Vacuum Technology for Ion Sources

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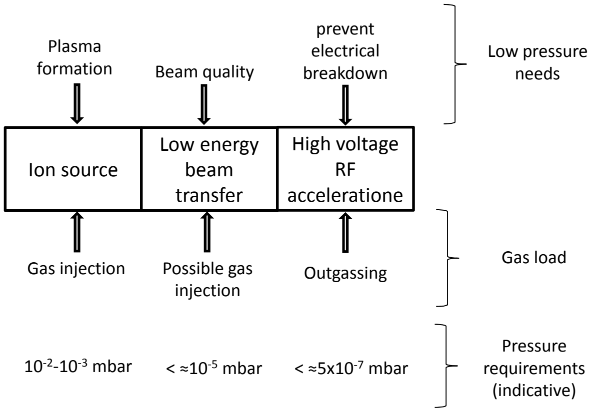
Outline

1. **Vacuum peculiarities of ion sources**.
2. **Gas flow in molecular regime**
   a. Conductance and pumping speed.
   b. Evaluation of pressure profiles.
   c. Transient behaviour.
3. **Electrical analogy**
4. **Outgassing**
5. **Gas pumping:**
   a. Momentum transfer pumps (turbomolecular)
   b. Sputter ion pumps
   c. Getter pumps
   d. Cryopumps
   e. Comparison of pumps
6. **Conclusions**

Appendix

1. ***Basic Notions***
2. ***Additional Examples of Electrical Analogy***
3. ***Extra Info about Outgassing***
5. ***Extra Info about Sputter Ion Pumps***
6. ***Regeneration of NEG Pumps***
7. ***Extra Info about Cryopumps.***

Vacuum Peculiarities of Ion Sources



Plasma formation
Beam quality
prevent electrical breakdown
Low pressure needs

Ion source
Low energy beam transfer
High voltage RF acceleratione

Gas injection
Possible gas injection
Outgassing
Gas load

10^{-2}-10^{-3} mbar
< ≈10^{-5} mbar
< ≈5×10^{-7} mbar
Pressure requirements (indicative)

- Ion sources are the only sector of accelerators in which gas is intentionally injected during operation (few exception exists).
- The main requirement of the ion source vacuum system is to evacuate the gas injected so that the vacuum in the rest of the LINAC is compatible with the high voltage RF acceleration and beam quality.
- Pressure in accelerators has a maximum in the ion source and its downstream beam pipe.

Vacuum Peculiarities of Ion Sources

- Typical hydrogen gas load in proton ion sources: 10^{-3}÷10^{-1} mbar l s^{-1} (10^{16}÷10^{18} molecules s^{-1}).
- Only turbomolecular pumps withstand such a flux in continuous operation without deterioration.
- To ensure lower pressure in the beam transport section, differential pumping is needed.
- Most of the injected gas has to be removed before entering the RFQ.

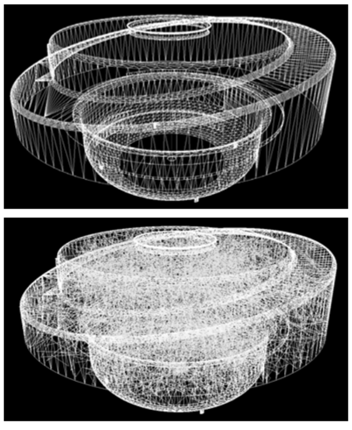
Basic Notions (see appendix 1)

- Ideal gas equation: $P\,V = n\,R\,T$ (thermodynamic)
  $P\,V = N\,k_B \mathrm{T}$ (statistical mechanics)
- Maxwell-Boltzmann model: $\varphi = \frac{1}{4} n \langle v \rangle = \frac{1}{4} n \sqrt{\frac{8\,k_B T}{\pi\,m}}$ m is the molecular mass [Kg]
  M is the molecular weight [Kg]
- Knudsen number: $K_n = \frac{l}{D}$ l is the mean free path of gas molecules, D typical distance of the vacuum system
- Molecular regime: $K_n > 1$ Collisions with the wall of the vacuum system more likely than those between molecules
- Gas flow Q in molecular regime: $Q = C\,(P_1 - P_2)$ C is the gas conductance indipendent on pressure
- Gas conductance of a wall slot: $C = \frac{1}{4} A \langle v \rangle = A\,C' \rightarrow \propto \frac{1}{\sqrt{M}}$ A is the wall slot area
- Gas conductance of a duct: Conductance of the duct aperture (A C’) x transmission probability (τ)

Gas Flow in Molecular Regime: Conductance

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.



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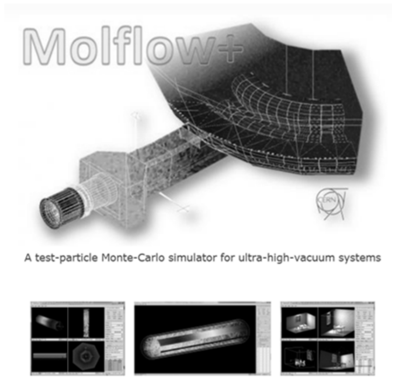
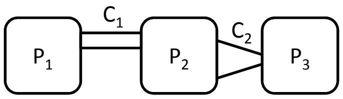


http://cern.ch/test-molflow

Gas Flow in Molecular Regime: Combination of Conductances



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

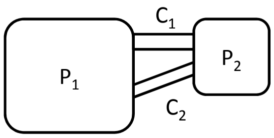
In stable conditions, there is no gas accumulation in the whole system:Q_1=Q_2=Q_3

It can be easily verified that: C_{TOT}= $\frac{C_1C_2}{C_1+C_2}$ 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** :

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

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 $\rightarrow C_{TOT} = C_1 + C_2 \rightarrow C_{TOT} = \sum_1^N C_i$

Gas Flow in Molecular Regime: Pumping Speed

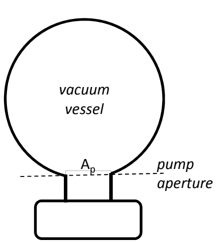
In vacuum technology a pump is any ‘object’ that remove gas molecules from the gas phase.

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:

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

In a more general way: $S = \frac{\delta Q_P}{\delta P}$

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 (Ho coefficient)

Gas Flow in Molecular Regime: Pumping Speed

As usual, in term of pressure and PV units:

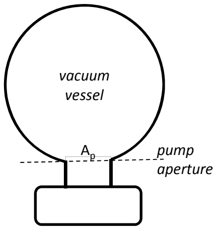
$$Q_P = A_P C' n\, \sigma (k_B T) = A_P C' \sigma\, P$$

From the definition of pumping speed:

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

S depends on the conductance of the pump aperture $A_P C'$ and the capture probability σ. σ is in general not a constant; it 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.

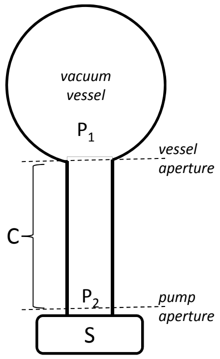


Maximum pumping speed [l s^{-1}]for different circular pump apertures

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

Gas Flow in Molecular Regime: Effective Pumping Speed

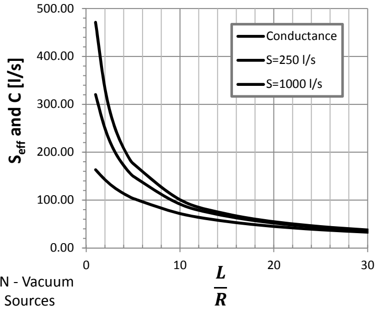
A gas flow restriction interposed between a pump and a vacuum vessel reduces the ‘useful’ pumping speed. The effective pumping speed S_{eff} seen by the vacuum vessel is easily calculated:



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

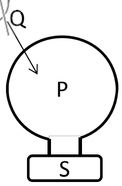
$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$

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

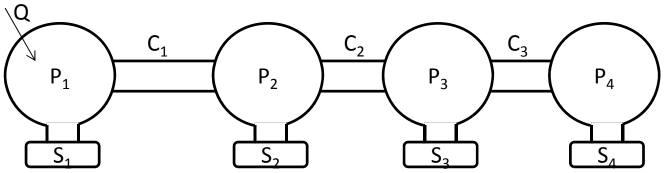


Example
Vessel and pump connected by a 100 mm diameter tube; nitrogen, S=250 l/s and 1000 l/s.

Gas Flow in Molecular Regime: Evaluation of Pressures Profiles

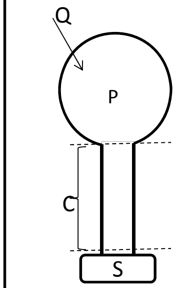


$$P = \frac{Q}{S}$$

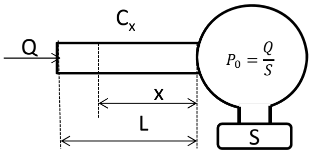


Flux balance at the connexions (node analysis):

$$\begin{cases} Q = P_1S_1 + C_1(P_1 - P_2) \\ C_1(P_1 - P_2) = C_2(P_2 - P_3) + P_2S_2 \\ C_2(P_2 - P_3) = C_3(P_3 - P_4) + P_3S_3 \\ C_3(P_3 - P_4) = P_4S_4 \end{cases}$$



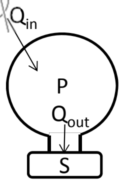
$$P = \frac{Q}{S_{eff}} = \frac{Q(C+S)}{C \times S}$$



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

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

Gas Flow in Molecular Regime: Time Dependance



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: $\frac{dN}{dt} = Q_{in} - Q_{out}$

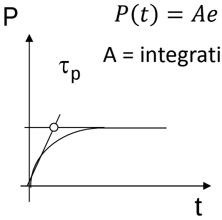
$V\frac{dP}{dt} = k_BT(Q_{in} - Q_{out})$; in PV units: $V\frac{dP}{dt} = (Q_{in} - Q_{out})$

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

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

A = integration constant

$$\begin{cases} P(0) = P_0 \rightarrow P(t) = \left(P_0 - \frac{Q_{in}}{S}\right)e^{-\frac{t}{\tau_p}} + \frac{Q_{in}}{S} \\ P(0) = 0 \rightarrow P(t) = \frac{Q_{in}}{S}\left(1 - e^{-\frac{t}{\tau_p}}\right) \end{cases}$$



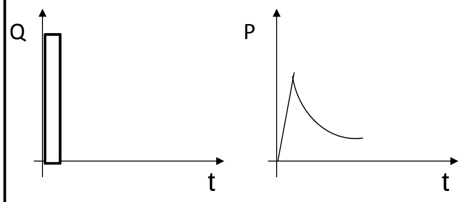
$\boldsymbol{\tau_p = \frac{V}{S}}$ characteristic time of pumping

Gas Flow in Molecular Regime: Time Dependance

When Q_{in} is a function of time:

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

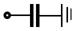
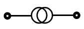
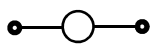
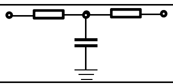
A = integration constant



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.

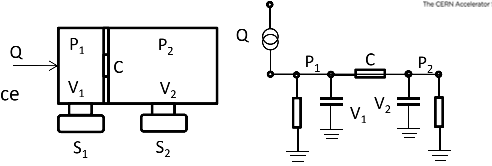
Electrical analogy

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 subdivided in smaller units and considered as single vacuum chambers (conductance + volume) in series.
- Non-linear electric characteristics can be used to simulate pressure and time dependent conductance and pumping speed.
- In this way pressure excursion into viscous regime can be evaluated

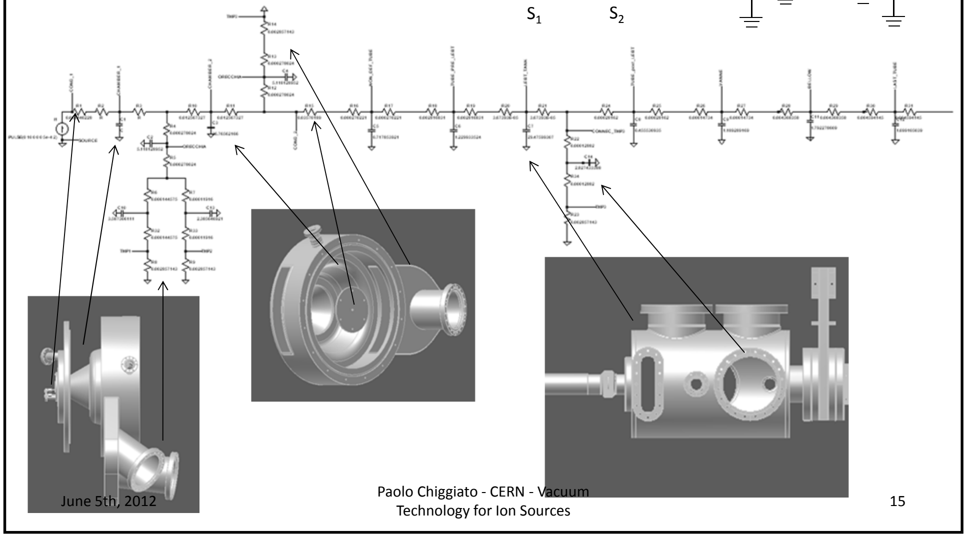
Electrical analogy

Simple example: differential pumping



A more complex example: part of the Linac4 H- source

(from C. Pasquino et al., CERN, ATS/Note/2012/043 TECH)



Outgassing

Materials of which a vacuum system is made of are spontaneous source of gas.

Two main categories of materials:

Metals

After state-of-art surface cleaning

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

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

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

- <u>If heated in situ</u> (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

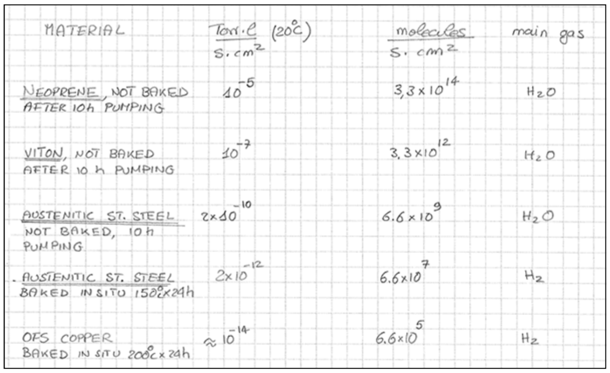
Organics (Polymers)

- 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:

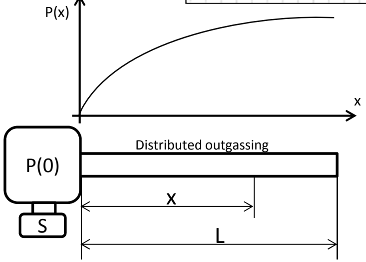
  $$q_{H_2O} \propto \frac{1}{\sqrt{t}}$$

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

Outgassing



MATERIAL	$\frac{Torr \cdot l}{s \cdot cm^2}$ (20°C)	$\frac{molecules}{s \cdot cm^2}$	main gas
NEOPRENE, NOT BAKED AFTER 10h PUMPING	10^{-5}	$3,3 \times 10^{14}$	H_2O
VITON, NOT BAKED AFTER 10 h PUMPING	10^{-7}	$3,3 \times 10^{12}$	H_2O
AUSTENITIC ST. STEEL NOT BAKED, 10 h PUMPING	2×10^{-10}	6.6×10^{9}	H_2O
AUSTENITIC ST. STEEL BAKED IN SITU 150°C x 24h	2×10^{-12}	6.6×10^{7}	H_2
OFS COPPER BAKED IN SITU 200°C x 24h	$\approx 10^{-14}$	6.6×10^{5}	H_2



Pressure profiles with distributed outgassing

- Analytical model works for simple geometry
- Electrical analogy can be applied subdividing the vacuum pipes in small volumes.
- Monte Carlo simulation is the best tool for complex geometry

Gas Pumping for Ion Sources

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**.

- 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:

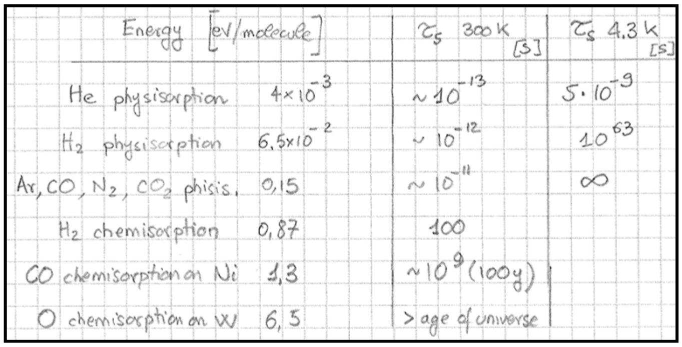
$$\boldsymbol{t_s = t_0 e^{\frac{E_a}{k_B T}}}$$

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 for Ion Sources



	Energy [eV/molecule]	τ_s 300 K [s]	τ_s 4.3 K [s]
He physisorption	4×10^{-3}	$\sim10^{-13}$	$5\cdot10^{-9}$
H_2 physisorption	6.5×10^{-2}	$\sim10^{-12}$	10^{63}
Ar, CO, N_2, CO_2 phisis.	0,15	$\sim10^{-11}$	∞
H_2 chemisorption	0,87	100	
CO chemisorption on Ni	1,3	$\sim10^{9}$ (100y)	
O chemisorption on W	6,5	> age of universe	

physisorption $E_a \leq 0.4$ eV/molec.

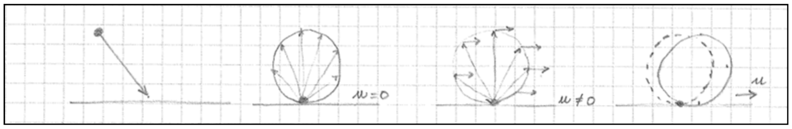
chemisorption $E_a > 0.4$ eV/molec.

Momentum Transfer Pumps: Turbomolecular Pumps

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

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 by the drift velocity of the wall → a moving wall produces a gas flow

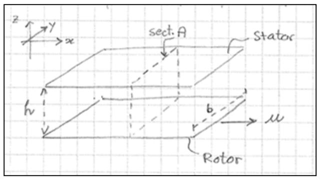


The most important characteristics of molecular pumps are:

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.

Momentum Transfer Pumps: Turbomolecular Pumps



At any point in time, half of the molecules has just collided with the moving surface and drift in the 'x' direction with velocity 'u'.

The other half comes from the stator where the drift component is lost.

The molecular flow toward an imaginary section (A) is:

$$Q = \frac{1}{2} n \cdot u \cdot bh = \frac{1}{2} \frac{P}{k_B T} \cdot u \cdot bh \quad \text{in PV units} \rightarrow \quad Q = \frac{1}{2} P \cdot u \cdot bh$$

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

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!

Momentum Transfer Pumps: Turbomolecular Pumps

It can be shown that the maximum compression ratio is:

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

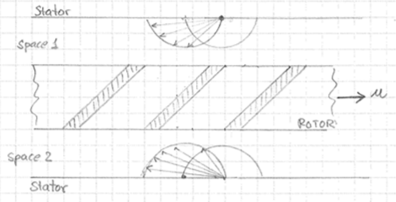
L and h
length and width
of the pump duct

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 maximun 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.

Momentum Transfer Pumps: Turbomolecular Pumps (TMP)

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



Courtesy of Pfeiffer Vacuum

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 if at least $\langle v \rangle \approx u$.

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

The indications given by the simplified model for molecular pumps hold 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

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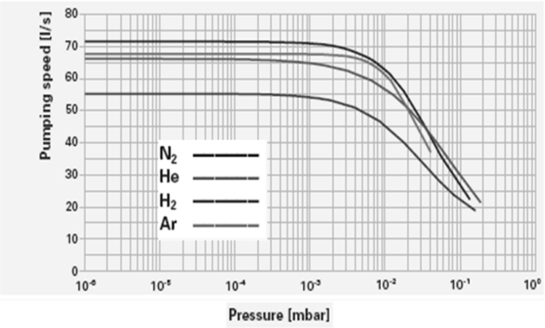
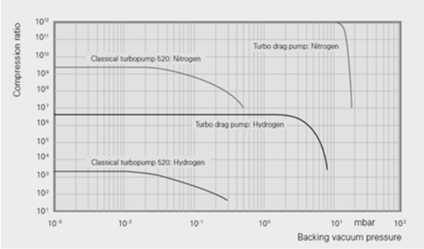
Momentum Transfer Pumps: Turbomolecular Pumps (TMP)

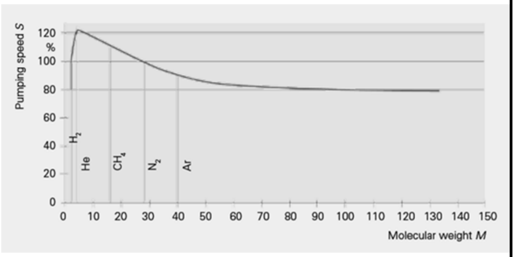


TMP pumping speeds are in the range from 10 l/s to 25,000 l/s.

Their ultimate pressure (H2) is of the order of 10^{-10}, 10^{-11} mbar

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





Momentum Transfer Pumps: Turbomolecular Pumps (TMP)

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:

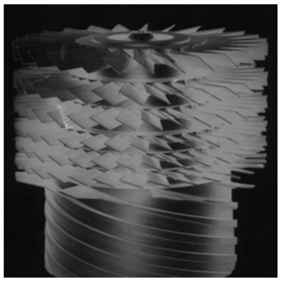
1. mechanical fragility
2. risk of contamination from the backing pump
3. need of venting anytime the pump is stopped to block backstreaming of contaminations→need of valve between TMP and vacuum vessel
4. intrinsic limitation in ultimate pressure of H_2

Present trend:

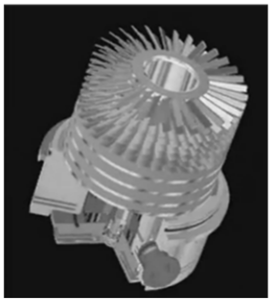
1. Use of dry pumps as backing pumps (but lower compression ratio than oil pumps)
2. Increase compression ratio by adding molecular drag stages below the set of TMP blades (very compact design)
3. Remove all lubricated mechanical bearing by magnetic rotor suspension (higher cost).

Momentum Transfer Pumps: Turbomolecular Pumps (TMP)

http://www.flickriver.com/photos/tags/turbopump/interesting/



Front page of J. F. O'Hanlon A user's Guide to Vacuum Technology



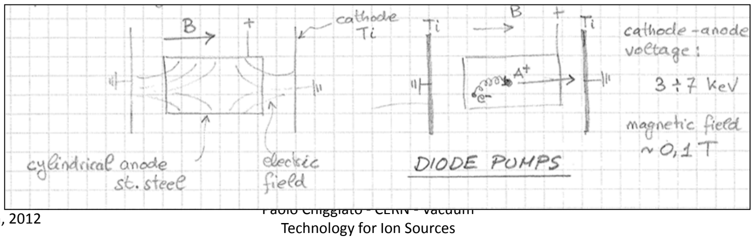
Courtesy of Agilent Vacuum

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

Capture Pumps: Sputter Ion Pumps (SIP)

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

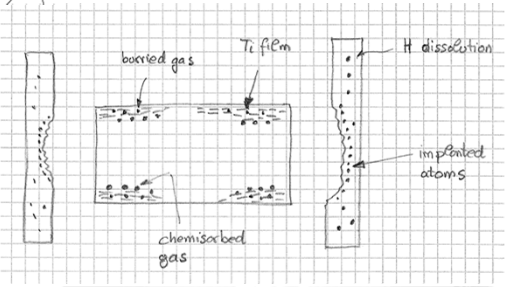
  1. **chemical adsorption onto the reactive metal layer** and subsequent burial by additional metallic atoms of gas molecules: all gases except rare gases
  2. **implantation of gas ions in the cathode and of energetic neutrals** bounced back from the cathode in the deposited film: only mechanism of pumping for rare gases
  3. **diffusion** into the cathode and the deposited film: only H_2



cathode-anode voltage: 3÷7 keV

magnetic field ~0,1 T

Capture Pumps: Sputter Ion Pumps (SIP)



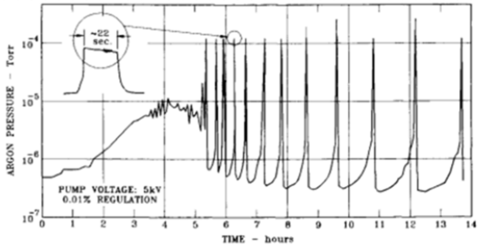


Figure 2.4.12. Example of instabilities in a system with one sputter–ion pump with titanium cathodes, after pumping argon at 5 x 10^{-7} Torr for a few hours.

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

An excessive quantity of noble gas implanted in the cathode can produce pressure instabilities:

- 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.

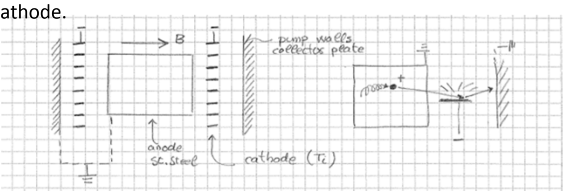
Capture Pumps: Sputter Ion Pumps (SIP)

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.

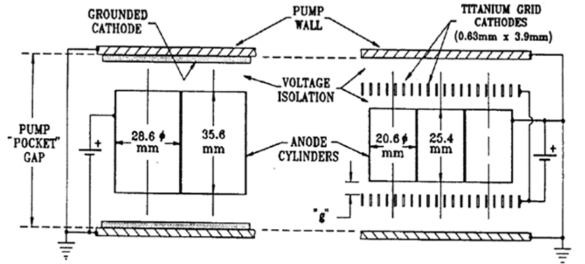
Two different approches:

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.

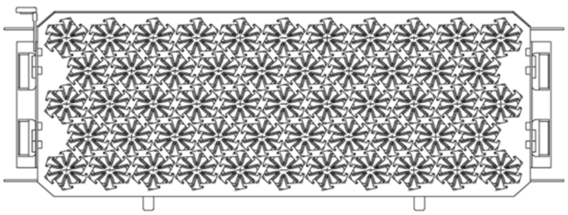


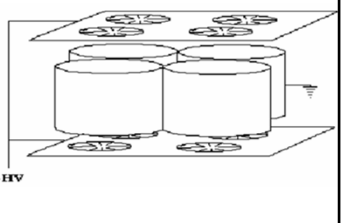
Capture Pumps: Sputter Ion Pumps (SIP)



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

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





Capture Pumps: Sputter Ion Pumps (SIP)

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

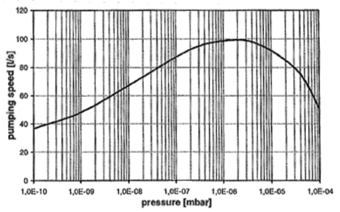


Fig. 5 Pumping speed vs pressure for a standard diode with $S_N = 100$ l/s (for air after saturation).

Nominal pumping speed for N_2:
Varian starcell

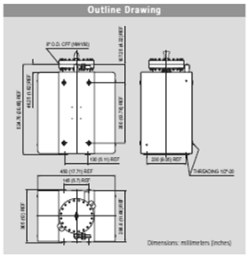
DN	S [l s^{-1}]
63	50
100	70/125
150	240/500

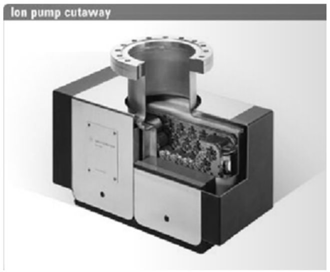
GAS	DIODE PUMPS	TRIOD PUMPS
AIR	1	1
N2	1	1
O2	1	1
H2	1.5-2	1.5-2
CO	0.9	0.9
CO2	0.9	0.9
H2O	0.8	0.8
CH4	0.6-1	0.6-1
Ar	0.03	0.25
He	0.1	0.3

Pumping speed normalized to air

Capture Pumps: Sputter Ion Pumps (SIP)

VacIon *Plus* 500





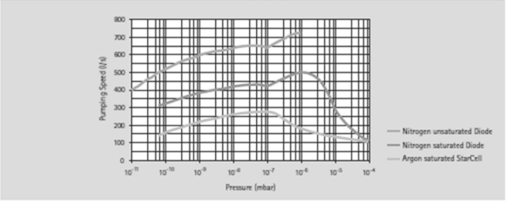
Courtesy of Agilent Vacuum
http://www.chem.agilent.com/en-US/Products/Instruments/vacuum

Technical Specifications

	StarCell®	Noble Diode	Diode
Nominal pumping speed for Nitrogen (*) (l/s)	410	440	500
Operating life at 1x10^{-6} mbar (hours)	80,000	50,000	50,000
Maximum starting pressure (mbar)	≤ 1x10^{-2}	≤ 1x10^{-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

VacIon *Plus* 500 – Pumping Speed vs Pressure



Capture Pumps: 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 :

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

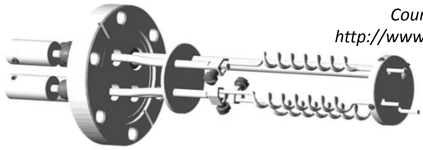
$$0 \leq \alpha \leq 1 \quad S = \alpha\, A_{getter} C'$$

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.

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.



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.

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

The sticking probability is negligible:

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

→ one additional sublimation is needed

Hydrogen diffuses in the Ti film→much higher capacity

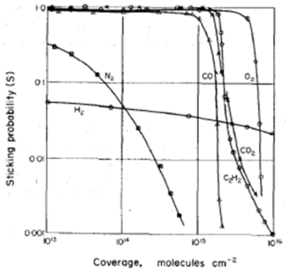
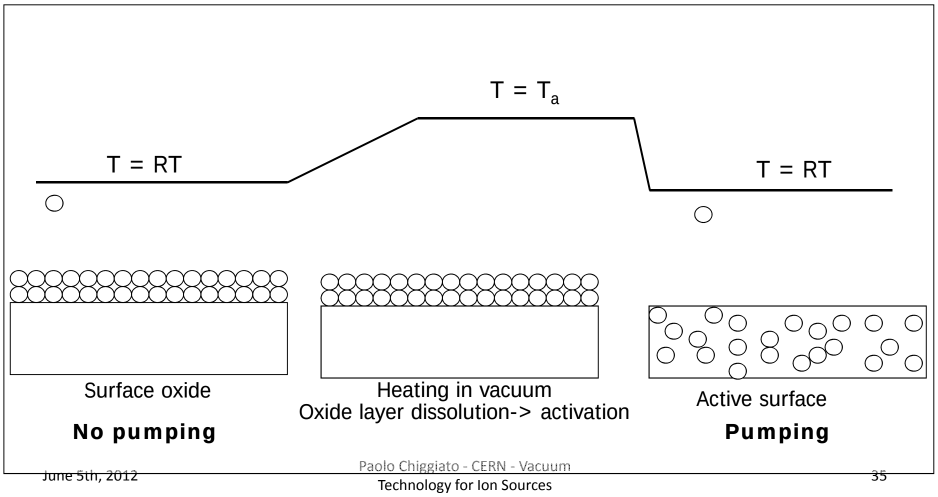


Figure 4. Room temperature sorption characteristics for pure gases on batch evaporated clean titanium films.

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

Capture Pumps: NEG 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.



Capture Pumps: NEG Pumps

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

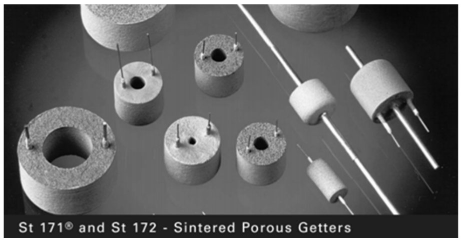
NEG materials are produced industrially by powder technology. Small grains are sintered to form pellets, discs or plates. The grains can also be pressed at room temperature on metallic ribbon.

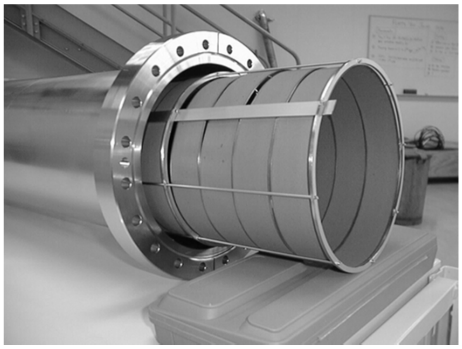
A typical alloy produced by SAES Getter is **St707**:

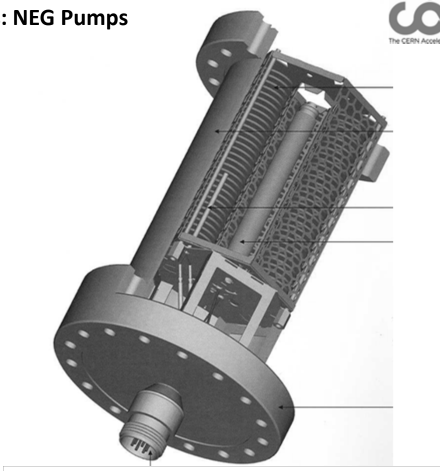
Element	Concentration [wt. %]	Main role in the alloy
Zr	70	- High O solubility limit. - Chemical reactivity
V	24.6	- Increases O diffusivity, - Chemical reactivity
Fe	5.4	- Reduces pyrophoricity

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

Capture Pumps: NEG Pumps







Courtesy of SAES Getters, www.saesgetters.com

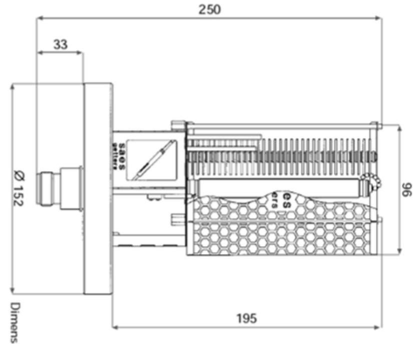
The maximum H_2 sorption capacity is limited by H_2 embrittlement of the NEG elements.
In general a safe limit is 20 Torr l/g is given by the supplier.

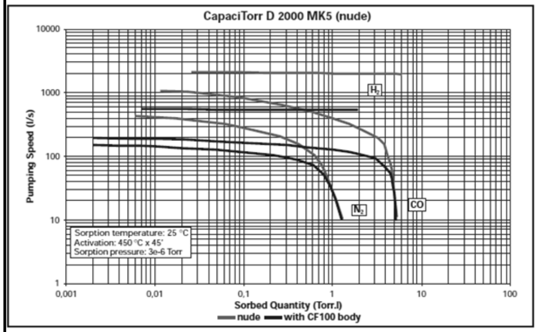
The stored H_2 can be desorbed by heating and pumping with an auxiliary pump (for example a TMP).

Capture Pumps: NEG Pumps

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 geometrical surface of active metal.

Courtesy of SAES Getters, www.saesgetters.com





Typical Pump Characteristics

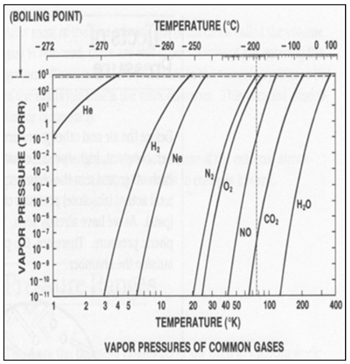
Alloy Type		St 172®
Alloy Composition		ZrVFe
Getter Mass(g)		225
Getter Surface (cm²)		1900
Pumping Speed (l/s)	H_2	2000
	CO	1000
Sorption Capacity (Torr l)	H_2	4500
	CO Room Temperature	5
	CO Total	2000

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.

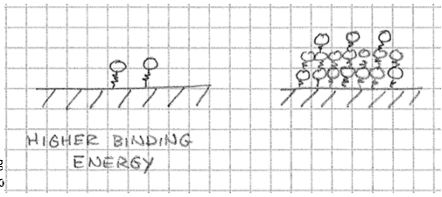
Capture Pumps: Cryopumps

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.
    b. Large quantity of gas can be cryocondensated (limited only by the thermal properties of the condensate phase)
    c. The attainable pressure is limited by the saturated vapour pressure.



d) Only Ne, H_2 and He have vapour pressures higher than 10^{-11} Torr at 20 K.
e) 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.



Capture Pumps: Cryopumps

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.

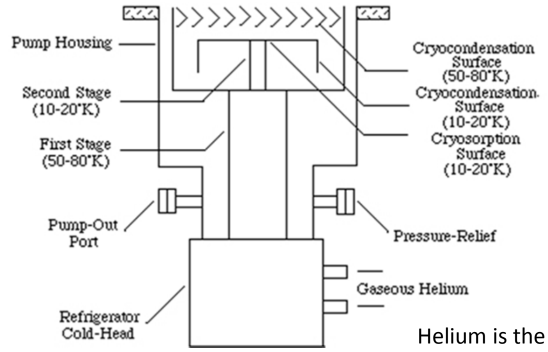
3. **Cryotrapping** is understood as the inclusion of a low boiling point gas which is difficult to pump such as hydrogen, in the matrix of a gas having a higher boiling point and which can be pumped easily such as Ar, CH_4 or CO_2. At the same temperature the condensate mixture has a saturation vapor pressure which is by several orders of magnitude lower than the pure condensate of the gas with the lower boiling point.

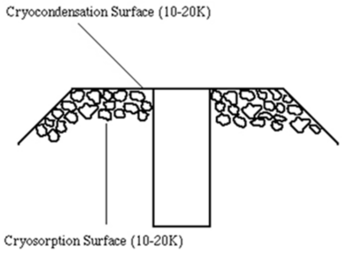
Capture Pumps: Cryopumps

Modern cryopumps take advantages of each mechanisms.

1. The cryocondensation takes place on a cold surfaces, in general at 80K for H_2O and 10 or 20 K for the other gases.

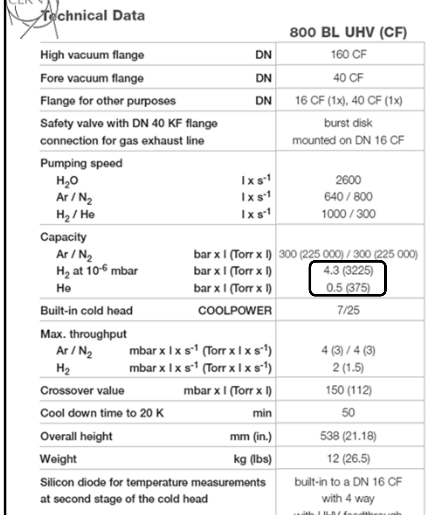
2. The cryosorption of H_2, Ne and He is localised on a hidden surface where a porous material is fixed. This surface is kept away from the reach of the other molecules.





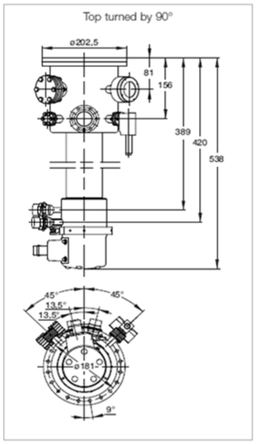
Helium is the working fluid of modern cryopumps.

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



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)

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.

Comparison of Pumps

	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
SIP	- Clean pumping - No maintenance - No vibrations - Installation in any orientation - Relatively long lifetime - Relatively low cost - Limited but high H_2 capacity	- 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

Comparison of Pumps

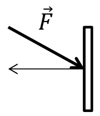
	Advantages	Disadvantages
Sublimation Pumps	- Clean vacuum - High pumping speed for reactive gases - With SIP, extremely low vacuum can be achieve - Low cost - Electrical power only for sublimation; it works in case of power cut - Limited maintenance (filament change) - No vibration	- Very limited capacity - Need frequent sublimations - 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 - Relatively low working pressure
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 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 embrittlement if regeneration is not applied - Formation of dust particles is not excluded - Possible peel-off of NEG deposited on metallic ribbons. - Safety issue: pyrophoric, it burns when heated in air at high temperature

Comparison of Pumps

	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

Conclusions

Appendix 1
Basic Notions : Gas Pressure



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

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

Conversion Table

	Pa	bar	atm	Torr
1 Pa	1	10^{-5}	$9.87\ 10^{-6}$	$7.5\ 10^{-3}$
1 bar	10^{2}	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 Notions : Gas Pressure

Degree of Vacuum

Operation of ion sources

	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 :

$$P\,V = n\,R\,T \quad \text{(thermodynamic)}$$

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

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

Appendix 1
Basic Notions : Gas Quantity

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

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

	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

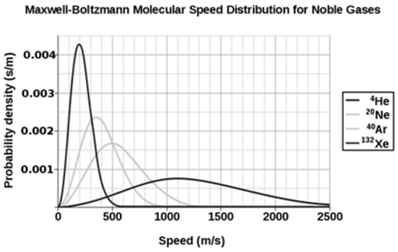
Gas quantities can be expressed in:

- 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 : $P\,V = N(k_BT)$

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

Appendix 1
Basic Notions : Molecular Mean Speed



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

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 molecular weight [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

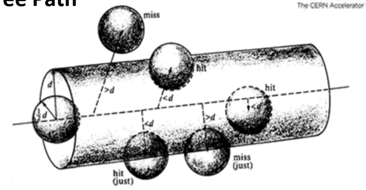
Appendix 1
Basic Notions : Impingement Rate with a Surface

Gas	Pressure [mbar]	Impingement rate 293 K [$cm^{-2}s^{-1}$]
H2	10^{-3}	$1.1\ 10^{18}$
	10^{-8}	$1.1\ 10^{14}$
	10^{-14}	$1.1\ 10^{8}$
N2	10^{-3}	$2.9\ 10^{17}$
	10^{-8}	$2.9\ 10^{13}$
Ar	10^{-3}	$2.4\ 10^{17}$
	10^{-8}	$2.4\ 10^{13}$

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

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

Appendix 1
Basic Notions : 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, is given by:

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

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

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

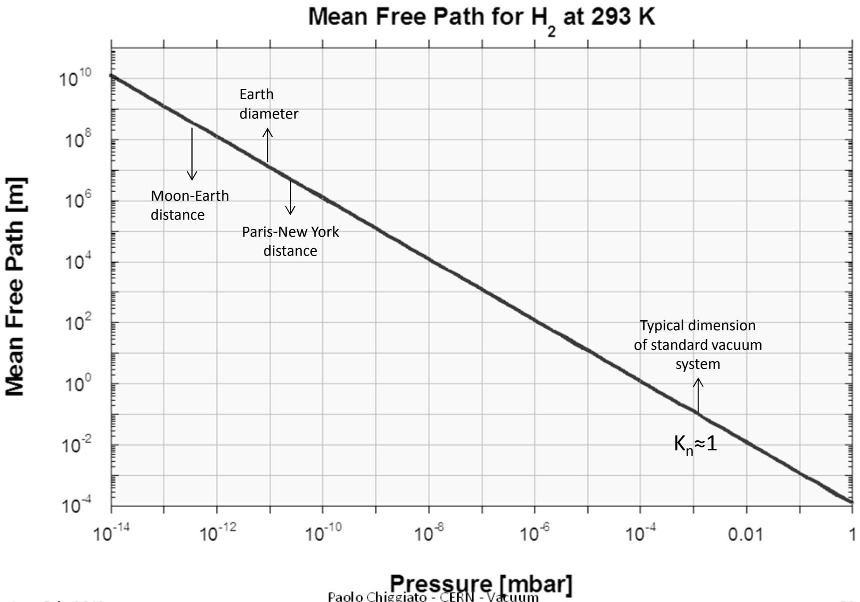
Appendix 1
Basic Notions : Knudsen Number

$$K_n = \frac{l}{D}$$

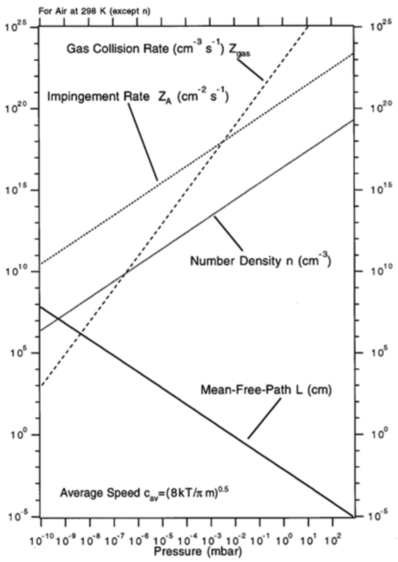
l is the mean free path and **D** is a characteristic dimension of a vacuum system (p.ex. the diameter of a beam pipe).

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

Appendix 1
Basic Notions : Knudsen Number



Appendix 1
Basic Notions : Knudsen Number



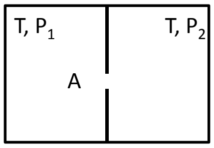
Appendix 1
Basic Notions : Conductance

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.

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



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

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

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

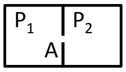
Appendix 1
Basic Notions : Conductance

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

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

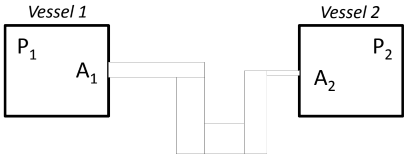


$$\rightarrow Q = 44 \times 0.8 \times (5\ 10^{-4} - 7\ 10^{-5}) = 1.5 \times 10^{-2}\,\frac{mbar\ l}{s}$$

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

Appendix 1
Basic Notions : Conductance

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



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

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

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

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

In PV units:

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

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

Appendix 1
Basic Notions : Conductance

The molecular transmission probabilities:

- depend only on the geometry of the vacuum system;
- can be calculated only for simple geometry;
- nowadays are accurately obtained by Monte Carlo methods.

Example:

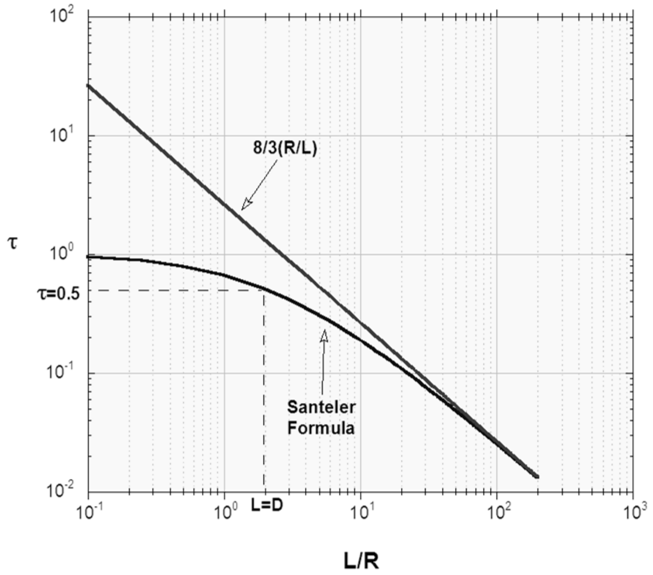
- Tubes of uniform circular cross section (L length, R radius); Santeler formula (max error 0.7%):

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

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 $\frac{L}{R} \gg 1 \to C = C' A\, \tau \approx 11.75 \times \frac{\pi D^2}{4} \times \frac{4D}{3L} = 12.3 \frac{D^3}{L} \left[\frac{l}{s}\right]$ $([D]\ and\ [l] = cm\ )$

Appendix 1
Basic Notions : Conductance



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 1
Basic Notions : Conductance

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

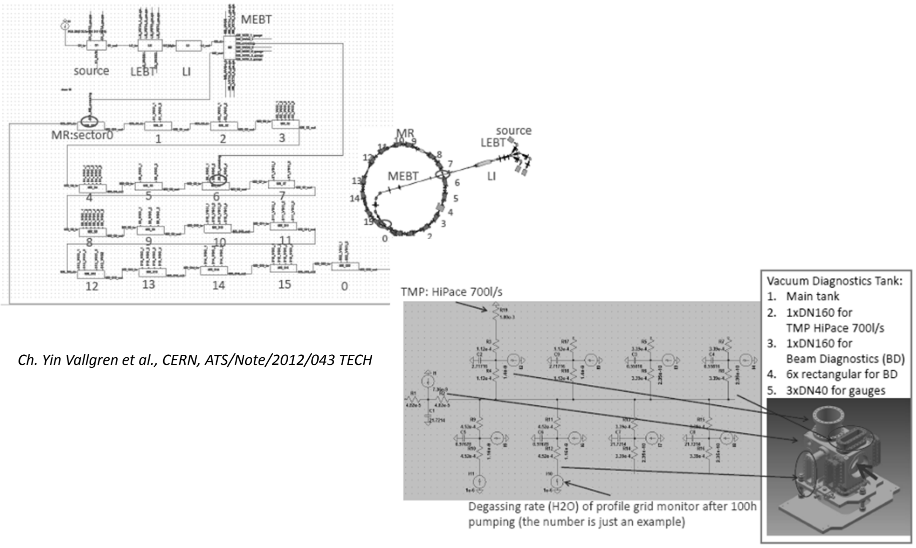
For more complicated geometry, Test-Particle Monte Carlo methods (TPMC) are used.

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
- the molecules are re-emitted from the wall again randomly
- 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)

Appendix 2: Additional Examples of Electrical Analogy

The full simulation of the MedAustron facility.

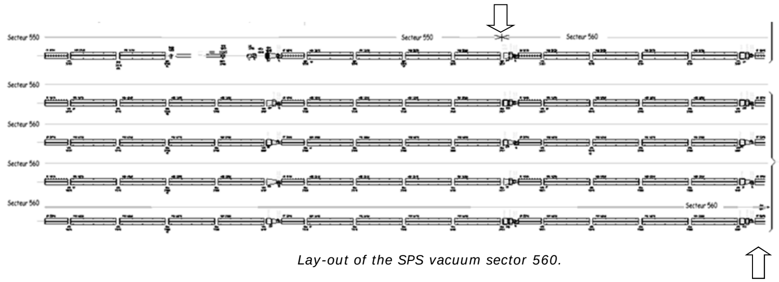


Vacuum Diagnostics Tank:
1. Main tank
2. 1xDN160 for TMP HiPace 700l/s
3. 1xDN160 for Beam Diagnostics (BD)
4. 6x rectangular for BD
5. 3xDN40 for gauges

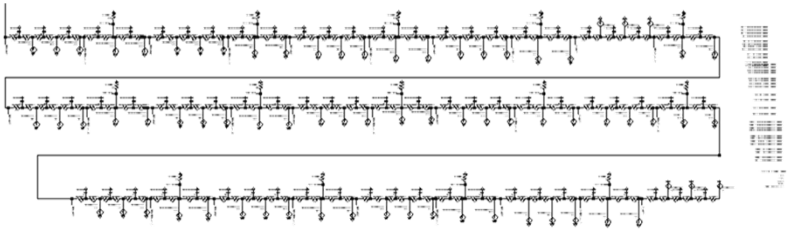
Ch. Yin Vallgren et al., CERN, ATS/Note/2012/043 TECH

Appendix 2: Additional Examples of Electrical Analogy

Evaluation of pressure profile during pump-down in the SPS ring *J. A. Ferreira Somoza, CERN, TE-VSC internal note, 05-2012*



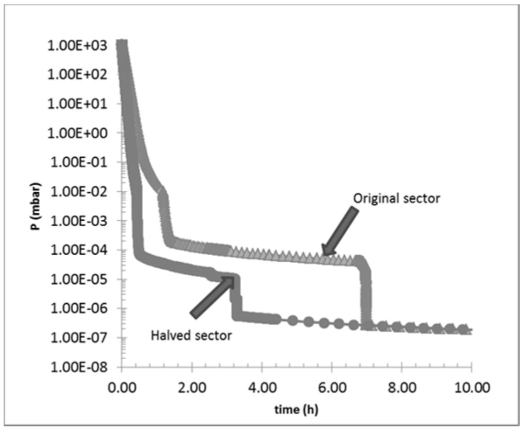
Lay-out of the SPS vacuum sector 560.



Equivalent electrical network for sector 560.

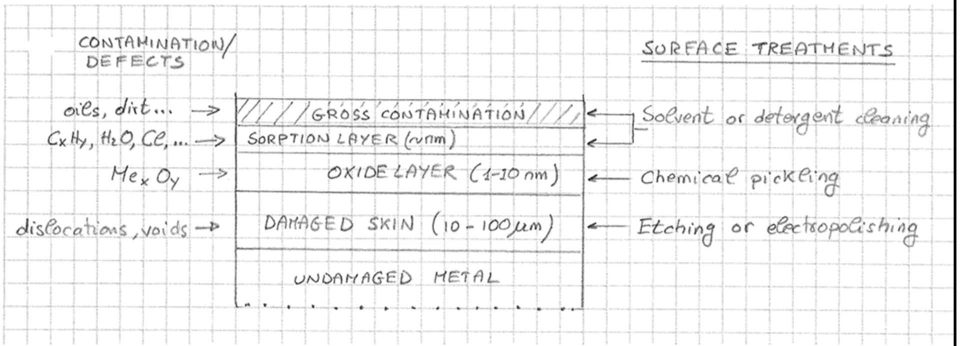
Appendix 2:
Additional Examples of Electrical Analogy

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.

Appendix 3:
Extra Info About Outgassing

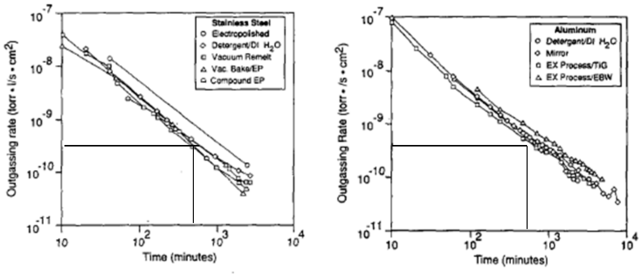


Solvents: their molecules interact and transport contaminants away by diffusion (dilution) -> quite selective! (C_2Cl_4, wide spectrum; HFC, more restricted action)

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

Appendix 3:
Extra Info About Outgassing

Outgassing rate of water vapour for unbaked metals

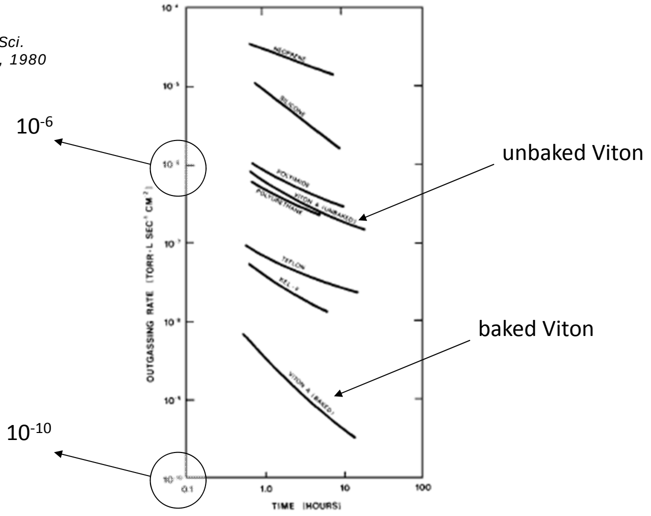


H.F. Dylla, D. M. Manos, P.H. LaMarche Jr. Journal of Vacuum Science and Tech. A, 11(1993)2623

Appendix 3:
Extra Info About Outgassing

Outgassing rate of water vapour for polymers

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



10^{-6}

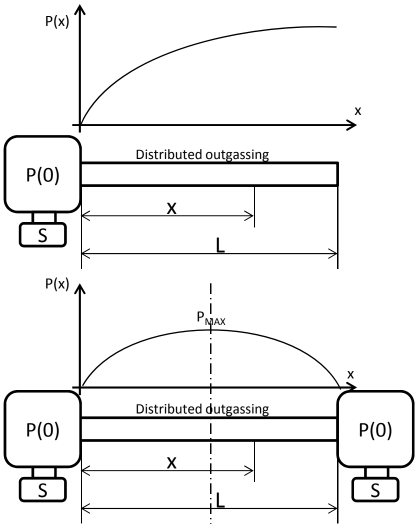
10^{-10}

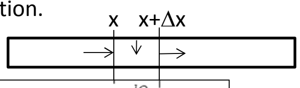
unbaked Viton

baked Viton

Appendix 3:
Extra Info About Outgassing

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:
Extra Info about SIP

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 H2 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)

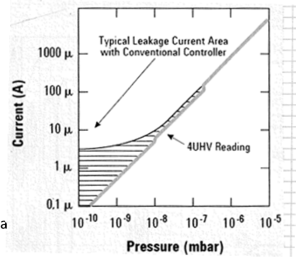
Appendix 4:
Extra Info about SIP

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).
- By reducing the applied voltage in the lower pressure range, the pressure measurement is possible down to 10^{-10} mbar.



Courtesy of Agilent Vacuum

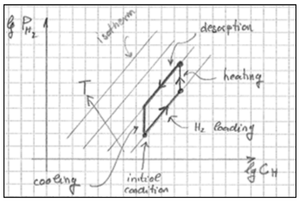
Appendix 5:
Regeneration of NEG pumps

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 may be desorbed by heating and pumping with an auxiliary pump (for example a TMP).

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

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



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 the mass of the NEG in g
A and B typical values of the NEG material
For St707: A=4.8, B= -6116

The pressure during the regeneration heating is given by: $Log(P) = A + 2Log(q) + \frac{B}{T}$
q is the actual hydrogen concentration

Appendix 5:
Regeneration of NEG pumps

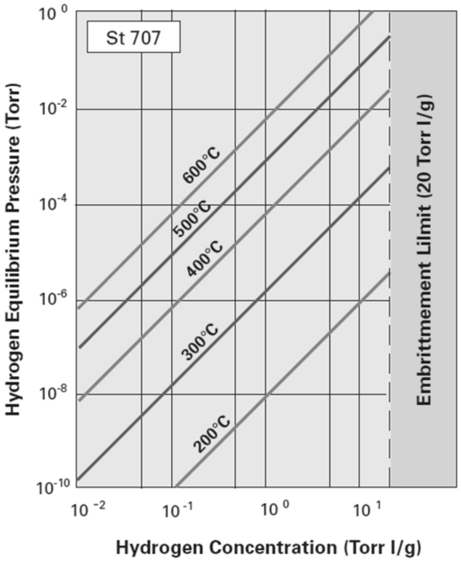


Figure 3 - Hydrogen equilibrium pressure for the St 707 alloy

Courtesy of SAES Getters, www.saesgetters.com

Appendix 6:
Extra Info about 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 intake of a specific gas, its pumping speed is reduced to below 50 % of the initial value.
    - 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.

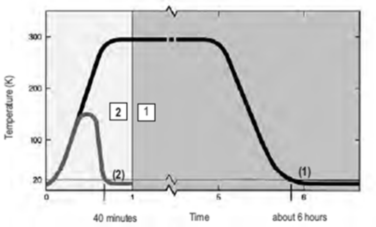
Appendix 6:
Extra Info about Cryopumps

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.



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