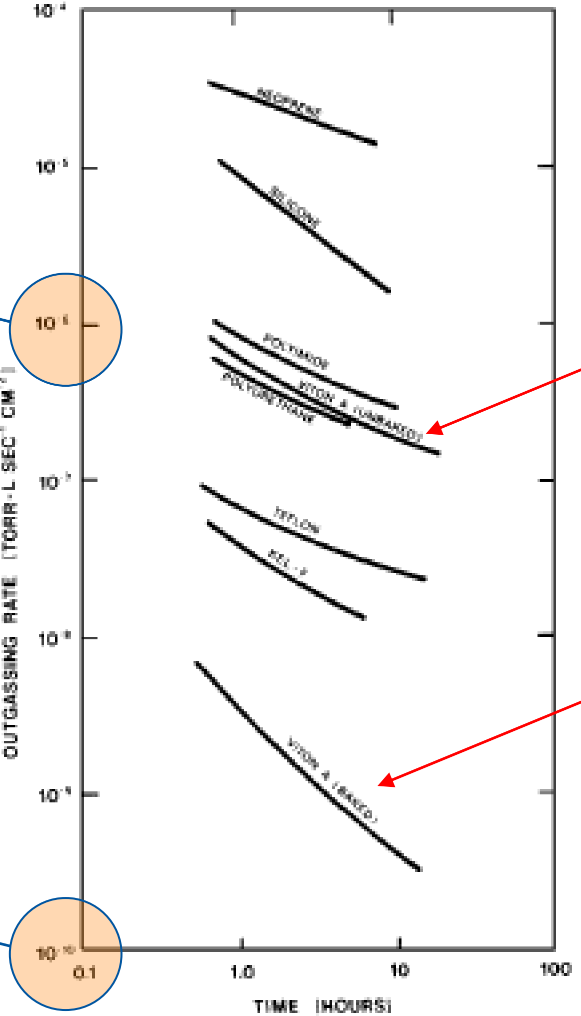
Compared to unbaked metals, thick polymers experience a much slower reduction of water outgassing rate.



Gas sources: outgassing of polymers

Outgassing rate of water vapour for polymers

R. N. Peacock, J. Vac. Sci. Technol., 17(1), p.330, 1980



10^{-6}

10^{-10}

unbaked Viton

baked Viton

Gas sources: outgassing of polymers

- Another important limitation of polymers used as seals is **the high gas permeability.**

- Gas penetrates into the material and diffuses towards the vacuum system. The permeation flow may **limit the ultimate water vapour pressure** in vacuum systems and **affect the sensitivity of helium leak-detection**.

- As an example, the permeation flow of atmospheric water through a Viton O-ring, 5 mm cross section diameter, 6 cm torus diameter, is about **10^{-7} mbar l s^{-1}** This value is equivalent to the outgassing of **1 m^2 of stainless steel** after 100 h of pumping.

Gas sources: outgassing of polymers

Application of polymers in UHV technology is hindered by the **huge outgassing and permeability**.

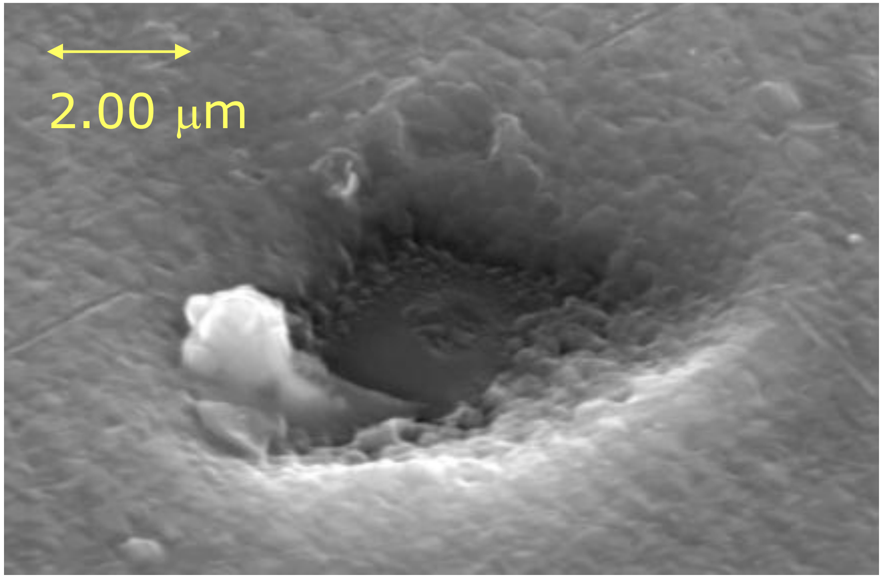
This drawback has been partially overcome in other technological domains (i.e. packaging) by **coating polymers with metals** or metal oxides (more recently also with a:C-H).

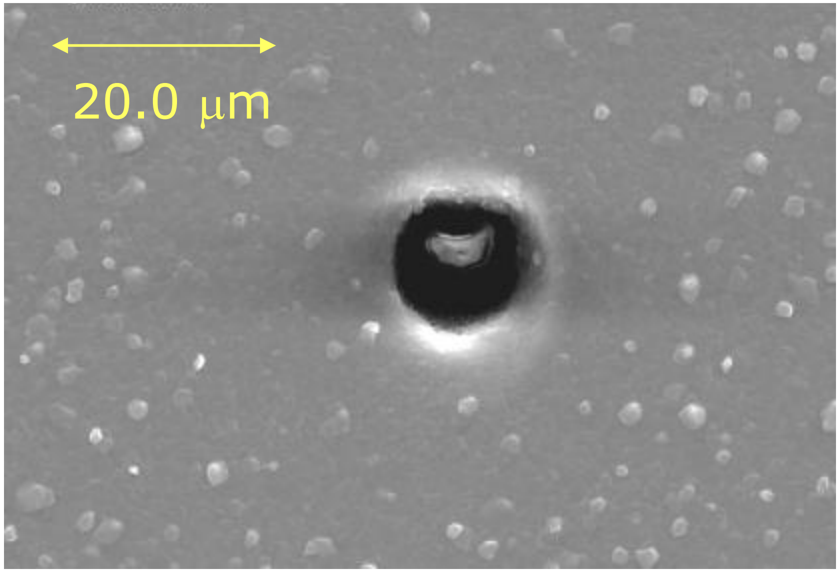
How effective are coatings in reducing outgassing and permeation rate?

- Since the permeability of metals is negligible for all gases, metallic coatings should entirely block the polymer outgassing and permeation.
- However, experimental results show that only a partial reduction of the flux is attained.
- This is attributed to defects on the coating (pinholes or scratches) that cause discontinuity on the surface coverage.
- Pinholes are produced during the deposition process and they are presumably due to atmospheric dust particles.

Gas sources: outgassing of polymers

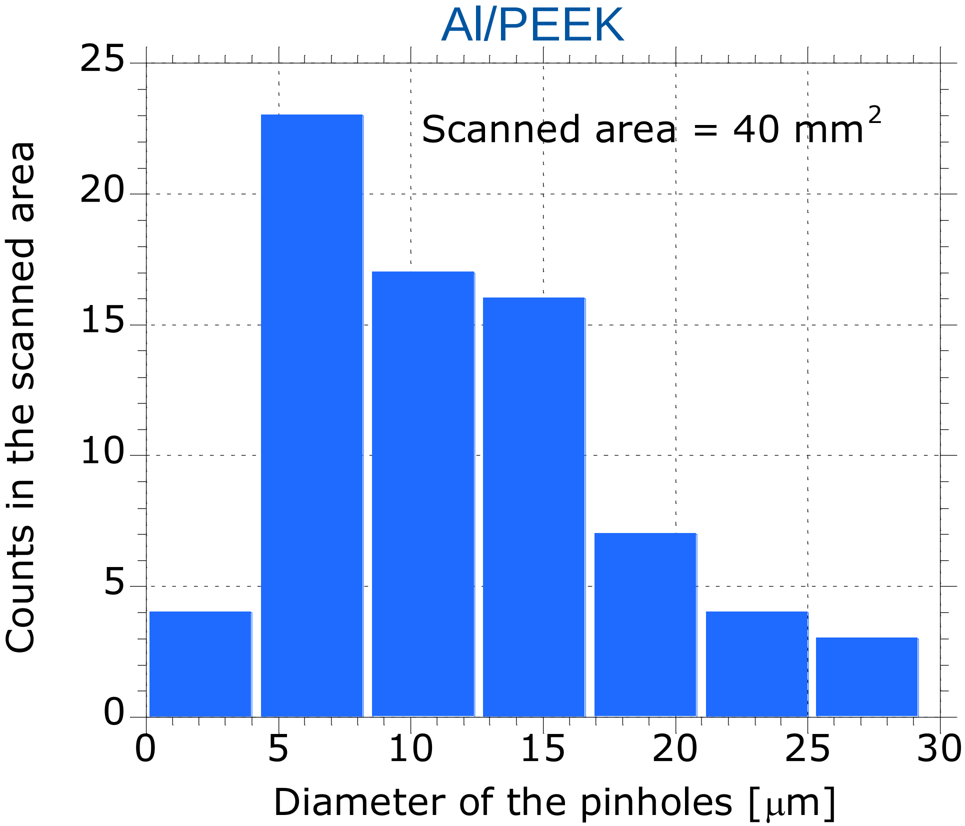
Examples of pinholes on Al coating deposited on PEEK





Gas sources: outgassing of polymers

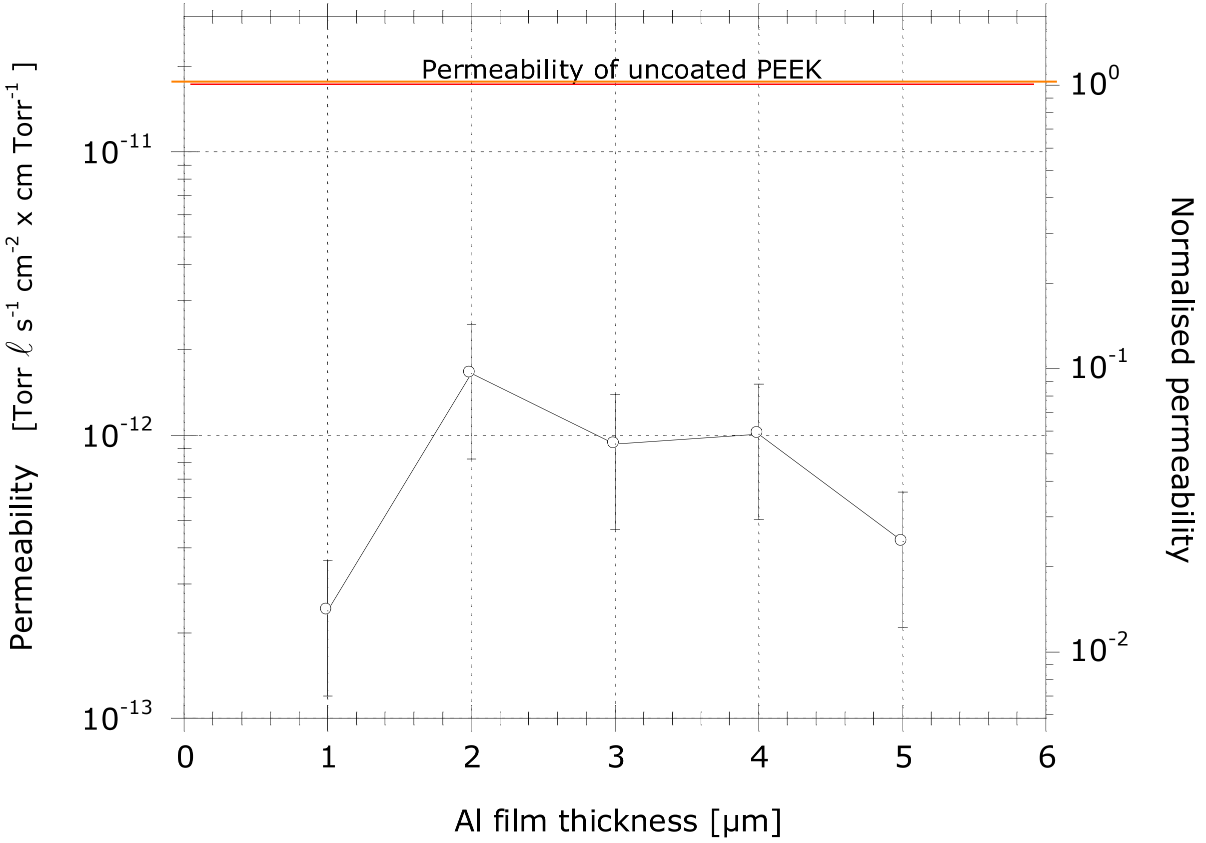
Transmitted light optical microscopy has been used to detect uncoated surfaces on metal films, showing that they mainly consist of pinholes of different diameters.



Normalised uncoated surface areas of the order of 10^{-4} are measured

Gas sources: outgassing of polymers

However, experiments have shown that the permeability is **reduced much less than expected** from the uncoated fraction



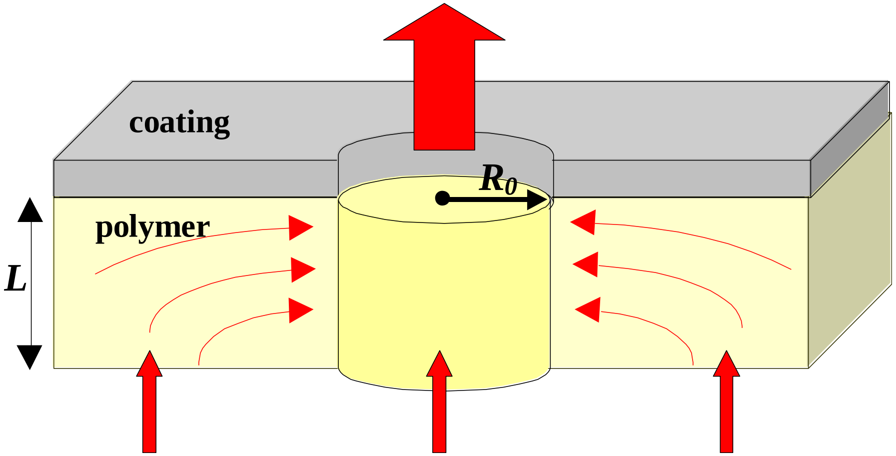
Example:
Al/PEEK(0.125 mm thick)
The uncoated fraction is **10^{-4}**, but the permeability of He is **10^{-2}** of that of the uncoated polymer.

Gas sources: outgassing of polymers

This apparent inconsistency can be justified considering that the pinhole gas throughput is enhanced by lateral diffusion.

ρ =Normalised permeability → order of 10^{-2}

Θ =Normalised uncoated area → order of 10^{-4}



For L/R_0 >0.3 :

$$\rho = \Theta \times \left(1 + 1.18 \frac{L}{R_0} \right) ^{*}$$

Amplification factor

* After W.Prins and J.J.Hermans, J.Phys.Chem., **63** (1959) 716.

Gas sources: outgassing of polymers

In the literature the barrier efficiency is called “**barrier improvement factor**” or BIF. It is the inverse of normalized permeability.

Normalized permeability:

$$\rho = \Theta \times \left(1 + 1.18\frac{L}{R_0}\right)$$

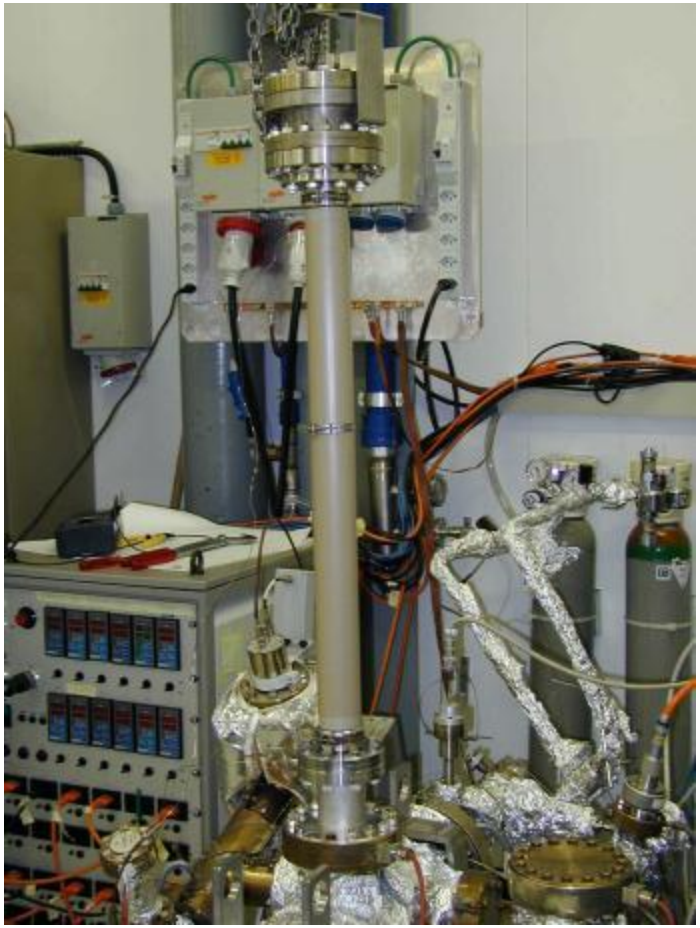
Barrier improvement factor:

$$BIF = \frac{1}{\rho} = \frac{1}{\Theta \times \left(1 + 1.18\frac{L}{R_0}\right)}$$

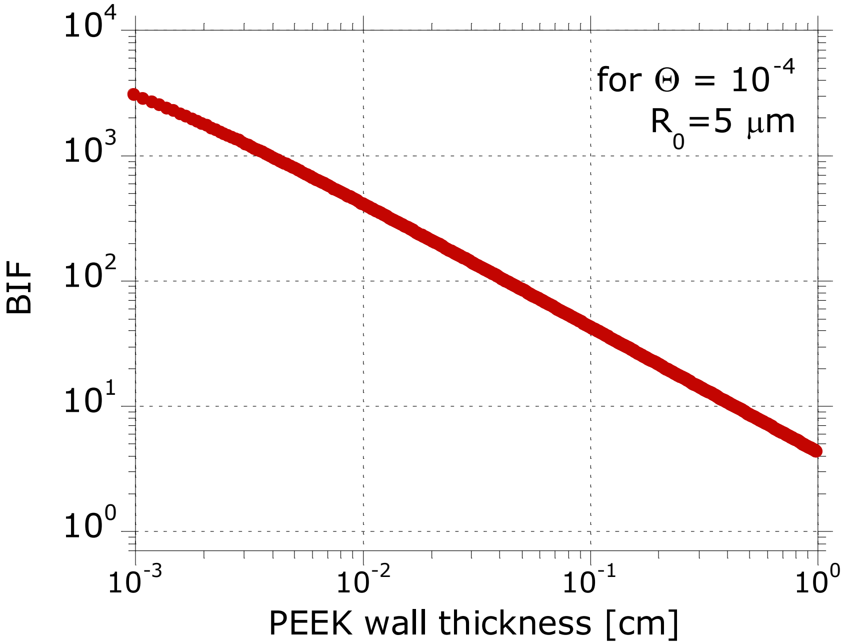
The fact that ρ depends on L means that for L>10R the flux value does not depend on the polymer thickness. In other terms, all the concentration gradient is localized near the pin-hole.

It follows also that, for similar coating, **the improvement due to the coating is less significant for thicker polymer substrates.**

Gas sources: outgassing of polymers



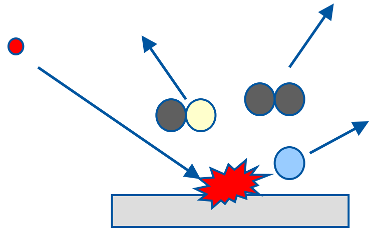
The BIF for Al coated PEEK.
For thickness larger than 5 mm, the coating is useless.



In conclusion, metallic coatings are very efficient in the reduction of the permeation and outgassing rate in thin polymers. For polymers thicker than 5 mm, the benefit of the coating is negligible.

Gas sources: beam induced desorption

The impingement of electrons and photons, of energy higher than some eV, on solid surfaces can result in ions and neutral molecules desorption.

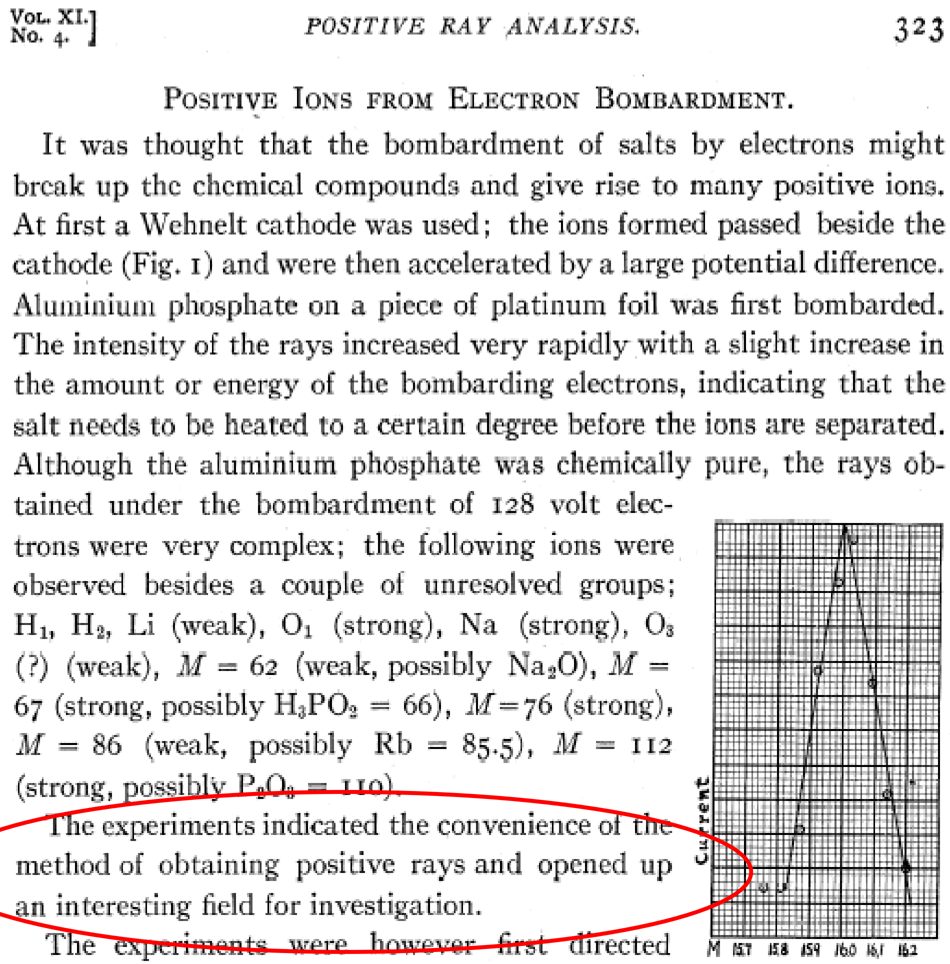


The first observations of induced desorption are very old and they go back to the origin of modern vacuum technology.

- In 1918, Dempster **observed ion desorption from electron** bombarded salts

(Phys. Rev. 11, 323)

ESD: electron stimulated desorption



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POSITIVE IONS FROM ELECTRON BOMBARDMENT.

It was thought that the bombardment of salts by electrons might break up the chemical compounds and give rise to many positive ions. At first a Wehnelt cathode was used; the ions formed passed beside the cathode (Fig. 1) and were then accelerated by a large potential difference. Aluminium phosphate on a piece of platinum foil was first bombarded. The intensity of the rays increased very rapidly with a slight increase in the amount or energy of the bombarding electrons, indicating that the salt needs to be heated to a certain degree before the ions are separated. Although the aluminium phosphate was chemically pure, the rays obtained under the bombardment of 128 volt electrons were very complex; the following ions were observed besides a couple of unresolved groups; H_1, H_2, Li (weak), O_1 (strong), Na (strong), O_3 (?) (weak), $M = 62$ (weak, possibly Na_2O), $M = 67$ (strong, possibly $H_3PO_2 = 66$), $M=76$ (strong), $M = 86$ (weak, possibly $Rb = 85.5$), $M = 112$ (strong, possibly $P_2O_3 = 110$).

The experiments indicated the convenience of the method of obtaining positive rays and opened up an interesting field for investigation.

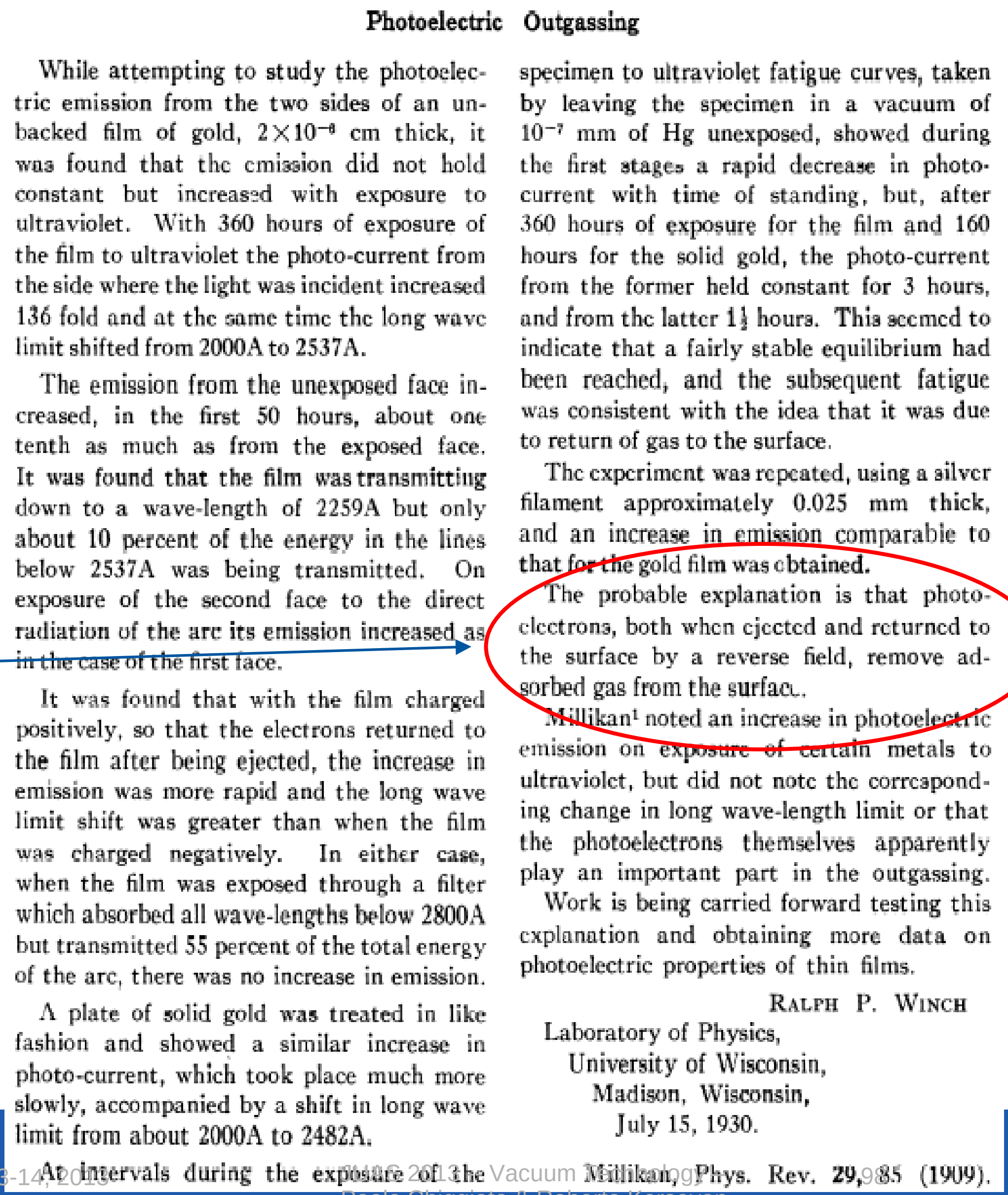
The experiments were however first directed

Gas sources: beam induced desorption

Millikan reported the first evidence of **photon induced desorption** in 1909 during the measurement of the photoelectric current of metals exposed to ultraviolet radiation. The first interpretation is given by Winch in 1930 (Phys. Rev. **36**, 601).

Winch was the first to see the implication of photoelectrons on photon induced desorption.

PSD: photon stimulated desorption



Photoelectric Outgassing

While attempting to study the photoelectric emission from the two sides of an unbacked film of gold, 2×10^{-6} cm thick, it was found that the emission did not hold constant but increased with exposure to ultraviolet. With 360 hours of exposure of the film to ultraviolet the photo-current from the side where the light was incident increased 136 fold and at the same time the long wave limit shifted from 2000A to 2537A.

The emission from the unexposed face increased, in the first 50 hours, about one tenth as much as from the exposed face. It was found that the film was transmitting down to a wave-length of 2259A but only about 10 percent of the energy in the lines below 2537A was being transmitted. On exposure of the second face to the direct radiation of the arc its emission increased as in the case of the first face.

It was found that with the film charged positively, so that the electrons returned to the film after being ejected, the increase in emission was more rapid and the long wave limit shift was greater than when the film was charged negatively. In either case, when the film was exposed through a filter which absorbed all wave-lengths below 2800A but transmitted 55 percent of the total energy of the arc, there was no increase in emission.

A plate of solid gold was treated in like fashion and showed a similar increase in photo-current, which took place much more slowly, accompanied by a shift in long wave limit from about 2000A to 2482A.

At intervals during the exposure of the specimen to ultraviolet fatigue curves, taken by leaving the specimen in a vacuum of 10^{-7} mm of Hg unexposed, showed during the first stages a rapid decrease in photo-current with time of standing, but, after 360 hours of exposure for the film and 160 hours for the solid gold, the photo-current from the former held constant for 3 hours, and from the latter $1\frac{1}{2}$ hours. This seemed to indicate that a fairly stable equilibrium had been reached, and the subsequent fatigue was consistent with the idea that it was due to return of gas to the surface.

The experiment was repeated, using a silver filament approximately 0.025 mm thick, and an increase in emission comparable to that for the gold film was obtained.

The probable explanation is that photoelectrons, both when ejected and returned to the surface by a reverse field, remove adsorbed gas from the surface.

Millikan[1] noted an increase in photoelectric emission on exposure of certain metals to ultraviolet, but did not note the corresponding change in long wave-length limit or that the photoelectrons themselves apparently play an important part in the outgassing. Work is being carried forward testing this explanation and obtaining more data on photoelectric properties of thin films.

RALPH P. WINCH

Laboratory of Physics,
University of Wisconsin,
Madison, Wisconsin,
July 15, 1930.

[1] Millikan, Phys. Rev. 29, 85 (1909).

Gas sources: beam induced desorption

The **desorption yield** η, i.e. the number of molecules desorbed per impinging particle, is needed to design the vacuum system of particle accelerators.

$$\eta = \frac{\text{number of molecules desorbed}}{\text{number of particules impinging on the surface}}$$

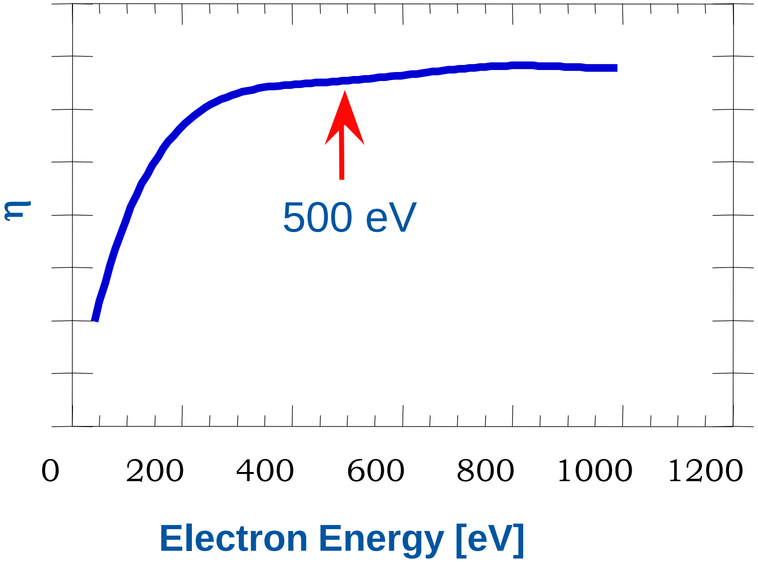
η depends on many parameters, in particular:

- on the nature and energy of the impinging particle;
- the material of the vacuum chamber;
- the nature of the desorbed gas;
- quantity of particles that have already impinged on the surface, namely the dose D $\left[\text{particles/cm}^2\right]$.

The cleanliness of the surfaces has also a crucial influence.

Gas sources: electron induced desorption

Typical values of η for baked structural vacuum materials vary between **10^{-1} and 10^{-3} molecules per electron** at 500 eV. Neutral desorption is much more likely than ion desorption, about 100 times higher.



For typical metals used in vacuum technology, η of hydrogen is the highest followed by those for CO, CO_2 and CH_4, in decreasing order.

$$\eta_{H_2} > \eta_{CO} > \eta_{CO_2} > \eta_{CH_4}$$

Gas sources: electron induced desorption

Electron bombardment cleans metallic surfaces by gas desorption.

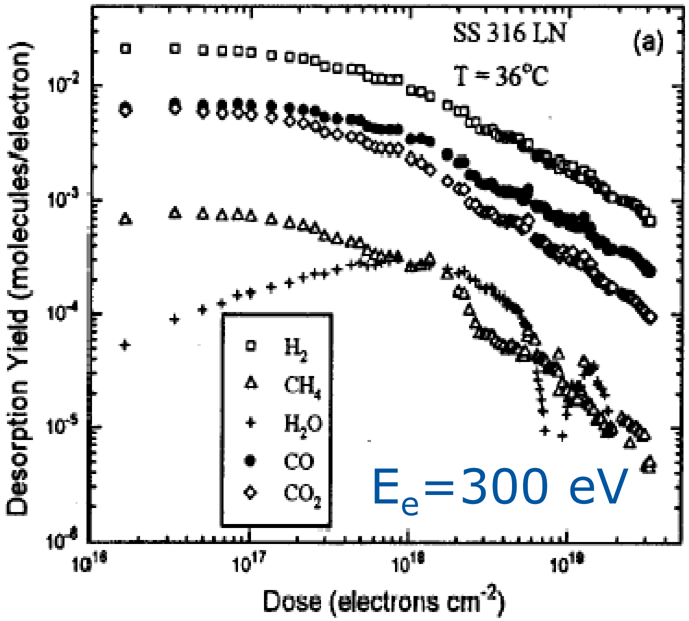
As a consequence, the desorption yields decrease when the electron dose increases.

η_e values have a power law dependence on the dose of electrons D_e (for doses higher than 10^{18} e^- cm^{-2}):

$$\eta = \eta_o \cdot D^{-\alpha}$$

where a is between 0.6 and 1.

α=0.77



E_e=300 eV

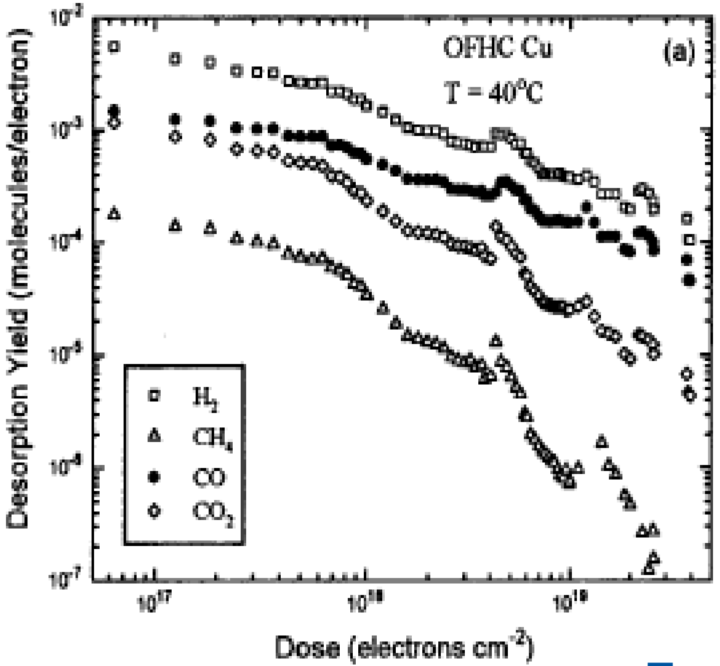
J. Gomez-Goñi and A. G. Mathewson

J. Vac. Sci. Technol. A **15**, 3093 (1997)

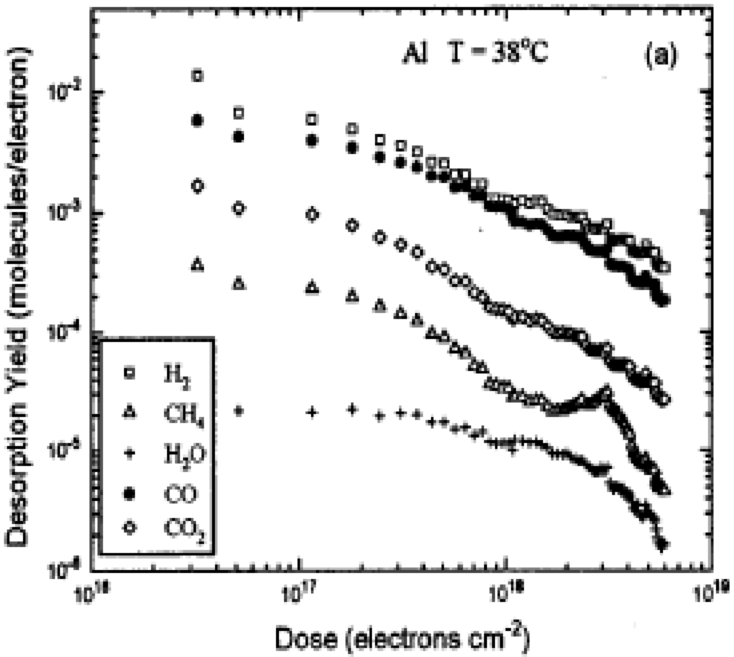
The samples were baked at 150 C for 24 h and at 300 C for 2 h

Gas sources: electron induced desorption

$\alpha=0.62$



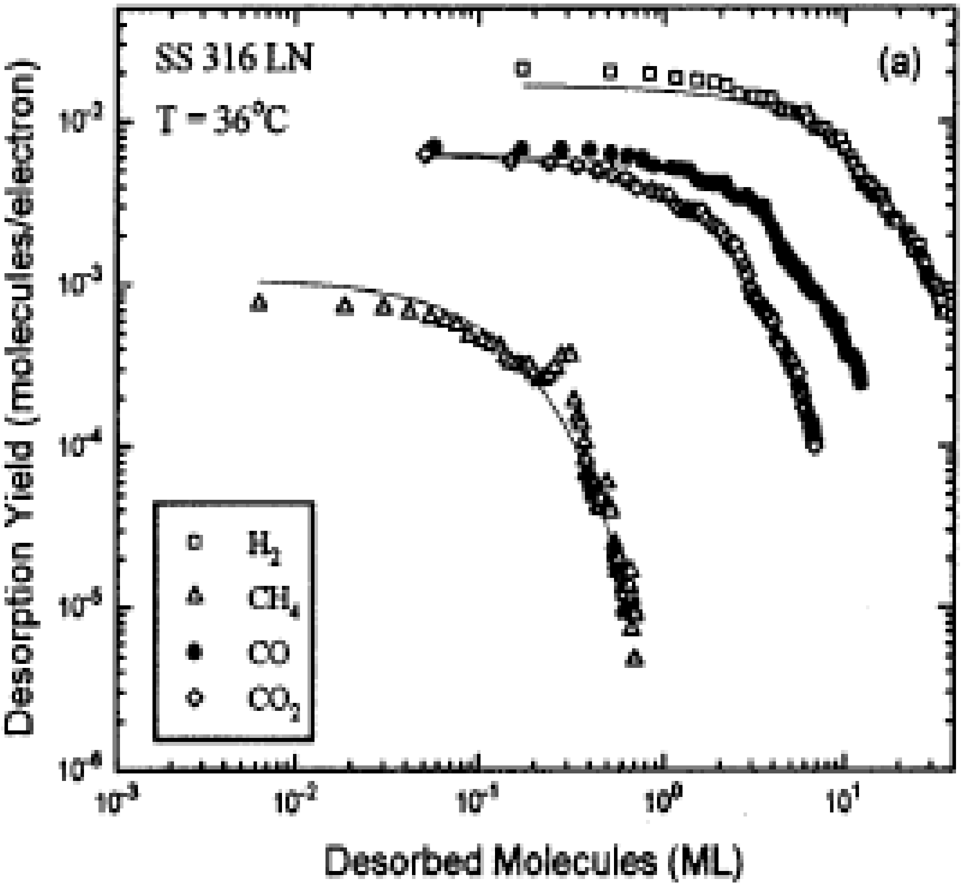
$\alpha=0.68$



E_e=300 eV

J. Gomez-Goñi and A. G. Mathewson J. Vac. Sci. Technol. A **15**, 3093 (1997)

Gas sources: electron induced desorption



1ML=2x10^{15} molecules/ cm^2

The total quantity of gas desorbed exceed by far one monolayer.

In order to explain the huge quantity of gas desorbed, some authors considered stimulated gas diffusion from the oxide layer

The **accumulated dose effect** is lost when the surface is vented to air for long time. For short exposure to air (for example a few hours) a residual effect is measured; it is called '**memory effect**': η values similar to those attained before venting are achieved after a smaller dose.

J. Gomez-Goñi and A. G. Mathewson J. Vac. Sci. Technol. A **15**, 3093 (1997)

Gas sources: electron induced desorption

The ESD process can be considered as an **isolated interaction between an electron and an adsorbate**.

The maximum energy ΔE transferred during the collision between a low energy electron of mass m_e and a molecule of mass M is calculated by classical kinematics. For hard-sphere scattering and m_e<<M, one can estimate that:

$$\frac{\Delta E}{E_e} \cong \frac{4m_e}{M}$$

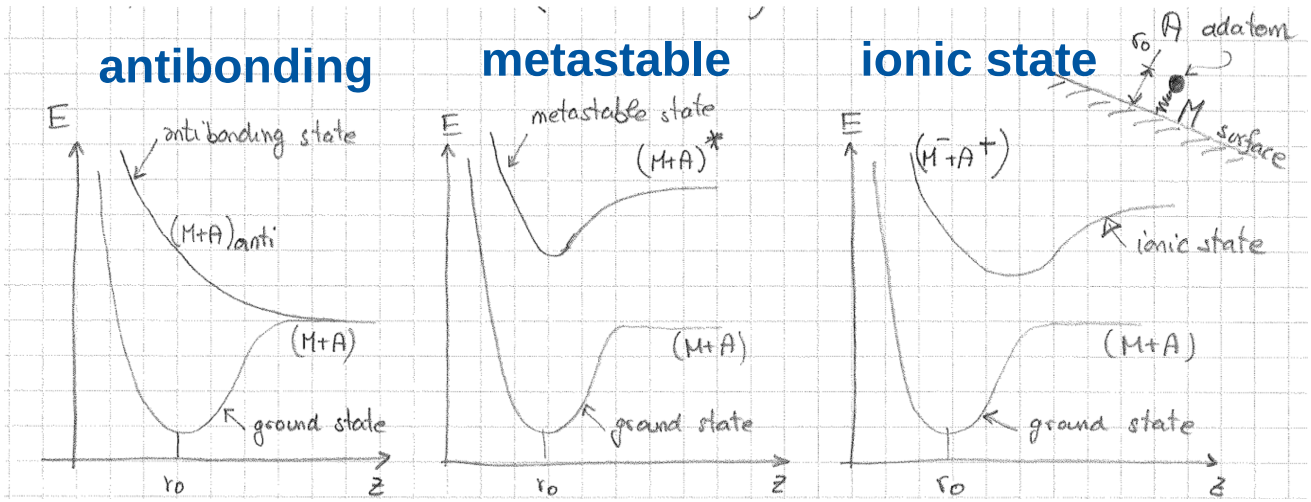
For **H_2** the fraction of energy transferred to the molecules is about $\mathbf{2/1840}$. For typical electron energy of about 300 eV, ΔE is of the order of 0.1 eV.

These values are much lower than the measured energies of desorbed molecules, typically in the **2-10 eV range**. Therefore, **the direct momentum transfer is not the dominant process in ESD**. Electronic energy transfers are then considered.

Gas sources: electron induced desorption

One of the earliest and general models to explain ESD from surfaces was introduced independently by Menzel, Gomer, and Redhead (MGR) in 1964.

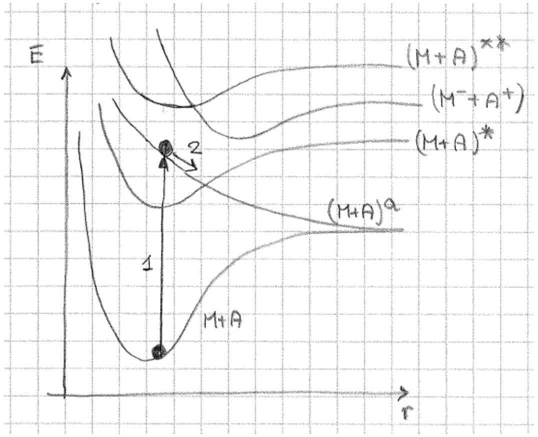
The interaction with the incident electron provokes an adiabatic transition (Franck-Condon principle) to exited states of different nature:

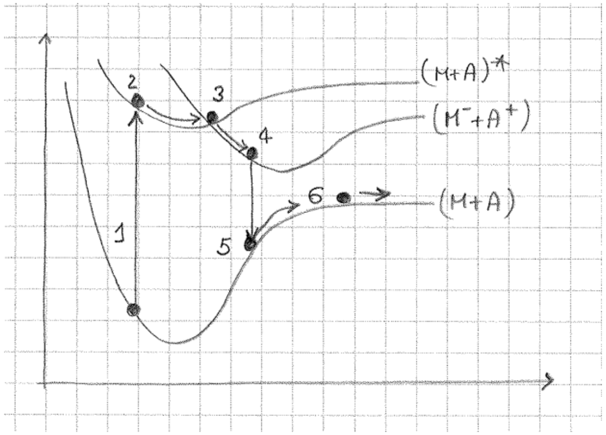


antibonding **metastable** **ionic state**

The adiabatic transition implies a change of electronic energy in about **10^{-16} s** with a frozen distance z between nuclei. The transition is vertical in potential energy vs. distance diagram.

Gas sources: electron induced desorption





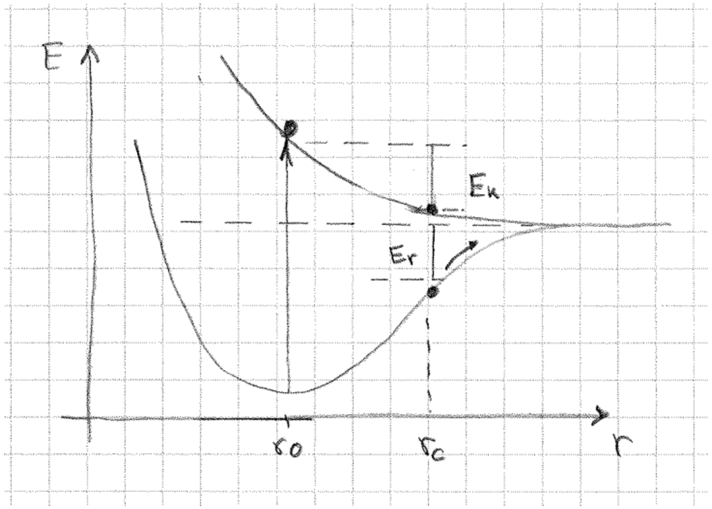
After the excitation, **nuclear motion may occur** over a time scale of about **10^{-13}-10^{-14} s**: part of the **potential energy is converted into kinetic energy**.

The crossing of potential curves is possible resulting in different de-excitation pathways.

Gas sources: electron induced desorption

Whenever the original state is reached during the downward transition (rebonding), **the molecule can escape if it has acquired enough kinetic** energy to overpass the potential binding energy at the position of transition.

The **desorption as a stable neutral** is possible when the downward transition occurs at a distance from the surface which is larger than **a critical distance r_c** .



Gas sources: photon induced desorption

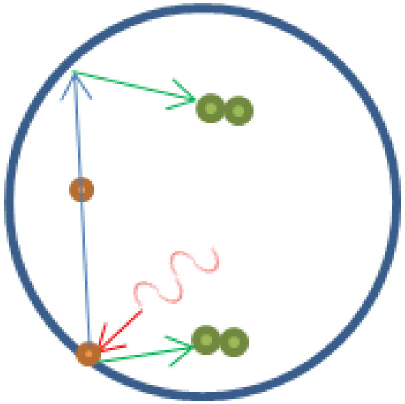
Particle beams emit photons whenever they are accelerated, namely whenever their velocity vectors are changed.

Synchrotron radiation (SR) is emitted when charged particles moving with relativistic speeds are forced to follow **curved trajectories in magnetic fields**.

The emitted photons impinge on the wall of the vacuum system and may **desorb gas** molecules.

There is experimental evidence that the photon stimulated desorption is generated by a two-step process:

1. The impinging photons extract photoelectrons.
2. The extraction and recapture of the photoelectrons stimulate the desorption of gas molecules by the ESD mechanism.



Gas sources: photon induced desorption

A particle of charge ‘e’, energy E and rest mass m_0, moving on a circular orbit (radius ρ) radiates electromagnetic radiation with the following power P_{rad}:

$$P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0 \left(m_0 c^2\right)^4} \frac{E^4}{\rho^2}$$

where ε_0 and c are the vacuum permittivity and the speed of light, respectively.

The emitted power depends strongly on the **beam energy** and the **radius of the bent trajectory**.

Consequently, **electrons emit much more synchrotron radiation power than protons** for the same bending radius and energy:

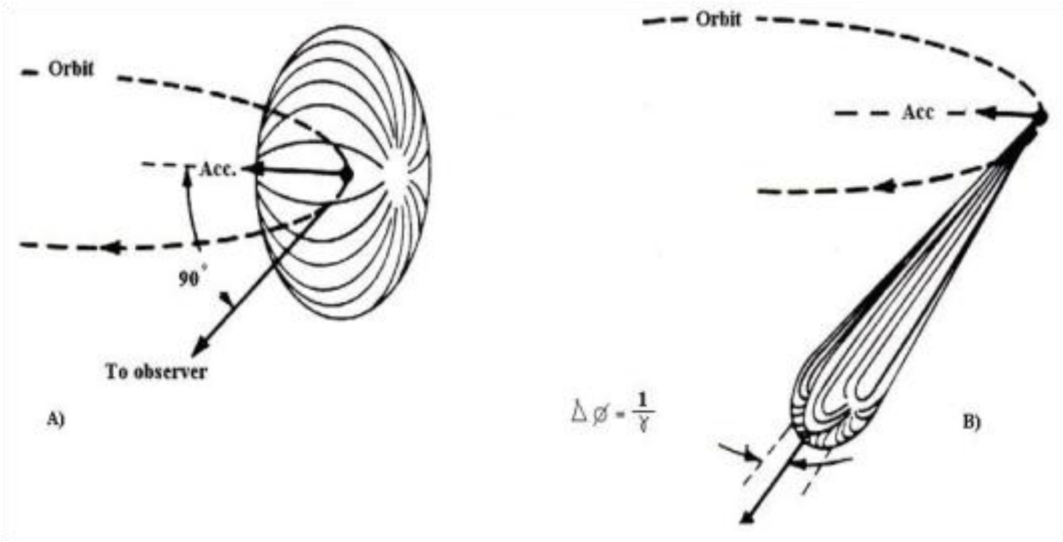
$$\frac{\left(P_{rad}\right)_{electrons}}{\left(P_{rad}\right)_{protons}} = \left(\frac{m_p c^2}{m_e c^2}\right)^4 = 1.13 \times 10^{13}$$

Gas sources: photon induced desorption

Synchrotron emission is **strongly beamed** along the direction of motion, which is perpendicular to the acceleration.

The emission is concentrated into an angle of the order of **2/γ rad** along the direction of motion:

$$\gamma = 1/\sqrt{1-(v/c)^2} = E/mc^2$$



Gas sources: photon induced desorption

Synchrotron radiation from bending magnets has a **very broad energy spectrum**, which is characterised by the **critical energy ε_c**:

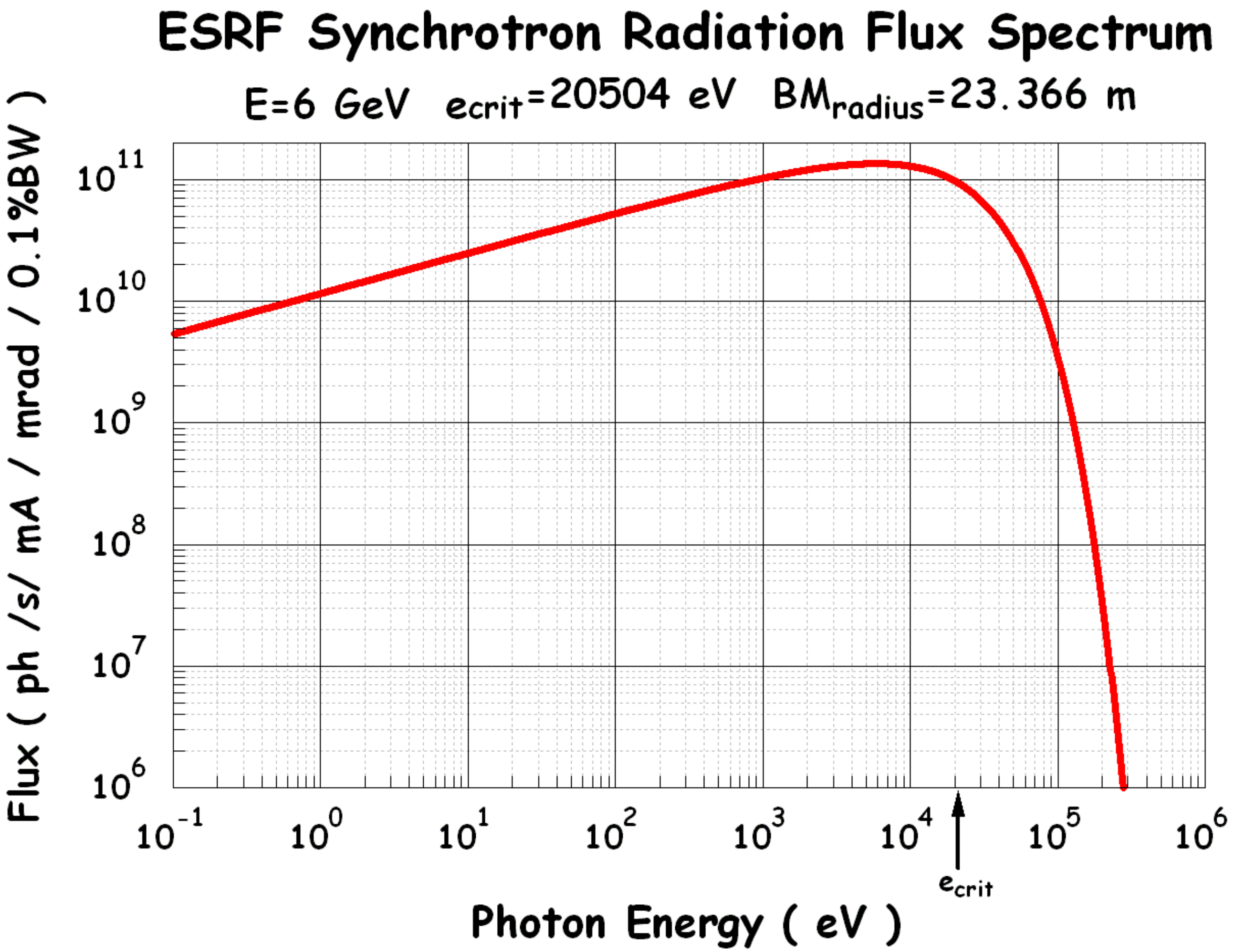
$$\varepsilon_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3 = \frac{3\hbar c}{2\left(mc^2\right)^3}\frac{E^3}{\rho}$$

The critical energy subdivide the photon spectrum in two parts of equal emitted power.

For electrons $\varepsilon_c[KeV] = 0.665 \times E^2\left[GeV^2\right] \times B[T]$

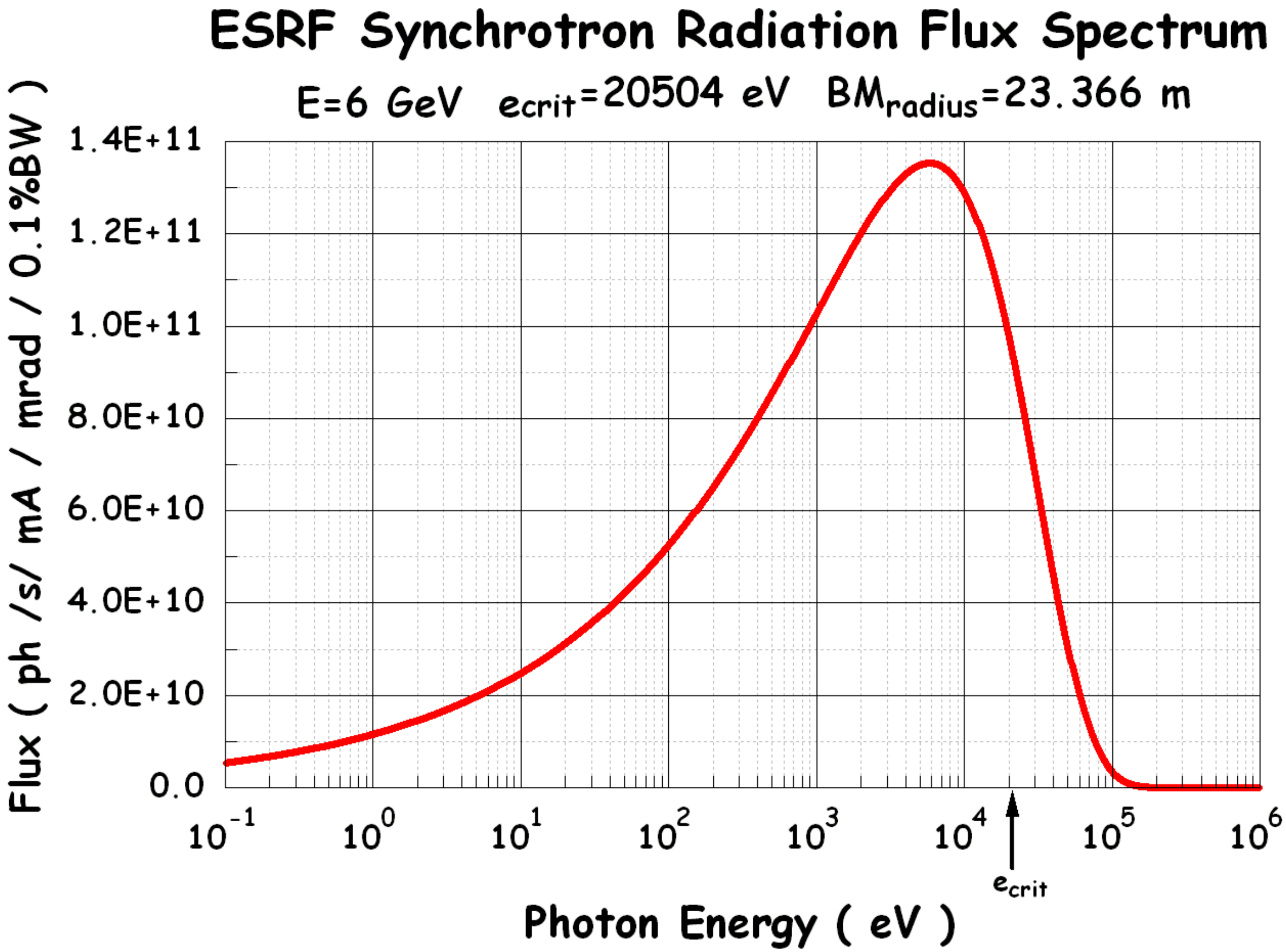
For protons $\varepsilon_c[KeV] = 1.1 \times 10^{-10} \times E^2\left[GeV^2\right] \times B[T]$

Gas sources: photon induced desorption



Courtesy of Roberto Kersevan

Gas sources: photon induced desorption



Courtesy of Roberto Kersevan

Gas sources: photon induced desorption

It can be shown that the number of emitted photon per unit time:

$$\dot{N} = \frac{15\sqrt{3}}{8}\frac{P_{rad}}{\varepsilon_c}$$

$$\dot{N} = \frac{P_{rad}}{\langle\varepsilon\rangle} \rightarrow \langle\varepsilon\rangle = \frac{8}{15\sqrt{3}}\varepsilon_c$$

Mean photon energy:
max of the distribution

For electrons

$$\dot{N} = 8.08 \times 10^{17} I[mA] E[GeV]$$

The linear flux, i.e. the emitted photons per second and meter, is given by

For electrons

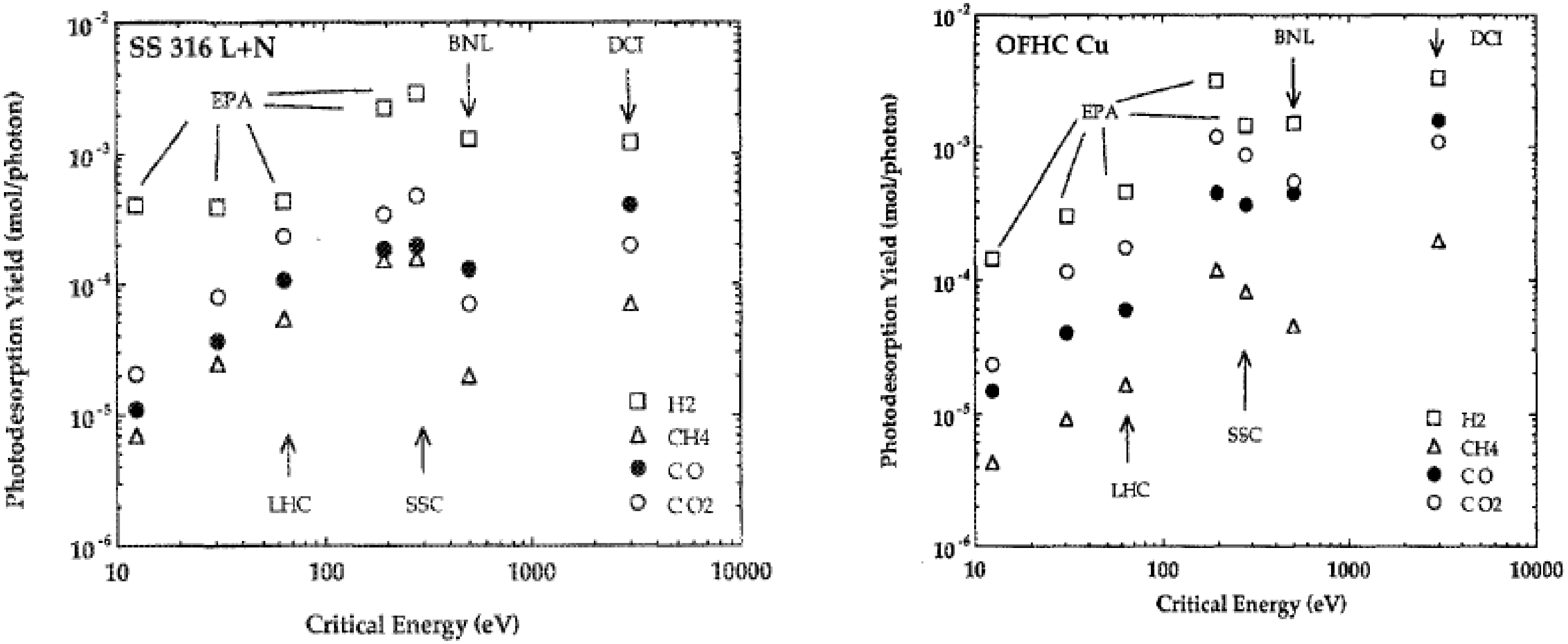
$$\frac{d\dot{N}}{ds} = 1.28 \times 10^{17} \frac{I[mA] E[GeV]}{\rho[m]}$$

Gas sources: photon induced desorption

Photons with energy lower than the photoelectron extraction threshold (workfunction, about 5 eV for metals used in UHV) do not stimulate gas desorption.

η_{ph} depends linearly on the critical energy of the photon spectrum when $\varepsilon_c < 280$ eV:

$$\eta_{ph} \propto \varepsilon_c^{\beta} \qquad 0.74 < \beta < 1.12$$

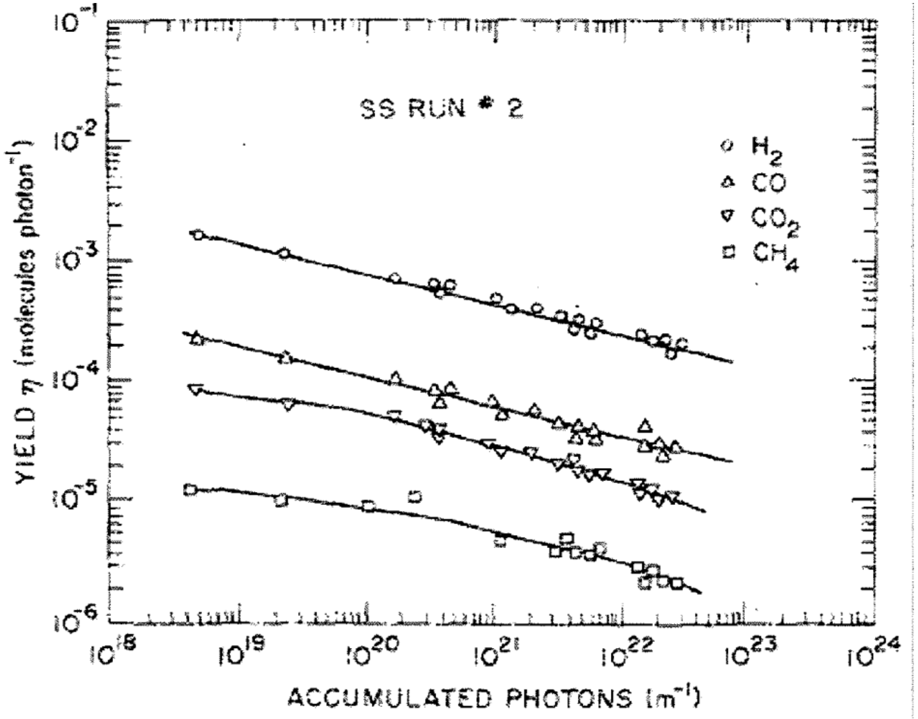


J. Gomez-Goñi, O. Groebner and A. G. Mathewson J. Vac. Sci. Technol. A **12**, 1714 (1994)

Gas sources: photon induced desorption

η_{ph} does not depend significantly on the photon dose D up to about 10^{20} photons/m. For higher doses, η_{ph} varies as a **power law function of the dose**:

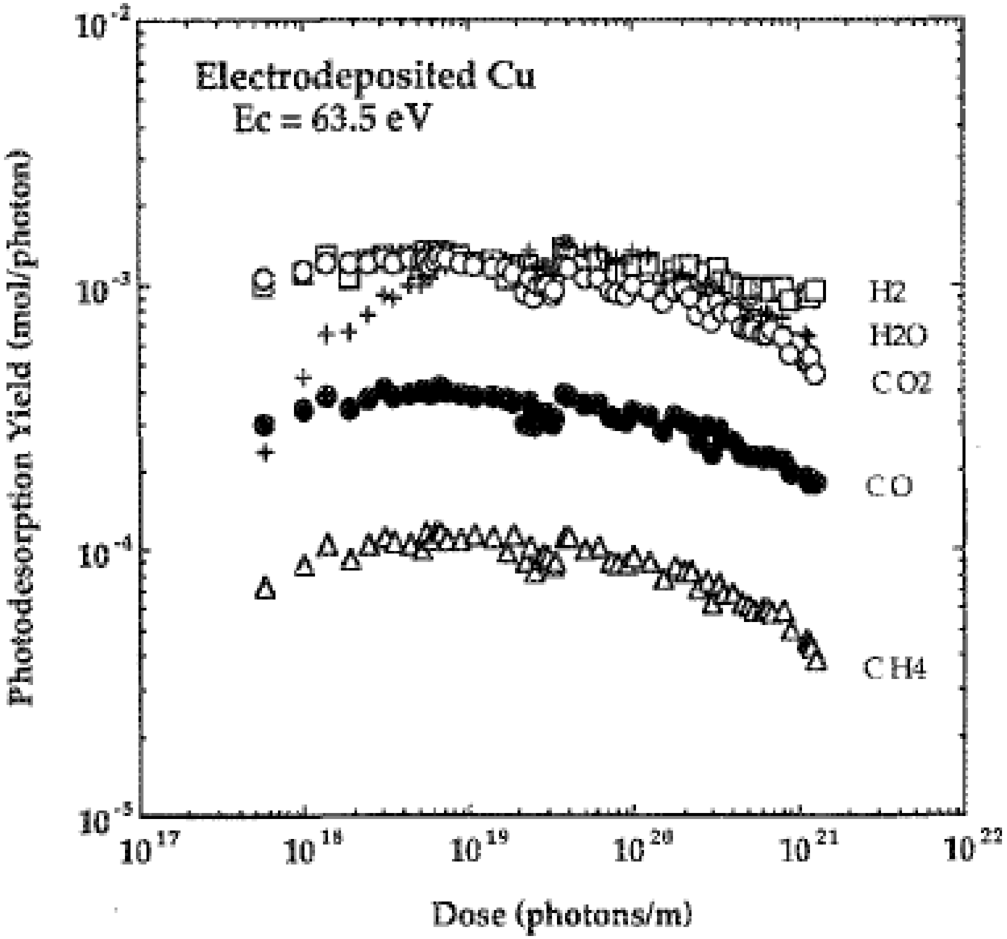
$$\eta_{ph} \propto D^{-\alpha}$$



Photon desorption yields for baked stainless steel as a function of the accumulated dose of photons.

Gas sources: photon induced desorption

unbaked chamber



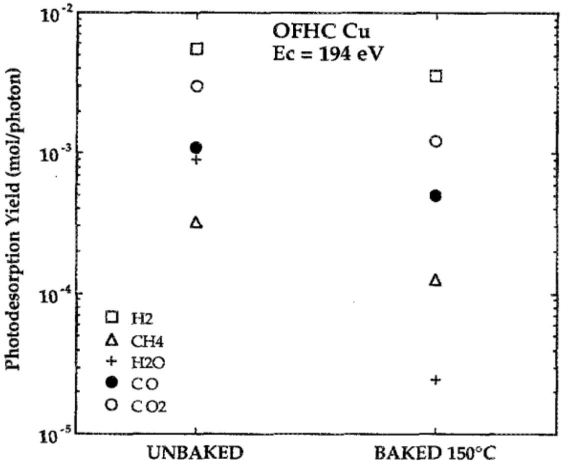
Gas sources: e$^-$ & ph induced desorption

Methods for the reduction of electron and photon induced desorption

The gas desorbed by electrons or photons is extracted from the surface of vacuum chambers or from the first tenths of atomic layers underneath.

Therefore, a state of art **surface cleaning** is essential to avoid excessive desorption.

A beneficial effect is obtained by **in situ bakeout** at temperature higher than 120°C; heating the material results in a cleaner surface; however, the effect on the η values is limited and, in general, less than a factor of 10.



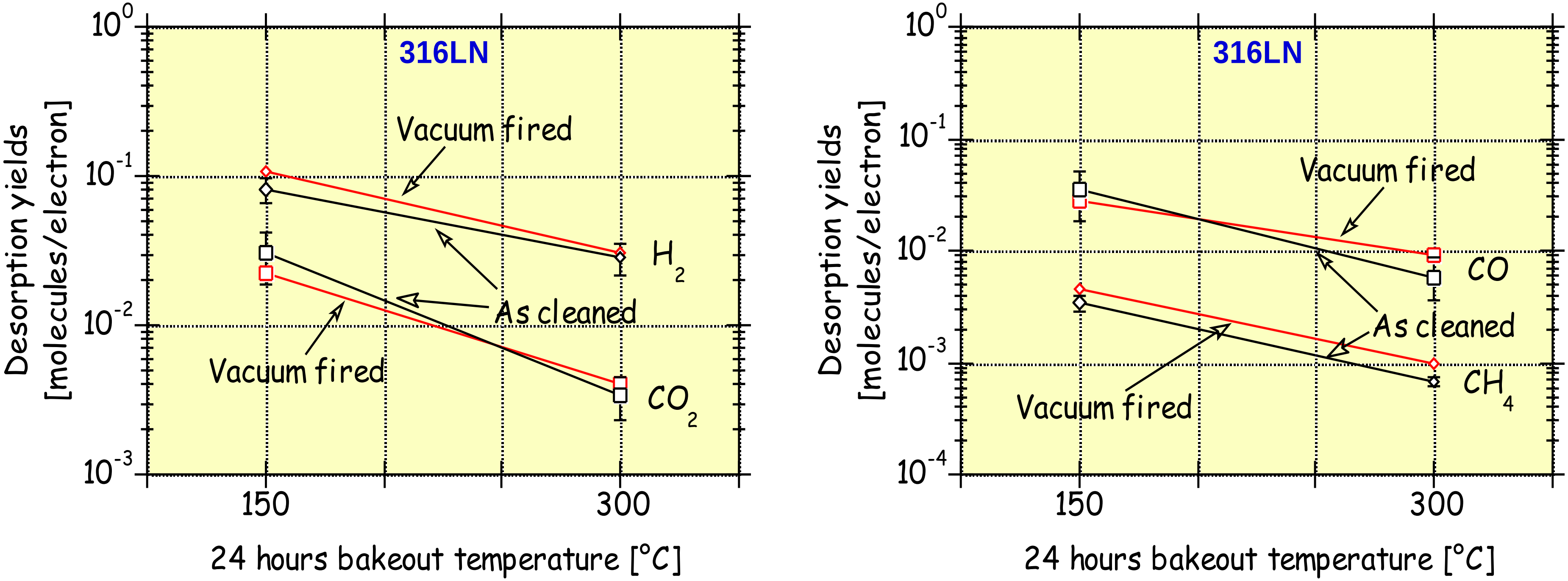
Gas sources: e⁻ & ph induced desorption

Methods for the reduction of electron and photon induced desorption

Electropolishing and **vacuum firing** have a very limited effect on the η values.

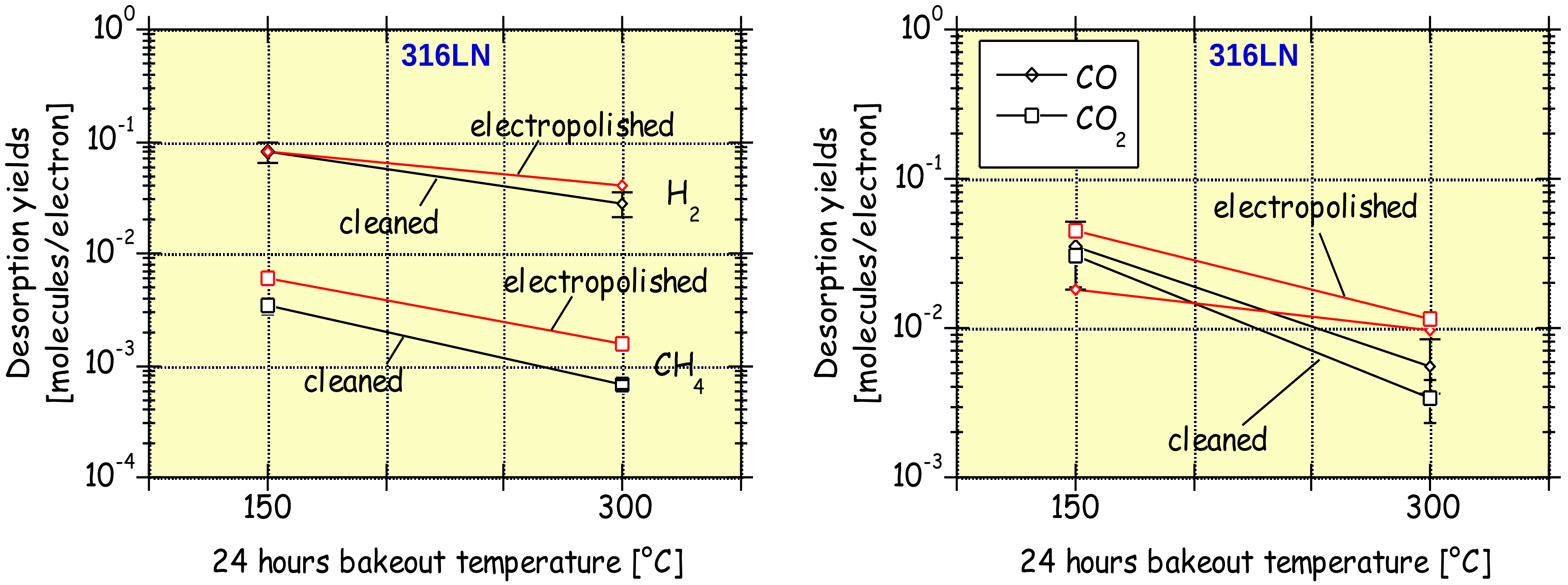
Air exposure after these treatments oxidizes again the surface and regenerates the gas source.

Electron energy: 500 eV



Gas sources: e⁻ & ph induced desorption

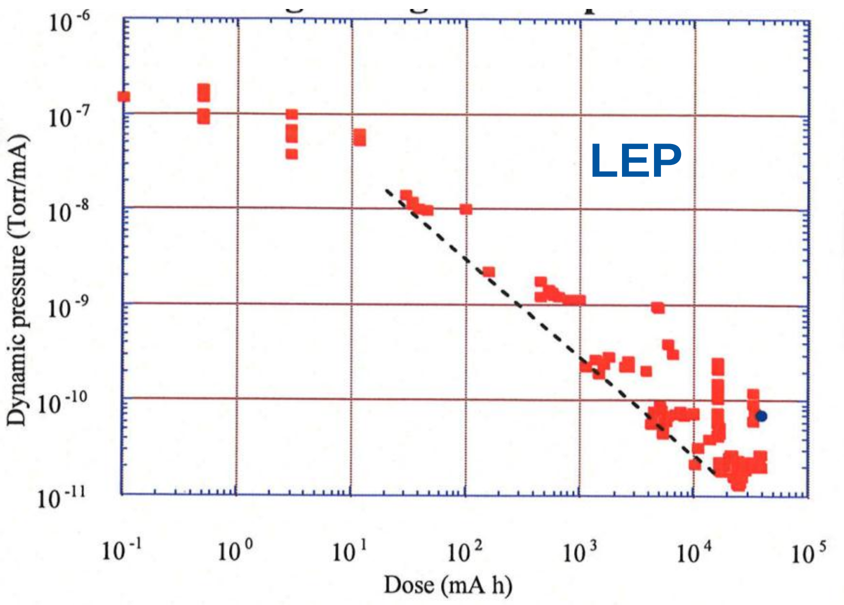
Electron energy: 500 eV



Electropolishing does not influence the desorption yield of H_2. Very small variations are recorded for the other gasses.

Gas sources: e$^-$ & ph induced desorption

The accumulated dose effect lead to a significant reduction of the desorption yields. Power law reductions are measured for both accumulated electron and photon impingements.



Particle accelerators, whose performance is limited by beam induced desorption, are run at progressively increasing current to accumulate photon or electron dose.

This operation is called '**beam conditioning**' or '**beam scrubbing**' of the vacuum chambers. It can last several hours to several days.

Gas sources: e^- & ph induced desorption

Another radical method to reduce stimulated desorption is **coating** the inner wall of the beam pipes with a **thin non-evaporable getter film**.

After in situ bakeout at temperature higher than 180°C, the oxide layer covering the film is dissolved leaving an extremely clean surface.

This treatment is considered in the chapter dedicated to pumps.

Gas sources: ion induced desorption

There are two sources of energetic ions:

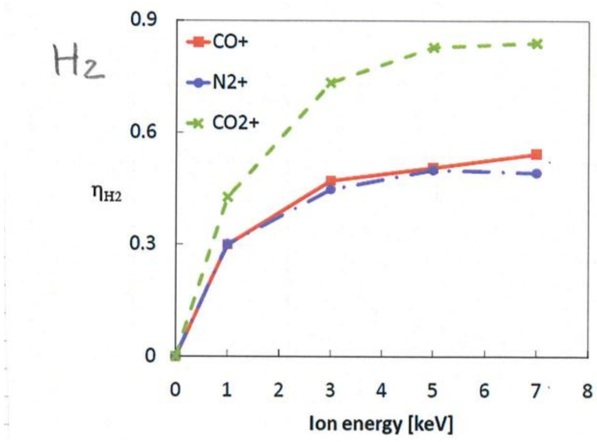
1. Beam particles may collide with the **residual gas** and create ions (H_2^+, CH_4^+, CO^+, CO_2^+, etc.). If the beam is positively charged, the ions are accelerated by the beam potential and collide on the nearby walls with energy between 1 eV to several KeV. The collision results in gas desorption.

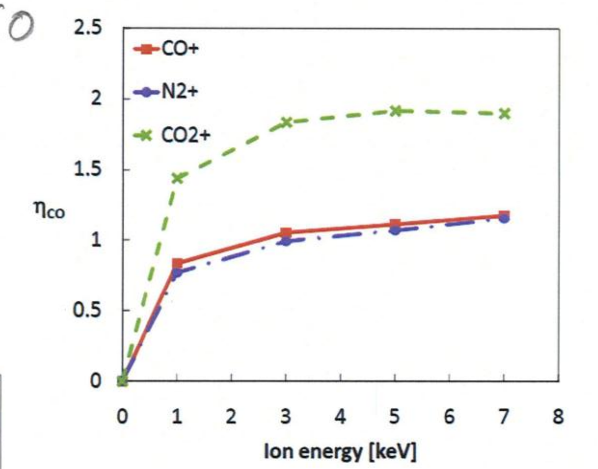
2. When **heavy ions are accelerated**, beam losses may lead to collision of high-energy heavy ions with the wall of the vacuum system. Typical ions are Pb^{53+}, U^{73+}, and Ar^{10+}. Experimental studies have been carried out with beam energy in the range from **1 MeV/nucleon to 100 GeV/nucleon**. In this case, the desorption yields may be orders of magnitude higher than those for residual-gas ions.

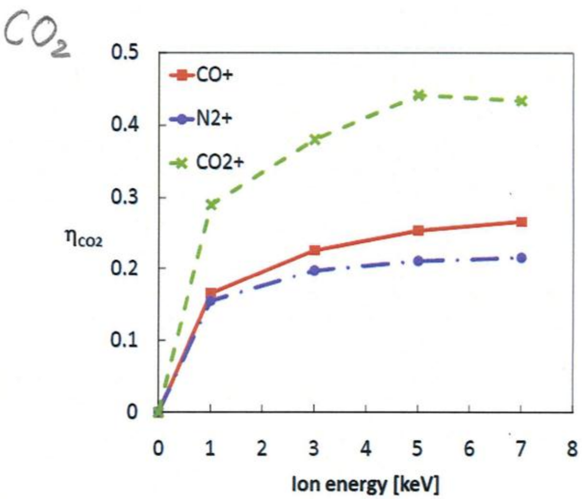
Gas sources: ion induced desorption

Residual-gas ion

Ions are more effective in desorbing gas than electrons and photons. Typical η_i values for baked copper and ion energy of about 1 KeV are about **1** for H_2 and CO; 5 and 10 times lower for CO_2 and CH_4, respectively.





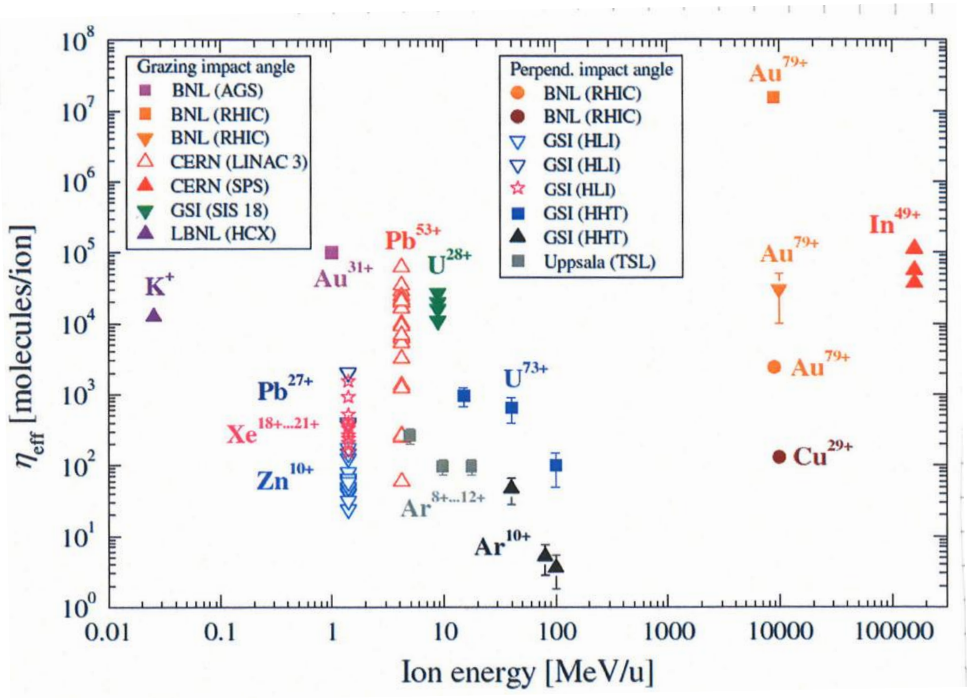


Gas sources: ion induced desorption

High-energy heavy-ions

In the last 15 years, several experiments have shown that high energy (E > 1 MeV/nucleon) ions can induce the desorption of a **huge quantity of gas molecules**.

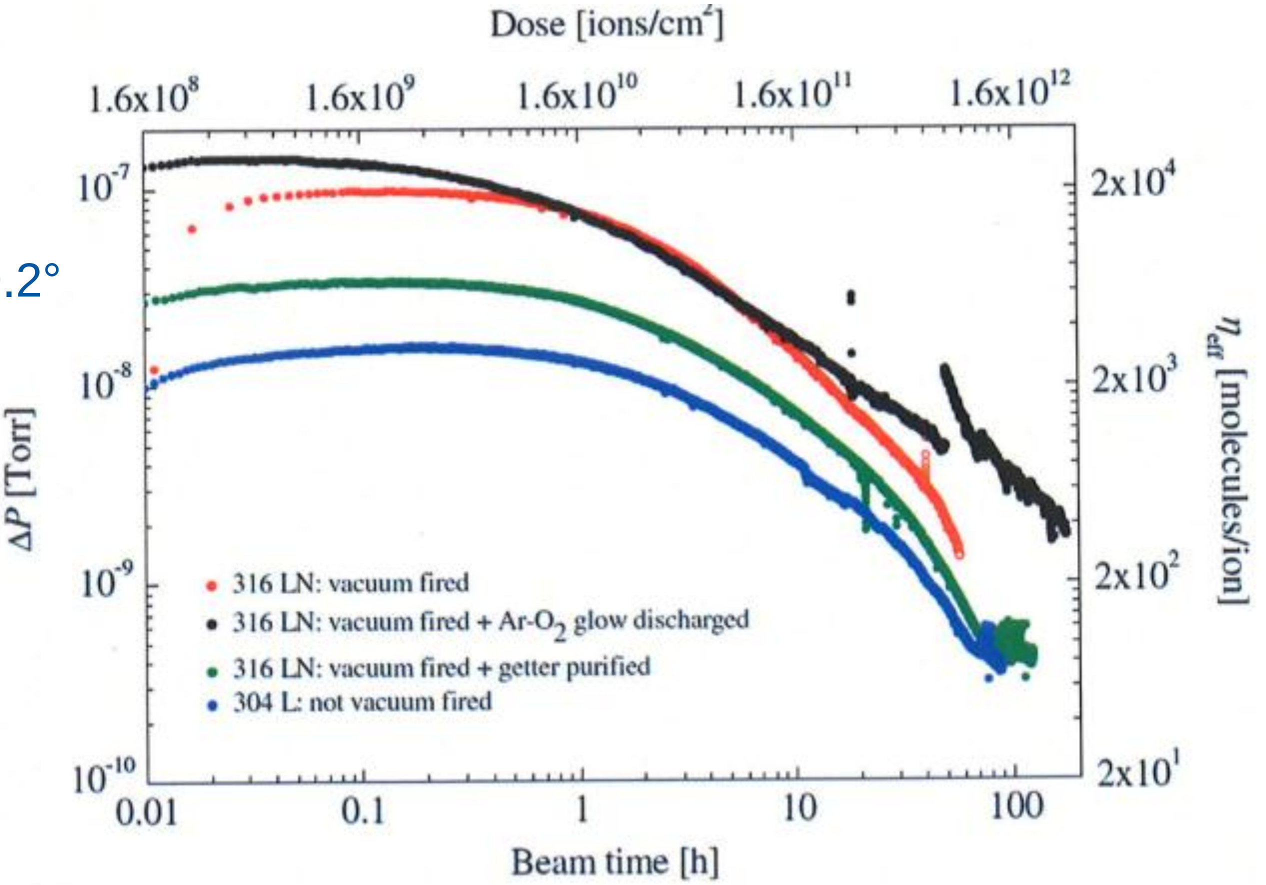
Desorption yield up to **10^5** molecules/ion were measured for In^{49+} at 158 GeV/nucleon at the CERN SPS.



Gas sources: ion induced desorption

High-energy heavy-ions

Pb 53+ ions
Grazing incidence:89.2°
4.2 MeV/u

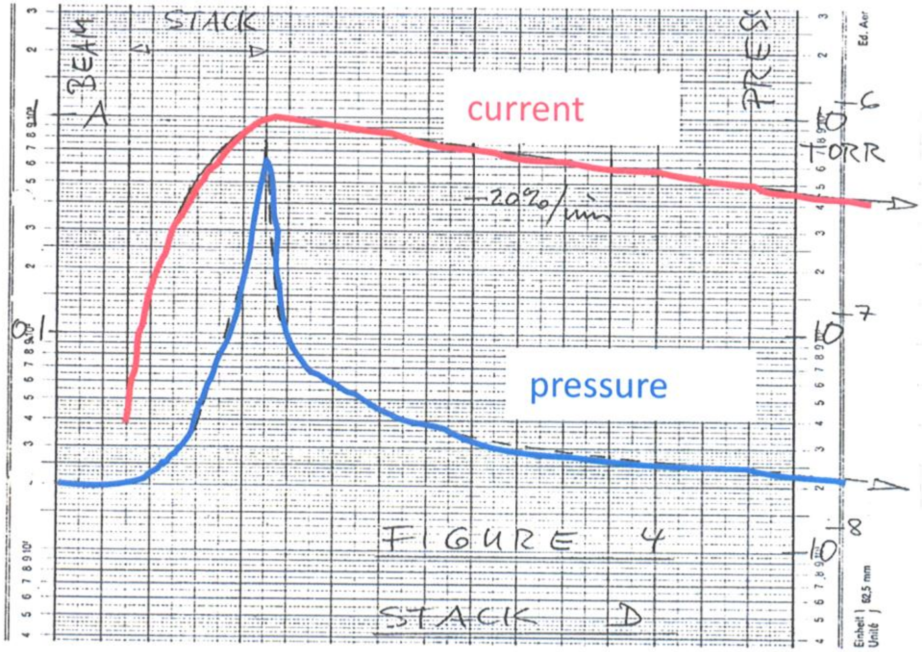


The accumulated dose has a beneficial effect also on the ion induced desorption

Gas sources: ion induced desorption

Ion induces desorption can trigger a rapid pressure rise in accelerators where positive beams circulate.

This phenomenon was shown first at the CERN ISR when increasing the proton current to about 1 A

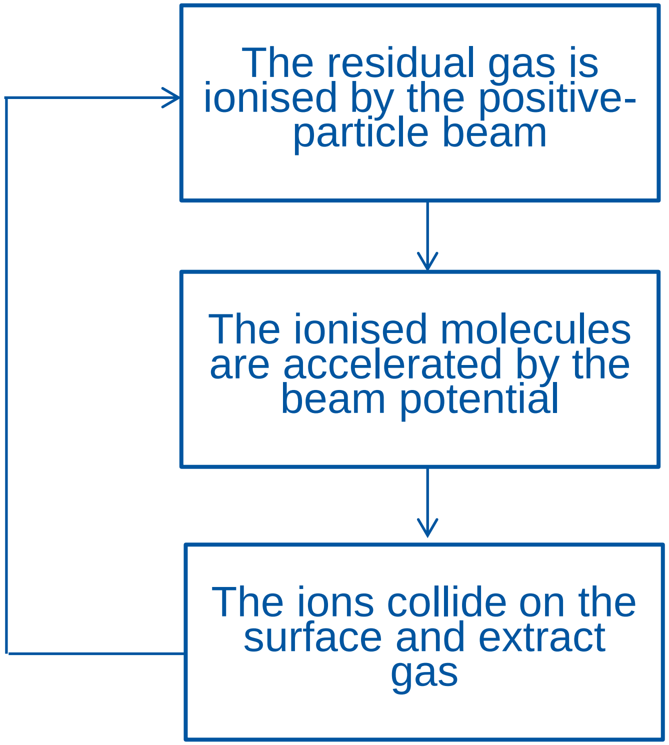


First documented pressure bump in the ISR

E. Fischer/O. Gröbner/E. Jones 18/11/1970

Gas sources: ion induced desorption

The pressure rise is generated by a positive feedback process that can be depicted with the following block diagram.



The residual gas is ionised by the positive-particle beam

The ionised molecules are accelerated by the beam potential

The ions collide on the surface and extract gas

Gas sources: ion induced desorption

The critical current at which the runaway process starts can be obtained in the following way:

1. The ionisation probability for one proton is $\sigma_i n = \sigma_i {}^{P}/_{k_B T}$ and the flow of circulating protons is ${}^{I}/_{e}$. Therefore, the total gas flow of desorbed molecules per unit length of vacuum chamber is:

$$Q = \eta_i \cdot \sigma_i \frac{PI}{e} + Q_{th}$$

2. The pressure in the beam pipe is:

$$P = \frac{Q}{S_{eff}} = \eta_i \sigma_i \frac{PI}{S_{eff} e} + \frac{Q_{th}}{S_{eff}} \rightarrow P = \frac{Q_{th}}{S_{eff} - \eta_i \sigma_i \frac{I}{e}}$$

3. The pressure diverges when:

$$S_{eff} - \eta_i \sigma_i \frac{I}{e} \rightarrow 0$$

Gas sources: ion induced desorption

Critical current:

$$I_c = \frac{S_{eff}e}{\eta_i \sigma_i}$$

Gas	σ_i [10^{-18} cm^2] 26 GeV	σ_i [10^{-18} cm^2] 7 TeV
H_2	0.22	0.37
He	0.23	0.38
CH_4	1.2	2.1
CO	1.0	1.8
CO_2	1.1	2.0
Ar	1.6	2.8

Example:

For an effective pumping speed of 10 l s^{-1} and an ionisation cross section of 10^{-18} cm^2 (CO ionised by protons at 26 GeV), the critical current is about 16 mA if the desorption yield is 1.

Part 5

Gas pumping in particle accelerators

Gas pumping

In molecular regime:

- gas molecules cannot be removed by suction: the molecules do not transfer energy and momentum amongst them; pumps act on each molecule singularly;

- pumps are classified in two families:

  1. **momentum transfer pumps**;
  2. **capture pumps**.

- In the first, molecules receive a momentum component pointing towards the pump outlet (foreline) where the gas is compressed and evacuated by pumps working in the viscous regime (for example: rotary vane, diaphragm, and scroll pumps).

- Capture pumps remove molecules from the gas phase by fixing them onto an internal wall.

Gas pumping: momentum transfer
Molecular pumps

In molecular pumps, molecules are headed for the outlet by **moving surfaces**.

Molecules impinge and adsorb on the moving surface; on desorption, the velocity distribution is superimposed to the **drift velocity** of the wall →

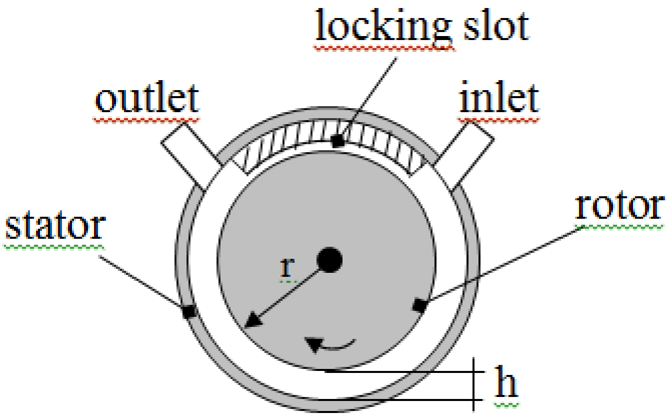
As a result, molecules are preferentially redirected towards the direction of the wall movement, i.e. the **density of molecules increases** in the same direction.

A moving wall produces a **gas flow**.

Gas pumping: momentum transfer

Molecular pumps

The first molecular pump was invented by W. Gaede. In the original design, the moving surface is a rotor revolving at high frequency



To prevent backstreaming, the inlet and the outlet were separated by a **very thin slot** (locking slot). The slot height was of the order of **10^{-2} mm**.

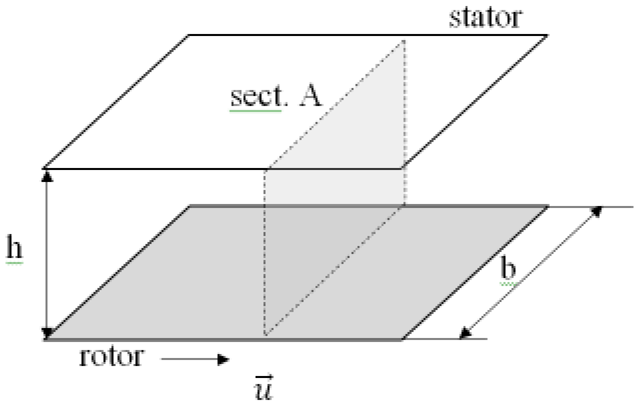
The most important characteristics of molecular pumps are:

1. Pumping speed S
2. Maximum compression ratio $K_0 = \left(\frac{P_{OUT}}{P_{IN}}\right)_{\text{MAX}}$

The **parameters affecting S and K_0** can be identified by a simple model.

Gas pumping: momentum transfer

Molecular pumps



At any time, **half of the molecules** have just collided with the moving surface (rotor) and drift in the direction of the velocity $\vec{u}$. The **other half** hits the stator where the drift component is lost.

As a result, the drifted molecular flow Q_p towards an imaginary section A is:

$$Q_p = \frac{1}{2} n \cdot u \cdot b \cdot h = \frac{1}{2} \frac{P}{k_B T} \cdot u \cdot b \cdot h$$

Where 'bh' is the area of the cross section A and '**ubh**' is the **gas volume drifting through section A in one second**.

Gas pumping: momentum transfer

Molecular pumps

Converting in pressure-volume units and dividing by P, the pumping speed is obtained:

$$S = \frac{Q_p}{P} = \frac{1}{2} u \cdot bh$$

The pumping speed of molecular pumps:

- Depends linearly on the speed of the moving wall
- Does not depend on the nature of the gas (in the frame of this model)→molecular pumps are not selective!

Gas pumping: momentum transfer

Molecular pumps

The moving wall produces a higher gas density near the pump outlet. In turn, the pressure gradient generates a gas backflow Q_{bf} that can be written as:

$$Q_{bf} = -\bar{c}\,\nabla P$$

where $\bar{c}$ is the conductance of the unit-length duct of cross section area bh. For h<<b:

$$\bar{c} = \frac{2}{3}\frac{(bh)^2}{b+h}\langle v\rangle$$

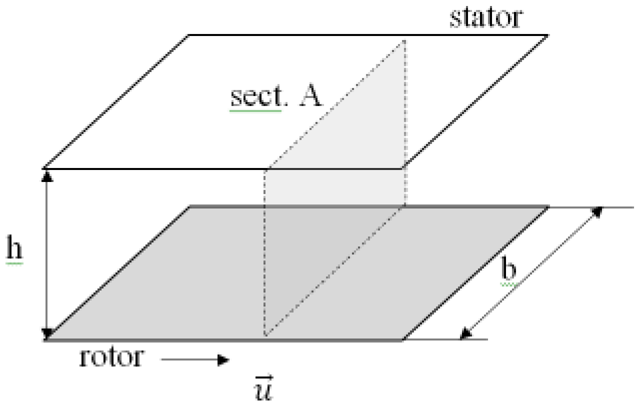
The net flow is therefore given by: $Q = Q_p - Q_{bf} = \frac{1}{2} P\, u\, bh - \bar{c}\,\nabla P$

When the net flux is zero, the maximum compression ratio is reached; in this case:

$$\frac{dP}{P} = \frac{1}{2}\frac{u\,bh}{\bar{c}}\,dx$$

Gas pumping: momentum transfer

Molecular pumps



Integrating between inlet and outlet (distance L) the maximum compression ratio is obtained:

$$K_0 = \left(\frac{P_{OUT}}{P_{IN}}\right)_{MAX} \propto \exp\left[\frac{u}{\langle v \rangle} \times \frac{L}{h}\right] \propto \exp\left[\left(u\sqrt{m_i}\,\frac{L}{h}\right)\right]$$

L and h length and width of the pump duct

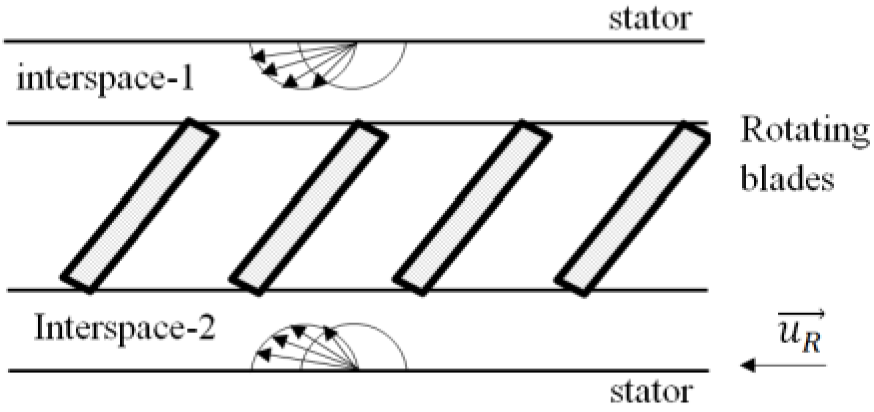
High compression ratio for molecular pumps can be obtained for:

- **Fast moving surfaces**: at least of the same order of the average molecular velocity (>100 ms^{-1}).
- **Narrow and long pumping ducts** (lower backstreaming).
- **Heavy masses** → the maximum compression ratio depends strongly on the molecular mass, the lowest being for H_2 → The ultimate pressure of molecular pumps is dominated by H_2.

Gas pumping: momentum transfer
Turbomolecular pumps

For many years, the industrialisation of molecular pumps was hindered by the machining of the locking slot. The narrow gap between rotor and stator created mechanical issues due to tolerances and thermal expansion.

The problem was overcome in 1957 when W. Becker invented the turbomolecular pump (TMP). In the TMP, the momentum transfer is produced by rapidly rotating blades rather than parallel surfaces.



The molecules **seen from the blades** have a velocity oriented toward the blades' channels when they come from space 1. From space 2, most of the molecules hit the blades and are backscattered.

A significant gas flow is set only if at least $\langle v \rangle \approx u$.

Gas pumping: momentum transfer

Turbomolecular pumps

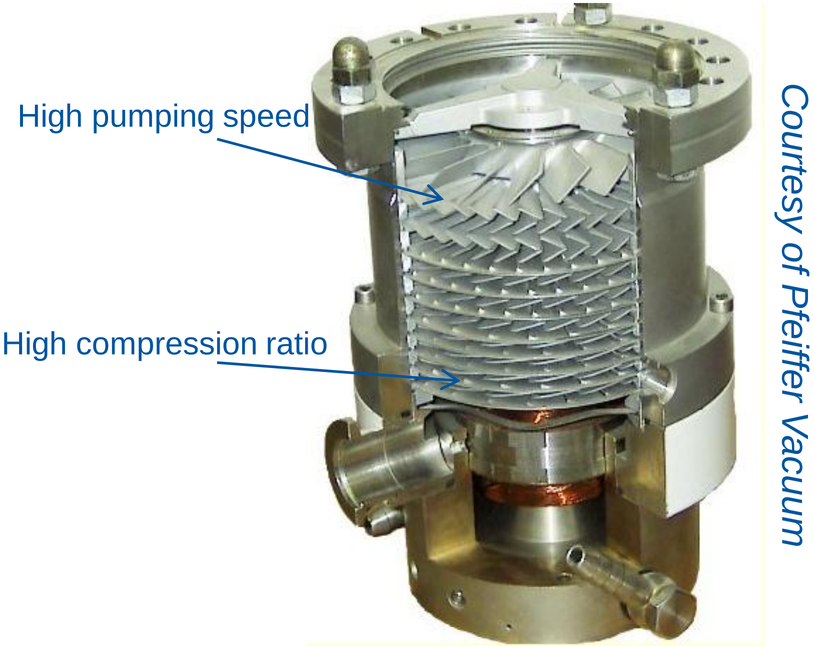
In the real turbomolecular pump, the gas is compressed by **several series of rotating blades**.

Every series of rotating blades is followed by a series of static blades. Molecules transmitted through the rotating blades' channels hit the static blades; as a result, the angular distribution of velocity is randomized and the molecules are ready for the **next compression stage**.

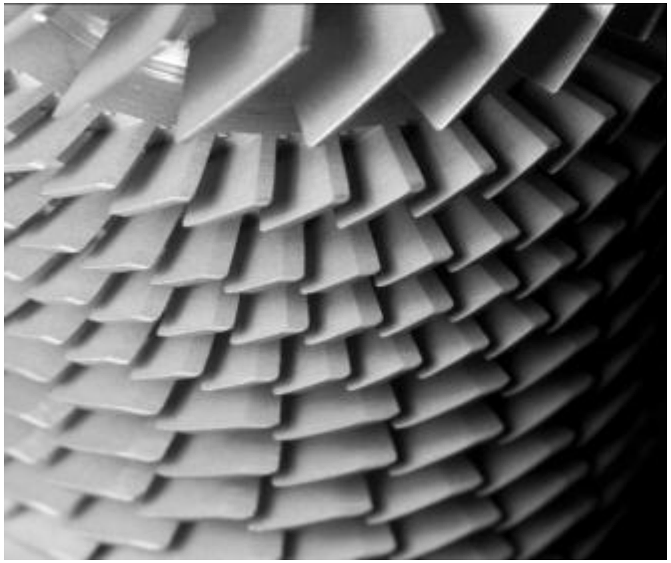
The momentum transfer is effective only if the molecules **do not experience inter-molecular collisions** after hitting the blades; this is equivalent to say that the mean free path has to be larger than the blade distances. As a result, this type of pumps works at full pumping speed **only in molecular regimes** ($P < 10^{-3}$ mbar).

Gas pumping: momentum transfer

Turbomolecular pumps



Courtesy of Pfeiffer Vacuum

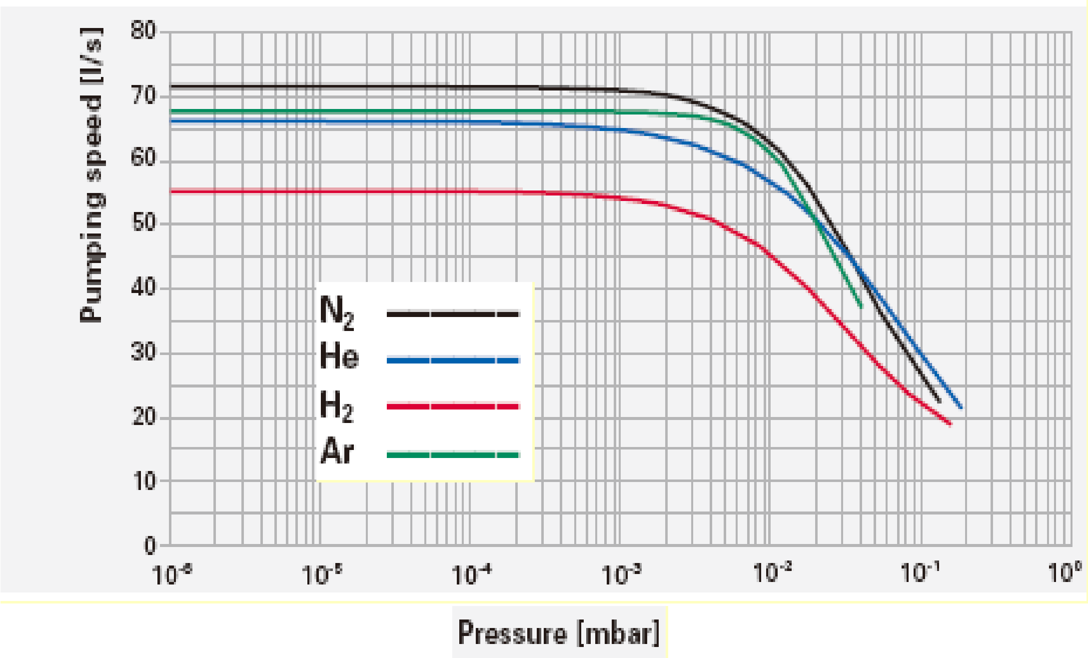


The indications given by the simplified model for molecular pumps are valid also for the TMP:

S: no strong influence of gas molecular mass + linear dependence on revolution speed

K_0: **exponentially** dependent on: revolution speed and square root of gas molecular mass

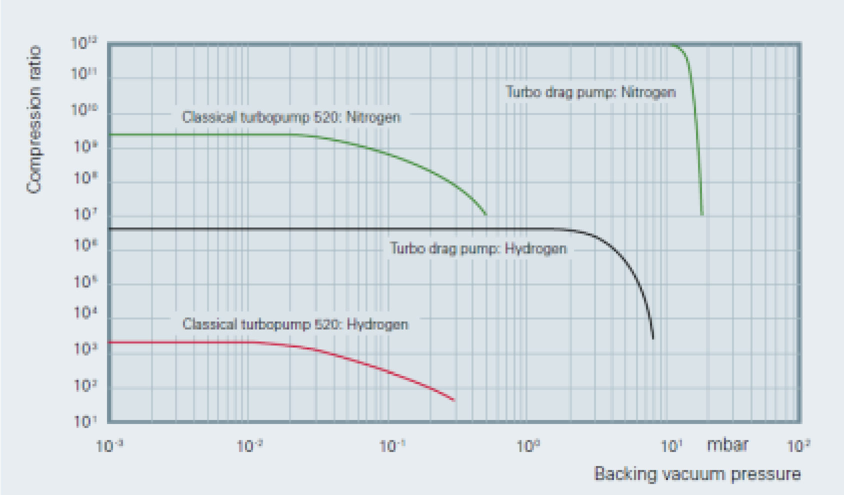
Gas pumping: momentum transfer

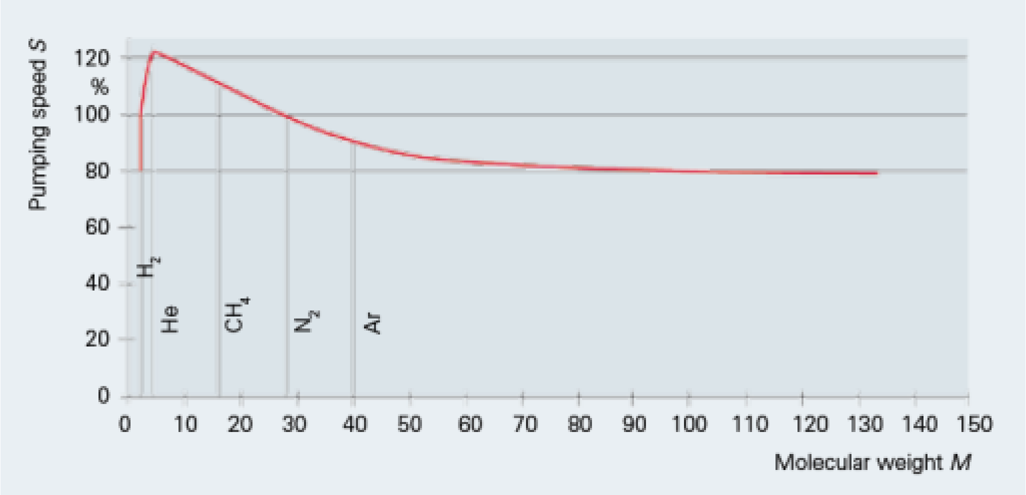


TMP pumping speeds are in the range from 10 l/s to 25,000 l/s.

Their ultimate pressure (H_2) is of the order of 10^{-10}, 10^{-11} mbar

Courtesy of Pfeiffer Vacuum
http://www.pfeiffer-vacuum.com
Vacuum Technology KnowHow

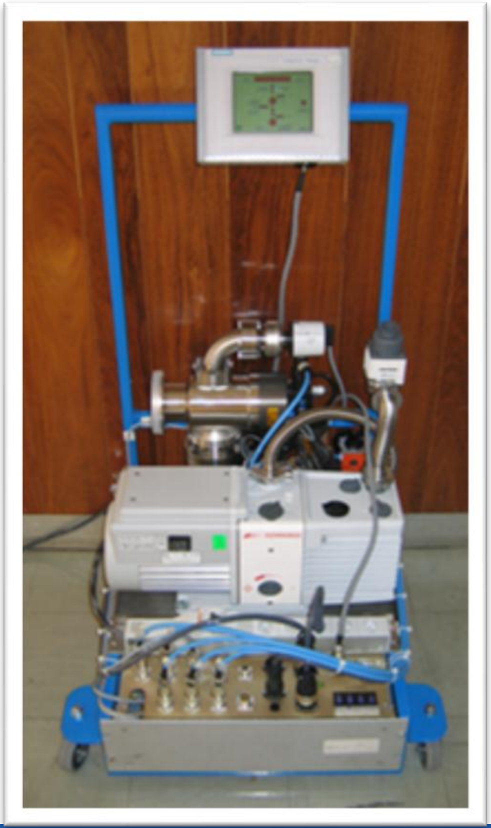




Gas pumping: momentum transfer

Turbomolecular pumps

At the pump outlet, the compressed gas is evacuated by a **mechanical pump** (often called backing pump) operating in viscous regime. The turbomolecular and its backing pump are in general **assembled in a single unit** that includes power supplies, controls and instrumentation.



Gas pumping: momentum transfer

Turbomolecular pumps

The main drawback of TMP is related to possible **mechanical failures** leading to definitive damage of the high-speed rotor.

Gas pumping: momentum transfer
Turbomolecular pumps

Advantages of TMP:

1. constant pumping speed in a large range of pressure
2. no memory effect (the gas is definitively evacuated) nor gas selectivity
3. start working at relatively high pressure (as soon as molecular regime is attained)

Disadvantages of TMP:

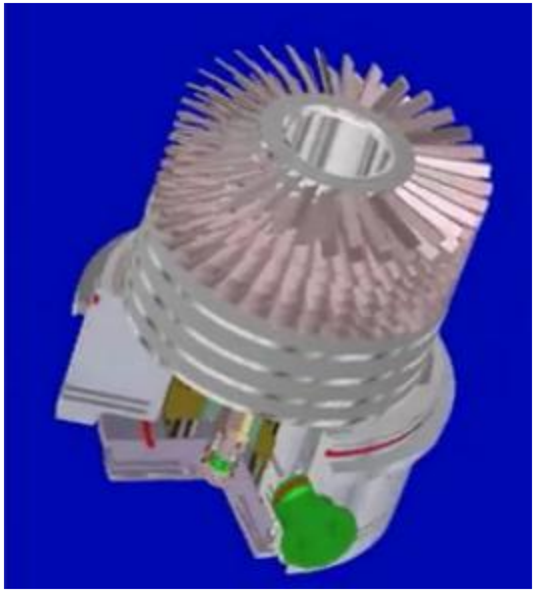
1. mechanical fragility
2. risk of contamination from the backing pump
3. need of venting anytime the pump is stopped to block backstreaming of contaminations→need of valve between TMP and vacuum vessel
4. intrinsic limitation in ultimate pressure of H_2

Present trend:

1. Use of dry pumps as backing pumps (but lower compression ratio than oil pumps)
2. Increase compression ratio by adding molecular drag stages below the set of TMP blades (very compact design)
3. Remove all lubricated mechanical bearing by magnetic rotor suspension (higher cost).

Gas pumping: momentum transfer

Turbomolecular pumps



http://www.youtube.com/watch?v=1xZe1H2XHhM&feature=youtube_gdata_player

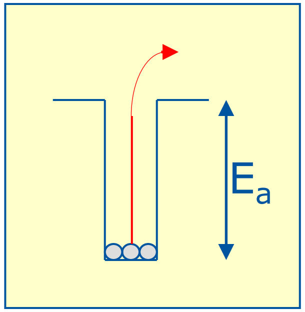
Gas pumping: capture pumps

Capture pumps remove gas molecules by fixing them on an internal wall.

To be efficient, capture pumps must block the gas molecules for an average time (**sojourn time t_s**) much longer than the typical running time of the accelerator.

To do so the sojourn time on the wall has to be much longer than the typical time of the accelerator run. An estimation of sojourn time is given by the Frenkel law *J. Frenkel, Z. Physik, 26, 117 (1924)*:

$$\boldsymbol{t_s = t_0 e^{\frac{E_a}{k_B T}}}$$



where E_a is the adsorption energy and $t_0 \approx \frac{h}{k_B T} \approx 10^{-13}$s.

$E_a >> k_B T$ → Chemical pumps (**getter pumps**)

$T << \frac{E_a}{k_B}$ → **cryopumps**

Gas pumping: capture pumps

In **chemical pumps**, the binding force involves electron exchange between gas molecules and surfaces (**chemisorption**). T

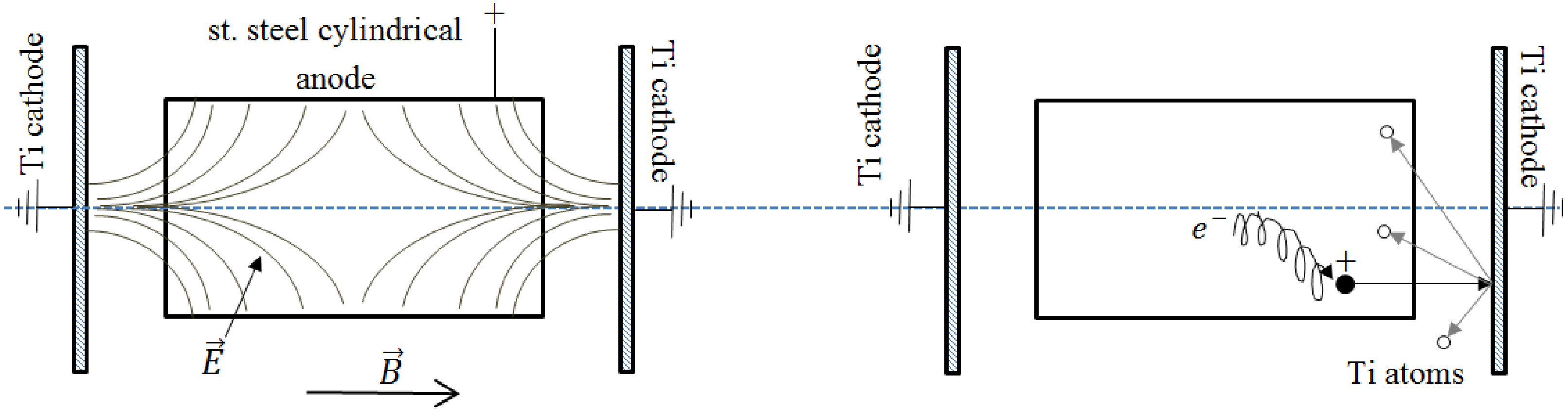
Typical binding energies for getter pumps are higher than **1 eV/molecule**.

In cryogenic pumps, Van der Waals interactions might be sufficiently strong to fix molecules to cold surfaces (**physisorption**).

In this case, the binding energy can be **much lower than 0.5 eV/molecule**.

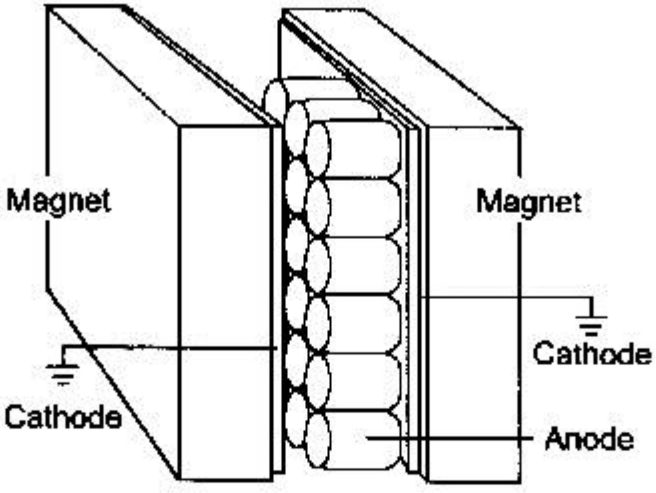
Gas pumping: capture pumps / sputter ion pumps

- In SIP the residual gas is ionized in a Penning cell.
- The ions are accelerated towards a cathode made of reactive metal
- The collisions provoke sputtering of reactive metal atoms that are deposited on the nearby surfaces.



Gas pumping: capture pumps / sputter ion pumps

In the diode SIP, the anode is composed of **several open cylinders** made of stainless steel at a positive electrical potential (from 3 to 7 kV). The **cathodes are plates of Ti** -at ground potential- placed a few millimetres from both anode extremities.



A **magnetic field parallel to the cells' axis** is generated by external permanent magnets (about **0.1 T**). In this configuration, the crossed electrical and magnetic fields trap electrons in long helical trajectories resulting in an increased probability of gas ionisation.

Gas pumping: capture pumps / sputter ion pumps

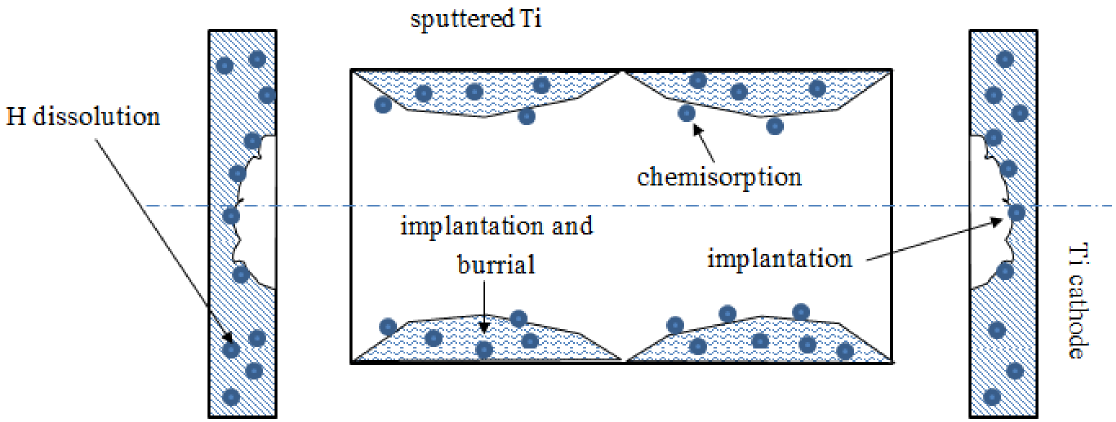
- The pumping action is given by:

  1. **chemical adsorption onto the reactive metal layer** and subsequent burial by additional metallic atoms of gas molecules: all gases except rare gases

  2. **implantation of gas ions in the cathode and of energetic neutrals** bounced back from the cathode in the deposited film: only mechanism of pumping for rare gases

  3. **diffusion** into the cathode and the deposited film: **only** H_2

Gas pumping: capture pumps / sputter ion pumps



Molecular **implantation in the cathodes is not a permanent pumping**; in fact, the progressive erosion due to gas ion sputtering soon or later frees the implanted gas.

Once released from the cathodes, reactive gas species are chemisorbed while rare gases remain in the gas phase until the next implantation.

Gas pumping: capture pumps / sputter ion pumps

Pressure instabilities have been reported after excessive pumping of rare gas:

the continuous **erosion liberates gas** that increases the pressure, which in turn increases the erosion.

Consequently, a pressure rise is generated; this is stopped when most of the rare gas is implanted in a deeper zone of the cathode.

This type of instability is typically observed when large quantities of air are pumped (Ar 1% in air) and are known as ‘**argon disease**’.

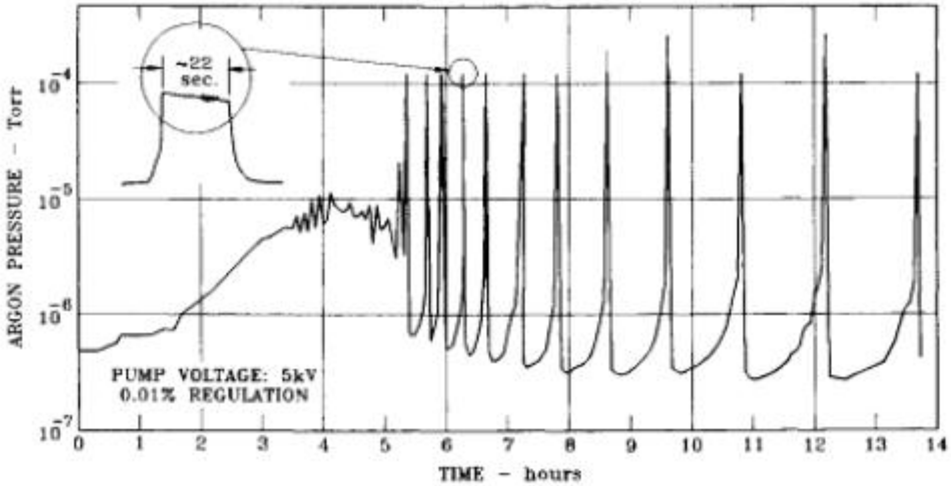


Figure 2.4.12. Example of instabilities in a system with one sputter-ion pump with titanium cathodes, after pumping argon at 5 x 10^{-7} Torr for a few hours.

Gas pumping: capture pumps / sputter ion pumps

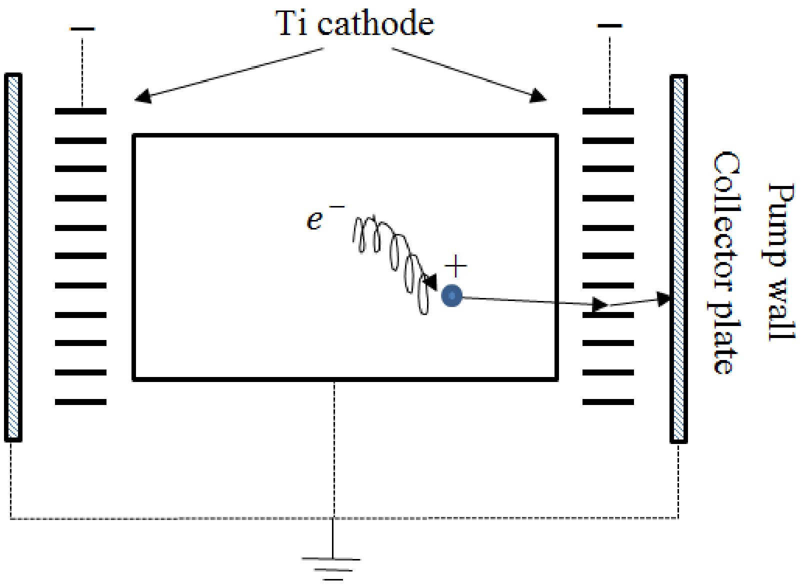
To increase the pumping efficiency of noble gas, **the rate of ions implantation in the cathode has to be reduced** while increasing the rate of energetic neutrals impingement on the anode and their burial probability.

Two different approaches:

1. **Heavier atoms for the cathode**
   Ta (181 amu) is used instead of Ti (48 amu). The ions, once neutralized, bounce back at higher energy and rate → these pumps are called '**noble diode**'

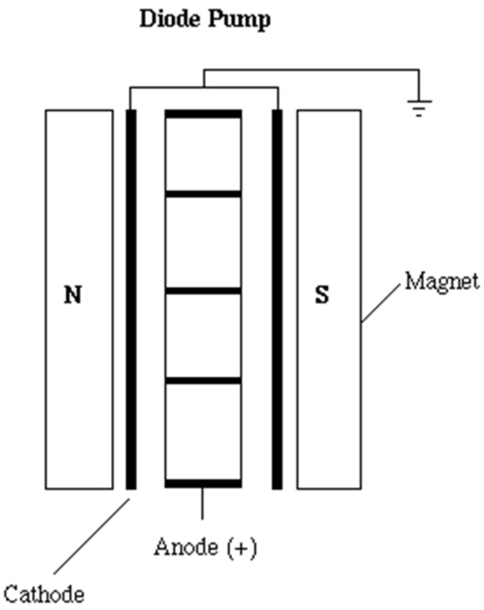
Gas pumping: capture pumps / sputter ion pumps

2. **Different geometry of the Penning cell**.
   a) Three electrodes are used: **triode pumps**. The cathodes consists of a series of small platelets aligned along the cell axis.
   b) The collisions ion-cathode are at glancing angle → higher sputtering rate of Ti atoms + higher probability of neutralization + higher energy of bouncing + lower probability of implantation in the cathode.

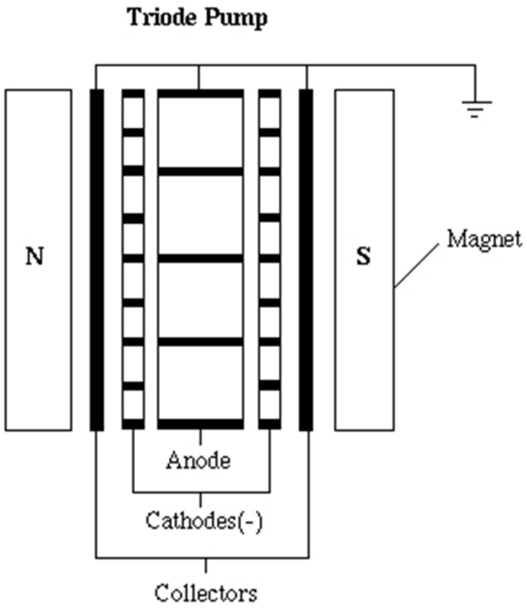


Gas pumping

DIODE

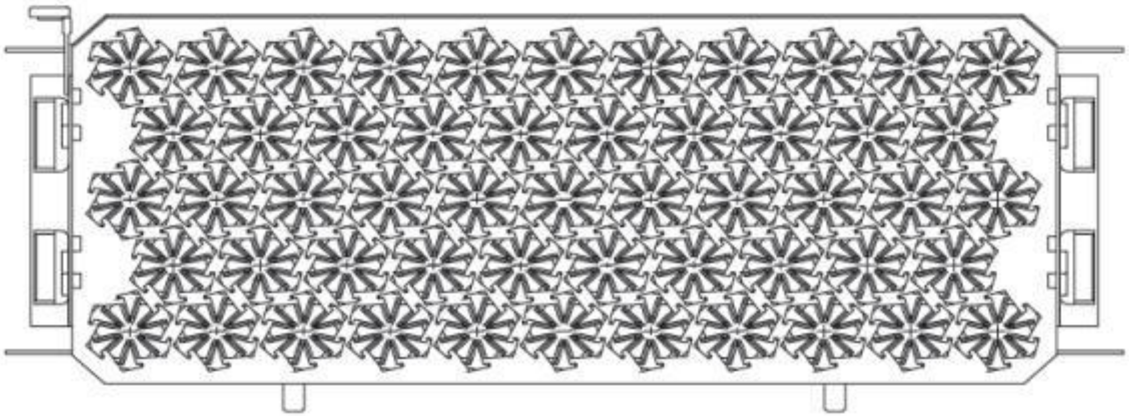


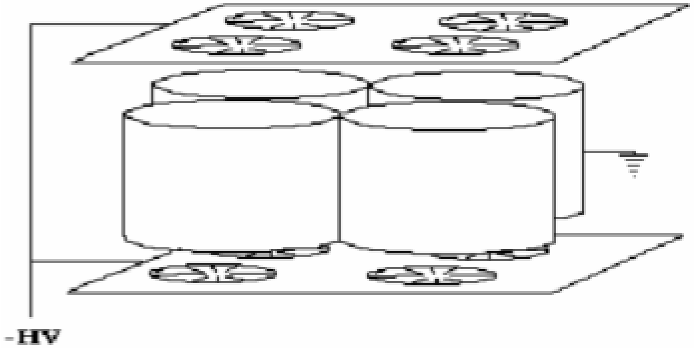
TRIODE



Gas pumping: capture pumps / sputter ion pumps

An improved triode pump is the **StarCell® produced by Agilent**. Two sheets of Ti that are cut and bent to form radial blades (see Fig 55) replace the series of small plates. This increases the rigidity of the cathode and reduces the risks of short circuits





Gas pumping: capture pumps / sputter ion pumps

Pumping speed for SIP depends on the **pressure at the pump inlet** and the **nature of the gas**.

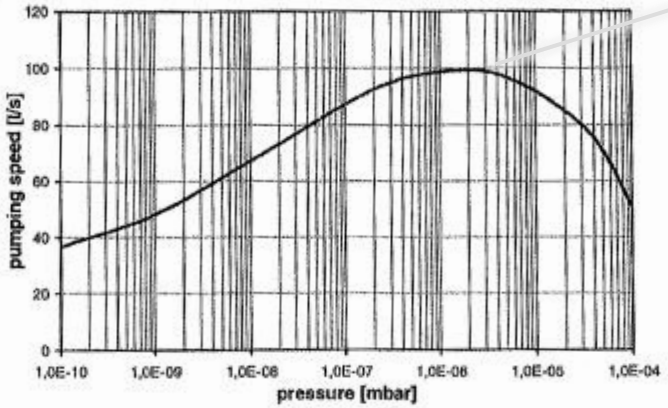


Fig. 5 Pumping speed vs pressure for a standard diode with S_N = 100 l/s (for air after saturation).

Nominal pumping speed

GAS	DIODE PUMPS	TRIODE PUMPS
AIR	1	1
N_2	1	1
O_2	1	1
H_2	1.5-2	1.5-2
CO	0.9	0.9
CO_2	0.9	0.9
H_2O	0.8	0.8
CH_4	0.6-1	0.6-1
Ar	0.03	0.25
He	0.1	0.3

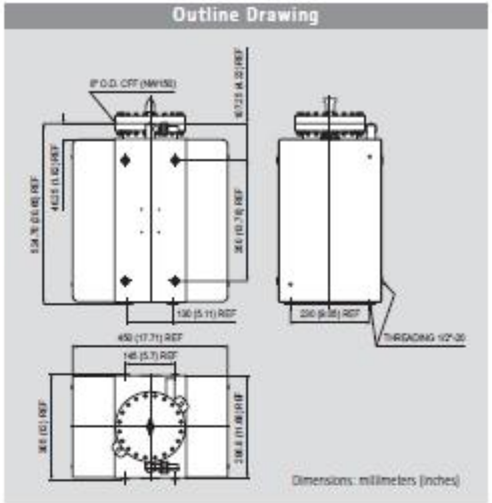
Pumping speed normalized to air

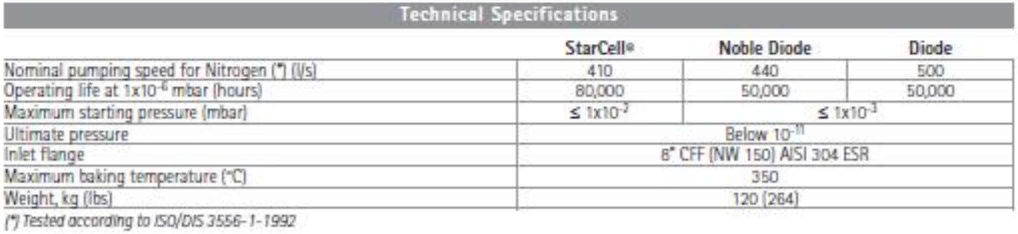
Nominal pumping speed for N_2:
Agilent StarCell®

DN	S [l s^{-1}]
63	50
100	70/125
150	240/500

Gas pumping: capture pumps / sputter ion pumps

VacIon *Plus* 500





Technical Specifications

	StarCell®	Noble Diode	Diode
Nominal pumping speed for Nitrogen (*) (l/s)	410	440	500
Operating life at 1×10^{-6} mbar (hours)	80,000	50,000	50,000
Maximum starting pressure (mbar)	$\leq 1\times10^{-2}$	$\leq 1\times10^{-3}$	
Ultimate pressure	Below 10^{-11}		
Inlet flange	8" CFF (NW 150) AISI 304 ESR		
Maximum baking temperature (°C)	350		
Weight, kg (lbs)	120 (264)		

(*) Tested according to ISO/DIS 3556-1-1992

Courtesy of Agilent Vacuum

http://www.chem.agilent.com/en-US/Products/Instruments/vacuum

Gas pumping: capture pumps / sputter ion pumps

Hydrogen pumping by SIP

- H_2 **is mainly pumped by diffusion** into the cathode.
- To be adsorbed, H_2 **must be dissociated**. Only 2.5% of the ions created in a low-pressure H_2 Penning discharge are H^+ ions.
- The dissociation is possible **only on atomically clean Ti**.
- H_2^+ ions have **poor sputtering yield**: 0.01 at 7 KeV on Ti.
- When H_2 is the main gas, **it takes a long time to clean the cathode surface** by sputtering.
- As a consequence, at the beginning of the operation the pumping **speed for H_2 is lower than the nominal and increases gradually** with time.

Gas pumping: capture pumps / sputter ion pumps

Hydrogen pumping by SIP

- The **simultaneous pumping** of another gas has strong effects on H_2 pumping speed.
    - Higher sputtering yield→faster cleaning→ higher pumping speed
    - Contaminating of the Ti surface→ lower pumping speed
    - Desorption of implanted H ions→ lower pumping speed
- When the concentration of H_2 is higher than the solubility limit in Ti, hydride precipitates are formed → **Ti expansion and hydrogen embrittlement** → short circuits and cathode brittleness (for 500 l/s pumps: typical value are 13000 mbar.l of H_2)

Gas pumping: capture pumps / sputter ion pumps

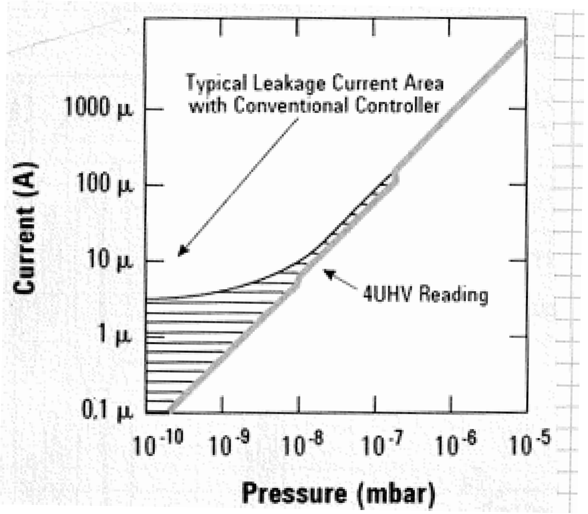
High Pressure Operation

- High pressure (>10^{-5} mbar) operation can **generate thermal run-away**. It is frequently noticeable during the pumping of H_2 or after the absorption of high quantity of H_2 (for example due to pumping of H_2O).
- The Penning discharge heats the cathode and provokes gas desorption, which enhance the discharge. This positive feedback mechanism can melt locally the cathode.
- The total electrical power given to the pump has to be limited at high pressure.

Gas pumping: capture pumps / sputter ion pumps

Pressure measurement by ion pumps

- The **discharge current of the penning cells** can be used for pressure measurement.
- In the low pressure range, the current measurement is **limited by field emission** (leakage current): pressure reading limitation in the 10^{-9} mbar range.
- By reducing the applied voltage in the lower pressure range, the pressure measurement is possible down to 10^{-10} mbar.



Courtesy of Agilent Vacuum

Gas pumping: capture pumps / getter

The surface of getter materials reacts with gas molecules by forming **stable chemical compounds**.

This is **possible only if** the surface is clean, **free of contamination and native oxide**.

The clean metallic surface is obtained by:

1. **Sublimating** the reactive metal in situ → **Evaporable Getters, Sublimation Pumps**
2. **Dissolving** the surface contamination into the bulk of the getter material by heating in situ (**activation**): Non-Evaporable Getters **NEG.**

Gas pumping: capture pumps / getters

Sticking probability

Getter surfaces are characterized by **the sticking probability** α :

$$\alpha = \frac{number\ of\ molecules\ captured}{number\ of\ molecules\ impinging}$$

$$0 \leq \alpha \leq 1$$

$$\boldsymbol{S = \alpha\, A_{getter} C'}$$

For α**=1**, the pumping speed of the surface is equal to its **maximum theoretical pumping speed**.

Getter materials **do not pump rare gases and methane** at room temperature.

In that respect, they **always need auxiliary pumping** to keep a stable pressure

Gas pumping: capture pumps / getters

Sticking probability

The sticking probabilities of homonuclear diatomic molecules are in general lower than that of molecules composed of dissimilar atoms.

The **values of α for common gas species** in vacuum systems may be ordered in a growing series as follows:

$$N_2 < H_2 < O_2 < H_2O < CO < CO_2$$

For **N_2** typical α are in the high **10^{-3} to low 10^{-2}** range; for **CO and CO_2**, α close to **1** may be measured (for negligible coverage).

Gas pumping: capture pumps / getters

Sticking probability

The sticking probability is **strongly dependent on the gas surface coverage**, i.e. the quantity of gas previously pumped on the getter material.

As the gas surface coverage increases, the sticking probability decreases. The pumping becomes **negligible when the surface is fully covered** by gas molecules. The pumping is restored by regenerating the surface.

As an example, complete saturation of a smooth NEG surface is obtained when about **10^{15} CO molecules cm^{-2}** are adsorbed. Quantities about 5-10 times higher are reported for H_2O and O_2.

H_2 dissociates on the getter surface and diffuses into the bulk of the NEG material. As a result, its pumping **does not block** the adsorption of other molecules.

The pumping capacity of hydrogen is orders of magnitude higher than that for other gas species.

Gas pumping: capture pumps / getters

Sievert's law

Due to the high mobility of H atoms and the relatively low binding energy, the **pumping of this gas is reversible**: H_2 may be released by heating.

The opposite effects of pumping and desorption set up an **equilibrium pressure** P_{H2} that depends on heating temperature T and hydrogen concentration c_H.

The three variables are correlated by the **Sievert's law**. In the logarithmic form:

$$\log P_{H2} = A + 2\log c_H - \frac{B}{T}$$

A and B are typical values for a given getter material.

Gas pumping: capture pumps / sublimation pumps

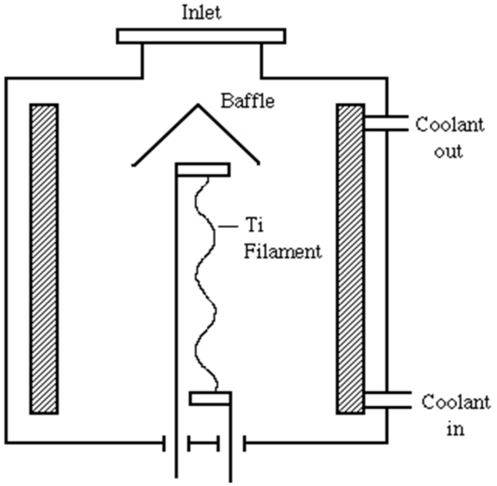
For particle accelerators Ti is the sublimated metal.

Ti alloy rods are heated up to 1500°C attaining a Ti vapour pressure of about 10^{-3} mbar.

The Ti thin film is deposited onto the pump vessel.

In some cases, the wall of the sublimation pumps may be cooled to liquid nitrogen temperature. In this case, the sublimated film is rougher and consequently the sticking probabilities are higher.

Courtesy of Kurt J. Lesker Company
http://www.lesker.com/newweb/Vacuum_Pumps



Gas pumping: capture pumps / sublimation pumps

The sticking probabilities depend on the nature of the gas and the quantity of gas already pumped.

$$\max \begin{cases} H_2:\ 10^{-2} \le \alpha \le 10^{-1} \\ CO: 5 \times 10^{-1} \le \alpha \le 1 \end{cases}$$

The sticking probability is negligible:

- For CO, one monolayer adsorbed
- For of O_2 several monolayer
- For N_2 fraction of monolayer

A new sublimation is needed.

Hydrogen diffuses in the Ti film→much higher capacity

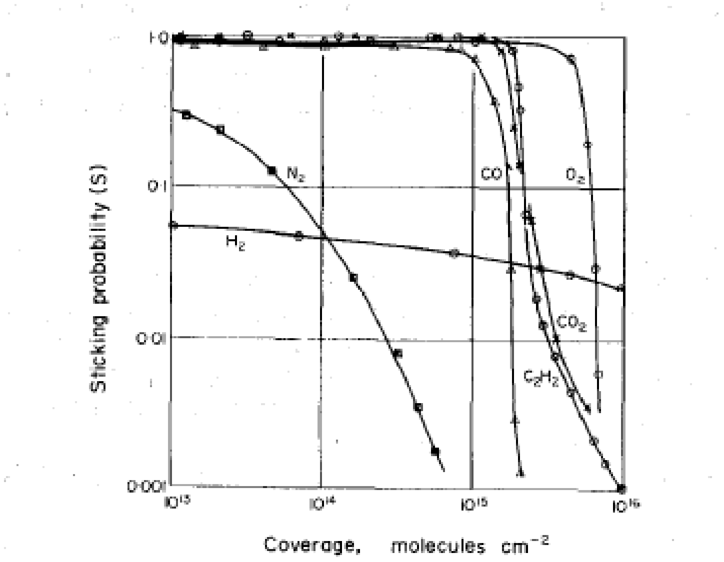
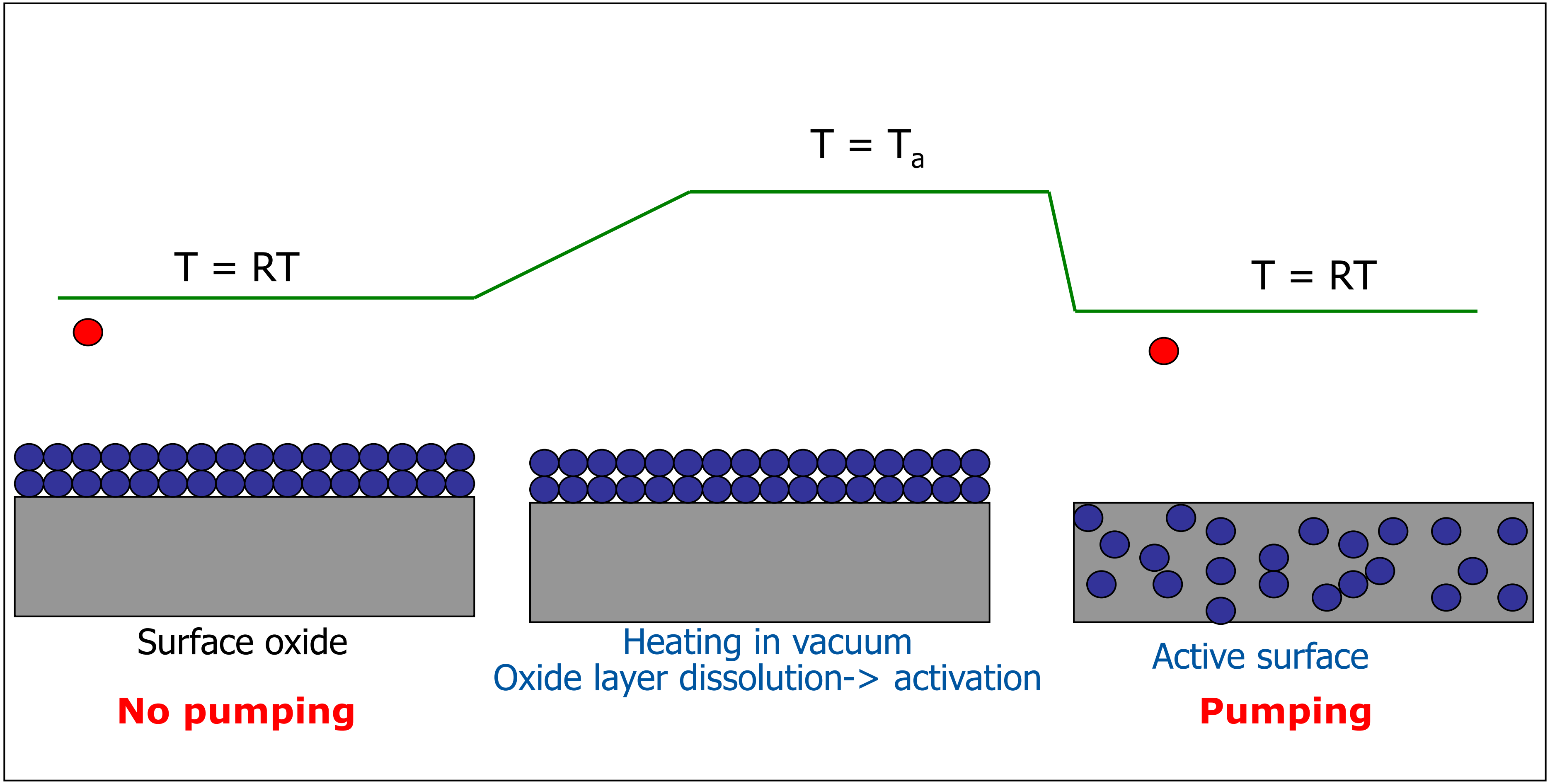


Figure 4. Room temperature sorption characteristics for pure gases on batch evaporated clean titanium films.

A K Gupta and J H Leek, Vacuum, 25(1975)362

Gas pumping: capture pumps / NEG

The dissolution of the native oxide layer (**ACTIVATION**) is possible only in metals having very high oxygen solubility limit, namely the elements of the 4th group: Ti, Zr and Hf.



Surface oxide

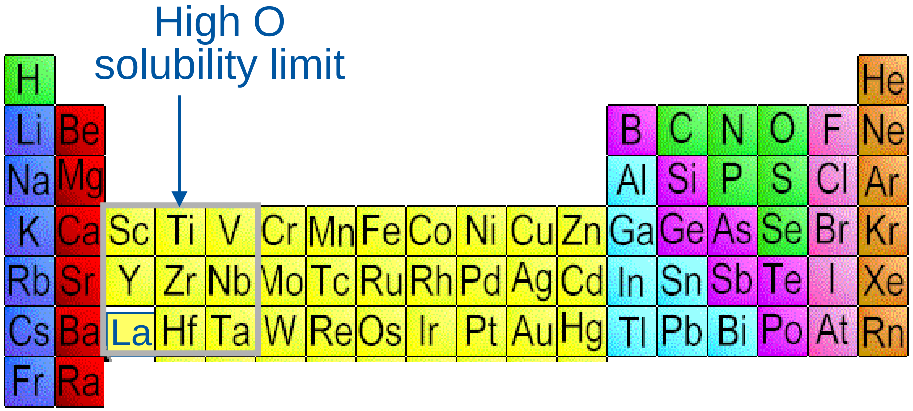
No pumping

Heating in vacuum
Oxide layer dissolution-> activation

Active surface

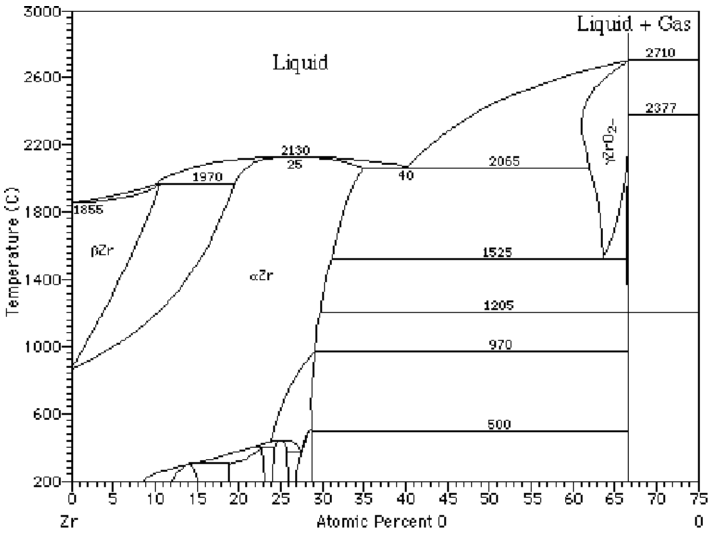
Pumping

Gas pumping: capture pumps / sublimation pumps



High O solubility limit

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																



Gas pumping: capture pumps / NEG

The activation temperature of the 4th group elements can be decreased by adding selected elements that increase oxygen diffusivity.

NEG materials are produced industrially by powder technology. Small grains are sintered to form pellets, discs or plates. The grains can also be pressed at room temperature on metallic ribbon.

A typical alloy produced by SAES Getter is **St707**:

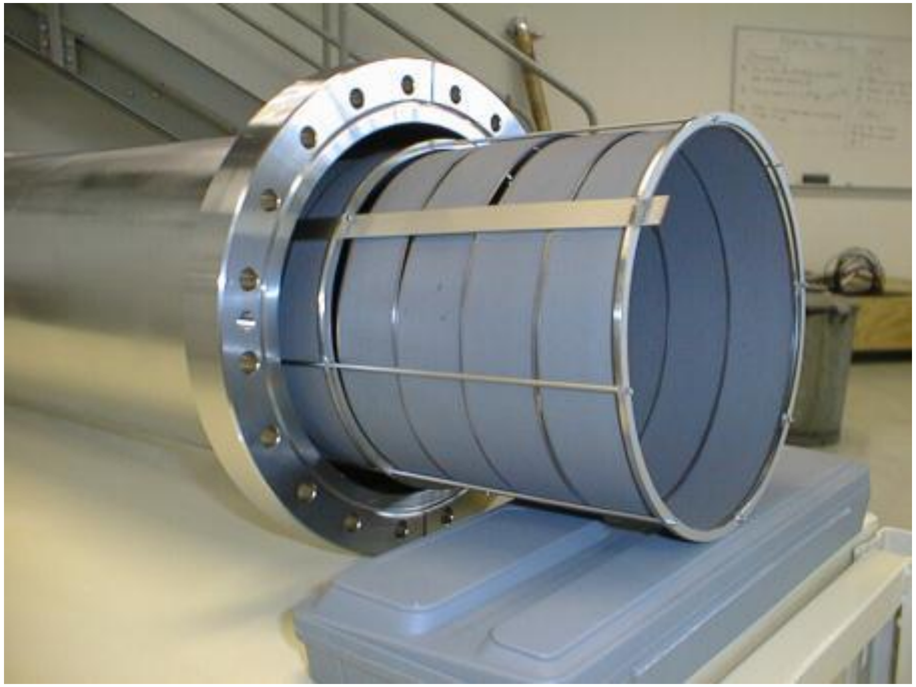
Element	Concentration [wt. %]	Main role in the alloy
Zr	70	- High O solubility limit. - Chemical reactivity
V	24.6	- Increases O diffusivity, - Chemical reactivity
Fe	5.4	- Reduces pyrophoricity

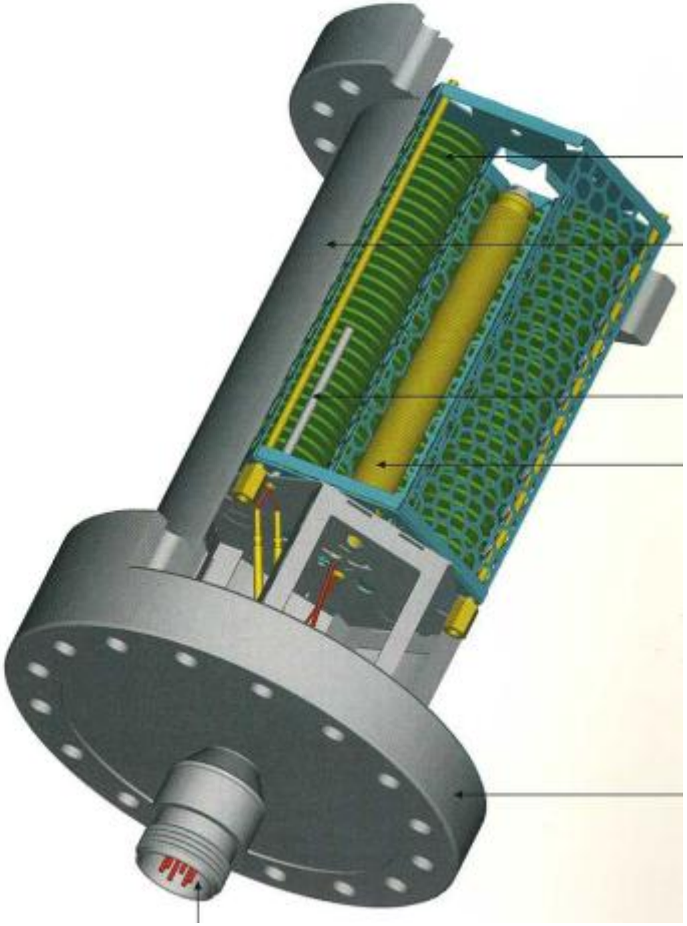
Full pumping speed is obtained after heating at 400°C for 45’ or 300°C for 24h

Gas pumping: capture pumps / NEG

St 171® and St 172 - Sintered Porous Getters

Different shapes of NEG pumps



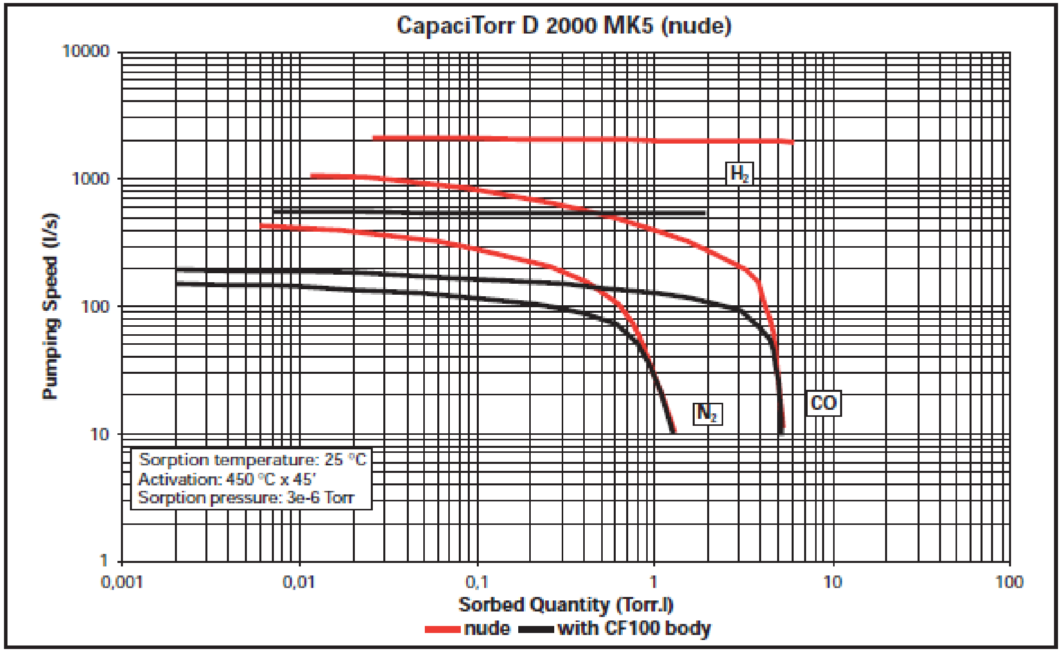


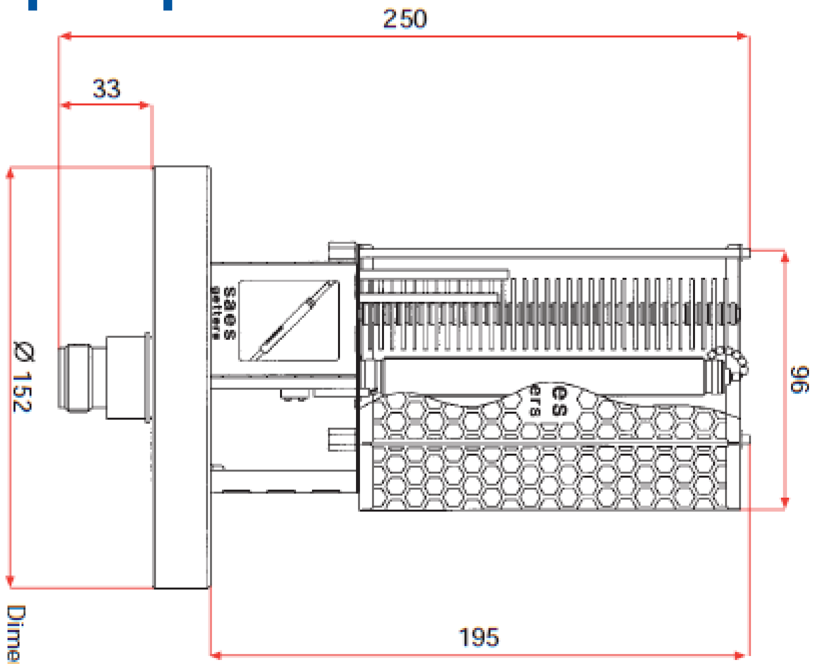
Courtesy of SAES Getters, www.saesgetters.com

Gas pumping: capture pumps / NEG

The **high porosity of NEG materials** allows pumping of relatively high quantities of gas without reactivation: for CO about 100 times higher than those for sublimation pumps per unit of geometrical surface of active metal.

Courtesy of SAES Getters, www.saesgetters.com





Dimensions in mm

Typical Pump Characteristics

Alloy Type		St 172®
Alloy Composition		ZrVFe
Getter Mass(g)		225
Getter Surface (cm²)		1900
Pumping Speed (l/s)	H_2	2000
	CO	1000
Sorption Capacity (Torr l)	H_2	4500
	CO Room Temperature	5
	CO Total	2000

Note: Pumping speed data refer to the initial values of the pump without the pump body. CO capacity based on speed below 50 l/s.

Gas pumping: capture pumps / NEG

The maximum H_2 sorption capacity is limited by H_2 embrittlement of the NEG elements.

In general a safe limit is 20 Torr l/g is given by the supplier.

The stored H_2 can be desorbed by heating and pumping out with an auxiliary pump (for example a turbomolecular pump).

Gas pumping: capture pumps / NEG

Courtesy of SAES Getters, www.saesgetters.com

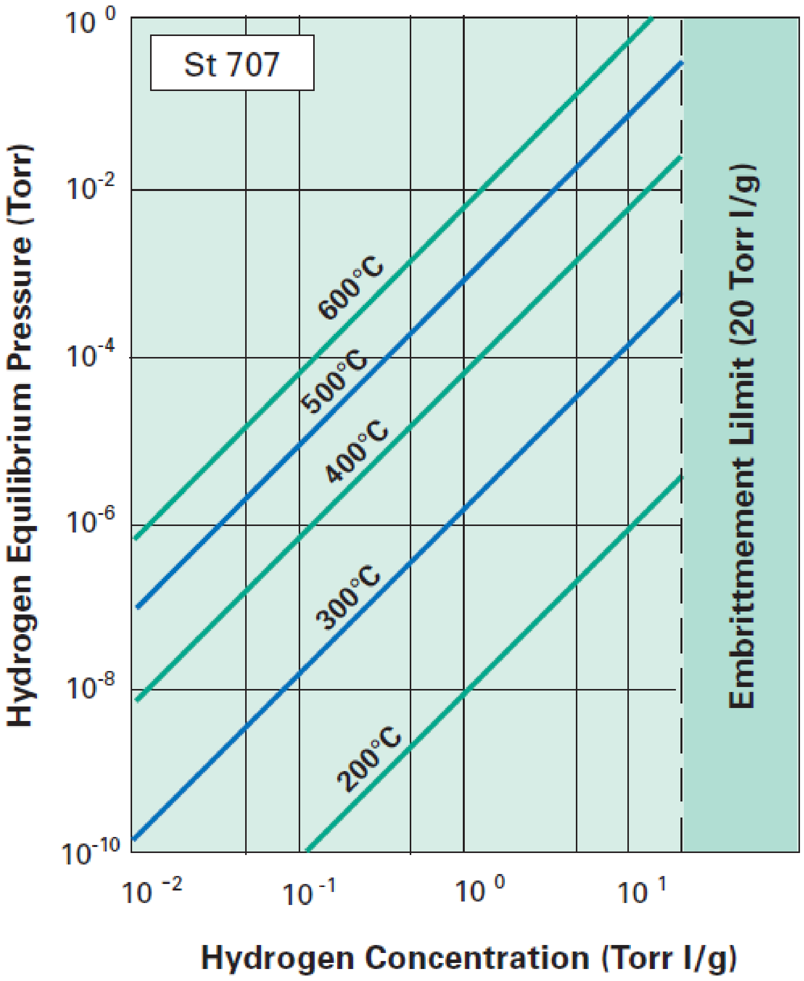


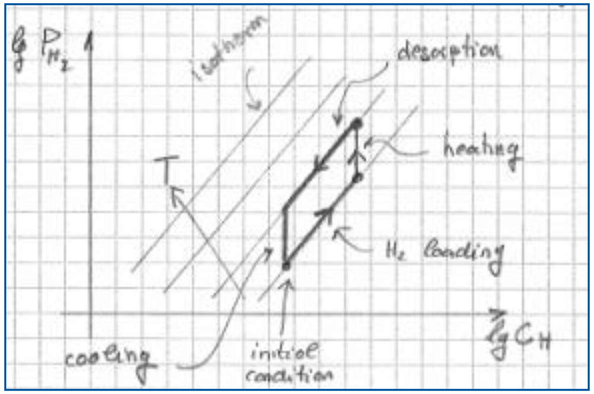
Figure 3 - Hydrogen equilibrium pressure for the St 707 alloy

Gas pumping: capture pumps / NEG

The time t_R needed to regenerate a NEG pump is given by:

$$t_R = \frac{M_{NEG}}{S_{aux}} \left(\frac{1}{q_f} - \frac{1}{q_i} \right) \cdot 10^{-\left(A + \frac{B}{T} \right)}$$

Where:



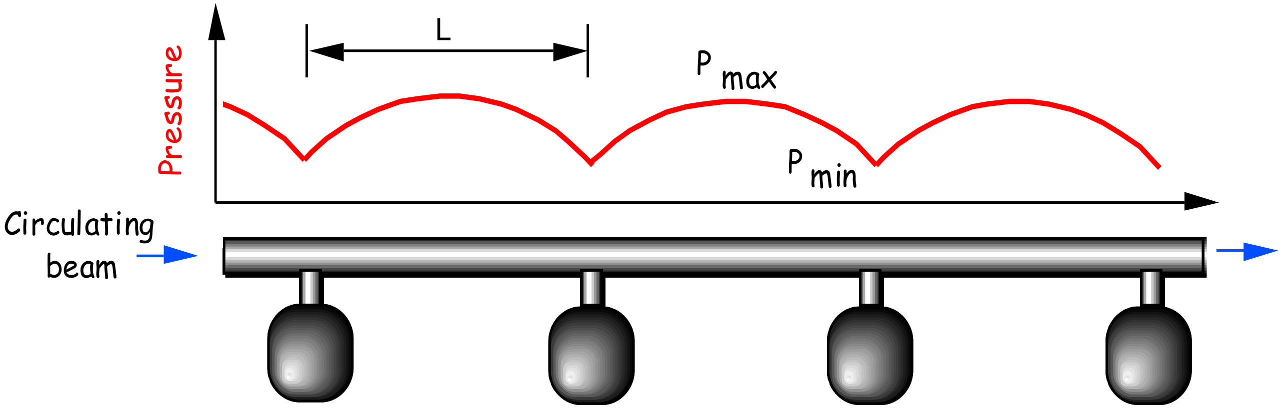
q_f and q_i are the final and initial concentrations in Torr l/g
S_{aux} is the pumping speed of the TMP
M_{NEG} the mass of the NEG in g
A and B typical values of the NEG material
For St707: A=4.8, B= -6116

The equilibrium pressure during the regeneration heating is given by:

$$Log(P) = A + 2Log(q) + \frac{B}{T}$$

q is the actual hydrogen concentration

Gas pumping: capture pumps / NEG



In general in particle accelerators the **gas source is uniformly distributed** along the beam pipe

Pumps located at regular distances from each other give rise to a **parabolic pressure profile** with minima at the pumps location.

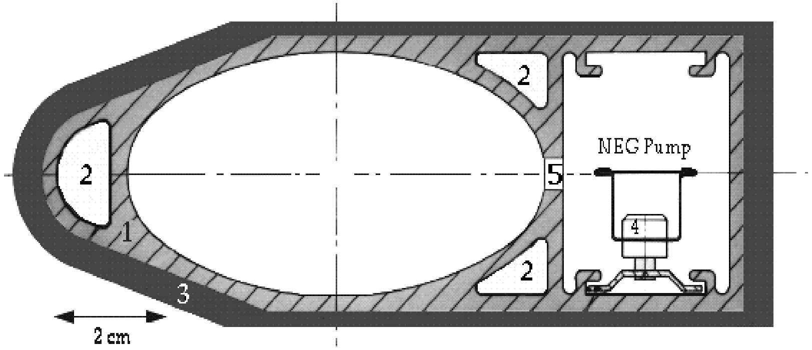
Even for large aperture, the average pressure is quickly limited by the chamber conductance when increasing the spacing between the pumps: **the benefit of increasing the lumped pumping speed is minimal**.

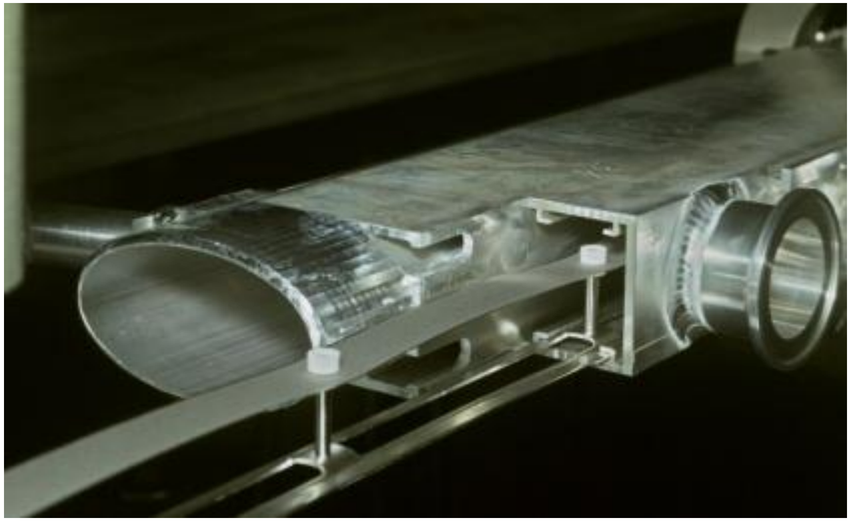
It is more efficient to **increase the number of pumps**. But this can be **very expensive** or not possible due to space limitation. **Linear pumping is the solution.**

Gas pumping: capture pumps / NEG

Linear pumping may be obtained by NEG ribbons.

LEP dipole vacuum chamber





The first application was in the LEP.

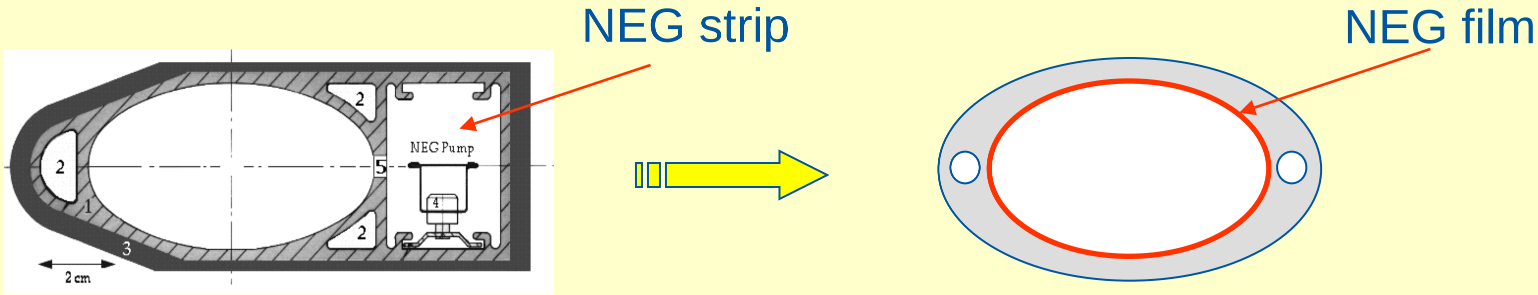
Gas pumping: capture pumps / NEG

The trend in vacuum technology consists in **moving the pump progressively closer to the vacuum chamber** wall.

The ultimate step of this process consists of transforming **the vacuum chamber from a gas source into a pump.**

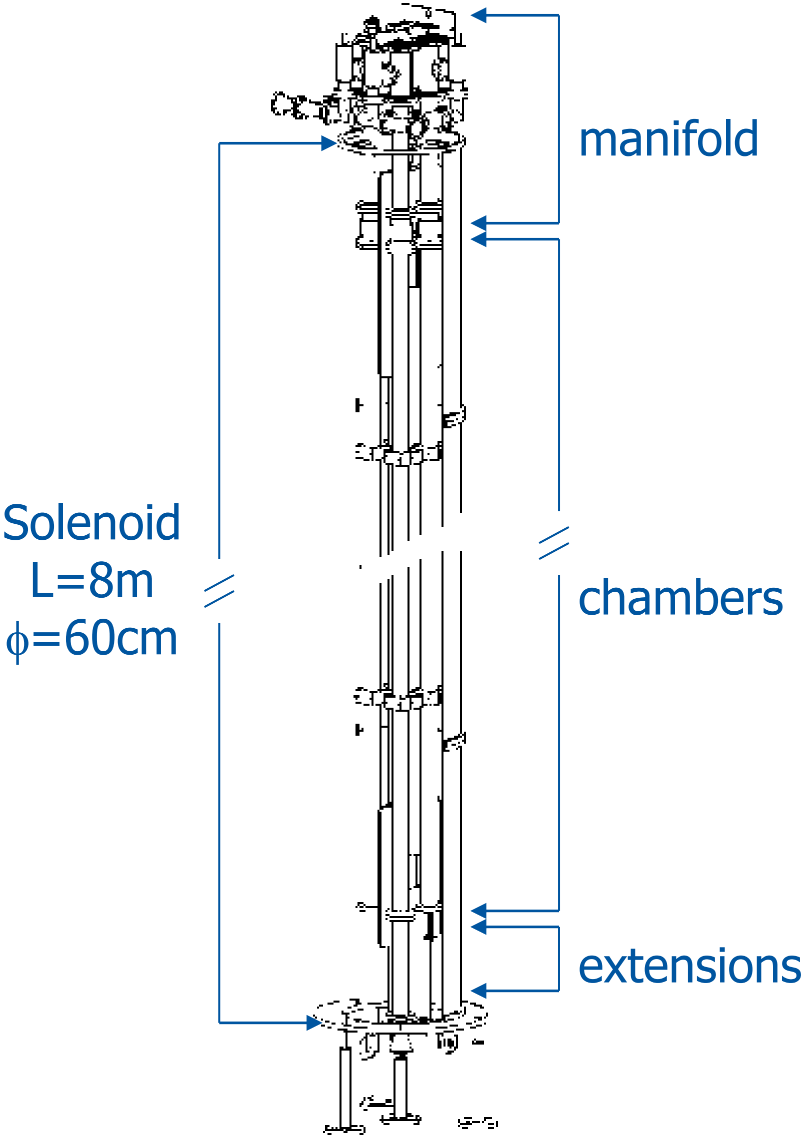
One way to do this is by **“ex-situ” coating** the vacuum chamber with a NEG thin film that will be activated during the “in situ” bakeout of the vacuum system.

NEG films do not need space, electric power, insulation and feedthroughs
⇒ simplified design and larger pumping speed

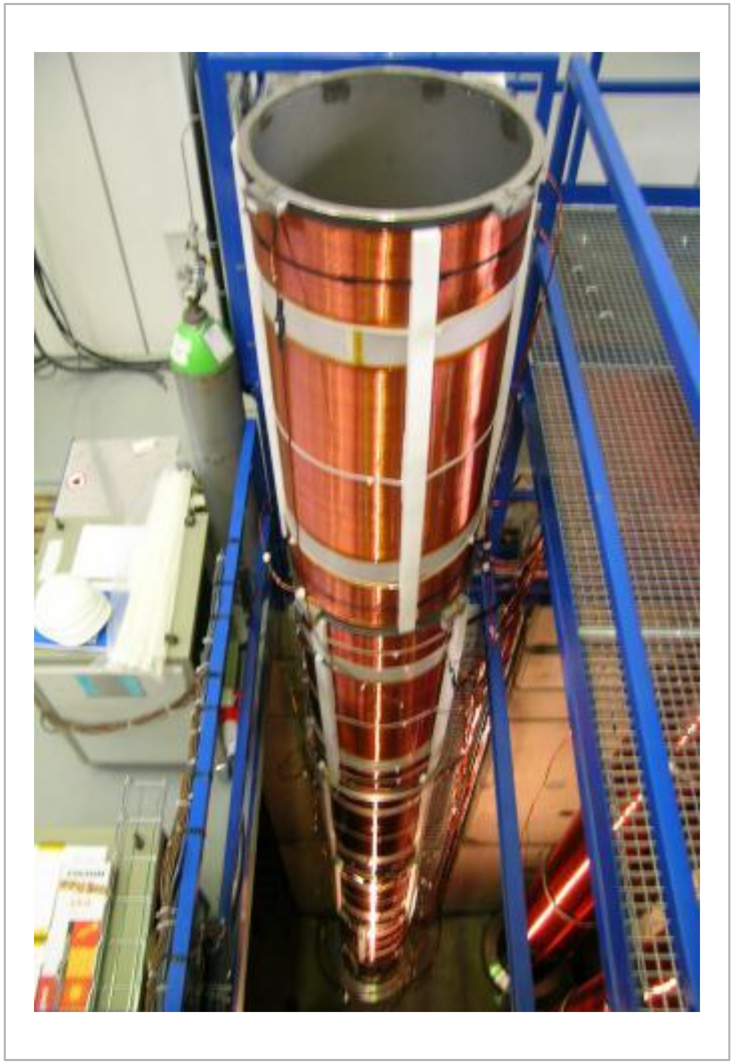


The coating techniques is **sputtering**.

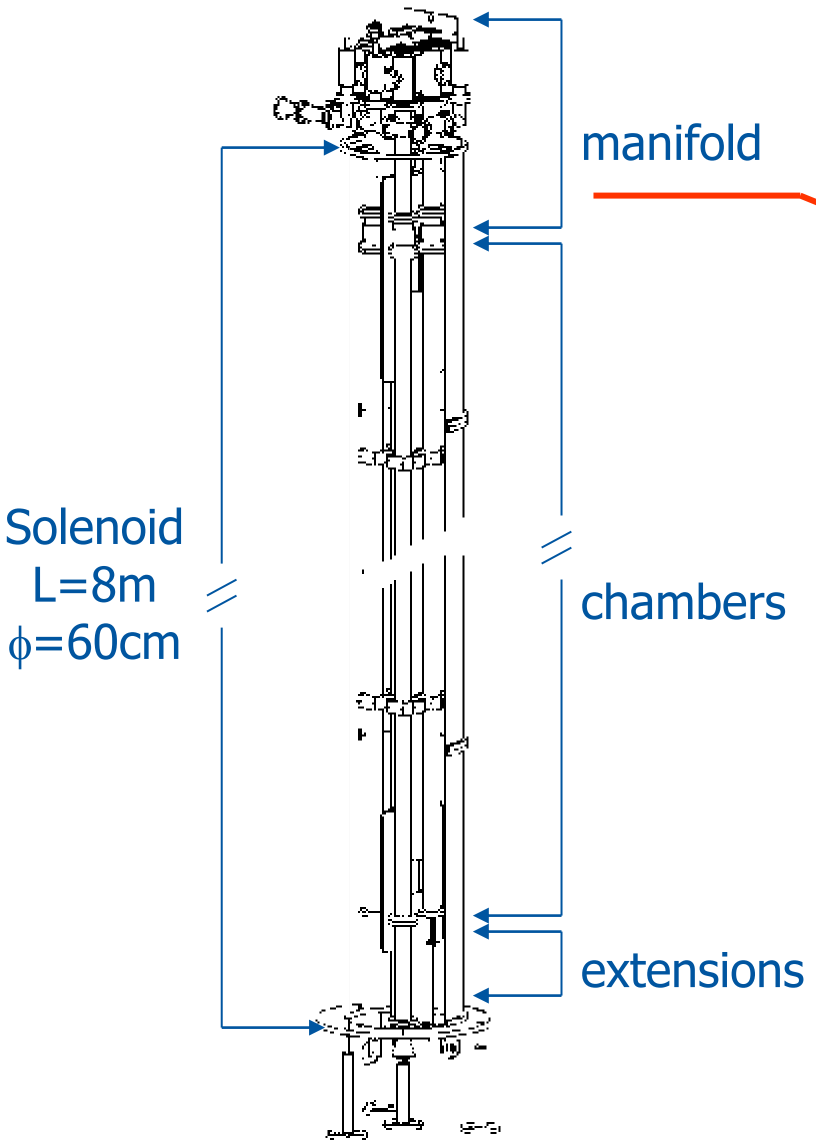
Gas pumping: capture pumps / NEG



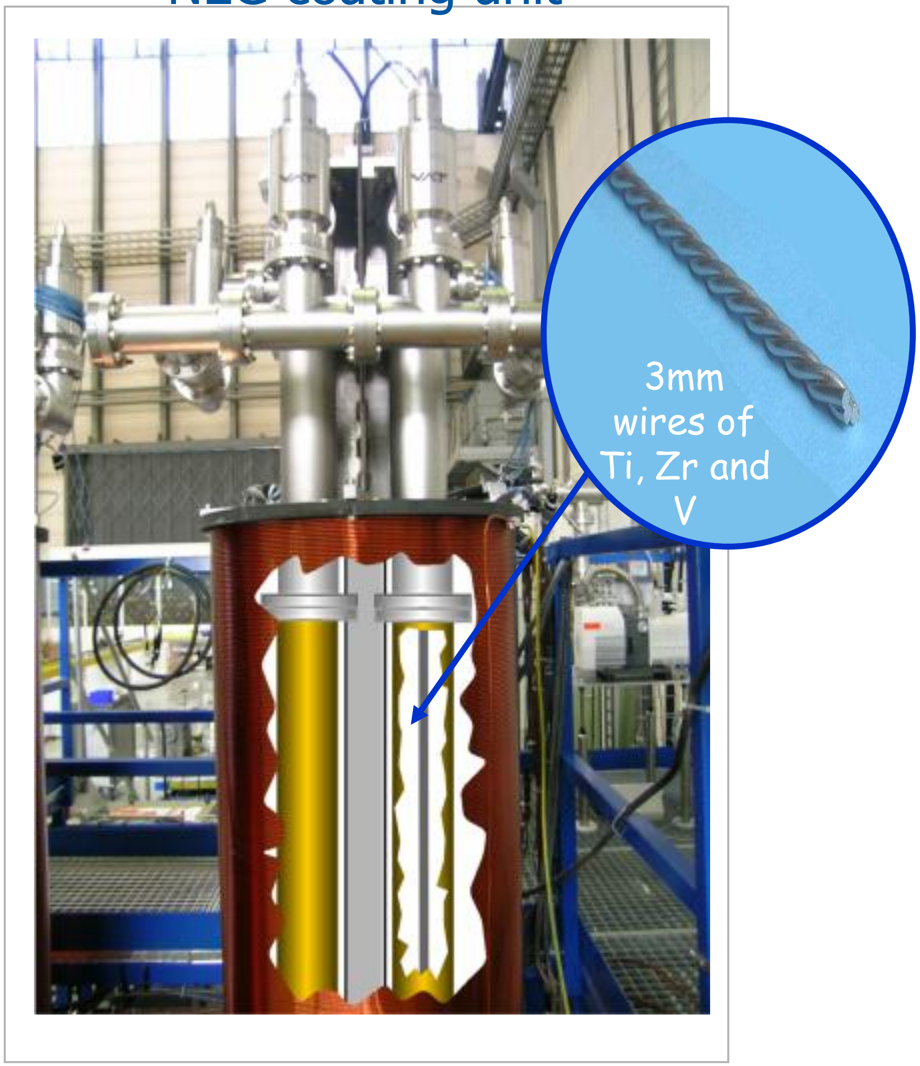
NEG coating unit at CERN



Gas pumping: capture pumps / NEG



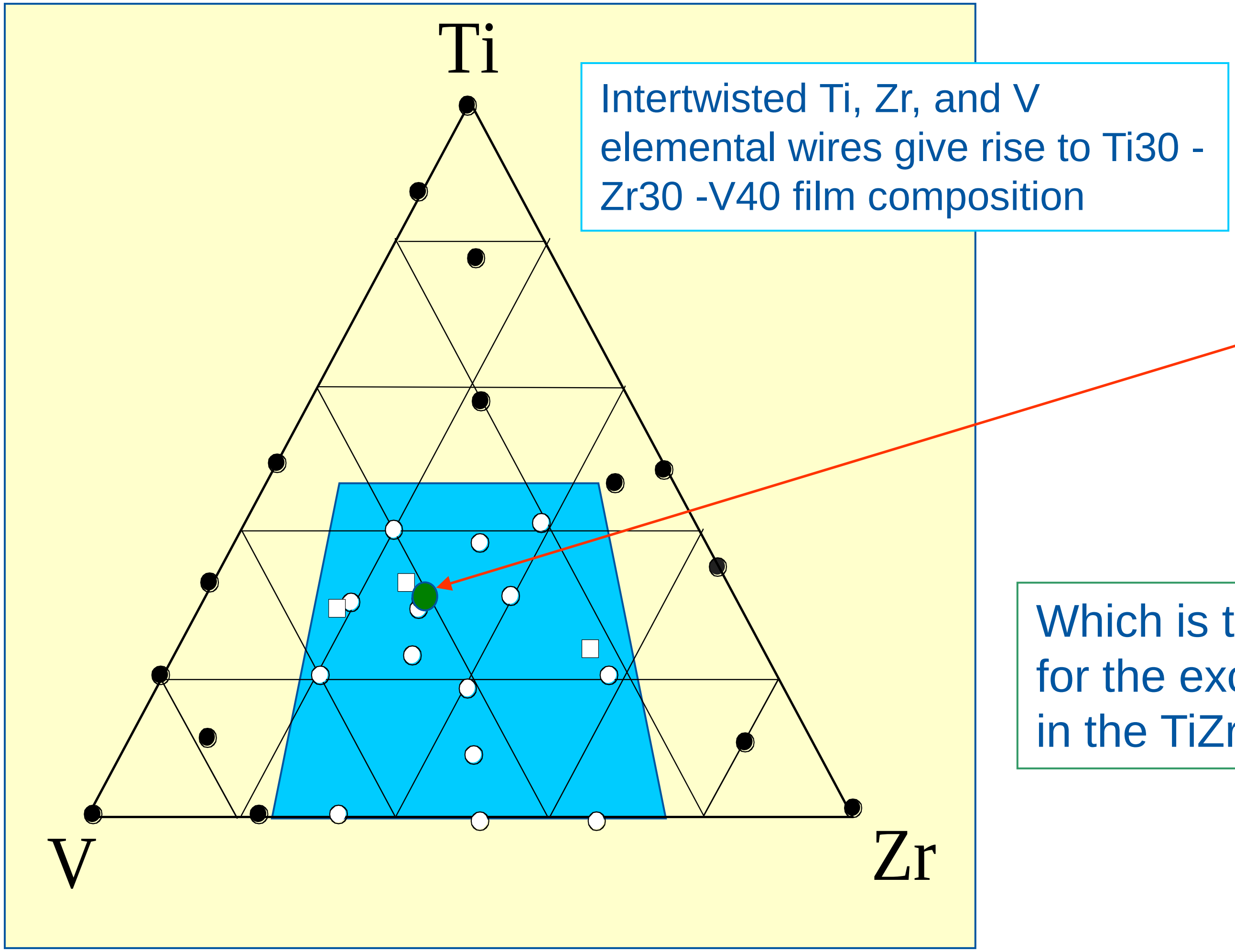
NEG coating unit



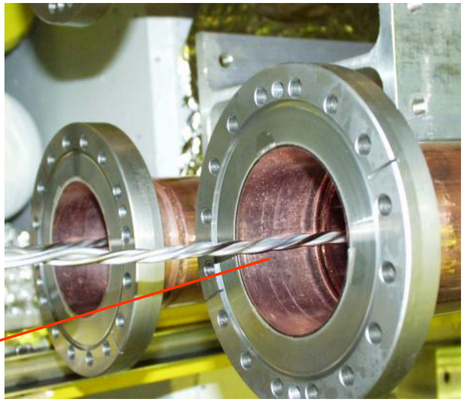
Gas pumping: capture pumps / NEG

Gas pumping: capture pumps / NEG

The lowest activation temperature has been found in a wide range of composition in the **Ti-Zr-V** system: **180 °C (24 h heating).**

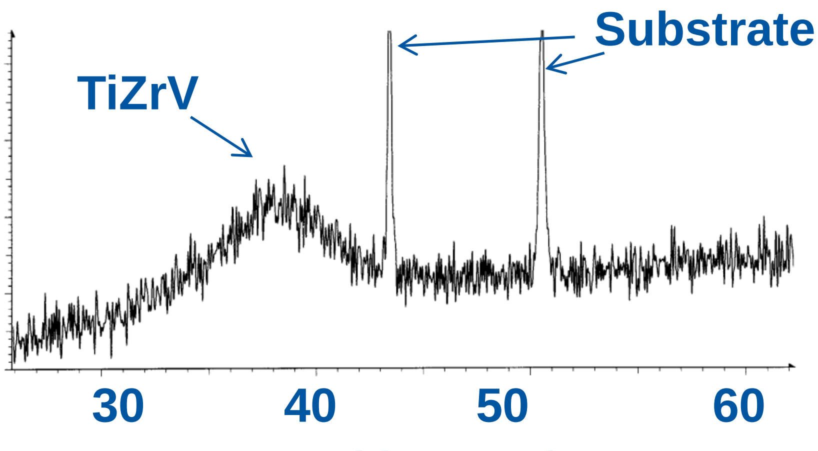


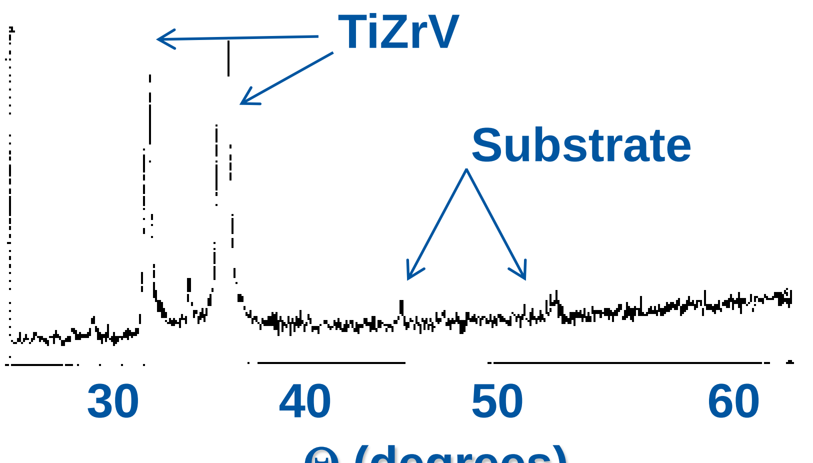
Intertwisted Ti, Zr, and V elemental wires give rise to Ti30 -Zr30 -V40 film composition

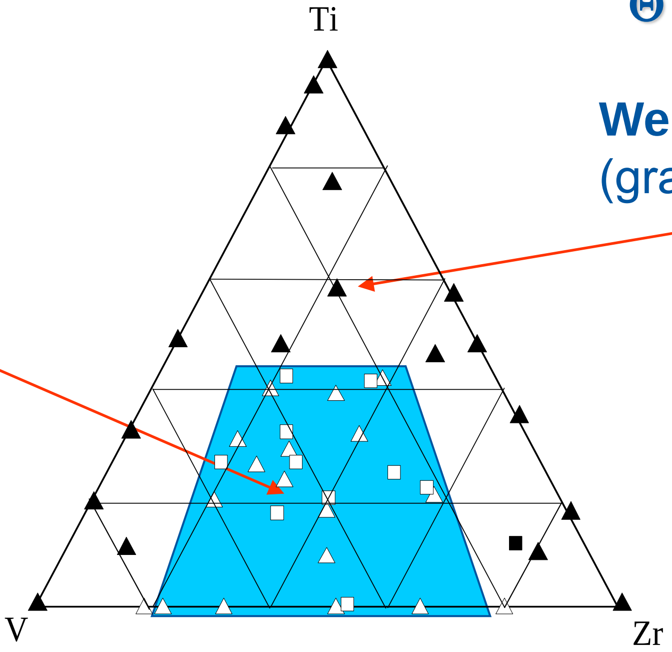


Which is the necessary condition for the exceptional fast activation in the TiZrV system?

Gas pumping: capture pumps / NEG







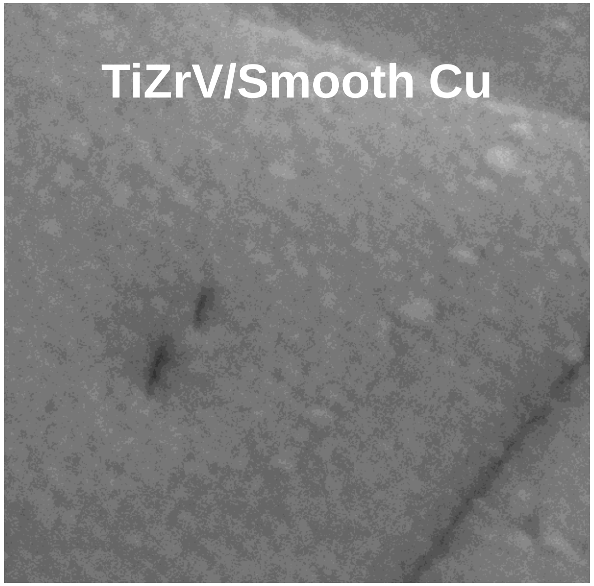
Nanocrystalline (3÷5 nm grain size) structure as confirmed by TEM

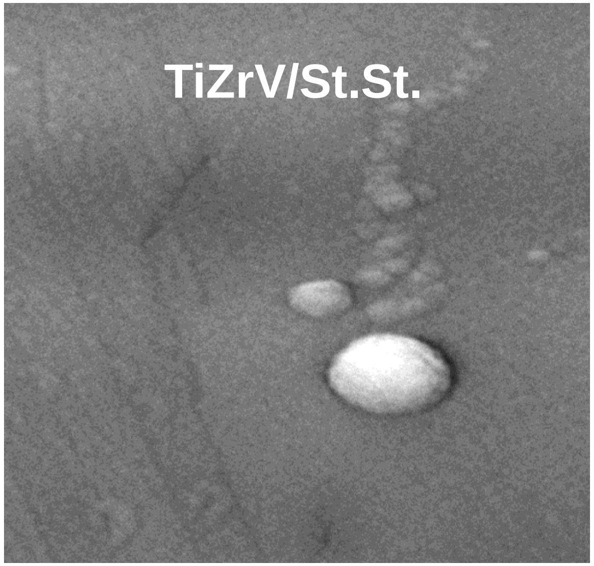
Well crystallised structure (grain size ≥ 100 nm)

Gas pumping: capture pumps / NEG

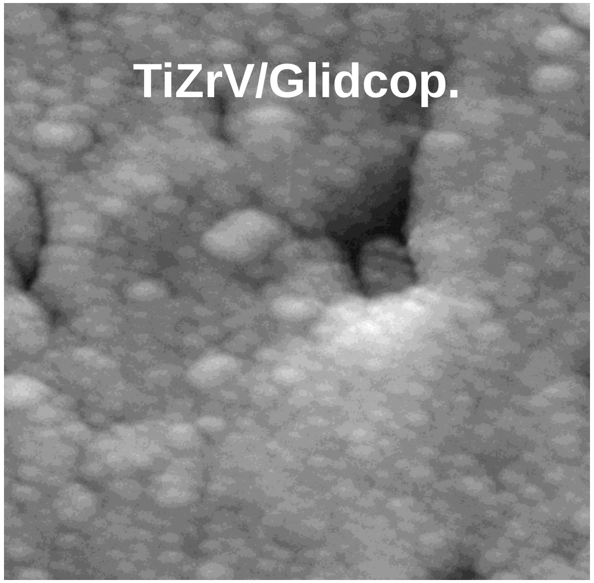
About 1400 chambers for the warm zones of the LHC were coated with a Ti-Zr-V film.

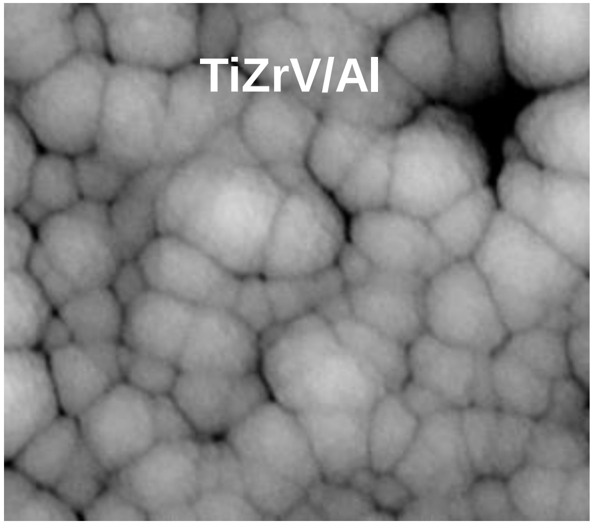
Gas pumping: capture pumps / NEG


TiZrV/Smooth Cu


TiZrV/St.St.

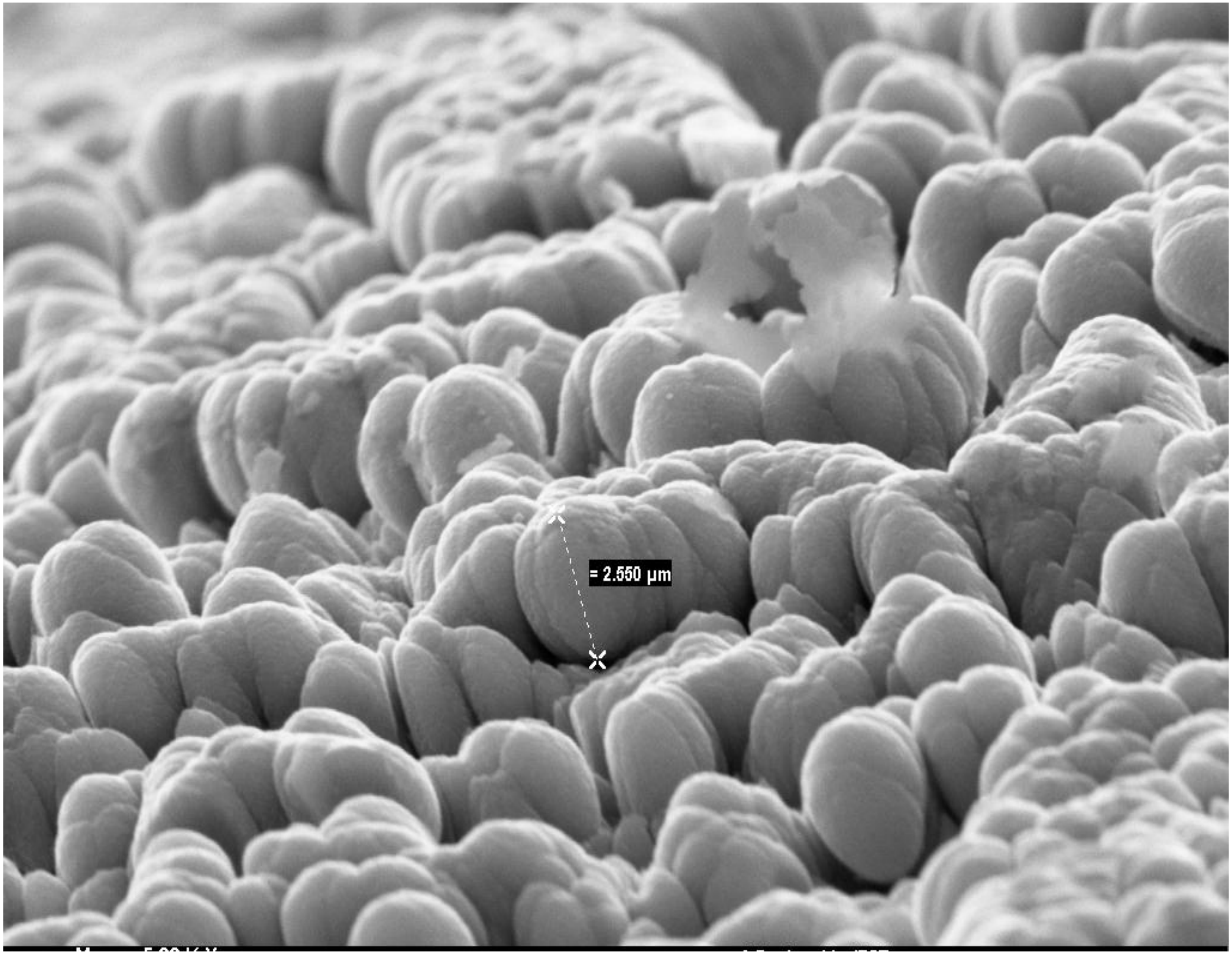
1 µm


TiZrV/Glidcop.

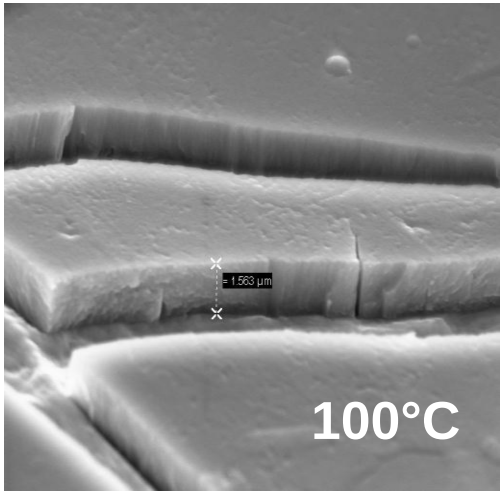

TiZrV/Al

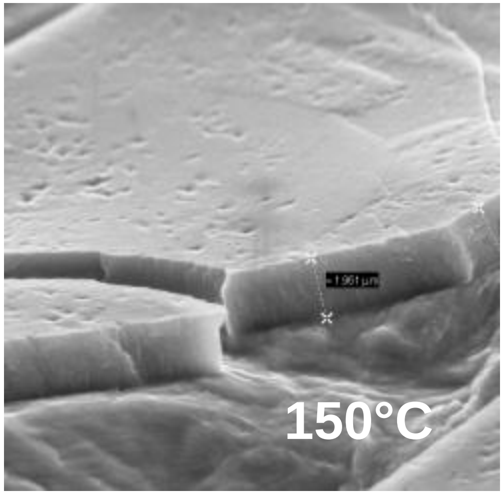
Gas pumping: capture pumps / NEG

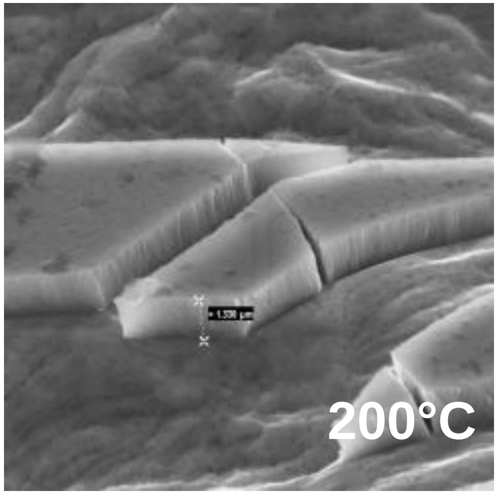
TiZrV on rough copper: Cu6



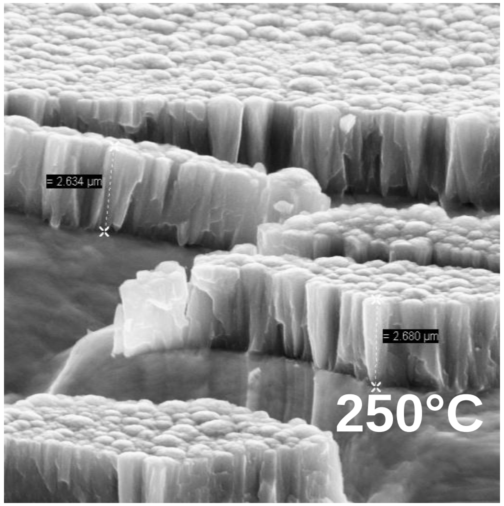
Gas pumping: capture pumps / NEG

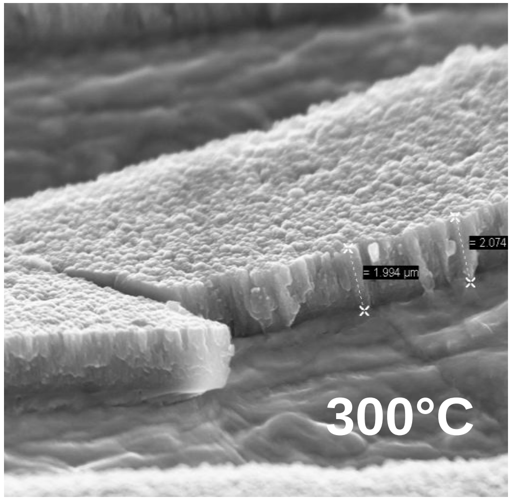


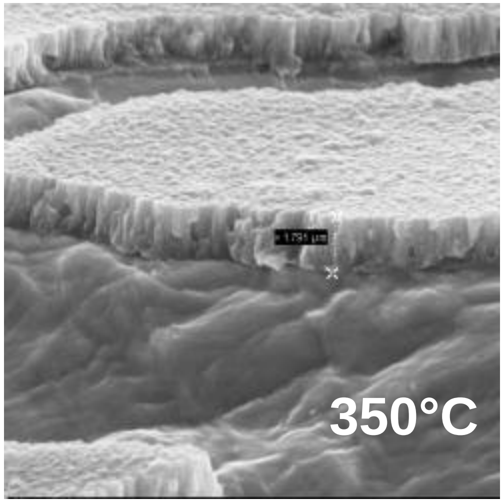




1 µm







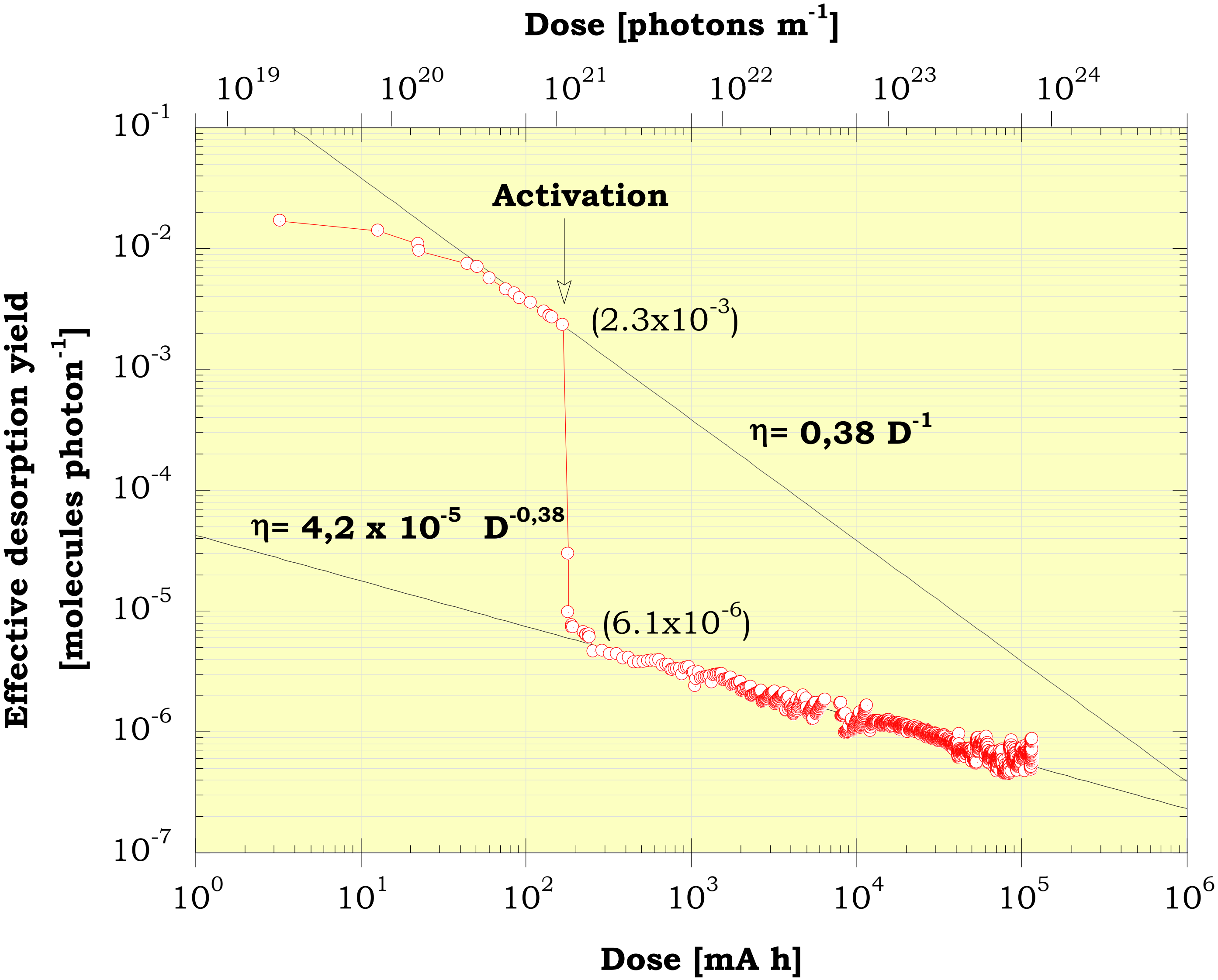
Gas pumping: capture pumps / NEG

After activation a NEG film surface is very clean resulting in both a large pumping speed and **reduced degassing** (both thermal and ion/radiation/electron induced).

Very important bonus: **low secondary electron yield**.

NEG films trap the gas coming from the substrate material

Gas pumping: capture pumps / NEG



PSD at ESRF

Gas pumping: capture pumps / cryo

Cryopumps rely on **three different pumping mechanisms**:

1. **Cryocondensation**: is based on the mutual attraction of **similar** molecules at low temperature:

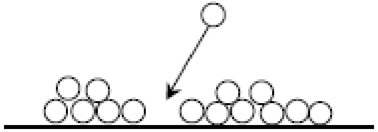
    a. the key property is the **saturated vapour pressure**, i.e. the pressure of the gas phase in equilibrium with the condensate at a given temperature. The attainable pressure is limited by the saturated vapour pressure.

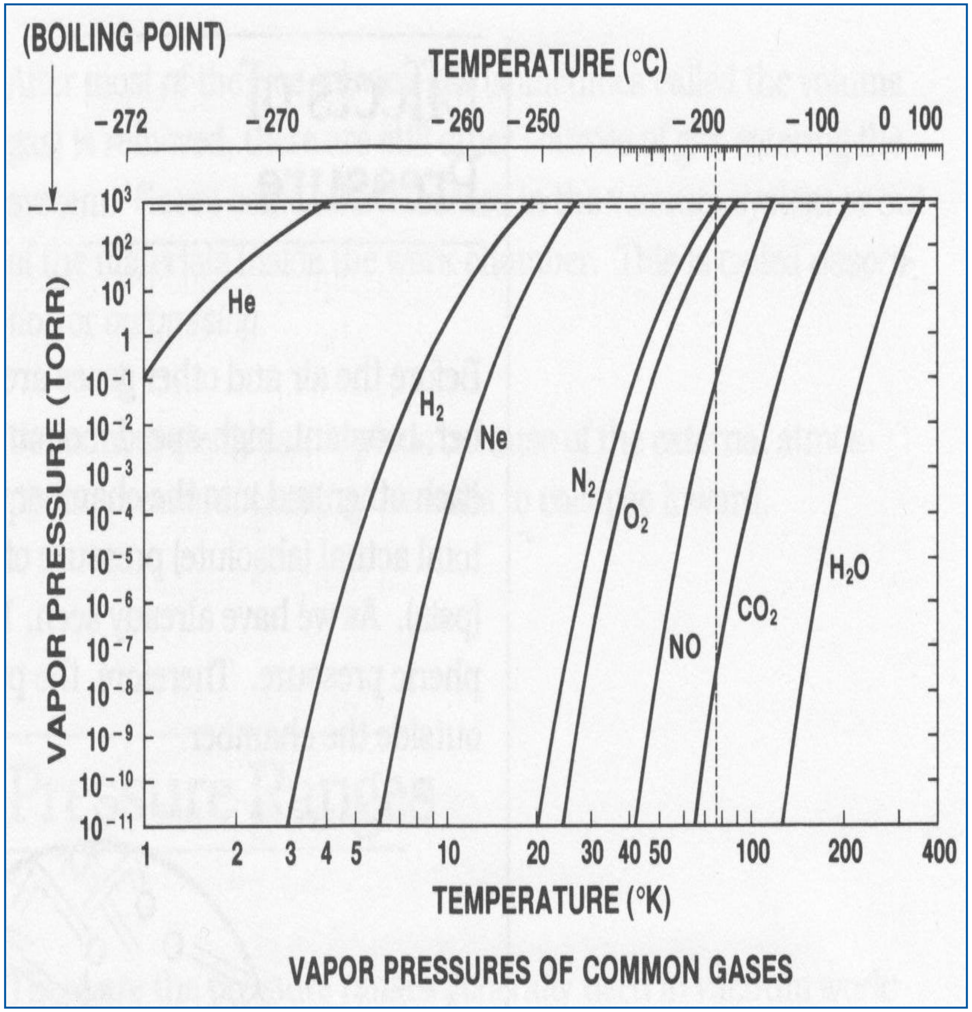
    b. Only **Ne, H_2 and He** have saturated vapour pressures higher than 10^{-11} Torr at **20 K**.

    c. The vapour pressure of **H_2 at 4.3 K is in the 10^{-7} Torr** range, at 1.9 lower than 10^{-12} Torr.

    d. Large quantity of gas can be cryocondensated (limited only by the thermal properties of the condensate phase)

Gas pumping: capture pumps / cryo





Gas pumping: capture pumps / cryo

2. **Cryosorption**: is based on the attraction between molecules and substrate. The van der Waals forces are much stronger than those between similar molecules:

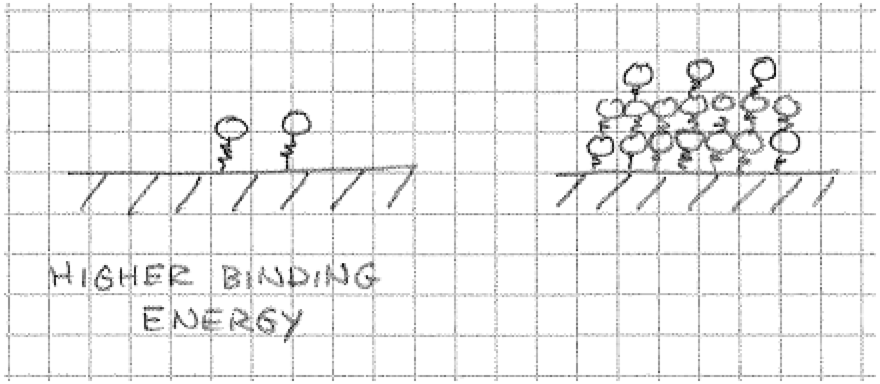
   a) Gas molecules are pumped at pressure much lower than the saturated vapour pressure providing the adsorbed quantity is **lower than one monolayer**.

   a) **Porous materials** are used to increase the specific surface area; for charcoal about 1000 m^2 per gram are normally achieved.

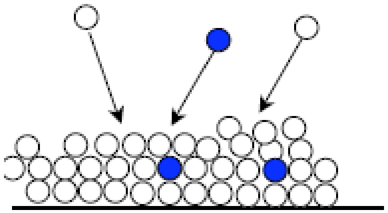
   b) The important consequence is that significant quantities of **H_2 can be pumped at 20 K and He at 4.3 K**.

   c) **Submonolayer quantities** of all gases may be effectively cryosorbed at their **own boiling temperature**; for example at 77 K all gases except He, H_2 and Ne.

Gas pumping: capture pumps / cryo



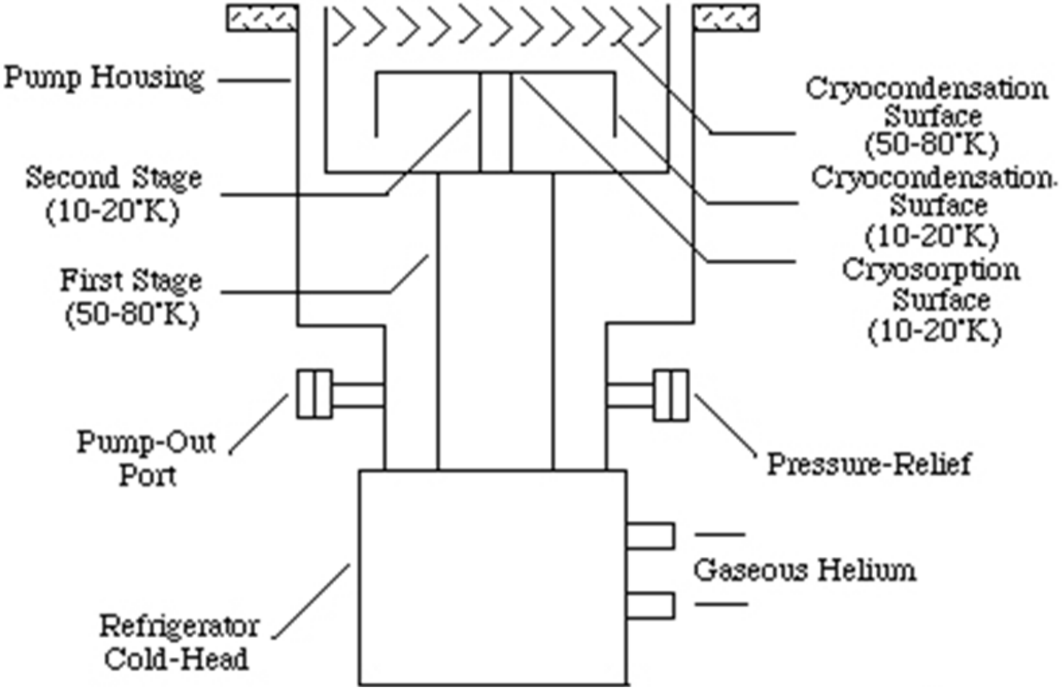
3. **Cryotrapping** : low boiling point gas molecules are trapped in the layer of an easily condensable gas. The trapped gas has a saturation vapor pressure by several orders of magnitude lower than in the pure condensate. Examples: **Ar trapped in CO_2 at 77 K**; **H_2 trapped in N_2 at 20 K**.

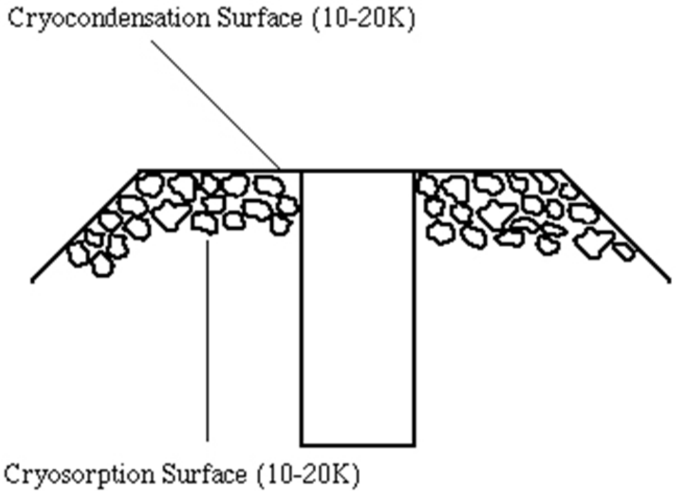


Gas pumping: capture pumps / cryo

Modern cryopumps take advantages of the first two mechanisms.

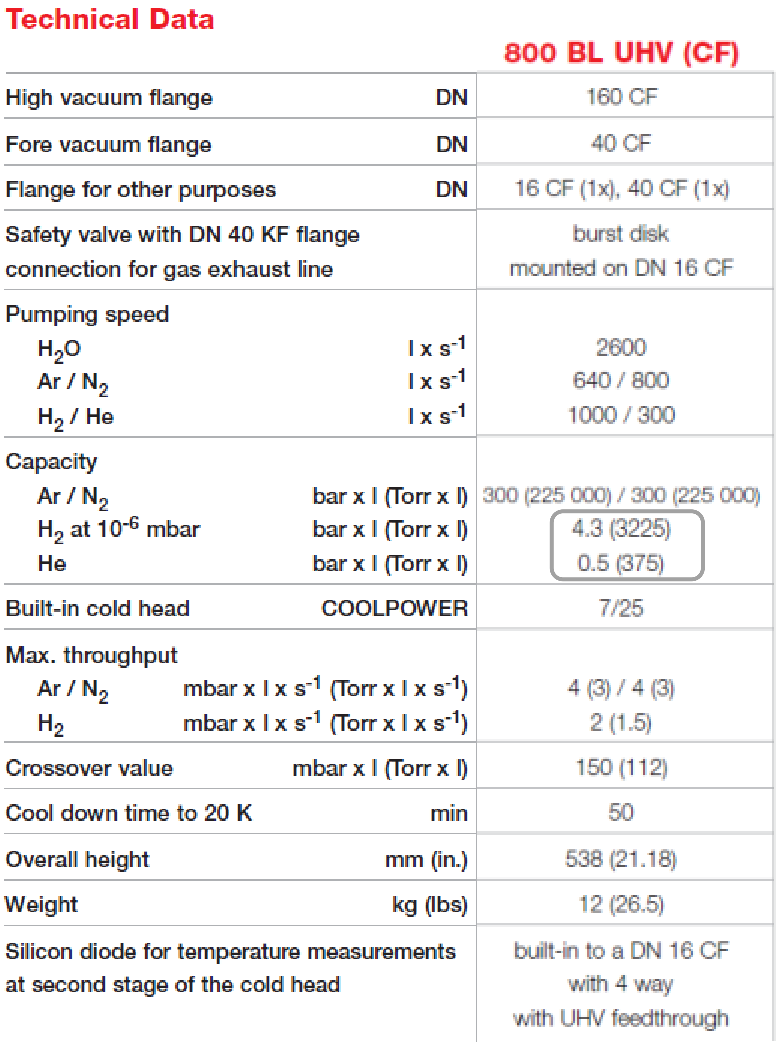
1. The cryocondensation takes place on a cold surfaces, in general at 80 K for H_2O and 10 or 20 K for the other gases.
2. The cryosorption of H_2, Ne and He is localised on a hidden surface where a porous material is fixed. This surface is kept away from the reach of the other molecules.





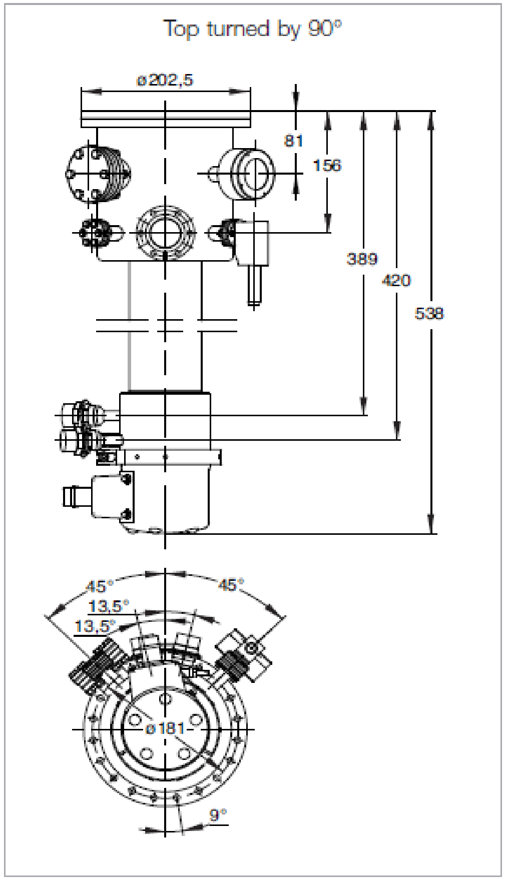
Helium is the working fluid of modern cryopumps.

Gas pumping: capture pumps / cryo



Technical Data

		800 BL UHV (CF)
High vacuum flange	DN	160 CF
Fore vacuum flange	DN	40 CF
Flange for other purposes	DN	16 CF (1x), 40 CF (1x)
Safety valve with DN 40 KF flange connection for gas exhaust line		burst disk mounted on DN 16 CF
Pumping speed		
H_2O	$l \times s^{-1}$	2600
Ar / N_2	$l \times s^{-1}$	640 / 800
H_2 / He	$l \times s^{-1}$	1000 / 300
Capacity		
Ar / N_2	bar x l (Torr x l)	300 (225 000) / 300 (225 000)
H_2 at 10^{-6} mbar	bar x l (Torr x l)	4.3 (3225)
He	bar x l (Torr x l)	0.5 (375)
Built-in cold head	COOLPOWER	7/25
Max. throughput		
Ar / N_2	mbar x l x s^{-1} (Torr x l x s^{-1})	4 (3) / 4 (3)
H_2	mbar x l x s^{-1} (Torr x l x s^{-1})	2 (1.5)
Crossover value	mbar x l (Torr x l)	150 (112)
Cool down time to 20 K	min	50
Overall height	mm (in.)	538 (21.18)
Weight	kg (lbs)	12 (26.5)
Silicon diode for temperature measurements at second stage of the cold head		built-in to a DN 16 CF with 4 way with UHV feedthrough



Dimensional for the COOLVAC 800 BL UHV (160 CF)

Courtesy of Oerlikon Leybold Vacuum www.oerlikon.com/leyboldvacuum

Gas pumping: capture pumps / cryo

Characteristics of Cryopumps

1. **Starting Pressure**

   - Cryopumps should be started when the **mean free path of molecules is higher than the pump vessel diameter**: $P<10^{-3}$ mbar. Otherwise the thermal load is too high.
   - In addition a **thick condensate layer must be avoided**.
   - They always need **auxiliary pumps**.

2. **Pumping speed**

   - **High effective pumping speed** for all gases. Pumping speed from 800 l/s up to 60000 l/s are commercially available .
   - Pumping speed for **water vapour close to the theoretical maximum**.

Gas pumping: capture pumps / cryo

3. Maximum Gas Intake (Capacity)

- At the maximum gas intake, the initial pumping speed of the gas is **reduced by a factor of 2**.
- Condensed gases: the limitation is given by **the thermal conductivity of the gas layer**.
- Adsorbed gases: the capacity depends on the quantity and **properties of the sorption agent**; it is pressure dependent and generally several orders of magnitude lower compared to that of condensable gases.

Gas pumping: capture pumps / cryo

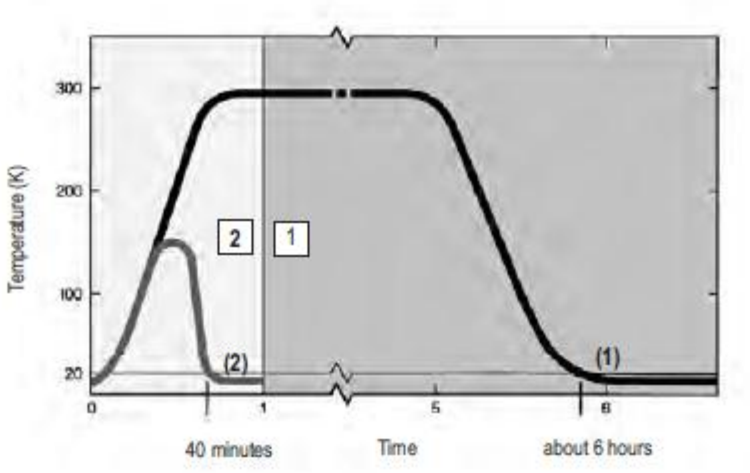
Cryopumps require **periodic regeneration** to evacuate the gas adsorbed or condensed.

To remove all captured gas, **the pump is warmed at room temperature**. The desorbed gas is removed by mechanical pumps (in general, for accelerators, mobile TMP).

During regeneration, the rest of the system must be separated by a valve.

In the majority of application, the performance deterioration is given by the gas adsorbed on the second stage (10-20 K). **A partial regeneration** may be carried out for a shorter time while water vapour is kept on the first stage at temperatures lower than 140 K.

Gas pumping: capture pumps / cryo



Courtesy of Oerlikon Leybold Vacuum www.oerlikon.com/leyboldvacuum

Gas pumping

	Advantages	Disadvantages
TMP	- No memory effects - Constant pumping speed for pressures lower than 10^{-3} mbar - Pumping speed independent of total gas load - Starts working at high pressures (molecular regime)	- Mechanical fragility - Risk of contamination from the backing pump - Need of venting anytime the pump is stopped - Need of valve on the main flange - Intrinsic limitation in ultimate pressure of H_2 - Possible vibrations - Maintenance
SIP	- Clean pumping - No maintenance - No vibrations - Installation in any orientation - Relatively long lifetime - Relatively low cost - Limited but high H_2 capacity - The pump current gives a pressure reading	- Low capture probability - Gas Selectivity and limited capacity - Memory effects (in particular for rare gases) - Ignition in 10^{-5} mbar range - Bulky - Difficult starting for old pumps - Production of charged particles in particular at start-up - Field emission problems for old pumps - Fringing magnetic field - Safety issue: high voltage

Gas pumping

	Advantages	Disadvantages
NEG pumps	- Clean vacuum - High pumping speed for reactive gases - With SIP, extremely low vacuum can be achieve - High gas capacity for porous NEG - Low cost - Electrical power needed only for activation; it works in case of power cut - No maintenance - No vibration	- Selective pumping (no pumping of rare gases and methane) - H_2 enbrittlement if regeneration is not applied - Formation of dust particles is not excluded - Safety issue: pyrophoric, it burns when heated in air at high temperature

Gas pumping

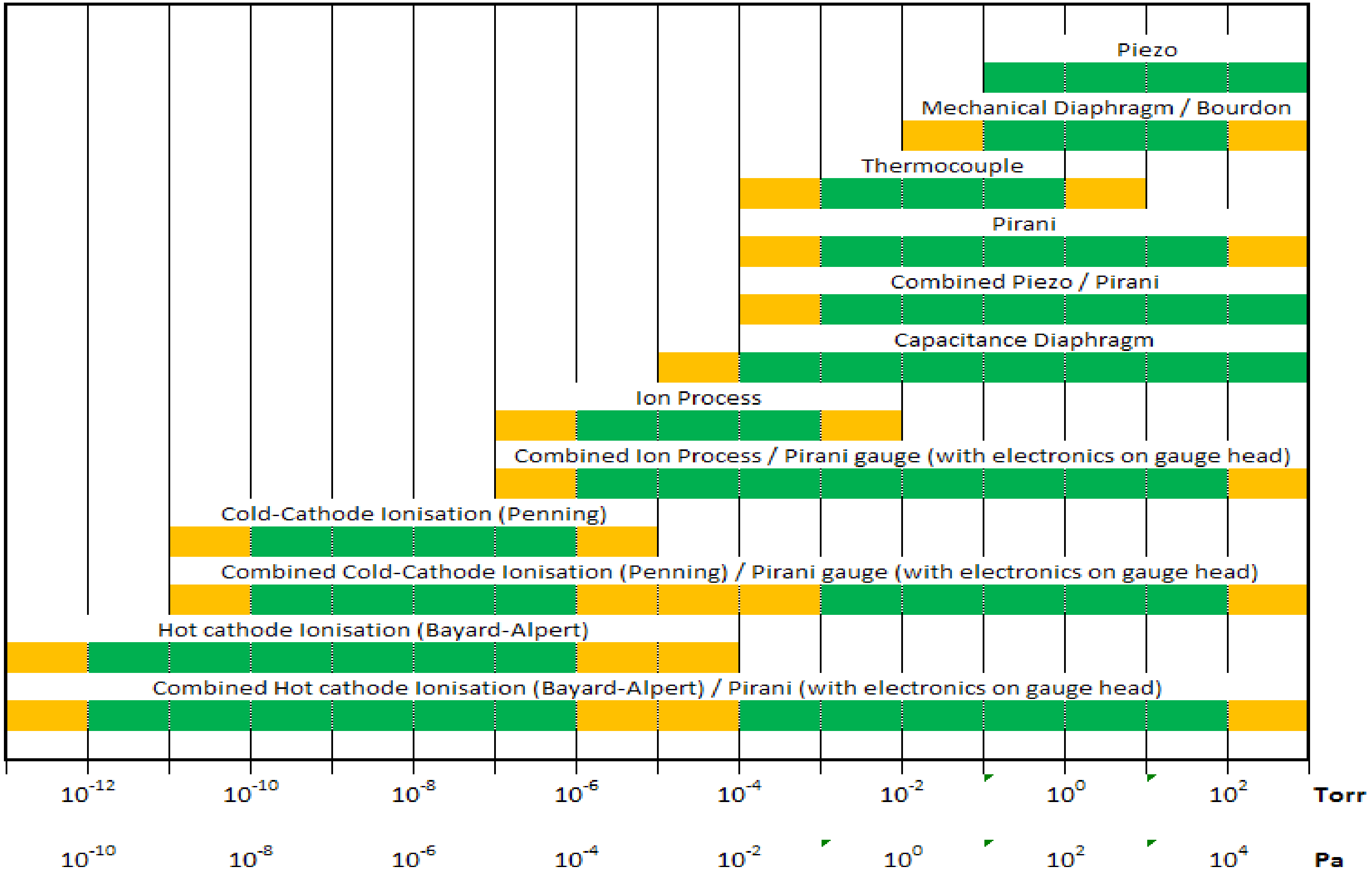
	Advantages	Disadvantages
Sublimation Pumps	- Clean vacuum - High pumping speed for reactive gases - With SIP, extremely low vacuum can be achieve - Low cost - Electrical power only for sublimation; it works in case of power cut - Limited maintenance (filament change) - No vibration	- Very limited capacity - Need frequent sublimations at high pressure - Ti film peel-off for high sublimation rates - Selective pumping (no pumping of rare gases and methane) - Risk of leakage current in high voltage insulators - Ideal for low pressure applications

Gas pumping

	Advantages	Disadvantages
Cryopumps	- Very large pumping speed for all gases - Clean vacuum - High pumping capacity - Limited selectivity	- Cost and maintenance - Relatively large volume needed (including refrigerator) - Gas release in case of power cut - Reduced pumping efficiency for H_2 for high quantity of gas adsorbed: regeneration needed - Need of valve on the main flange

Part 6
Instrumentation

Instrumentation



Instrumentation

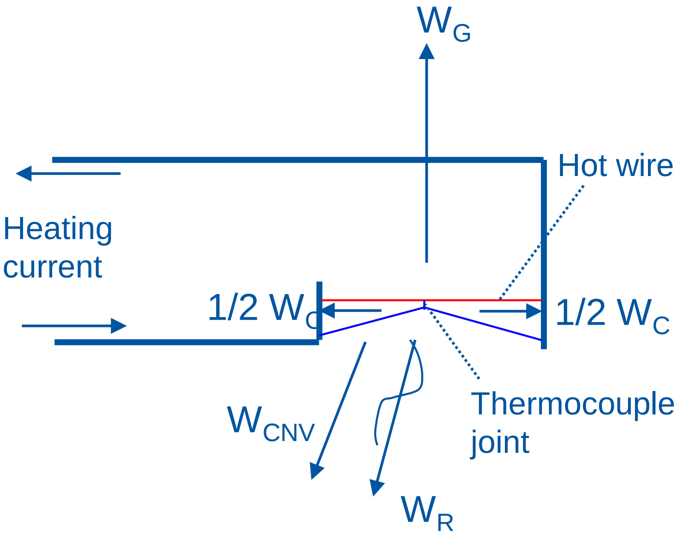
Thermal Conductivity Gauges

Principle of operation:

Pirani gauge: temperature dependent resistance of a hot wire

Thermocouple gauge: temperature dependent voltage from a thermocouple joint

- Four possible mechanisms to take heat away from sensing element:
  - **Radiative** heat transfer to surroundings
  - **Conduction** along the sensing element
  - **Conduction** through the residual gas
  - **Convective** heat flow to the residual gas



Instrumentation

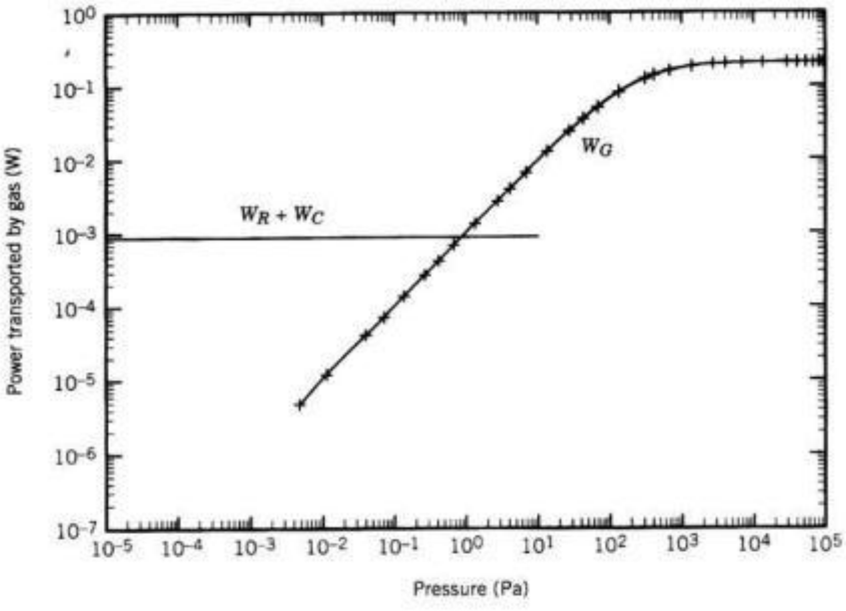
Thermal Conductivity Gauges

Radiative heat transfer: does not depend on pressure

Conduction along the wire: does not depend on pressure

Convection for pressure higher than 100 mbar

Conduction through the residual gas: linear with pressure. Gas properties determine variation in sensor response to pressure



Instrumentation

Thermal Conductivity Gauges

Constant current mode:

As pressure decreases, less heat is removed by conduction through the gas from the sensing element, and temperature increases.

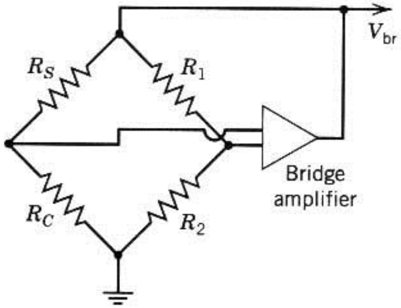
→Measure temperature dependent change of resistance (or TC voltage).

Constant temperature mode:

Adjust current to heater to maintain constant sensor property (resistance or voltage)

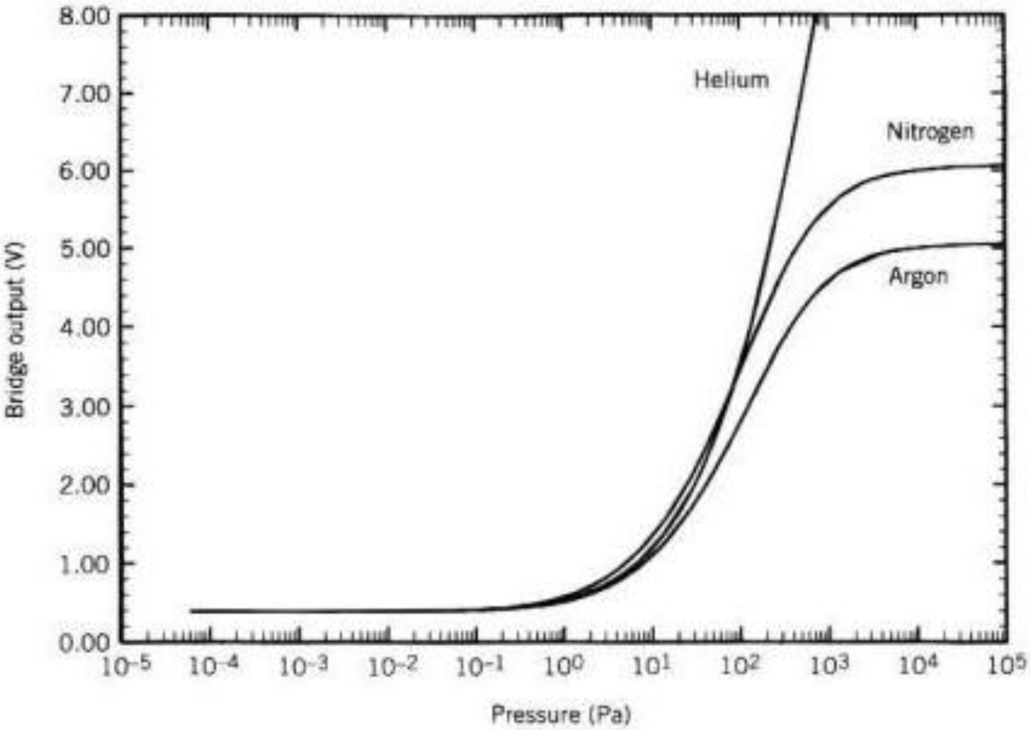
Use Wheatstone bridge arrangement to optimize sensitivity

→Correlate current flow against pressure



Instrumentation

Thermal Conductivity Gauges



Instrumentation

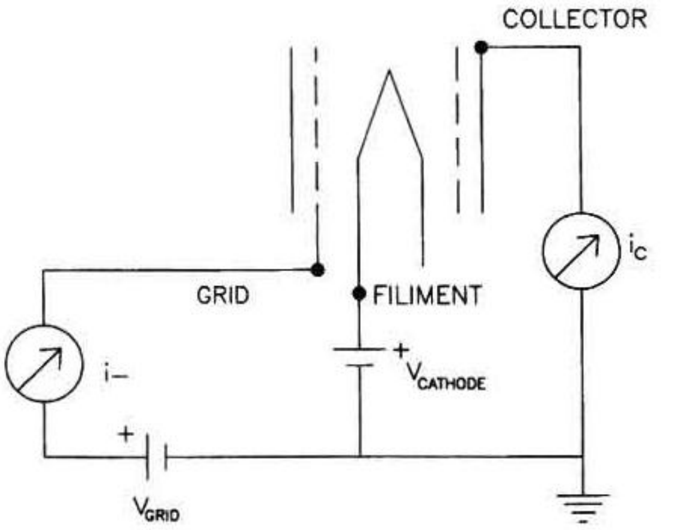
Ionization Gauges

Hot cathode gauge

Thermionic source (electrons) cause inelastic collisions with gas, producing ions

Ions collected at (-) biased surface

Electrons travel to a grid

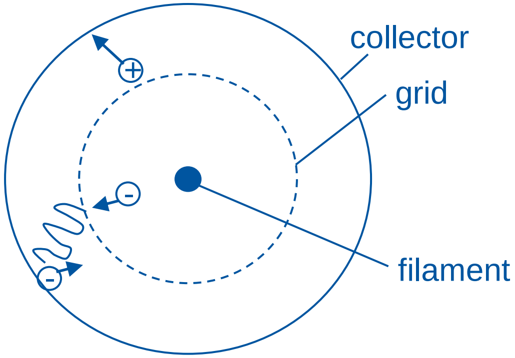


Basic circuit for operating a hot-cathode ionization gauge

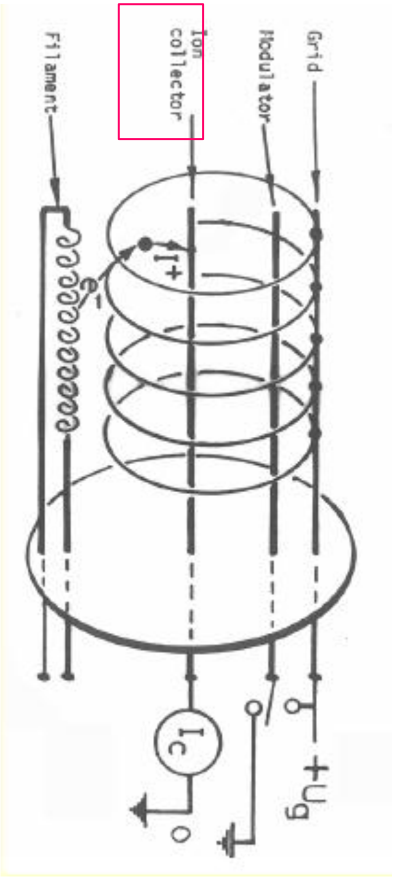
Pre-1950 lower limit of 10^{-8} mbar

Soft x-rays produced at grid result in photo-electron flow away from collector (same as ion flow to collector)

Bayard-Alpert modification: fine wire collector surrounded by grid ⇒ range extended to 10^{-12} mbar



- Bayard-Alpert gauges are used for vacuum measurement purposes in the range 10^{-5} -10^{-12} mbar.
- It is a hot filament ionization gauge. Electrons emitted by the filament perform oscillations inside the grid and ionize the molecules of the residual gas. Ions are then collected by an electrode.



$$\boxed{I^+ = I^- \sigma n L}$$

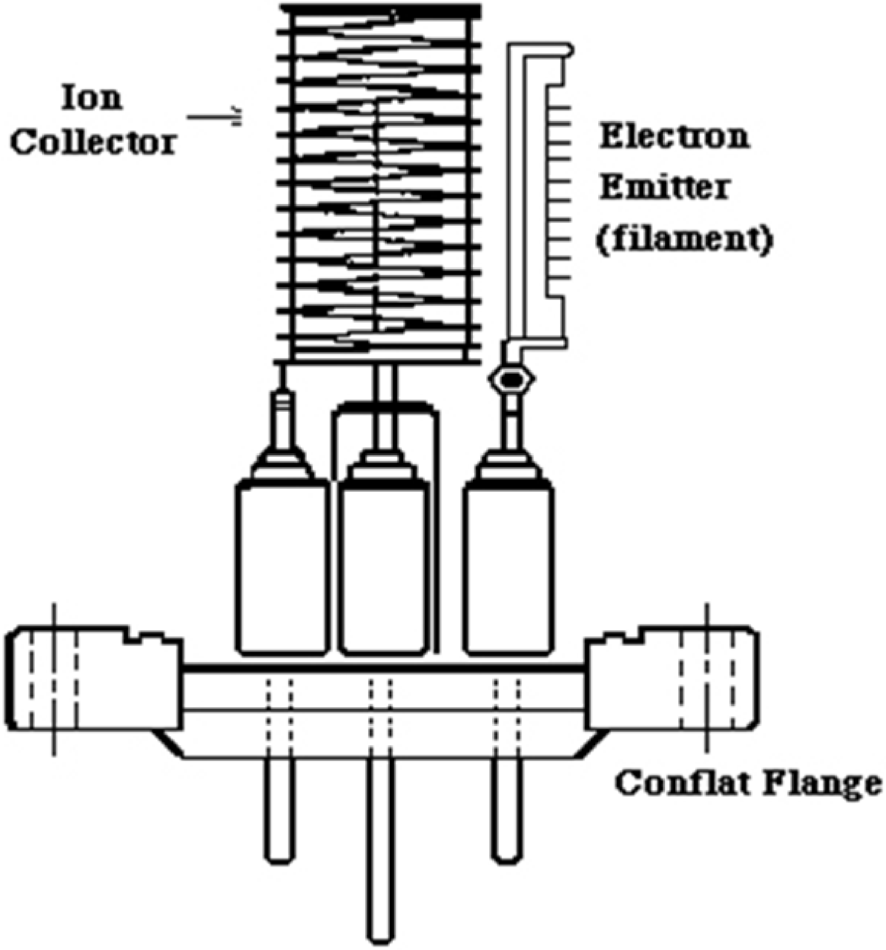
Where :

  - I^+ is the ion current
  - I^- is the filament current
  - σ is the ionisation cross section
  - n the gas density
  - L the electron path lenght

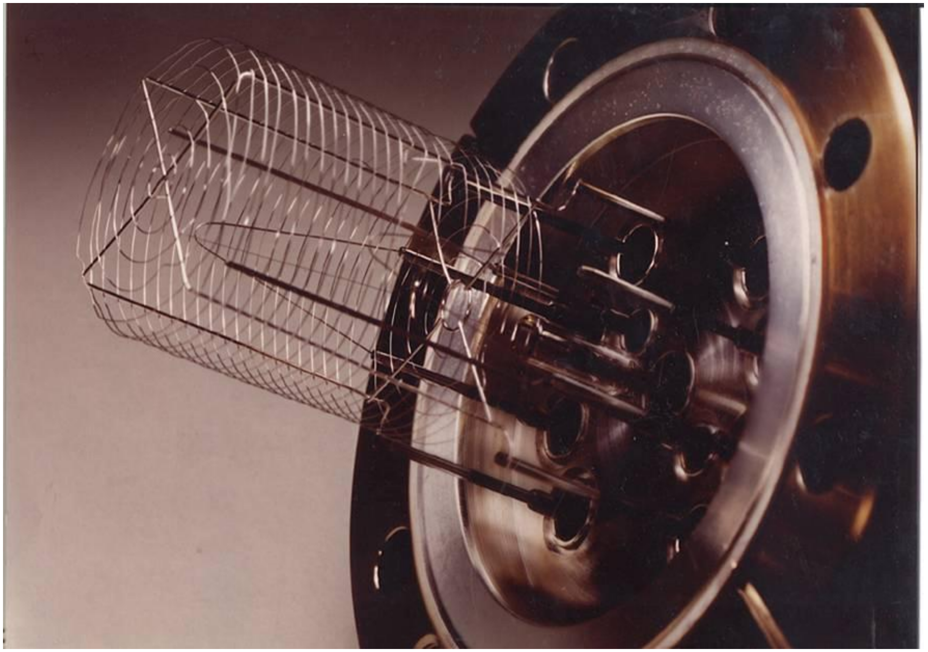
- The gauge needs to be calibrated
- X-ray limit of a few 10^{-12} mbar

Instrumentation

Ionization Gauges



Collisions between electrons, with sufficient energy, and gas molecules results in the ionization of the gas species. The resultant ion current can be measured and correlated with gas pressure.



SVT Bayard Alpert modulated gauge 10^{-12} Torr

Instrumentation

Ionization Gauges

Cold Cathode Gauge: Invented by Penning in 1937 - electrical configuration like diode SIP

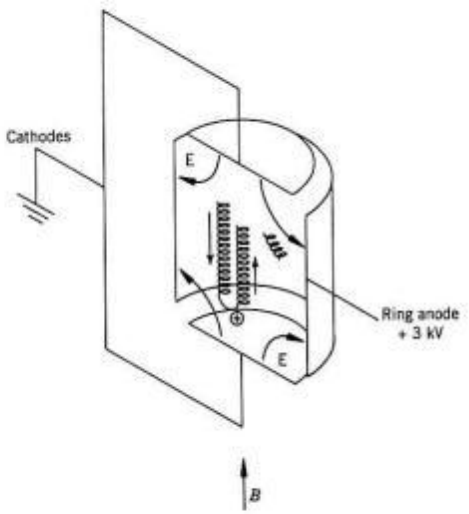
1952 design of wire-in-cylinder with reverse polarity (+ wire) provides key performance improvement

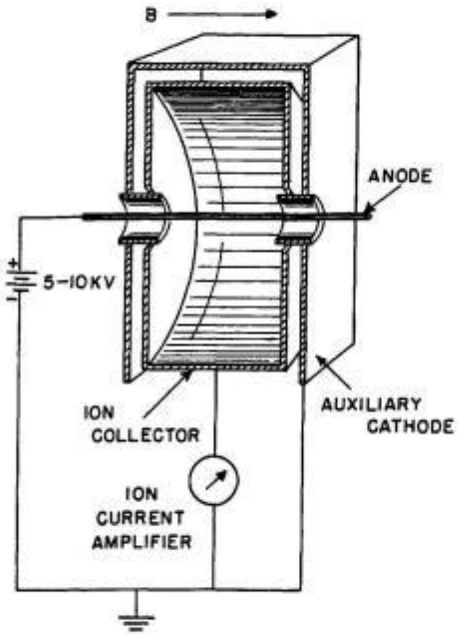
“Inverted Magnetron” - Magnetic field produces long helical path for electrons & ions ⇒ many collisions

Ionizing electrons part of self-sustaining gas discharge

No background current to mask the ion current

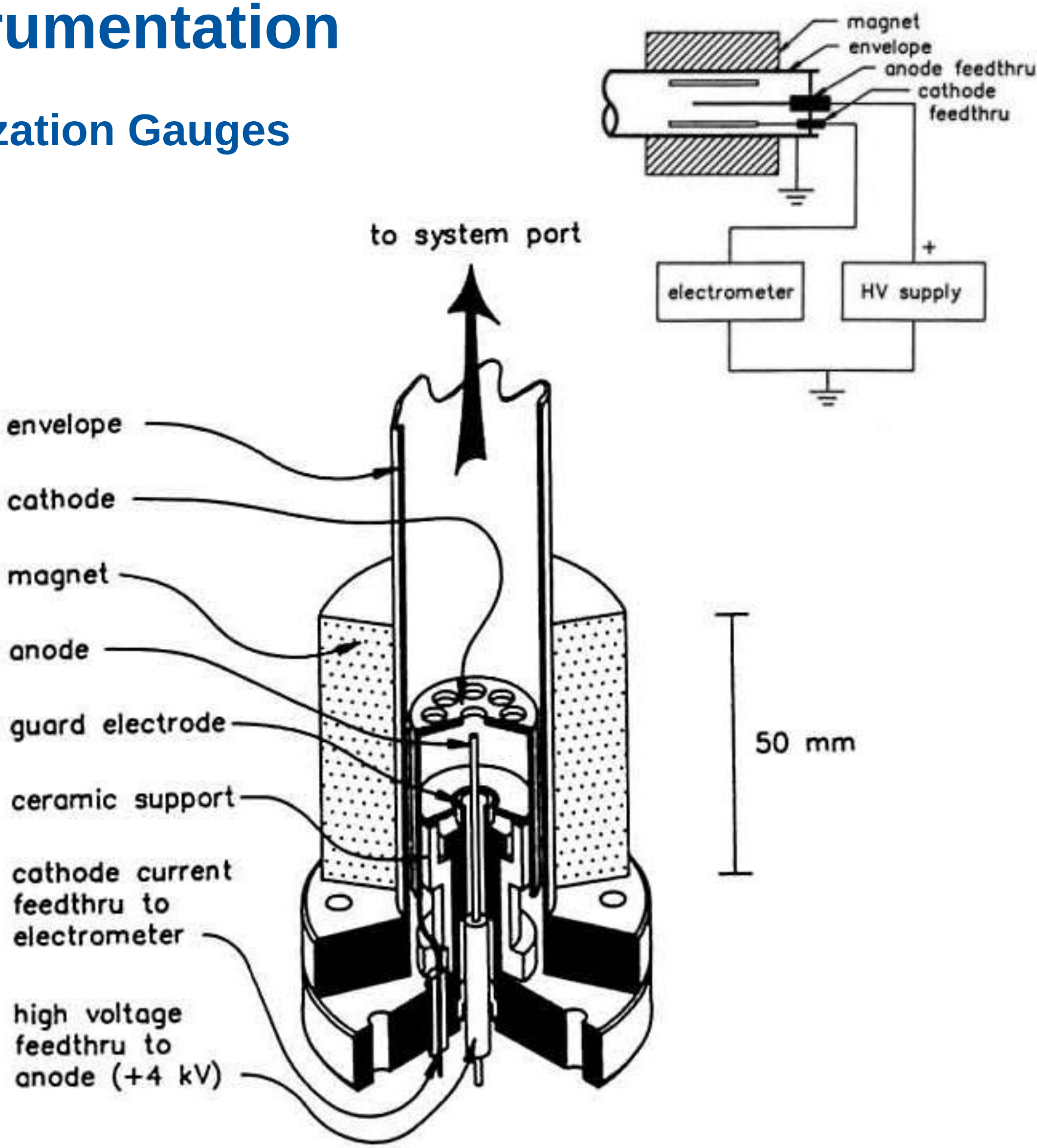
Power into CCG ~ 0.1 W





Instrumentation

Ionization Gauges



"**Striking time**" is delay before discharge starts.

At 10^{-4} Pa, t_s ~ seconds; at 10^{-8} Pa, t_s ~ hours or days

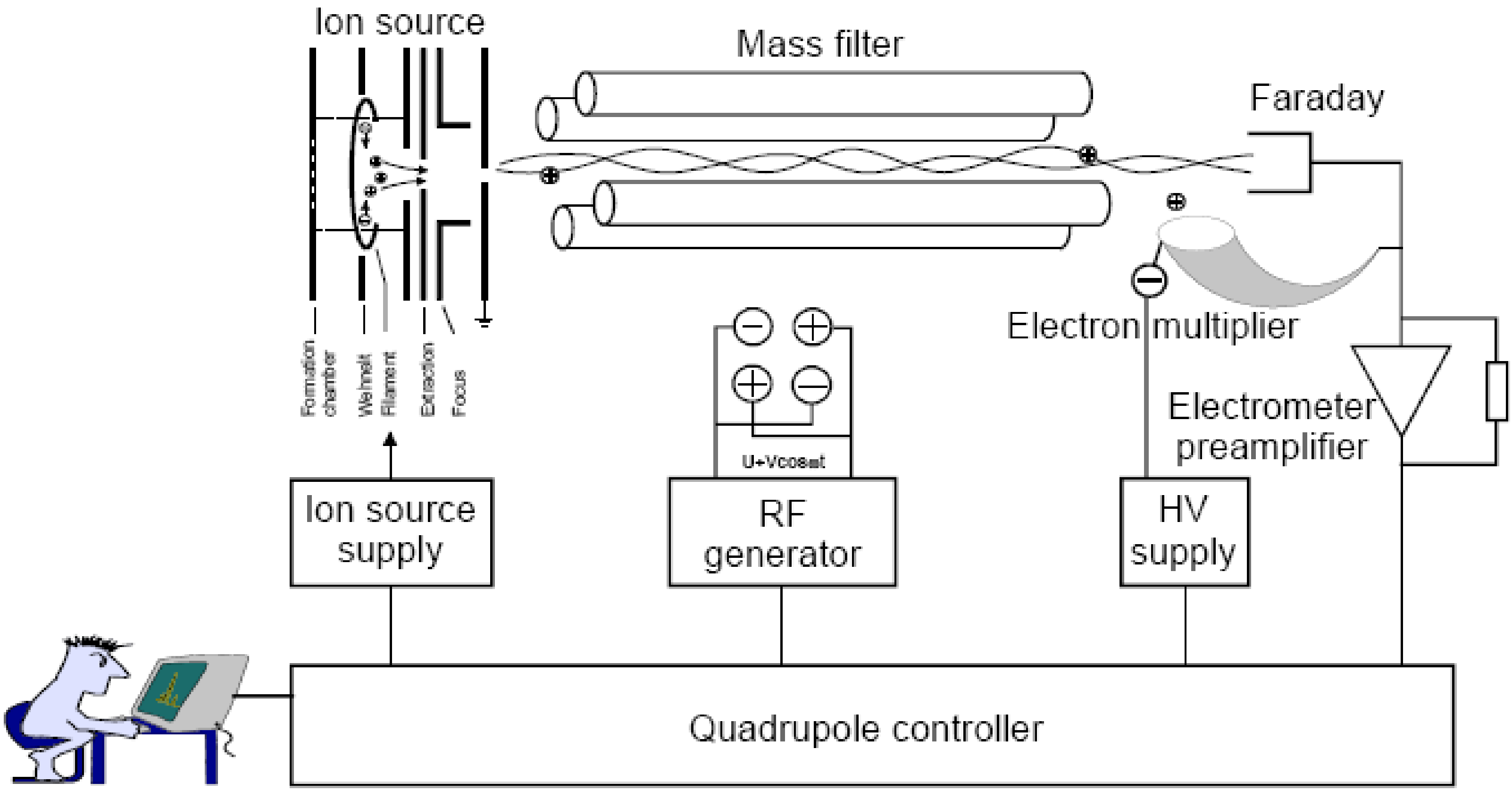
Nearly linear dependence of ion current with pressure:

$$i_g = KP^n; \quad n = 1.05 - 1.2$$

Typical anode voltage +3 kV

Instrumentation

Residual gas analyzers



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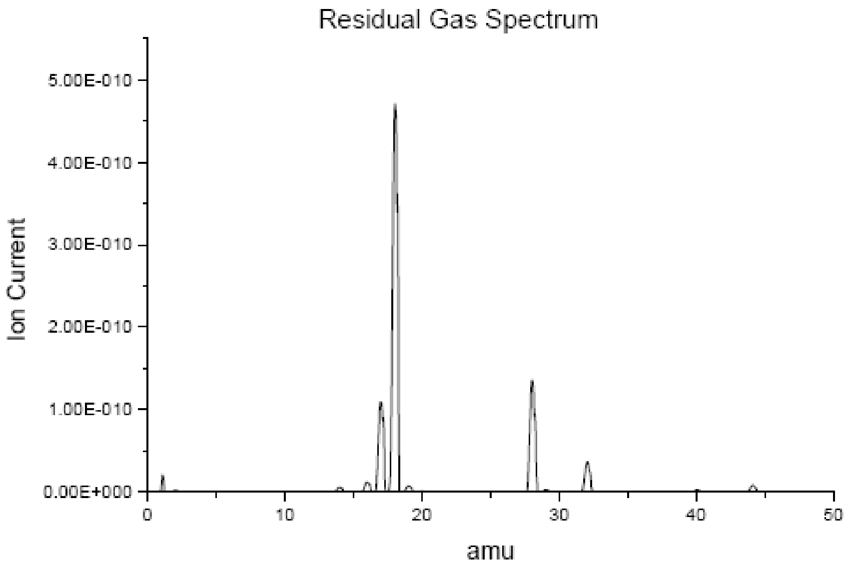
RGA


Residual Gas Spectrum
Ion Current
5.00E-010
4.00E-010
3.00E-010
2.00E-010
1.00E-010
0.00E+000
0
10
20
30
40
50
amu

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