Vacuum Technology for Superconducting Devices

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Outline

- **Some definitions and degree of vacuum.**
- **Thermal transport at low pressure.**
- **Mass transport at low pressure:**
  - ❖ Conductance
  - ❖ Pumping speed.
  - ❖ Electrical analogy.
- **Gas sources:**
  - ❖ Outgassing.
  - ❖ Inleakeage.
- **Pumping technologies:**
  - ❖ Momentum transfer.
  - ❖ Capture pumps.
- **Pressure measurement in vacuum.**

Appendices

1. Basic elements.
2. Numerical values for slides 6 and 7.
3. Numerical values of conductances.
4. Pressure profiles.
5. Outgassing values.
6. Complement of info about sputter ion pumps.
7. A few notes about cryopumps.

Some Definitions and Degree of Vacuum

Vacuum for superconductivity in particle accelerators:

1. Thermal insulation for cryogenic systems.
2. Physical vapour deposition of superconducting thin films

	Pressure boundaries [mbar]	Pressure boundaries [Pa]
Low Vacuum LV	10^3-1	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	$<10^{-12}$	$<10^{-10}$

Some Definitions and Degree of Vacuum

The framework:

1. **Ideal gas** :

$$PV = N_{moles}RT \implies PV = N_{molecules}k_BT \Rightarrow N_{molecules} = \frac{PV}{k_BT};\, n = \frac{P}{k_BT}$$

2. **Maxwell-Boltzmann model**:

molecular mean speed

$$\langle v\rangle = \sqrt{\frac{8k_BT}{\pi\, m}}$$

RT: $\langle v\rangle_{H2} = 1761\,\frac{m}{s}$

LHe: $\langle v\rangle_{H2} = 213\,\frac{m}{s}$

impingement rate

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

$\mathrm{RT} - 10^{-8}Pa - N_2$

$\varphi = 1.1\ 10^{11}\,\frac{collisions}{cm^2 s}$

mean free path

$$l = \frac{1}{\sqrt{2}\,n\,\pi\,\delta^2}$$

$\mathrm{RT} - 10^{-8}Pa - N_2$

$l \cong 700\ km$

Knudsen number $\Rightarrow$ $\boldsymbol{K_n = \frac{l}{D}}$

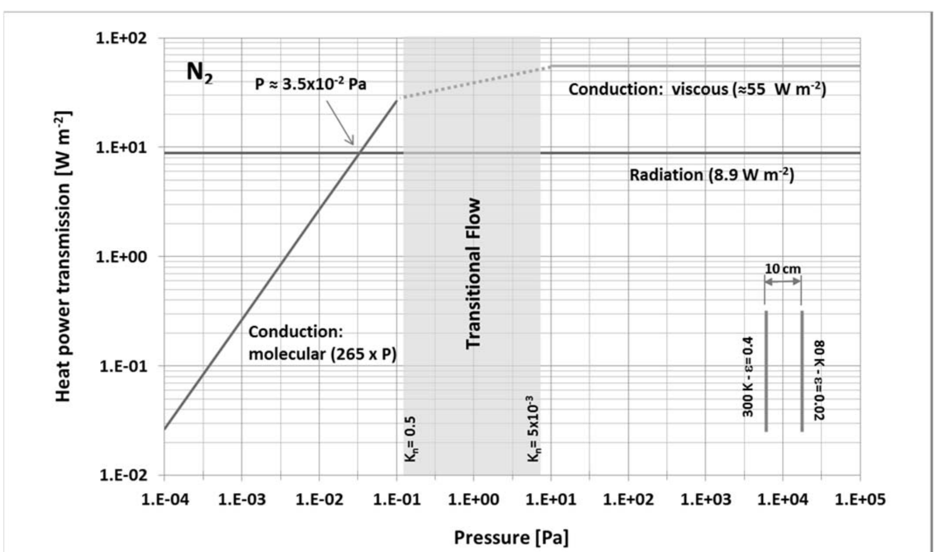
D is a characteristic dimension of a vacuum system (e.g. the diameter of a beam pipe).

Some Definitions and Degree of Vacuum

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

Both heat and mass transport are strongly dependent on the gas flow regime.

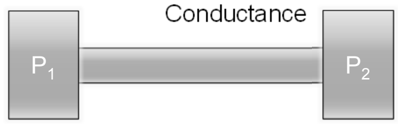
Thermal Transport at Low Pressure



Mass Transport at Low Pressure: Conductance

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

Gas flow → Q; Conductance → C; Pressure difference → $(P_1 - P_2)$



$$[Q] = \frac{[P]\,[V]}{[t]} \rightarrow \frac{mbar\ l}{s}$$

$$[C] = \frac{[V]}{[t]} \rightarrow \frac{l}{s}$$

For N_2:
T = 300K
Cylindrical duct
L = 2 m; D = 0.1 m

In molecular: **C ≈ 60 l/s**

In viscous: **C ≈ 70000 l/s**
for P_1-P_2 = 1000 Pa

C depends on:

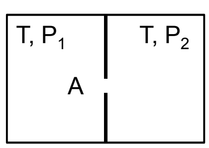
molecular regime:
- Geometry of the duct
- Mass of the gas molecule
- Temperature of the gas

viscous regime (all of the above, plus):
- Viscosity
- ***Pressure***
- Reynolds number

Conductances are much lower in molecular regime.

Mass Transport at Low Pressure: Conductance

Wall slot of area A and infinitesimal thickness; molecular regime:



$$C = \frac{1}{4}A\langle v\rangle = AC' \rightarrow \frac{l}{s}$$

$$C' = \frac{1}{4}\langle v\rangle \rightarrow \frac{l}{s.\,cm^2}$$

In general, the transmission probability τ is introduced:

(see appendix 3, p. 53)

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

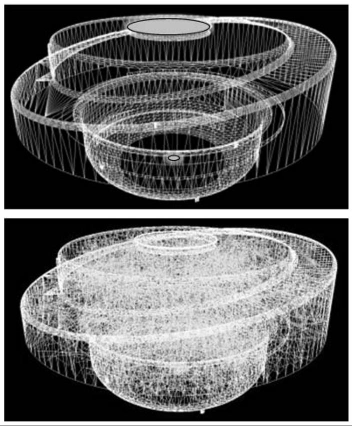
$$C = [AC' = conductance\ of\ the\ aperture] \times [molecular\ transmission\ probability]$$

Mass Transport at Low Pressure: Conductance

Analytical expressions for the transmission probability can be found for ducts of circular, rectangular and elliptical cross section. For long cylindrical tubes: $\tau \approx \frac{8}{3}\frac{R}{L}$.

$$\rightarrow C = C'A\,\tau \approx 11.75 \times \frac{\pi D^2}{4} \times \frac{4D}{3L} = \mathbf{12.3}\,\frac{\boldsymbol{D^3}}{\boldsymbol{L}} \left[\frac{l}{s}\right] \;([D]\;and\;[l] = cm\;)$$

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



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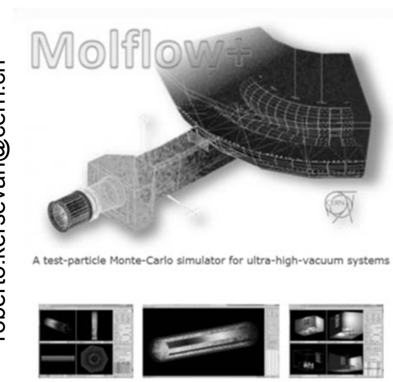
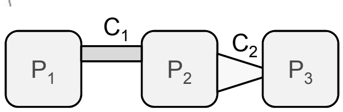


http://cern.ch/test-molflow

Mass Transport at Low Pressure: Conductance



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

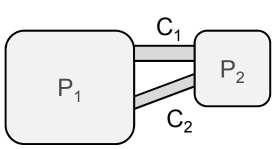
In steady conditions, there is no gas accumulation in the whole system: Q_1=Q_2=Q_3

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** :

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

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



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

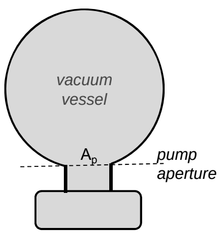
Q_{TOT}=Q_1+Q_2 → $C_{TOT} = C_1 + C_2$ → $\boldsymbol{C_{TOT}} = \sum_{\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{C_i}$

Mass Transport at Low Pressure: 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:

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

The molecule removal rate can be written as $\frac{1}{4} A_P\, n\langle v\rangle\, \sigma = A_P\, C' n\, \sigma = A_P\, C' \frac{P}{k_B T} n\, \sigma$



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

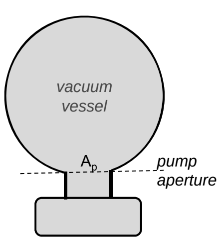
Mass Transport at Low Pressure: Pumping Speed

As usual, in term of pressure and PV units:

$$Q_P = A_P C' \sigma\, P \rightarrow \boldsymbol{S = A_P C' \sigma}$$

S depends on the conductance of the pump aperture $A_P C'$ and the capture probability σ.
σ may depend on many parameters including pressure, kind of gas, and quantity of gas already pumped.

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

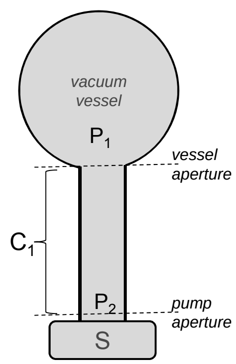
ID [mm]	H_2	N_2	Ar
36	448	120	100
63	1371	367	307
100	3456	924	773
150	7775	2079	1739

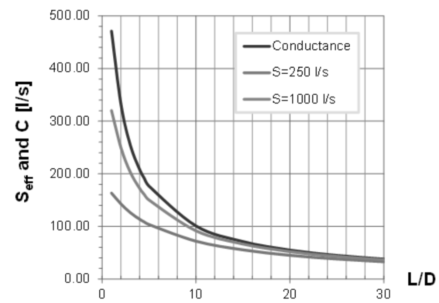
Mass Transport at Low Pressure: Pumping Speed

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:

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

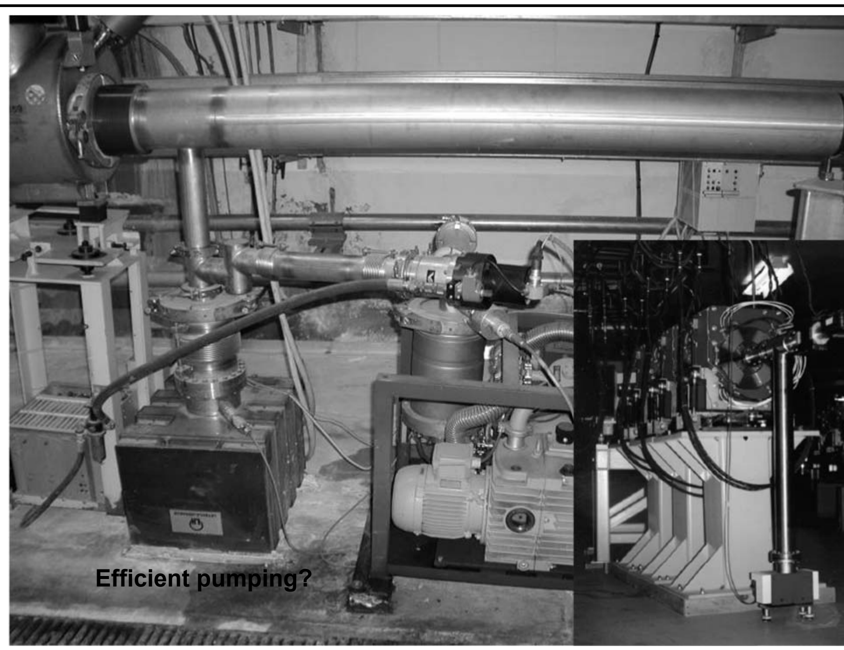
$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$ when C<<S: $S_{eff} \approx C$



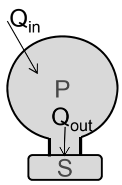


Example

Vessel and pump connected by a 100 mm diameter tube; $\mathbf{N_2}$, S=250 l/s and 1000 l/s.



Mass Transport at Low Pressure: Transient

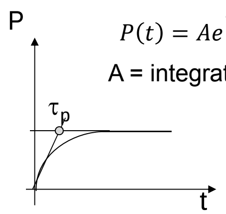


From the ideal gas equation: $PV = Nk_BT \rightarrow V\frac{dP}{dt} = k_BT\frac{dN}{dt}$

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

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

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



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

A = integration constant

$P(0) = P_0 \rightarrow P(t) = \left(P_0 - \frac{Q_{in}}{S}\right)e^{-\frac{t}{\tau_p}} + \frac{Q_{in}}{S}$

$P(0) = 0 \rightarrow P(t) = \frac{Q_{in}}{S}\left(1 - e^{-\frac{t}{\tau_p}}\right)$

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

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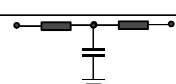
CAS Superconductivity for Accelerators, Erice.
Vacuum Techniques for Superconducting Devices

May 3rd, 2013

15

Electrical analogy

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 divided into 'n' subparts in order to evaluate the pressure profile along the main axes. $C_n = C_{TOT} \times n$ and $V_n = V_{TOT}/n$.
- **Non-linear** electric characteristics can be used to simulate pressure and time dependent conductance and pumping speed.
- In this way pressure profiles and transients in **viscous regime** can be calculated.

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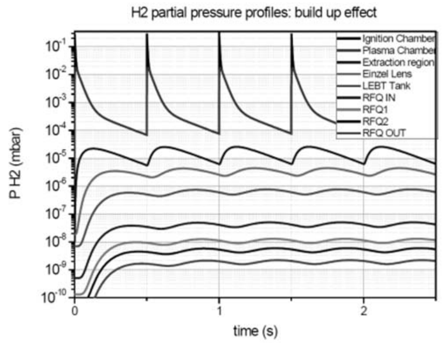
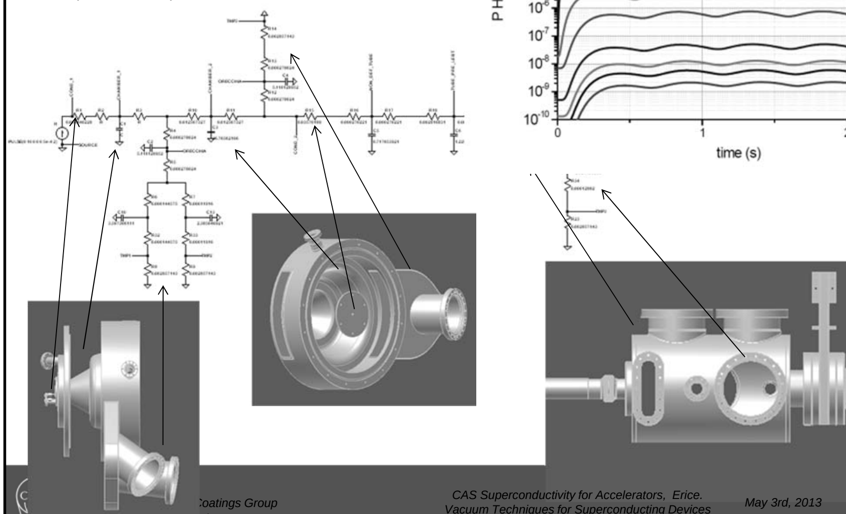
16

Electr

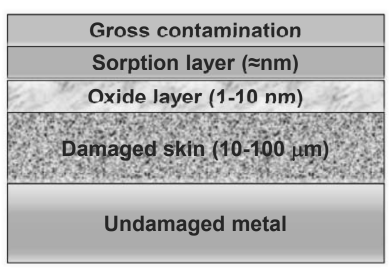
Simple example: differential pumping

A more complex example: part of the Linac4 H- source *(from C. Pasquino et al., CERN, ATS/Note/2012/043 TE*





Gas Sources



Courtesy of M. Taborelli

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 **a**ge**nt**). Based on molecule with hydrophilic heads and lipophilic tail: less selective than solvents

Gas Sources: Outgassing

Any material in vacuum is a spontaneous source of gas.

Metals

After state-of-art surface cleaning:

- If not heated in situ: mainly **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 **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 **H_2O.**
- In general, the outgassing process is dominated by H_2O release.
- In the initial phase of pumping:

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

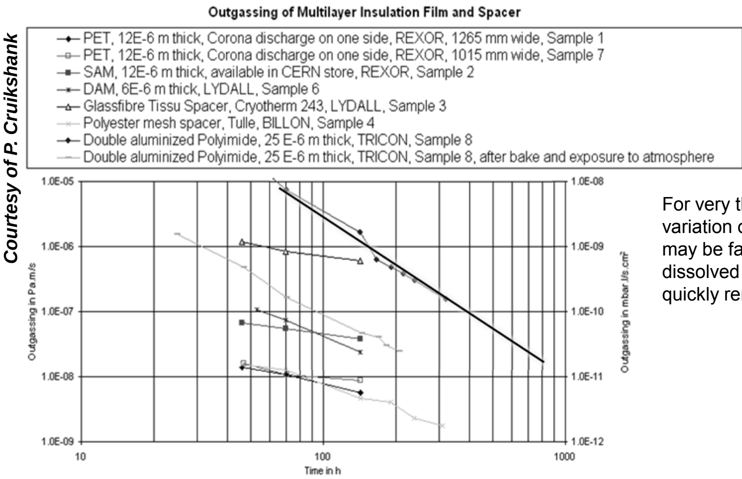
- Heavier gas molecules can be outgassed (remnant of polymerization, fraction of polymeric chains).
- The **permeation** of light molecules is not negligible, in particular He.

Gas Sources: Outgassing

At room temperature

Material	q (mbar l s^{-1} cm^{-2})	Main gas species
Neoprene, not baked, after 10 h of pumping	order of 10^{-5}	H_2O
Viton, not baked, after 10 h of pumping	order of 10^{-7}	H_2O
Austenitic stainless steel, not baked, after 10 h of pumping	3×10^{-10}	H_2O
Austenitic stainless steel, baked at 150°C for 24 h	3×10^{-12}	H_2
OFS copper, baked at 200°C for 24 h	order of 10^{-14}	H_2

Courtesy of P. Cruikshank



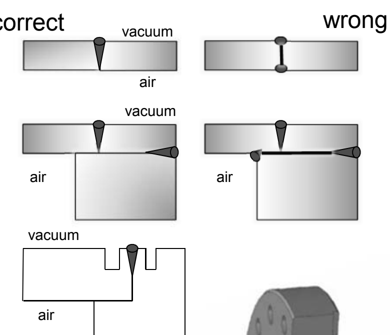
For very thin polymer foils, the variation of the outgassing rate may be faster than 1/t: the dissolved water vapour is quickly removed.

For an **LHC insulation vacuum** sector exposed to ambient air for several weeks, we obtain ~ 5 10^{-3} mbar at RT after ~ **200 hrs pumping** (S = 100 l/s, 250 m^2 of MLI per metre of length).

Equivalent to ~ **10^{-9} mbar.l.s^{-1}.cm^{-2} per layer of MLI** (equivalent to the outgassing rate of 2 soccer fields of stainless steel per metre of sector).

Gas sources: Inleakage

Other gas sources: virtual leaks → trapped air and impossible leak detection



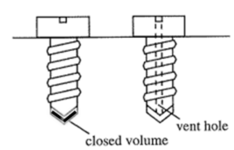
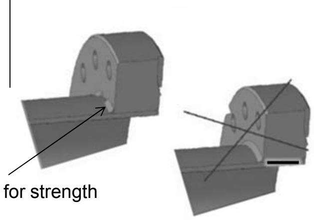
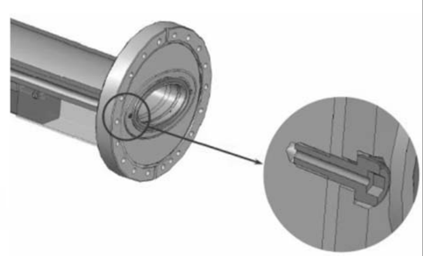


Fig 1 The screw to the right has a bored through ventilation hole to prevent virtual leaks and slow pump-down

Courtesy of L. Westerberg, CAS Vacuum 1999





Courtesy of K. Zapfe, CAS Vacuum 2006

Gas Pumping

In molecular regime:

- Gas molecules cannot be removed by suction: the molecules do not transfer energy and momentum among them; the pumps act on each molecule singularly.
- Pumps are classified in two families:

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

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

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

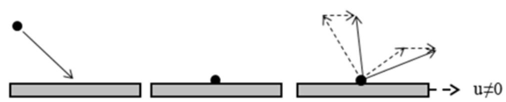
where E_a is the adsorption energy and $t_0 \approx \frac{h}{k_B T} \approx 10^{-13}$s.

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

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

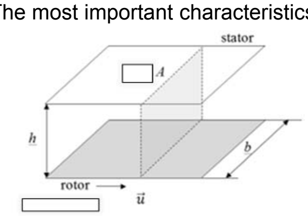
Gas pumping: Momentum Transfer Pumps

Molecules impinge and adsorb on the moving surface; on desorption the velocity distribution is superimposed by the drift velocity of the wall → a moving wall generates a gas flow.



The molecules receive a momentum components pointing towards the pump outlet where the gas is compressed and finally evacuated by pumps working in viscous regime.

The most important characteristics of molecular pumps are:



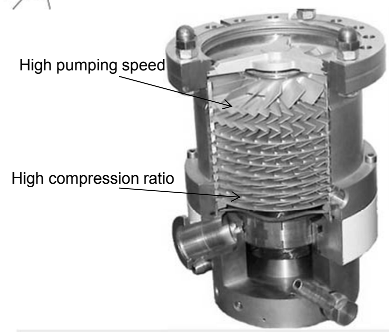
1.Pumping speed ⟹ $S \propto u \times A$

2.Maximum compression ratio:

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

S does not depend significantly on the mass of the molecule.
K_o depends exponentially on the wall speed and square root of the gas molecule mass.

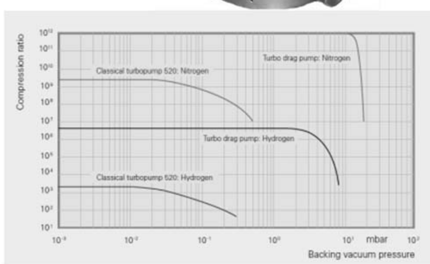
Gas pumping: Momentum Transfer Pumps

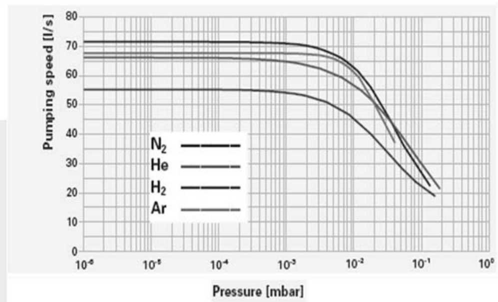


Courtesy of Pfeiffer Vacuum

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

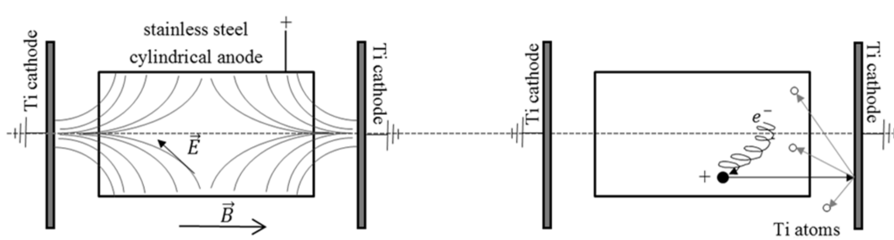




Courtesy of Pfeiffer Vacuum
http://www.pfeiffer-vacuum.com

Gas Pumping: Sputter Ion Pumps (SIP)

- In SIP the residual gas is ionized in a Penning cell.

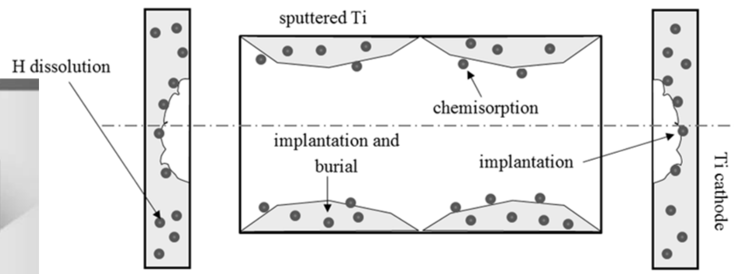


- The ions are accelerated towards a cathode made of a reactive metal.
- The collisions provoke sputtering of reactive-metal atoms that are deposited on the nearby surfaces.

Gas Pumping: Sputter Ion Pumps (SIP)

- 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 into the cathode and of energetic neutrals** bounced back from the cathode into the deposited film: only mechanism of pumping for rare gases
3. **diffusion** into the cathode and the deposited film: only H_2



Gas Pumping: Getter Pumps

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.**

Getter surfaces are characterized by the sticking probability α :

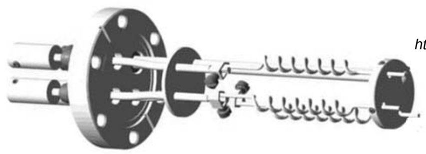
$$\alpha = \frac{number\ of\ molecules\ captured}{number\ of\ molecules\ impinging}$$

$$0 \le \alpha \le 1 \quad S = \alpha\, A_{getter} C'$$

For α=1, the pumping speed of the surface is equal to its maximum pumping speed.
Getter materials do not pump rare gases, and methane at room temperature.

Gas Pumping: Evaporable Getter 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.



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

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

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

The sticking probability is negligible:
- For CO, one monolayer adsorbed
- For of O_2 several monolayer
- For N_2 fraction of monolayer

Hydrogen diffuses in the Ti film→much higher capacity

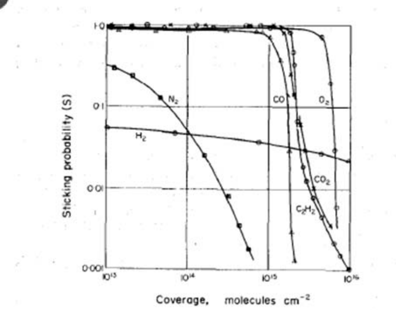
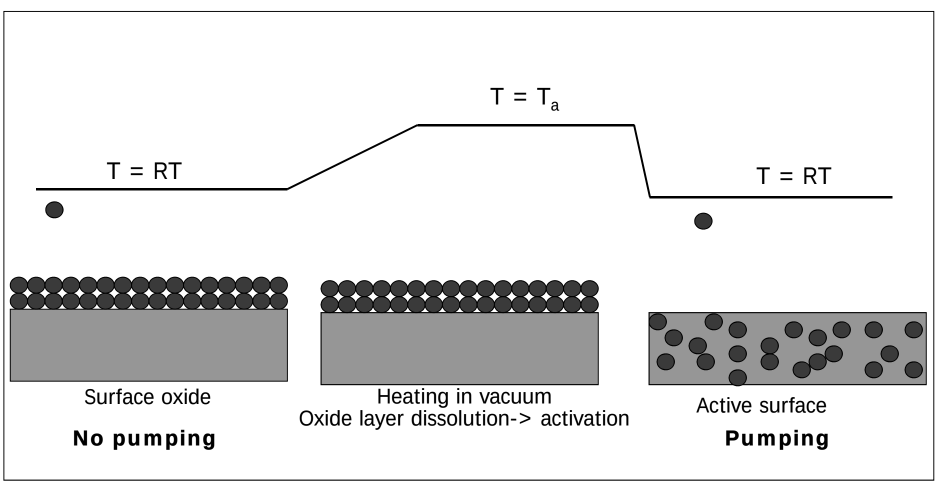


Figure 4. Room temperature sorption characteristics for pure gases on batch evaporated clean titanium films.

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

Gas Pumping: Non-Evaporable Getter Pumps

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



Gas Pumping: Non-Evaporable Getter Pumps

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

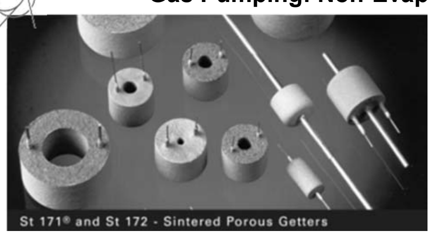
NEG materials are produced industrially by powder technology. Small fragments are sintered to form pellets, discs or plates. The powder can also be pressed at room temperature on metallic ribbon.

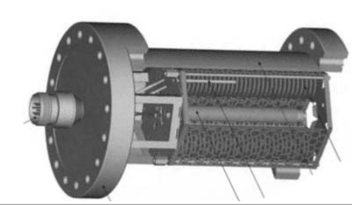
A typical alloy produced by SAES Getter is **St707**:

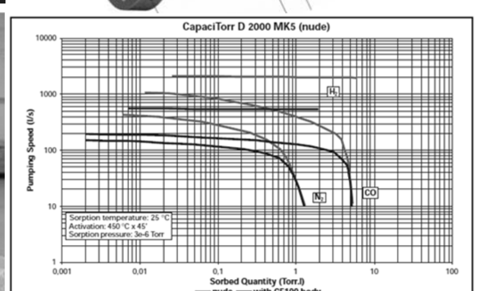
Element	Concentration [wt. %]	Main role in the alloy
Zr	70	- High O solubility limit. - Chemical reactivity
V	24.6	- Increases O diffusivity, - Chemical reactivity
Fe	5.4	- Reduces pyrophoricity

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

Gas Pumping: Non-Evaporable Getter Pumps







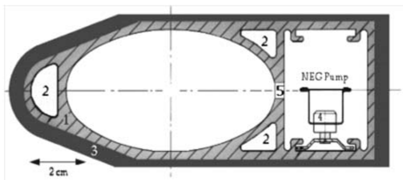
Courtesy of SAES Getters, www.saesgetters.com

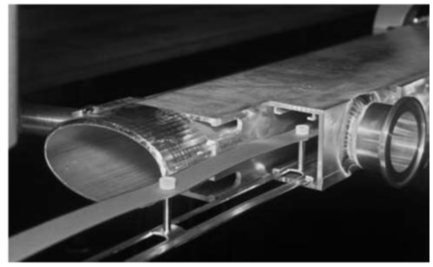
The **high porosity of NEG materials** allows pumping of relatively high quantities of gas without reactivation.

Gas Pumping: Non-Evaporable Getter Pumps

Linear pumping may be obtained by NEG ribbons.

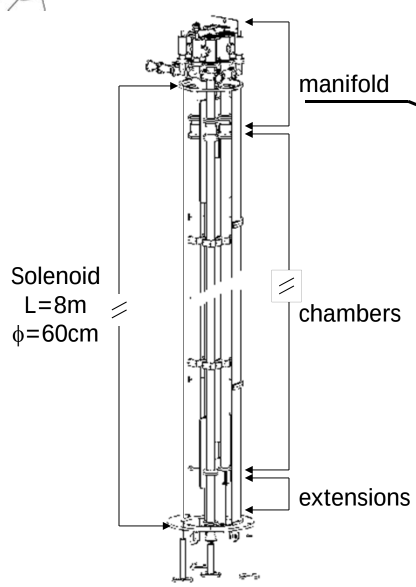
LEP dipole vacuum chamber



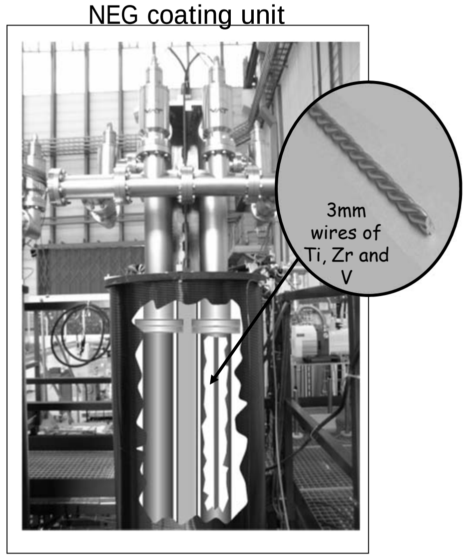


The first application was in the LEP**.**

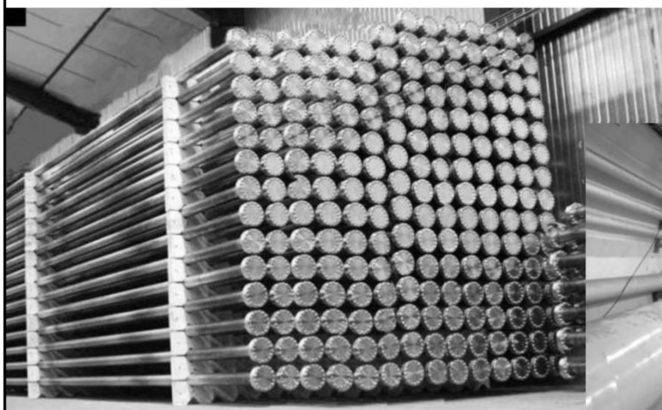
Gas Pumping: Non-Evaporable Getter Coatings



NEG coating unit



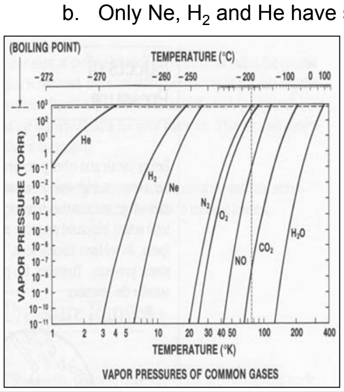
Gas Pumping: Non-Evaporable Getter Coatings



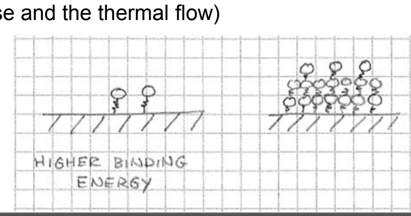
Gas Pumping: Cryopumping

Cryopumping relies 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. It limits the attainable pressure.
   b. Only Ne, H_2 and He have saturated vapour pressures higher than 10^{-11} mbar at 20 K.



   c. The vapour pressure of H_2 at 4.3 K is in the 10^{-7} mbar range, at 1.9 lower than 10^{-12} mbar.
   d. Large quantity of gas can be cryocondensed (limited only by the thermal conductivity of the condensate phase and the thermal flow)



Gas Pumping: Cryopumping

2. **Cryosorption**: is based on the **attraction between molecules and substrate**. The interaction is much stronger than that between similar molecules:

   a) Gas molecules are pumped at pressures 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.

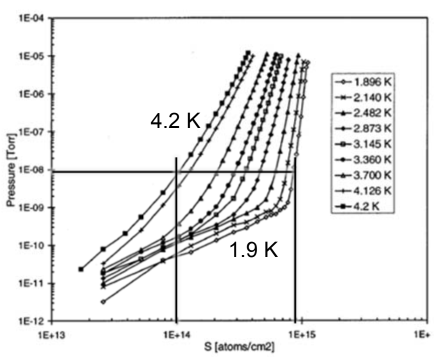
   b) The important consequence is that significant quantities of H_2 can be pumped at 20 K and He at 4.3 K.

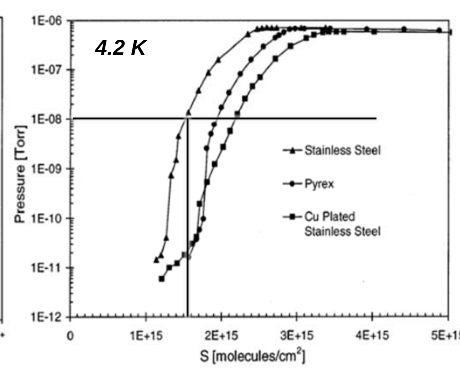
   c) Submonolayer quantities of all gases may be effectively cryosorbed at their own boiling temperature; for example at 77 K all gases except He, H_2 and Ne.

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: Cryopumping
LHC beam vacuum in the arcs

→ **Requirement**: 100 h beam life time (nuclear scattering) equivalent to ~ 10^{15} H_2/m^3 (10^{-8} mbar of H_2 at 300 K).





Pumping capacity of He decreases by an order of magnitude between 1.9K and 4.2 K

E. Wallén, J. Vac. Sci. Technol. A 15, 265 (1997)

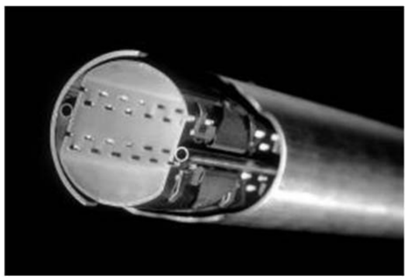
Gas Pumping: Cryopumping

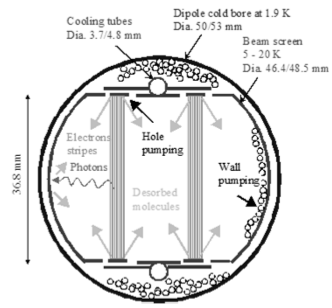
→ **Main gas source**: desorption stimulated by photon, electron and ion bombardment.

→ **Pumping:**

Molecules with a low vapour pressure are first cryopumped onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore.

Most of the H_2 is cryopumped onto the cold bore.





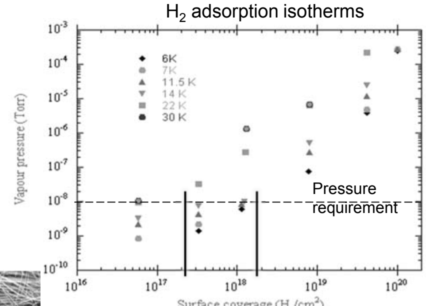
Courtesy of V. Baglin

Gas Pumping: Cryopumping

In a few cases, the cold bore temperature is higher than 1.9 K (stand alone magnets).

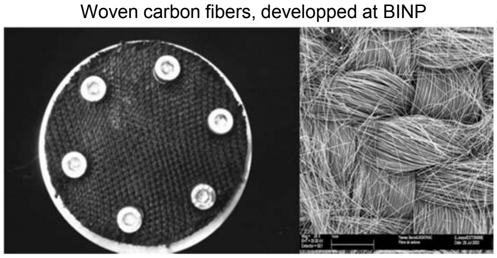
High specific surface materials are used to cryosorb H_2.

H_2 adsorption isotherms



Courtesy of V. Baglin

Woven carbon fibers, developped at BINP



Coverage limits :

- **10^{18} H_2/cm^2 at 6 K**
- **10^{17} H_2/cm^2 at 30 K**

Pressure Measurement

Physical phenomena	Name of gauges	Pressure range of gauge family	Fields of application	Advantages/ Limitations
Force measurement due to ∆P	• Manometers. • McLeod. • Bourdon. • Capacitance.	10^{-2}-10^{5} Pa	Metrology. Gas dosing. Gas line pressure.	Absolute gauges Easy to use
Viscous drag	• Spinning rotor.	10^{-4}-10^{3} Pa	Metrology.	High precision Cost Gas dependence To be used by trained technicians
Gas thermal conductivity	• Pirani. • Thermocouple.	10^{-1}-10^{3}	Rough measurement during pump-down.	Inexpensive Limited precision Fast response
Gas ionization	• Bayard-Alpert • Cold-cathode • Extractor	10^{-3}-10^{-12}	HV-UHV monitoring XHV measurement	Low pressure BA:X-ray limitation Sensitive to contamination

Conclusion

First Nb thin-film coated Cu cavity, at CERN by the Cris Benvenuti team in 1983.

The sputtering technique was used for the RF SC cavities of LEP2.

The experience in UHV technology achieved by the team during the ISR construction and upgrade was a key factor of their success.

On the other hand, the experience in Nb thin films led to the invention of Non-Evaporable Getter thin film coatings

Acknowledgements

I wish to thank all my colleagues of the Vacuum, Surfaces and Coatings group of the Technology Department at CERN, including students and visitors.

The VSC group has become a centre of excellence in Europe encompassing all aspects of vacuum technology, from surface treatments to computation, operation and control of unique facilities.

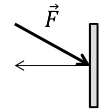
I am indebted with Giovanna Vandoni, Chiara Pasquino, Roberto Kersevan, and Jose Antonio Ferreira Somoza for their kind corrections of this lecture.

www.cern.ch

Appendices

Appendix 1: Basic Elements, Pressure Units

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



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

In vacuum technology: **mbar** or **Pa**

Still used in vacuum technology (particularly in USA): **Torr**
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

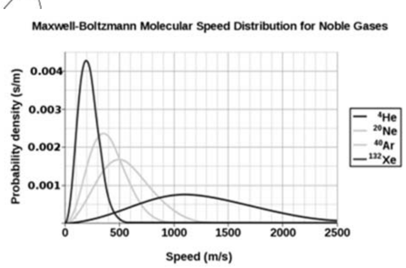
Appendix 1: Basic Elements, Gas Density

$P = n\, k_B \mathrm{T}$

Gas Density

	Pressure (Pa)	293 K (molecules cm^{-3})	4.3 K (molecules cm^{-3})
Atmospheric pressure at sea level	1.013×10^5	2.5×10^{19}	1.7×10^{21}
Typical plasma chambers	1	2.5×10^{14}	1.7×10^{16}
LHC experimental beam pipes	10^{-9}	2.5×10^{5}	1.7×10^{7}
Lowest pressure ever measured at room temperature	10^{-12}	250	1.7×10^{4}

Appendix 1: Basic Elements, Mean speed of a molecule



Courtesy of Wikipedia: http://en.wikipedia.org/wiki/Maxwell%E2%80%93Boltzmann_distribution

Mean speed of a molecule

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]

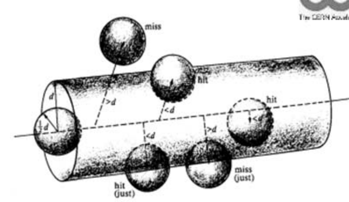
Gas	$\langle v \rangle$ *at* 293 *K* $\left[\frac{m}{s}\right]$	$\langle v \rangle$ *at* 4.3 *K* $\left[\frac{m}{s}\right]$
H_2	1761	213
He	1244	151
CH_4	622	75
N_2	470	57
Ar	394	48

Appendix 1: Basic Elements, Impingement rate

$$\varphi = \frac{1}{4} n \langle v \rangle = \frac{1}{4} n \sqrt{\frac{8\, k_B T}{\pi\, m}} \qquad \varphi[cm^{-2} s^{-1}] = 2.635\ 10^{22} \frac{P\ [mbar]}{\sqrt{M[g] T[K]}}$$

Gas	Pressure [mbar]	Impingement rate 293 K [$cm^{-2}s^{-1}$]
H_2	10^{-3}	$1.1\ 10^{18}$
	10^{-8}	$1.1\ 10^{13}$
	10^{-14}	$1.1\ 10^{7}$
N_2	10^{-3}	$2.9\ 10^{17}$
	10^{-8}	$2.9\ 10^{12}$
Ar	10^{-3}	$2.4\ 10^{17}$
	10^{-8}	$2.4\ 10^{12}$

Appendix 1: Basic Elements, 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 l , i.e. the average distance travelled by a molecule between collisions:

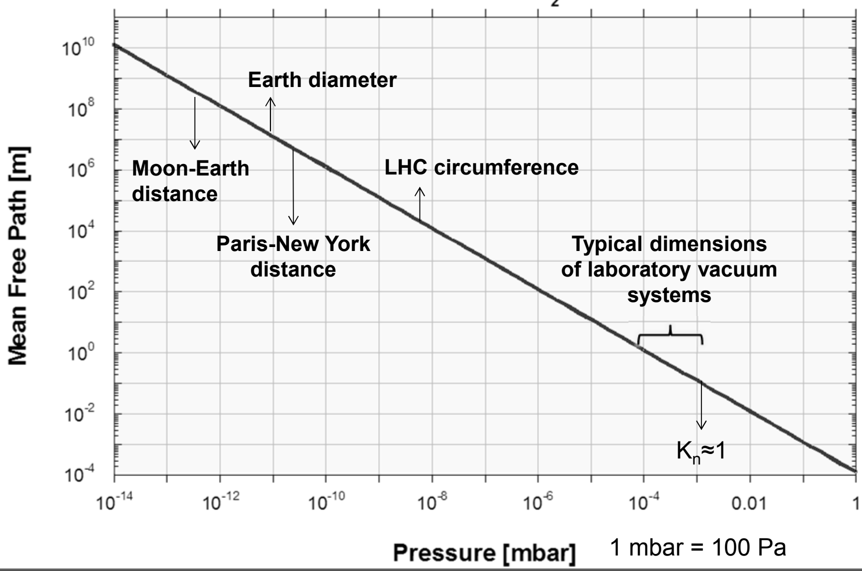
$$l = \frac{\langle v \rangle}{\omega} = \frac{1}{\sqrt{2}\, \pi\, n\, \delta^2} = \frac{k_B T}{\sqrt{2}\, \pi\, P\, \delta^2}$$

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

$$l_{H_2}[m] = 4.3\ 10^{-5} \frac{T[K]}{P[Pa]} \qquad l_{N_2}[m] = 2.3\ 10^{-5} \frac{T[K]}{P[Pa]}$$

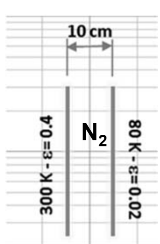
Appendix 1: Basic Elements, Mean Free Path

Mean Free Path for H_2 at 293 K



1 mbar = 100 Pa

Appendix 2: Numerical values for slide No. 6



Conduction in viscous regime

$$k_{th} = 25.3\ {}^{mW}/_{K\,m}$$
$$q_{th} \approx k_{th}\frac{\Delta T}{L} = 55.7\ \frac{W}{m^2}$$

For diatomic molecules:

$$k_{th} = \frac{1}{4}(9\gamma - 5)\,\eta\, c_V \left[\frac{W}{m\,K}\right]$$
$$\eta = \frac{5}{16}\frac{1}{\delta^2}\sqrt{\frac{m_{N_2}k_B T}{\pi}}$$
$$\gamma = \frac{c_P}{c_V} = \frac{7}{5}\ ;\ c_V = \frac{5}{2}\frac{k_B}{m_{N_2}};\ c_P = c_V + \frac{k_B}{m_{N_2}}$$
$$m_{N_2} = 4.6 \times 10^{-26} Kg \quad \delta = 370\ pm$$

Conduction in molecular regime

$$q_{th} \approx 265\ P\ \frac{W}{m^2}$$

$$q_{th} = \frac{P}{8}\langle v\rangle a_E \frac{\gamma + 1}{\gamma - 1}\frac{T_1 - T_2}{\frac{T_1 + T_2}{2}}$$

$\langle v\rangle$ at the average temperature=381m/s

a_E equivalent accommodation coefficient

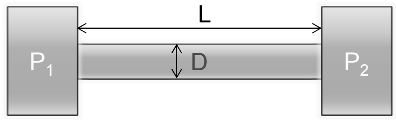
$a_E \approx 0.8$

Radiation

$$q_{rad} \approx 8.9\frac{W}{m^2}$$

$$q_{rad} = \sigma\frac{T1^4 - T2^4}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$
$$\sigma = 5.7 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$$

Appendix 2: Numerical values for slide No. 7



Poiseuille equation for long circular pipes in **viscous regime**:

$$C = \frac{\pi D^4}{128\,\eta L}\,(P_1 - P_2) \qquad \eta = \frac{5}{16}\frac{1}{\delta^2}\sqrt{\frac{m k_B T}{\pi}}$$

For N_2:
$\delta = 370$ pm
m = $4.6\text{x}10^{-26}$ Kg

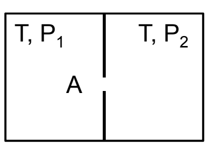
T = 300K
P_1-P_2 = 1000 Pa
L = 2 m; D = 0.1 m

$\eta = 17.5 \times 10^{-6}$ Pa.s

C =70 m^3/s = 70000 l/s

Appendix 3: Numerical Values of Conductances

Wall slot of area A and infinitesimal thickness; molecular regime:



Gas flow 1 → 2 : $\varphi_{1\to2} = \frac{1}{4} A\, n_1 \langle v \rangle$

Gas flow 2 → 1 :$\varphi_{2\to1} = \frac{1}{4} A\, n_2 \langle v \rangle$

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 $(PV = N k_B T) \rightarrow Q = \frac{1}{4} A \langle v \rangle (P_1 - P_2) \rightarrow \boldsymbol{C = \frac{1}{4} A \langle v \rangle = AC'}$

For other gas flow restrictions, the transmission probability τ is introduced:

Gas flow 1 → 2 : $\varphi_{1\to2} = \frac{1}{4} A_1 n_1 \langle v \rangle\, \tau_{1\to2}$

Gas flow 2 → 1 :$\varphi_{2\to1} = \frac{1}{4} A_2\, n_2 \langle v \rangle\, \tau_{2\to1}$

$Q = \frac{1}{4} A_1 \langle v \rangle\, \tau_{1\to2} (P_1 - P_2) \rightarrow \boldsymbol{C = A_1 C'\, \tau_{1\to2}}$

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

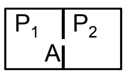
Appendix 3: Numerical Values of Conductances

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	117.5	11.75
Ar	394	98.5	9.85

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



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

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

Paolo Chiggiato
Vacuum, Surfaces & Coatings Group
Technology Department

Appendix 3: Numerical Values of Conductances

Santeler formula for transmission probabilities of cylindrical tubes

- 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 $\frac{L}{R} \gg 1$

$\rightarrow C = AC'\,\tau \approx 11.75 \times \frac{\pi D^2}{4} \times \frac{4D}{3L} = 12.3\,\frac{D^3}{L}\left[\frac{l}{s}\right]$ ($[D]$ and $[l] = cm$)

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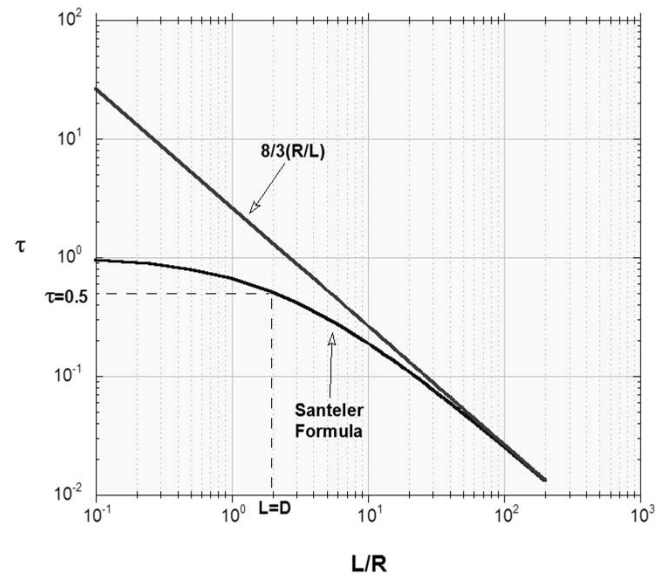
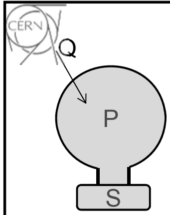
Technology Department

Appendix 3: Numerical Values of Conductances

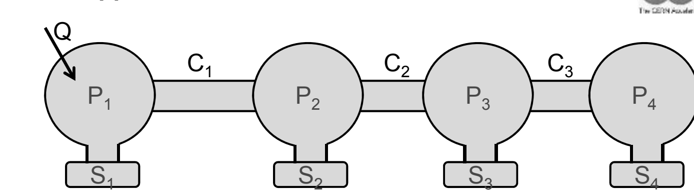


L/R	Cole mean value[e]
0.1	0.952 398 907
0.2	0.909 215 028
0.3	0.869 928 148
0.5	0.801 271 420
0.7	0.743 409 790
0.9	0.694 043 732
1.0	0.671 983 902
1.2	0.632 228 253
1.4	0.597 364 010
1.6	0.566 507 335
1.8	0.538 974 541
2.0	0.514 230 527
3.0	0.420 055 30
4.0	0.356 572 25
5.0	0.310 524 62
6.0	0.275 438 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

Appendix 4: Pressure Profiles

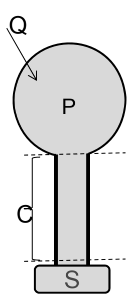


$$P = \frac{Q}{S}$$

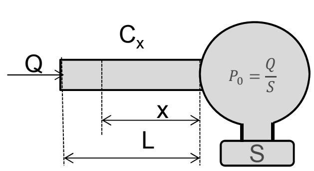


Flux balance at the connexions (node analysis):

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



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

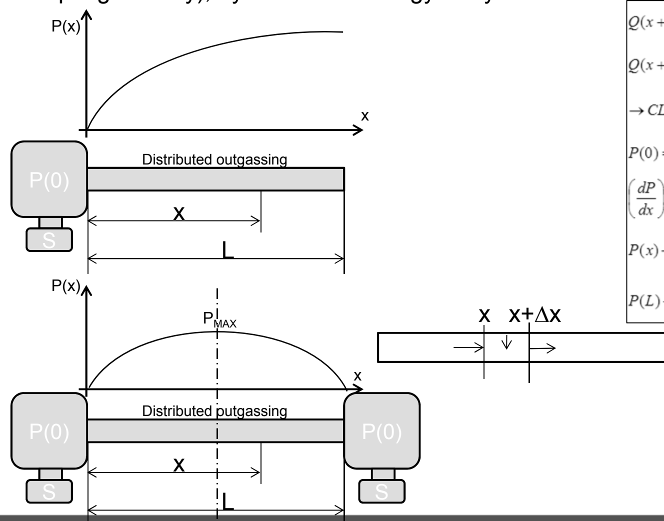


$$P_x = P_0 + \frac{Q}{C(x)}$$

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

Appendix 4: Pressure Profiles

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



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

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

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

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

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

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

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

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

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

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

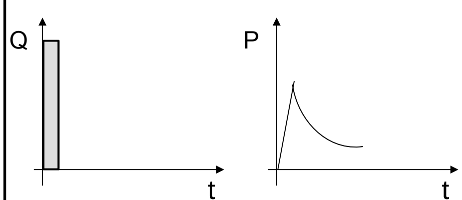
$$P(\frac{L}{2})-P(0)=\frac{Q_{TOT}}{8C}$$

Appendix 4: Pressure Profiles, Time Variation (with reference to slide 15 and 60)

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

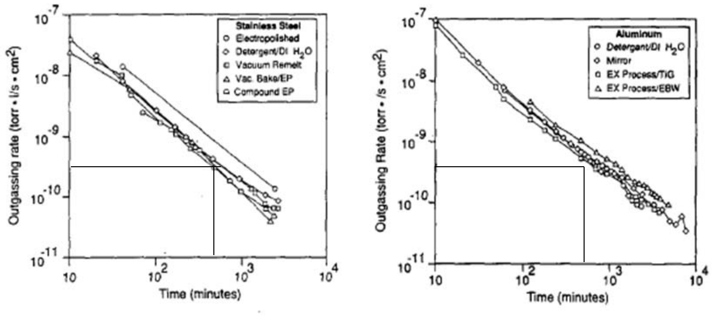


For a network of vacuum chambers, systems of coupled differential equations for each chamber have to be solved.

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.

Appendix 5: Outgassing of Water Vapour for Metals

Outgassing rate of water vapour for unbaked metals

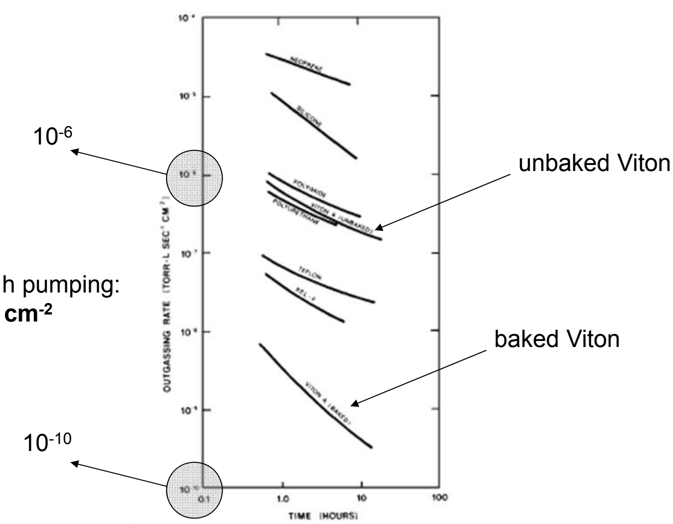


H.F. Dylla, D. M. Manos, P.H. LaMarche Jr. Journal of Vacuum Science and Tech. A, 11(1993)2623

Appendix 5: Outgassing Rates of Polymers

Outgassing rate of water vapour for polymers

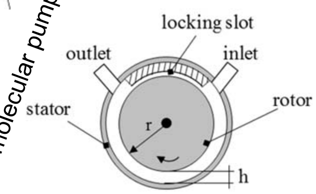
R. N. Peacock, J. Vac. Sci. Technol., 17(1), p.330, 1980



Stainless Steel after 10 h pumping:
2×10^{-10} Torr l s^{-1} cm^{-2}

Appendix 6: Momentum Transfer Pumps

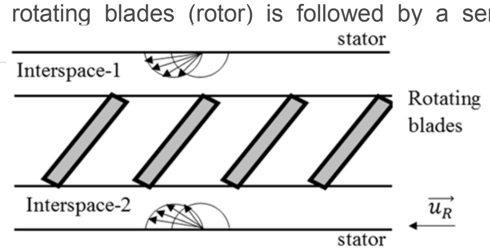
Old molecular pump



To overcome the problem of the required narrow pump duct, in 1957 Backer introduced the turbomolecular pumps (TMP) based on rapidly rotating blades.

The molecules seen from the blades have a velocity oriented towards 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 if $\langle v \rangle \approx u$.

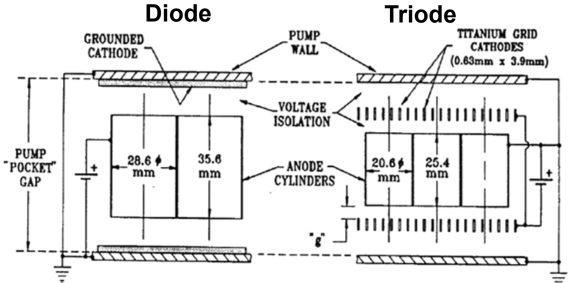
Every series of rotating blades (rotor) is followed by a series of static blades (stator).



Appendix 6: Sputter Ion Pumps (SIP)

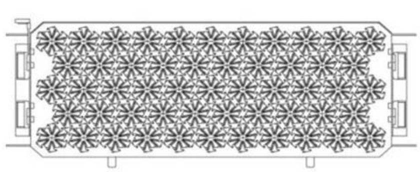
Two different configurations:

- **Diode**
- **Triode**: better pumping for noble gas *(see appendix 6, p.65)*



K. M. Welch, Capture Pumping Technology, North-Holland, p.113

An improved triode ion pump is the StarCell (Agilent Vacuum)



Appendix 6: Sputter Ion Pumps (SIP)

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

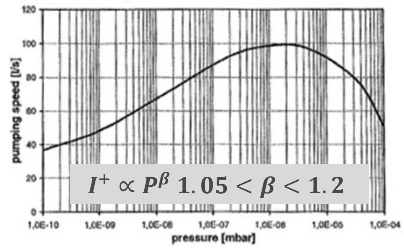


Fig. 5 Pumping speed vs pressure for a standard diode with S_N = 100 l/s (for air after saturation).

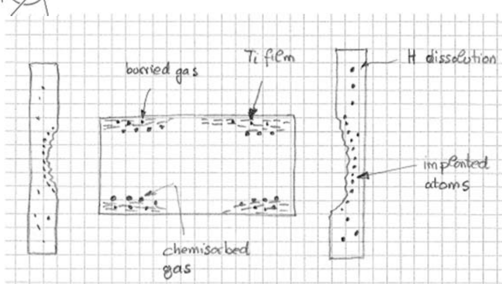
Nominal pumping speed for N_2:
Agilent starcell

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

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

Appendix 6: Triode Sputter Ion Pumps



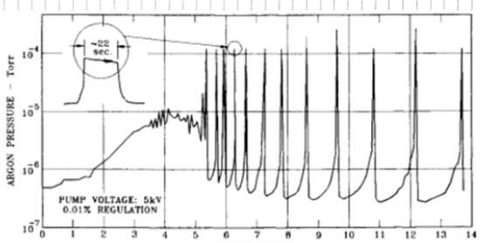


Figure 2.4.12. Example of instabilities in a system with one sputter-ion pump with titanium cathodes, after pumping argon at 5 x 10^{-7} Torr for a few hours.

An excessive quantity of noble gas implanted in the cathode can produce pressure instabilities (Ar disease):

- the continuous erosion extract noble gas atoms from the cathode;
- as a result the pressure increases and the erosion is accelerated;
- a pressure rise is obtained, which terminate when most of the gas is implanted again in the sputtered film or in a deeper zone of the cathode.

Kimo M. Welch, Capture Pumping Technology, North-Holland, p.106

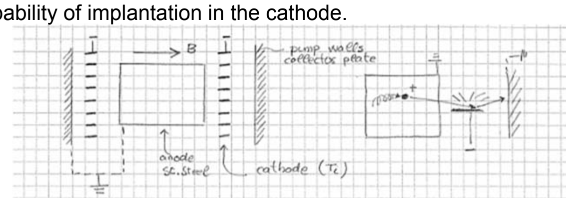
Appendix 6: Triode Sputter Ion Pumps

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 approches:

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**'

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.



Appendix 6: H_2 Pumping by 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.
- 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 10000 Torr l of H_2)

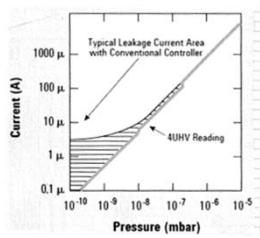
Appendix 6: Operation of Sputter Ion Pumps

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.

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 is limited 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.

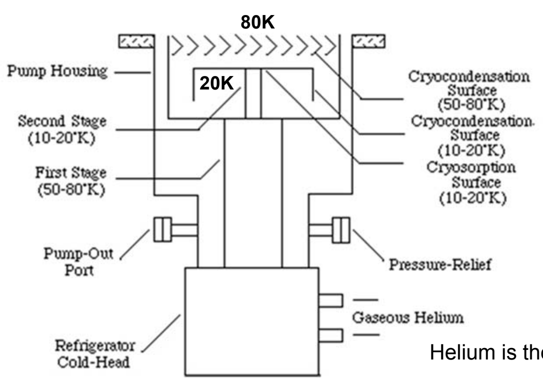


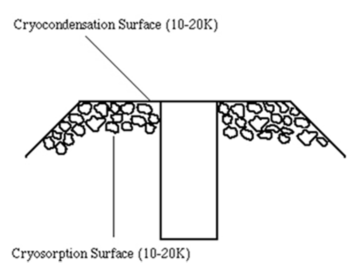
Courtesy of Agilent Vacuum

Appendix 7: Cryopumps

Modern cryopumps take advantages of both cryocondensation and cryosorption.

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.



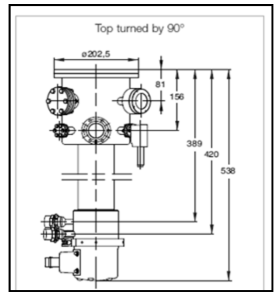


Helium is the working fluid of refrigerators.

Appendix 7: Cryopumps

Pumping speeds and maximum gas capacities of a commercial cryopump (Oerlikon-Leybold 800 BL UHV); the pump inlet diameter is 160 mm. Courtesy of Oerlikon-Leybold.

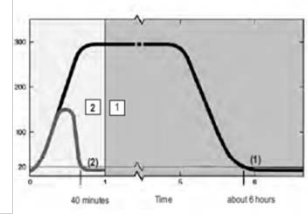
	H_2O	N_2	Ar	H_2	He
S [$l\ s^{-1}$]	2600	800	640	1000	300
Capacity [Torr l]		225 000	225 000	3225	375



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 shall 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.



Appendix 7: Cryopumps

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 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.

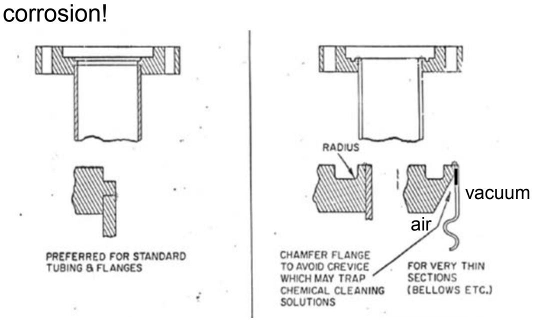
3. **Maximum Gas Intake (Capacity)**
   - At the maximum gas intake, the initial pumping speed of the gas is reduced by a factor of 2.
   - Condensed gases: the limitation is given by the thermal conductivity of the gas layer and the heat flux on the cold surface.
   - Adsorbed gases: the capacity depends on the quantity and properties of the sorption agent; the capacity is pressure dependent and generally several orders of magnitude lower than that of condensable gases.

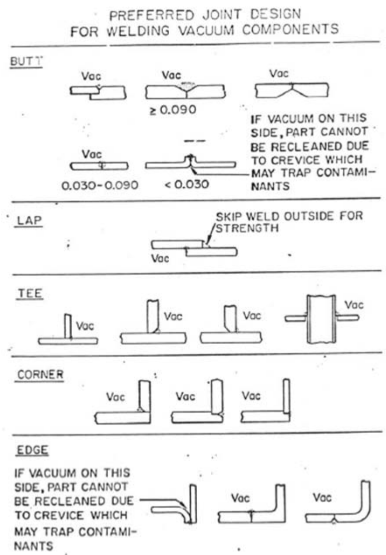
Spare Slides

Gas Sources: Inleakeage

Good practice: avoid trapped liquids

Trapped liquids could be harmful even on the external parts of thin-wall components: corrosion!





Courtesy of C. Hauviller (copied from his presentation at CAS Vacuum 2006)

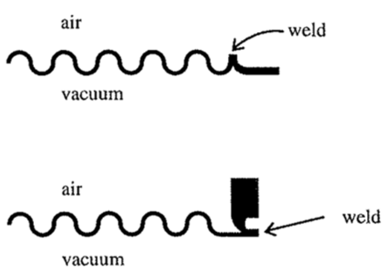


Fig. 5 Two examples of welding lips for bellows

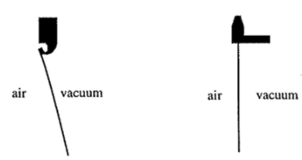
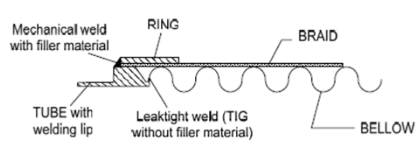


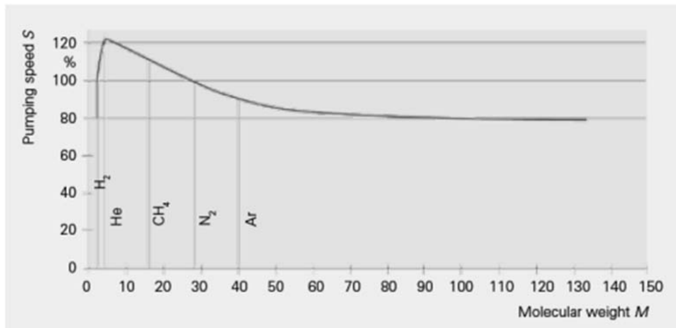
Fig. 6 Examples of thin-window welding



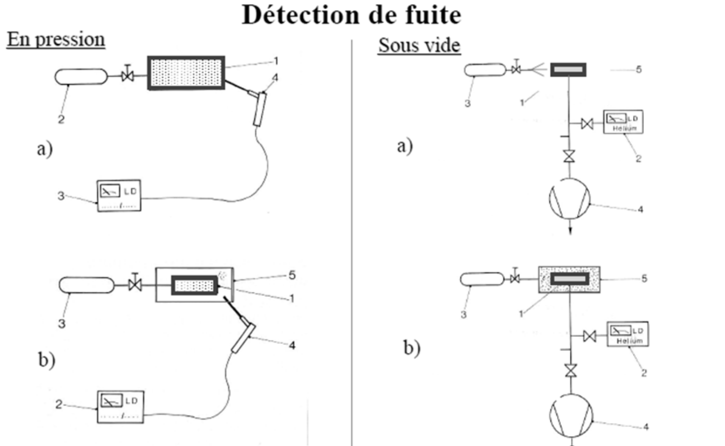
REQUIRED DESIGN

Pumping Speed of Turbomolecular Pumps (TMP)

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



Détection de fuite



Test par reniflage avec détecteur He
a) Direct = contrôle local
b) Sous pochon = contrôle global

Test sous vide avec détecteur He
a) Par aspersion local= contrôle local
b) Sous atm He = contrôle global