

UNIT 3 !

PUMPS FOR PARTICLE ACCELERATORS

3.1 INTRODUCTION

In this unit, we consider only pumps (gas sinks) working in the molecular regime, namely when a molecule collides much more frequently with the walls of the vacuum system than with any other molecule.

For typical beam pipes the transition to molecular regime is at about 10^{-3} Torr. Pumps working at higher pressures are mechanical pumps that trap the gas, compress it and expel it from the vacuum system.

- Gas in molecular regime cannot be considered as a fluid and, as a consequence, it cannot be removed by suction because the molecules cannot transfer energy and momentum amongst them.
- In molecular regime, pumps act on each molecule singularly.
- They can be classified in two big families:

1) Momentum transfer pumps

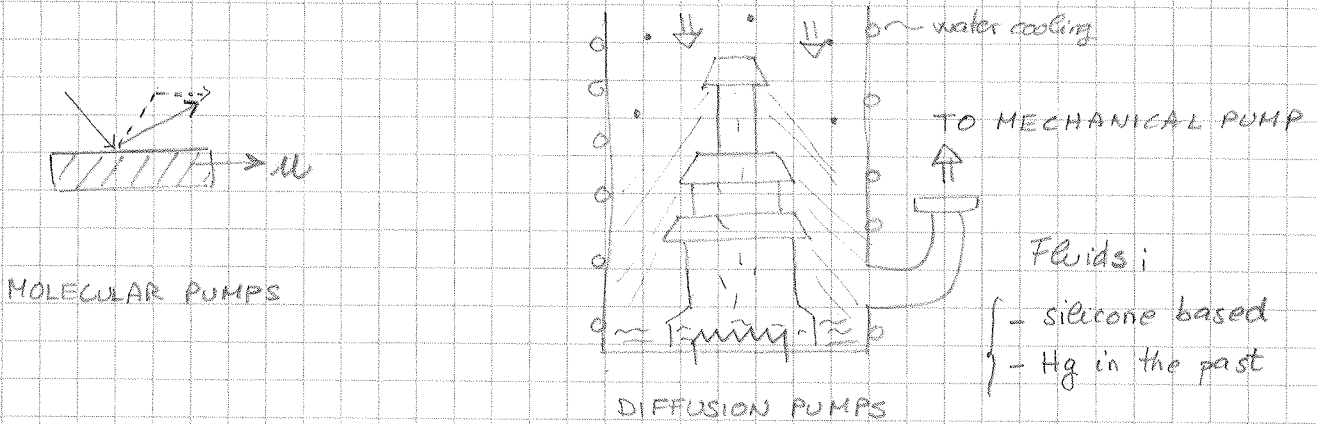
2) Capture pumps

In the first family, the molecules receive a momentum component pointing toward the pump outlet where the gas is compressed and finally evacuated by pumps working in viscous regime.

In the second one, the molecules are not evacuated; they are "captured" on the walls of the pump where they are bound or buried by other atoms. These pumps are much more selective than the first ones.

3.2 MOMENTUM TRANSFER PUMPS; MOLECULAR PUMPS

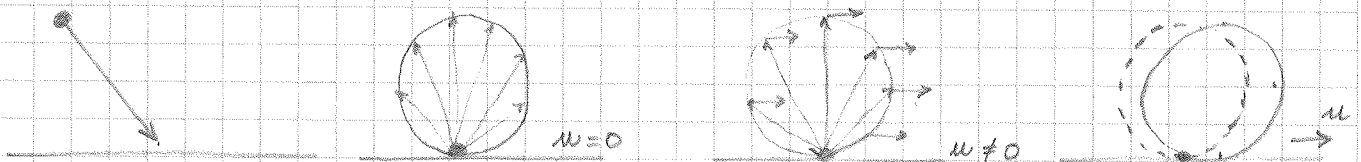
The momentum transfer can be obtained either by impact on surfaces attaining speed close to the mean velocity of molecules or by collision with the molecules of a fluid projected toward the outlet of the pump at supersonic speed ($M \approx 3$ to 8)



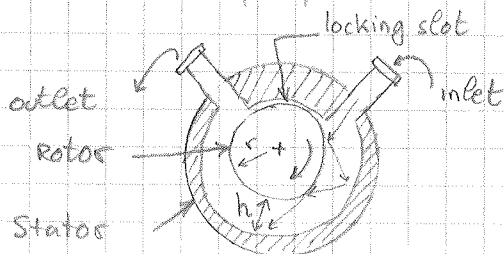
Diffusion pumps are not anymore used in modern particle accelerators.

Molecular pumps are based on the fact that gas molecules that collide on a surface is adsorbed for a finite time.

On desorption, their velocity distribution is isotropic and corresponds to the wall temperature. If the surface moves with velocity u , then the velocity distribution will be superimposed by the drift velocity \Rightarrow a moving wall produce a gas flow.



The first molecular pump was invented by W. Gaede. In the original design, the molecules entering from the inlet hit a rotor revolving at high frequency.



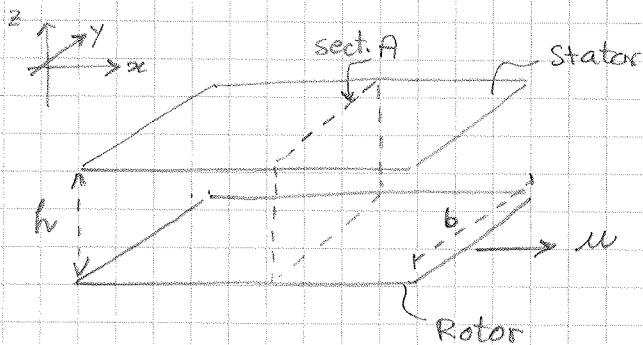
To prevent backstreaming, inlet and outlet must be separated by a very thin slot (locking slot). This aperture is of the order of $1/100$ mm.

The two most important characteristics of a molecular pump are

- pumping speed $\Rightarrow S = \frac{Q}{P_{IN}}$
- compression ratio = maximum $\frac{P_{OUT}}{P_{IN}} = k_0$

The parameters of pump and gas that determine S and k_0 can be identified with the help of a simple geometrical model.

Consider a plane section of the Gaede pump:



at any point in time half of the molecules has just collided with the rotor and drift in the x direction with velocity v . The other half comes from the stator where the

drift component is lost. The flow of molecules toward an imaginary section (A)

is :

$$q_N = \frac{1}{2} \cdot n \cdot u \cdot b \cdot h$$

\uparrow
 density of molecules volume of the gas passing through A in one second.

$$\Rightarrow q_N = \frac{1}{2} \frac{P}{k_B T} \cdot u \cdot b \cdot h \Rightarrow Q_P = \frac{1}{2} P (u \cdot b \cdot h)$$

molecule units
P.V units

$$\Rightarrow S = \frac{Q_P}{P} = \frac{1}{2} u \cdot (b \cdot h)$$

FIRST CONCLUSION: || the pumping speed of a molecular pump is proportional to the speed of the rotor and, in the frame of this simple model, does not depend on the nature of the gas.

The gas flow from the entrance toward the exit generates a pressure gradient (higher pressure at exit). This gradient causes a backflow that can be written as:

$$Q_{bf} = -\bar{c} \cdot \frac{dP}{dx}$$

\bar{c} is the conductance of a unit length duct which section is $b \times h$

The net flux is therefore:

$$Q = Q_p - Q_{bf} = \frac{1}{2} P w (bh) - \bar{c} \frac{dP}{dx}$$

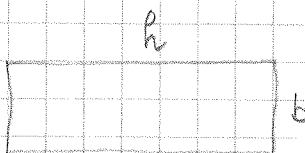
When the net flux is zero:

$$\frac{dP}{P} = \frac{1}{2} \frac{w b h}{\bar{c}} dx$$

Integrating between inlet and outlet:

$$\frac{P_{out}}{P_{in}} = \exp\left(\frac{w b h L}{2 \bar{c}}\right) \quad L = \text{length of the duct.}$$

The unit-length conductance of a rectangular duct is



$$\bar{c} = \frac{2}{3} \cdot \frac{N_{th} (b \cdot h)^2}{b+h}$$

for $h \ll b$

N_{th} = thermal velocity

$$\Rightarrow \frac{P_{out}}{P_{in}} \approx \exp\left(\frac{6}{8} \cdot \frac{w}{N_{th}} \cdot \frac{L}{h}\right)$$

For zero net flux, the pressure ratio is the maximum; it is called the maximum compression ratio K_0 :

$$K_0 \approx \exp\left(\frac{6w}{8N_{th}} \cdot \frac{L}{h}\right)$$

To attain high K_0 , the revolution speed of the rotor has to be the highest possible, in any case close to the molecular thermal velocity.

In addition, the pumping channel has to be long and narrow.

Because the thermal velocity is:

$$v_{th} \propto \frac{1}{\sqrt{M_i}}$$

$$\Rightarrow k_0 \approx \exp\left(\alpha \cdot \omega \cdot \sqrt{M_i} \cdot \frac{L}{h}\right) \quad \alpha = \text{constant at constant } T$$

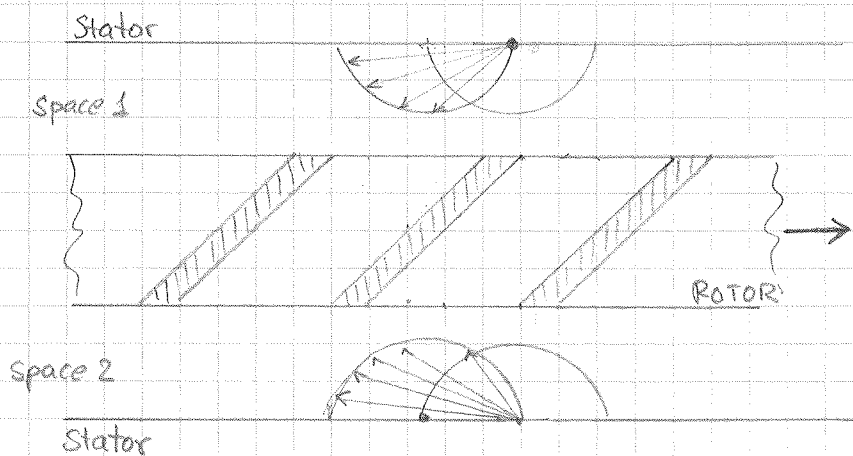
SECOND CONCLUSION: The maximum compression ratio depends on the mass of the gas molecule

The ultimate pressure at the output depends on the characteristic of the mechanical pump (primary pump) \Rightarrow we expect the worst ultimate pressures for H_2 in the vacuum system. (smallest M_i)

3.2.1 Turbomolecular pumps

The development of molecular pumps was hindered by the very ^{small} gap between stator and rotor; these pumps had poor reliability and low pumping speed.

In 1957, Becker invented the first turbomolecular pump. It is based on rapidly rotating blades.



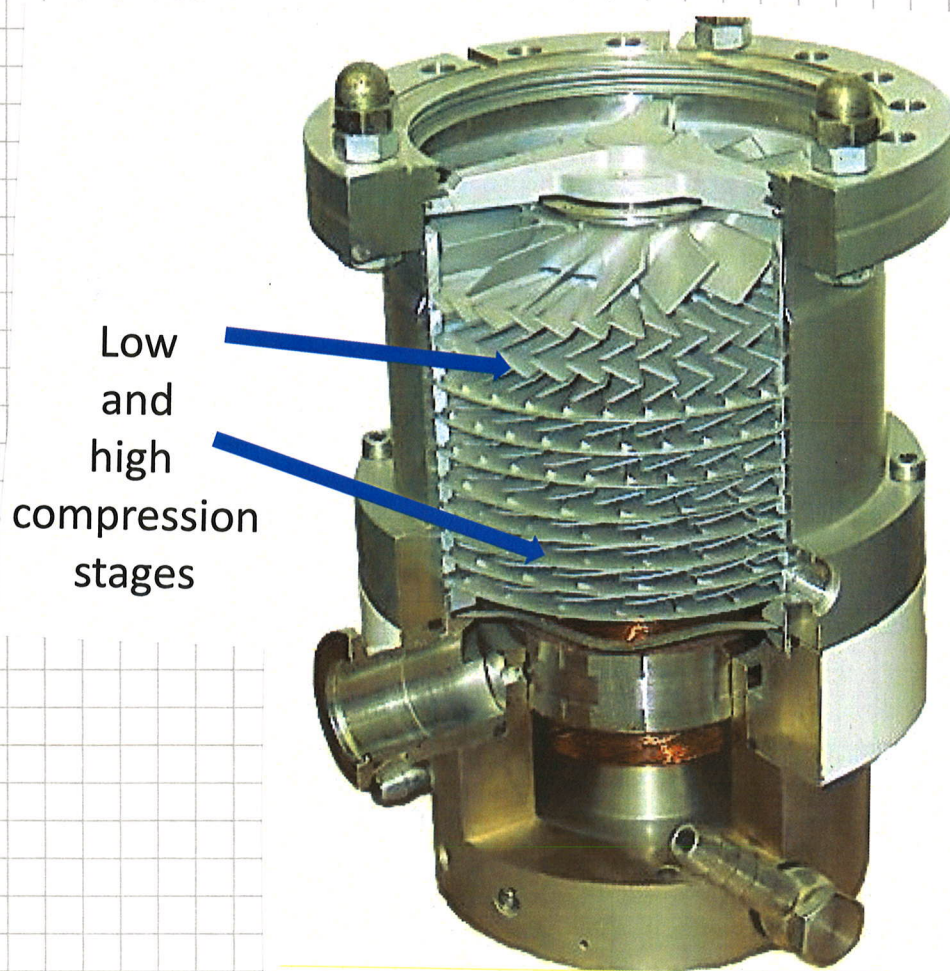
The molecules seen from the blade have a velocity much more oriented toward the blades' channel when they come from space 1. From space 2, most of the molecules hit the

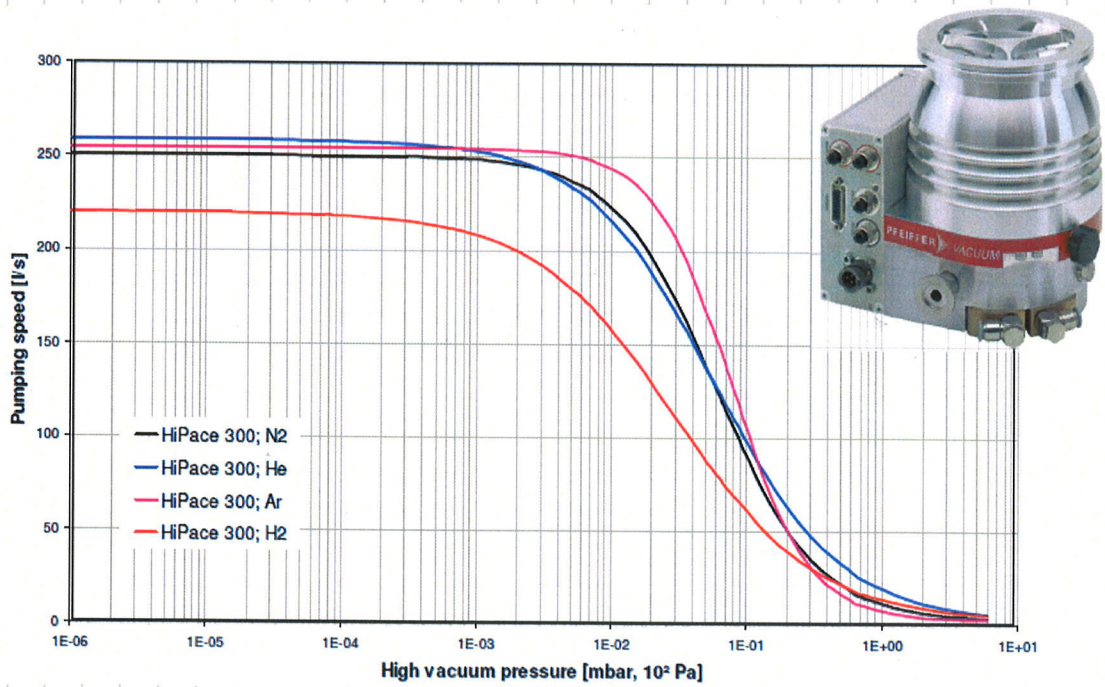
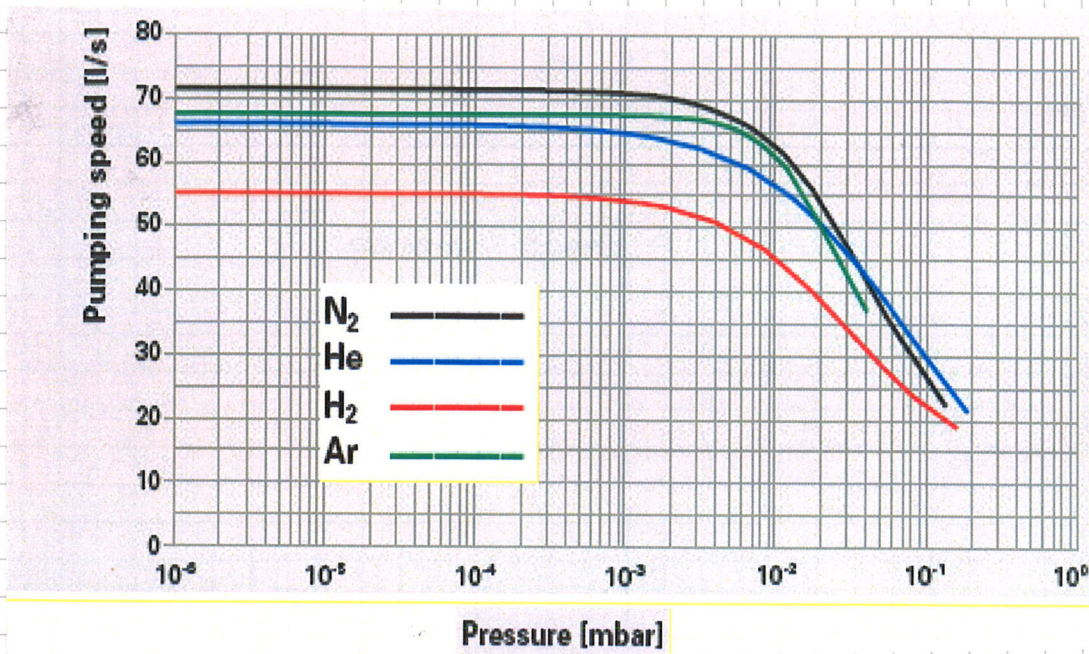
blades and are backscattered. Of course this works only if the deformation of the velocity angular distribution is significant, namely if

$$u \approx v_{th}$$

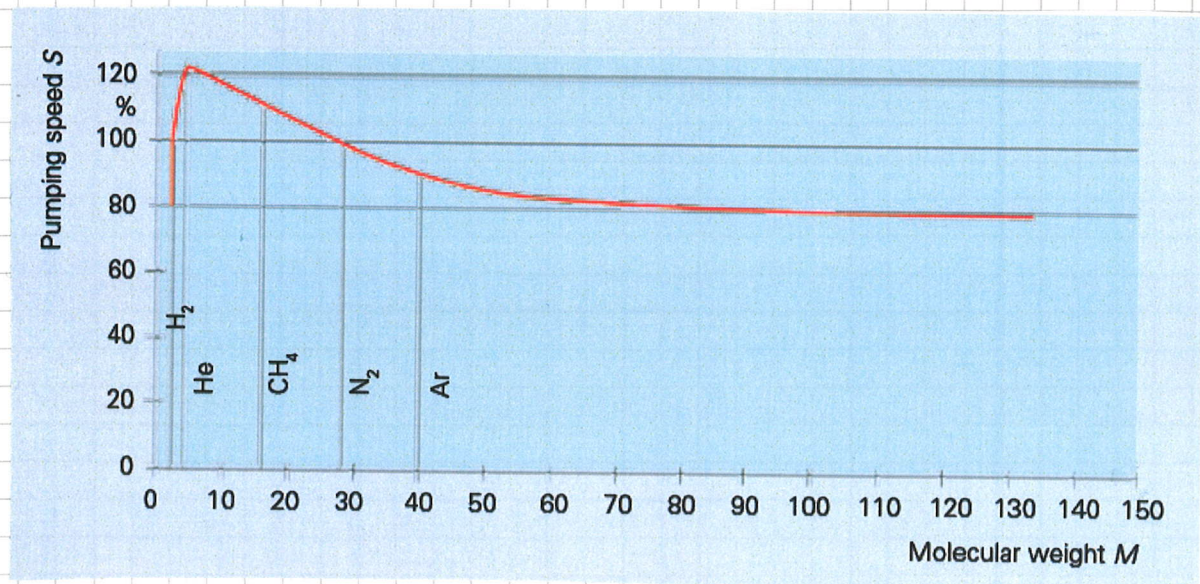
In a real pump, the gas enters through the pump's flange and is compressed by several turbomolecular stages. Any blade series must be followed by a series of static blades (stator).

To increase the compression ratio, the gas compressed by the turbomolecular pump is transported to a classical molecular pump. Finally it is removed by a backing pump





As expected, the mass of the molecule has a small influence on S_v .



The rotor blades are made of high-strength aluminium alloys.

They reach circumferential speeds up to 500 m/s; for 100 mm diameter pump this implies a rotation frequency of roughly 1 kHz.

The pumping speed range of turbomolecular pumps varies from 10 to 3000 l/s.

The pumping speed is constant in the molecular regime ($P < 10^{-3}$ Torr).

As expected the lowest compression ratio is the one for H_2 ; in classical design it was limited to 10^3 . Nowadays values up to 10^6 can be obtained.

In general, turbomolecular pumps and backing pumps are assembled in pump units which include power supplies and instrumentation.

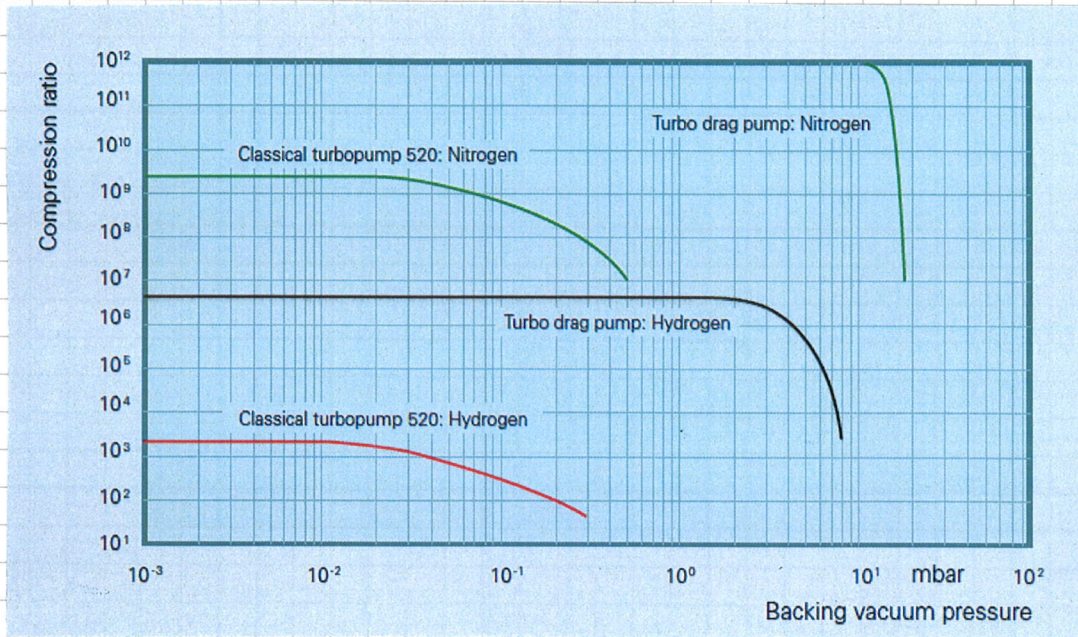
In particle accelerators, they are largely used to evacuate beam pipes to pressures at which capture pumps can safely work. In some specific cases, when high flux of gas must be removed, the turbo pumps the vacuum system continuously. This is the case of H^+ , H^- or ion sources.

The lowest pressure that can be attained by turbomolecular pumps is in the order of 10^{-10} Torr (baked and all-metal systems).

- MAIN ADVANTAGES :
- constant pumping speed in large range of pressure.
 - no memory effect nor selectivity.
 - start working at relatively high pressure.

- MAIN DISADVANTAGES :
- mechanical fragility.
 - intrinsic limitation in ultimate pressure
 - risk of venting the system in case of damage

- relatively high cost per given l/s
(including backing pump and maintenance)



3.3 CAPTURE PUMPS

As already written, capture pumps remove gas molecules by fixing them to a surface.

The sorption mechanism is based either on chemical bonding on reacting surfaces or physisorption on cooled walls. Both mechanisms results in a long mean sojourn time τ_s :

|| physisorption $E_a \leq 0.4 \text{ eV/molec.}$
 || chemisorption $E_a > 0.4 \text{ eV/molec.}$

$$\tau_s = \tau_0 \cdot e^{E_a / k_B T} \quad \tau_0 \approx 10^{-13} \text{ s}$$

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

definition { pumping by low T \rightarrow cryopumps
 { pumping by high $E_a \rightarrow$ chemical pumps \rightarrow getter pumps

Another family of capture pumps associates chemical pumping with physical burying by reactive metal atoms. These pumps are named sputter ion pumps. They are the most important pumps in particle accelerators.

3.3.1 Sputter-ion pumps (SIP)

In sputter ion pumps the residual gas is ionized in a Penning cell.

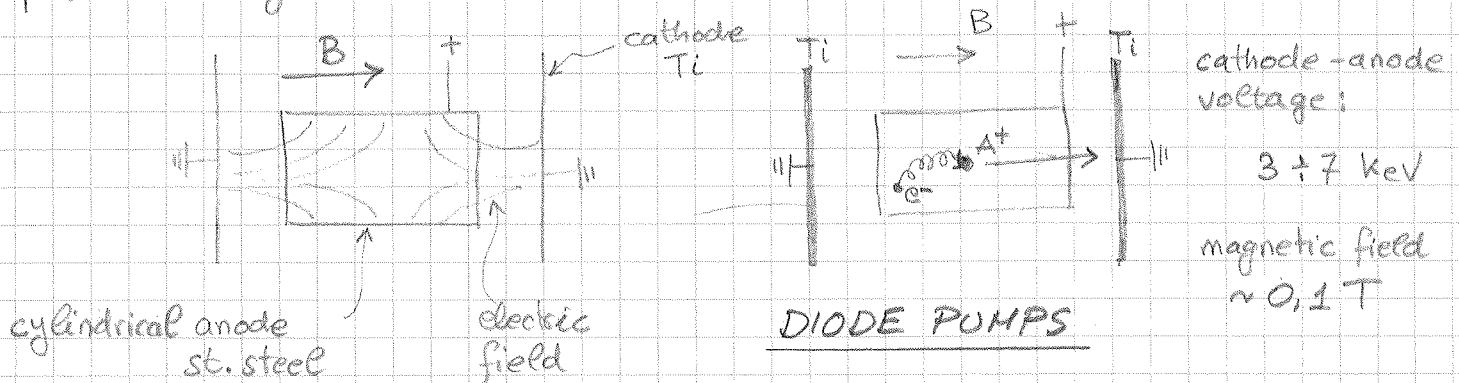
The ions are accelerated toward a cathode made of a reactive metal.

The collision generates sputtering of the reactive metal atoms that are deposited on the nearby surfaces.

The deposited atoms adsorb gas molecules that are then covered by other metal atoms.

In general the reactive metal is Ti.

Schematically a SIP consist of two electrodes (anode and cathode) and a permanent magnet.



The anode is an open cylinder and the magnetic field is parallel to the cylinder axis.

In this configuration, the crossed electrical and magnetic field trap electrons in long helical trajectories, resulting in an increased probability of gas ionization.

The created ions are accelerated to the cathode.

The ions collide on the Ti cathode and they:

- sputter Ti atoms on the nearby surface (mainly anode)
- can be implanted in the cathode
- can rebound as a neutral and be implanted in the

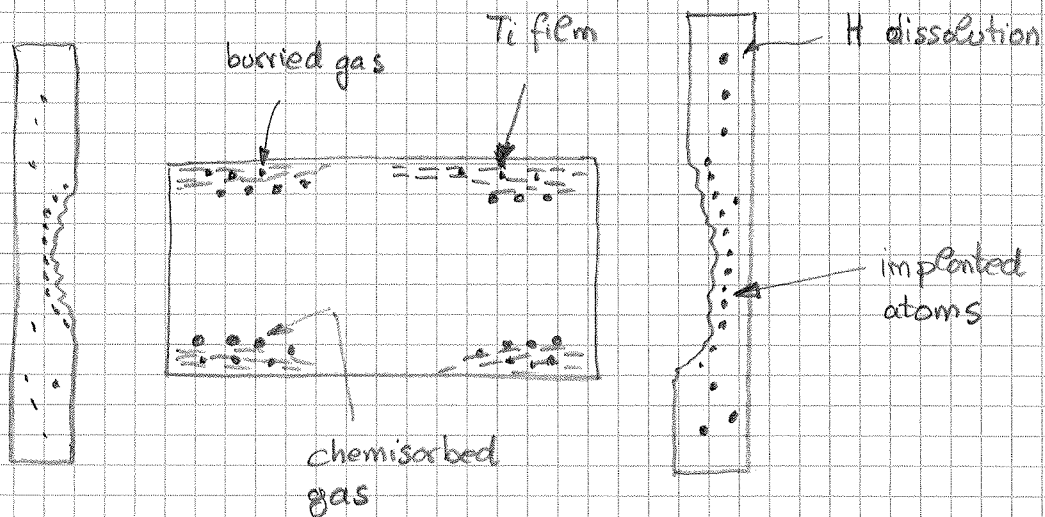
Ti film.

- The Ti film reacts with most of the gas species and definitely remove them from the gas phase.
- Noble gases can be pumped only by implantation in the cathode or in the Ti film.

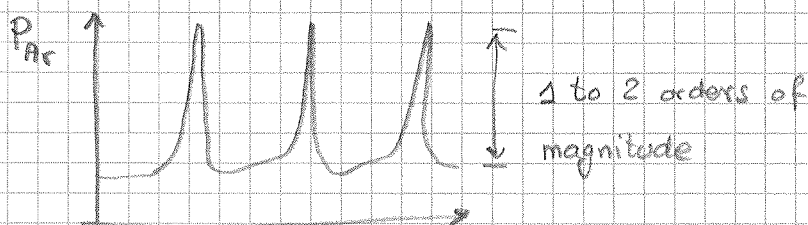
In the cathode the pumping is reversible because, soon or later, the progressive erosion frees the implanted atom.

In the Ti film, the pumping is permanent because the implanted atoms are covered by additional Ti atoms.

In addition H_2 can also be pumped by dissolution into the cathode once the native oxide layer covering the Ti sheets is removed by sputtering.



An excessive quantity of noble gas implanted in the cathode can produce pressure instabilities. In fact, the continuous erosion can extract noble gas implanted; as a result the pressure increases and the erosion is accelerated. The feedback is positive; a pressure spike is produced. The pressure rise terminate when most of the noble gas is implanted again but in a deeper zone. A new pressure spike appears when the erosion reaches the new noble atoms' front.



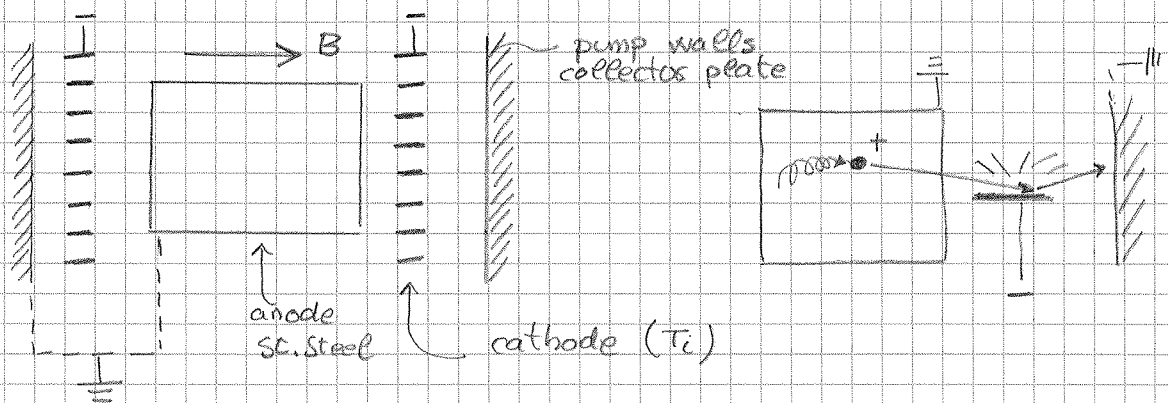
To increase the pumping efficiency for noble gases, the number of ions implanted in the cathode has to be reduced while increasing the rebounding neutralized atoms and their probability to be buried by Ti on the anode.

Two different approaches:

- 1) change material.
- 2) change geometry of the Penning cell.

In the first case Ta is used instead of Ti for the cathode. Ta atoms are much heavier ($Ta = 181 \text{ amu}$, $Ti = 48 \text{ amu}$). Gas ions, once reneutralized, rebound at higher energy when colliding with Ta and, as a consequence, have a much higher probability to be implanted into the anode. The quantity of gas implanted in the cathode is reduced because most of the gas ions rebound. This kind of pump is called "noble diode" or "differential ion pumps".

In the second case, a new arrangement is chosen based on 3 "electrodes". This pump is called "triode pump".

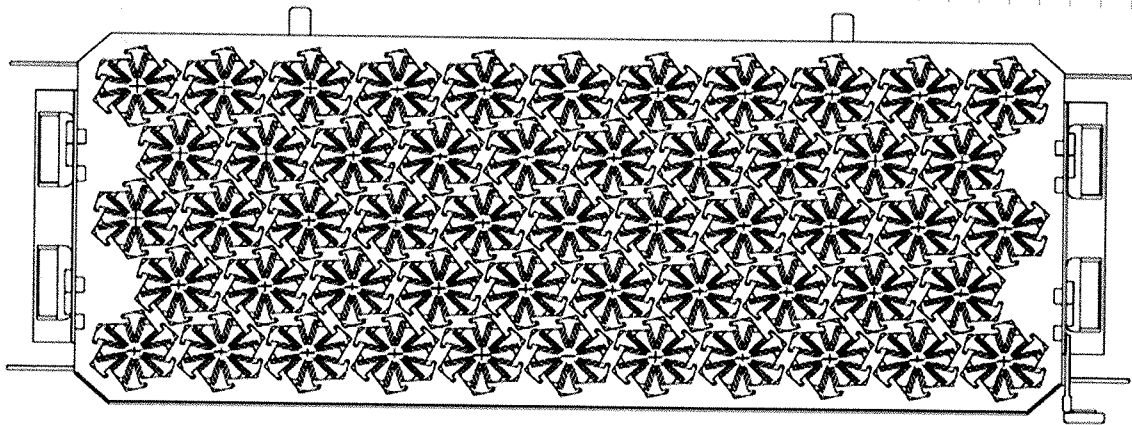
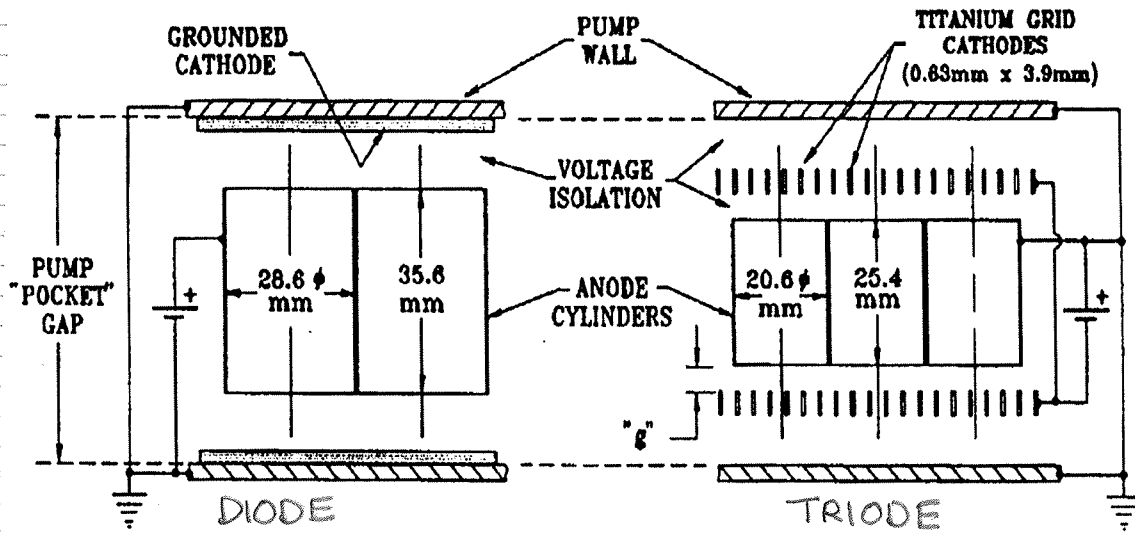


In this pumps, the cathode consists of a series of small Ti plates aligned along the cell axis. In this configuration the collisions ion-cathode are at glancing angle.

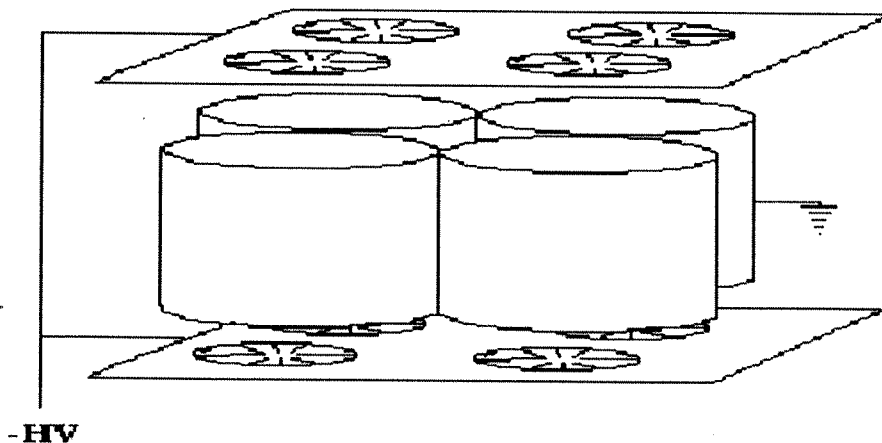
The glancing angle collisions increase the sputtering rate \rightarrow more Ti on the collector plate and anode. In addition, the ions have higher probability of neutralization and rebound at higher energy \rightarrow more efficient implantation in the collector plate.

An improved triode pump is the StarCell (produced by Agilent Vacuum).

In commercial pumps, many penning cells are assembled to form honeycomb structures.



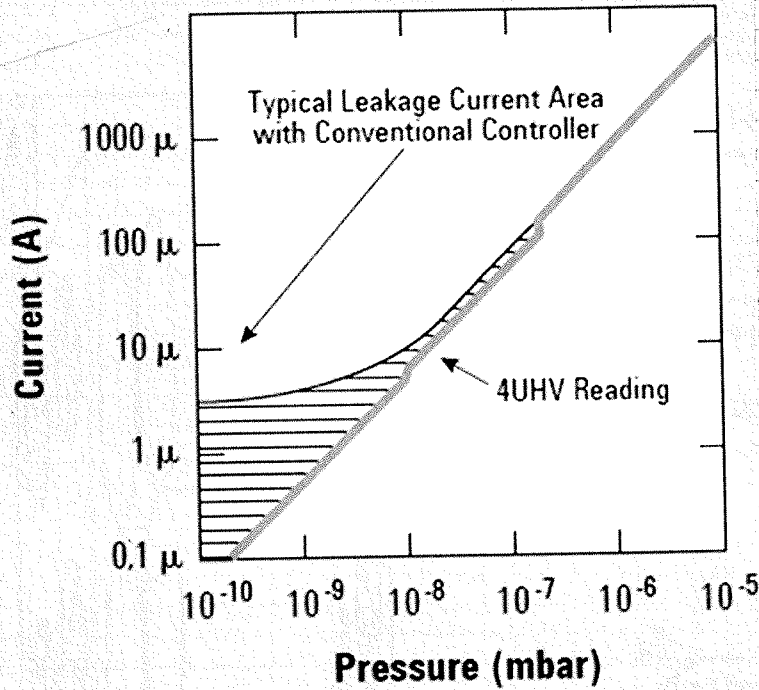
STAR CELL ION PUMP DESIGN



PRESSURE VERSUS PENNING DISCHARGE CURRENT

The discharge current of the penning cells is proportional to gas pressure for $P < 10^{-4}$ Torr. In the lower pressure range, pressure lower than 10^{-9} Torr cannot be measured by standard power supplies because of leak current (field emission).

Typical Current vs Pressure Curve



Ion pumps are extensively used in particle accelerators for the measurement of pressures.

PUMPING SPEEDS

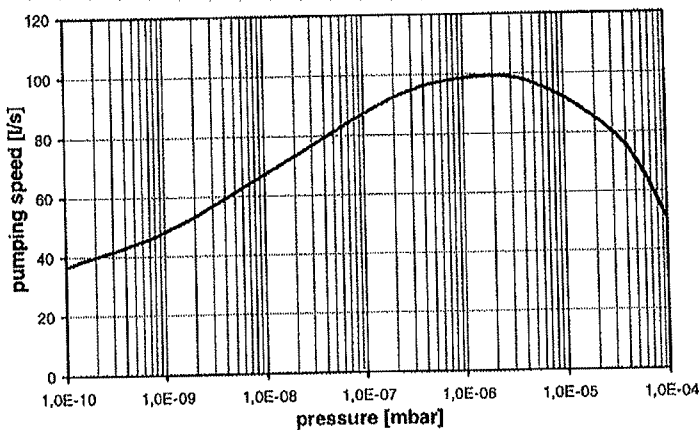


Fig. 5 Pumping speed vs pressure for a standard diode with $S_N = 100$ l/s (for air after saturation).

Pumping speed for ion pumps depends on

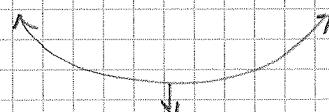
- the pressure at the inlet;
- the nature of the gas

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

pumping speed for N_2
nominal (star cell) →

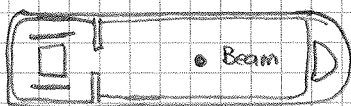
- The pumping speed in general reaches a smooth maximum at about 10^{-6} Torr. This is due to the fact that at lower pressure there are less ionizations, so a lower number of electron to maintain the discharge.
- The gas molecules that are chemisorbed by Ti have high pumping speed. The noble gases have lower pumping speed.

GAS	DIODE PUMPS	TRIODE PUMPS
AIR	1	1
N ₂	1	1
O ₂	1	1
H ₂	1,5-2	1,5-2
CO	0,9	0,9
CO ₂	0,9	0,9
H ₂ O	0,8	0,8
CH ₄	0,6-1	0,6-1
Ar	0,03	0,25
He	0,1	0,3


 normalized to
 S for air

Typical nominal pumping speed for air varies from a few l/s to ~ 1000 l/s.

DISTRIBUTED ION PUMPS



Ion pumps can also be distributed along the beam pipe of accelerators. The magnetic field is provided by the dipole magnets that steer the beam.

The development of this pump was hindered by the B field limitation during beam injection and also by the introduction of getter ribbon and films.

3.3.2 Getter pumps

Some definitions:

a) sticking probability: $\alpha = \frac{\text{nr of molecules captured by a surface}}{\text{nr of molecules impinging on a surface}}$
= probability of pumping for a molecule.

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

For $\alpha=1$, all impinging molecules are pumped

$$\Rightarrow q_p = \frac{1}{4} n v_{th} = \frac{1}{4} \cdot \frac{p}{k_B T} \cdot v_{th} \Rightarrow \frac{q_p}{p} = \frac{1}{4} \frac{v_{th}}{k_B T}$$

in pressure-volume units $S = \frac{q_p}{p} = \frac{1}{4} v_{th}$ (conductance of unit area)

$$\Rightarrow \alpha=1 \quad S_{H_2} \approx 44 \text{ l/s} \quad S_{N_2} \approx 11.7 \text{ l/s} \quad S_{H_2O} = 14.7 \text{ l/s}$$

b) monolayer coverage:

the quantity of gas needed to cover the unit area
(depends on roughness and porosity); for "technical" surface:

$$N_{HL} \approx 10^{15} \text{ molecules} = \frac{10^{15}}{3.3 \times 10^{19}} = 3 \times 10^{-5} \text{ Torr} \cdot \ell$$

c) monolayer formation time:

for $\alpha=1$ and a smooth surface, for N_2 :

$$t_{sat} = 10^6 \cdot p \text{ [s]}$$

For $10^{-6} \text{ Torr} \rightarrow 1 \text{ s}$ is needed to cover a surface.

Getter surface adsorb most of the gas molecules present in vacuum system. They react with the gas and form stable chemical elements.

This is possible only if their surface is clean, free of contamination and native oxide layer. The metal atoms have to be free to exchange electrons with the gas molecules.

Depending on how the clean, metallic, surface is produced two family of getters can be defined:

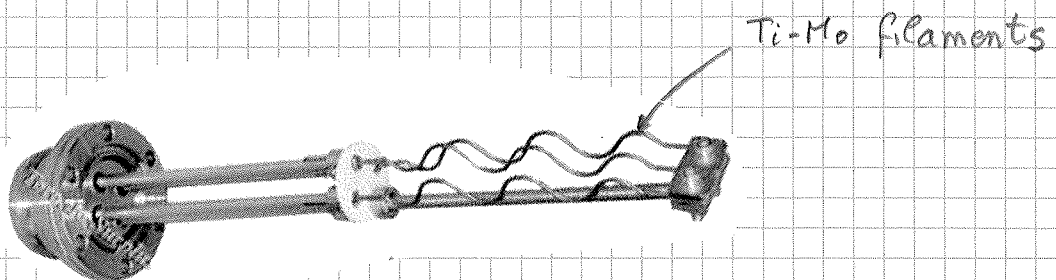
① evaporable getters: the active surface is generated by sublimation of a metal in-situ.

② non-evaporable getters (NEG): the active surface is produce by dissolving the surface contamination into the getter bulk by heating in vacuum. The dissolution process is called "ACTIVATION".

3.3.2.1 EVAPORABLE GETTERS (SUBLIMATION PUMPS)

For particle accelerators, Ti is the metal of choice.

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



The material of the rods is not pure Ti because otherwise cross-section of lower dimensions would result in higher temperature, higher sublimation, faster diameter reduction and finally melting.

In case of Ti-Mo, the Ti sublimation increases the concentration of Mo which reduces the sublimation rate of Ti and melting point.

In commercial rods: Ti-Mo(15%).

Sticking probabilities α for Ti sublimated at 300°C are:

$$\text{H}_2 : 1 - 5 \times 10^{-2}$$

$$\text{CO} : 0,4 - 0,8$$

α depends on the quantity of gas already pumped: $S = S(Q)$. The molecules already adsorbed block adsorption sites. The S reaches negligible values when Q approaches a saturation values that depends on the gas nature.

For CO: $Q_{\text{SAT}} \approx N_{\text{ML}}$; for O_2 : $Q_{\text{SAT}} \approx 5 \div 10 N_{\text{ML}}$; for N_2 : $Q_{\text{SAT}} \approx N_{\text{ML}} / (3 \div 6)$

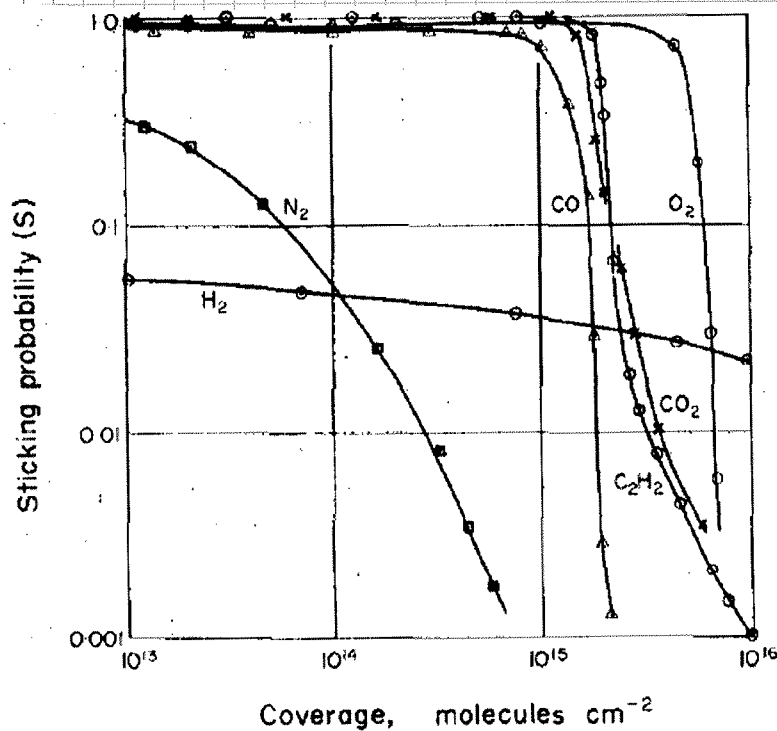
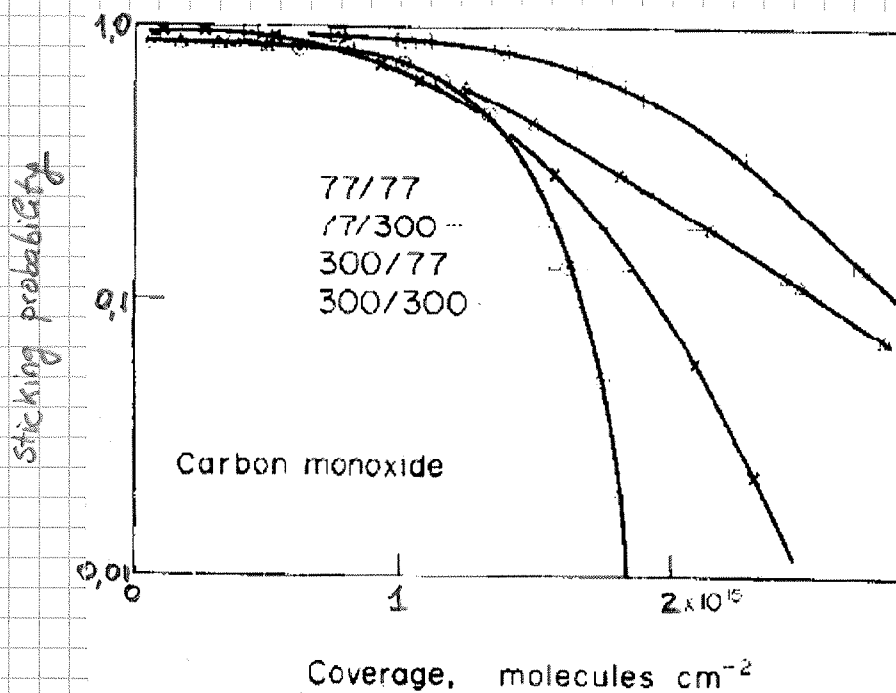


Figure 4. Room temperature sorption characteristics for pure gases on batch evaporated clean titanium films.

When Ti is sublimated on a surface at 77 K, the Q_{SAT} increases \rightarrow the roughness of the film is higher.



The experimental curves $S=S(\theta)$ indicate that at room temperature all gases adsorbed on Ti remain on the surface. The only exception is H_2 : this gas, after molecular dissociation, diffuses in the Ti film. As a result the quantity of gas already pumped has a limited effect on the pumping speed.

When the surface is saturated, the pumping capacity can be restored by additional sublimations.

This pump does not adsorb rare gases and CH_4 at room temperature. As a consequence, it is always coupled with other kind of pumps; in general with sputter ion pumps.

Ti sublimation pumps do not have intrinsic pressure limitations.

One of the lowest ever measured pressures at room temperature was produced by Ti subl. pumps + sputter ion pumps ($\sim 2 \times 10^{-14}$ Torr).

With this pump, distributed pumping is unfeasible along beam pipes.