

## Rotary Pumps

Single stage and double stage pumps

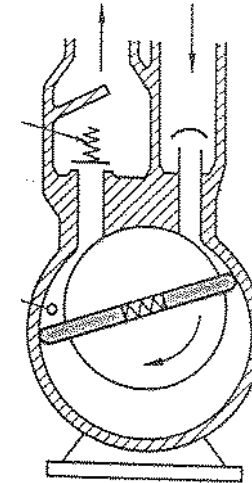
Oil sealed

Typical end pressures :  $10^{-2}$  to  $\sim 10^{-3}$  mbar

Typical pumping speeds : 4 to  $\sim 40$  m<sup>3</sup>/h  
(used for systems with small volume)

Filter for oil vapour is required.

**Dry pumps**, without oil are now available but very expensive!



## Turbomolecular Pump

Molecules collide with the surface and gain a velocity component in the direction of the movement.

Pumping speed of a turbomolecular pump  $S = v A$

$S$  independent of pressure

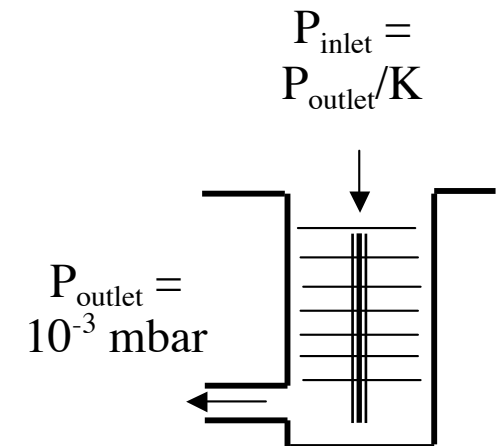
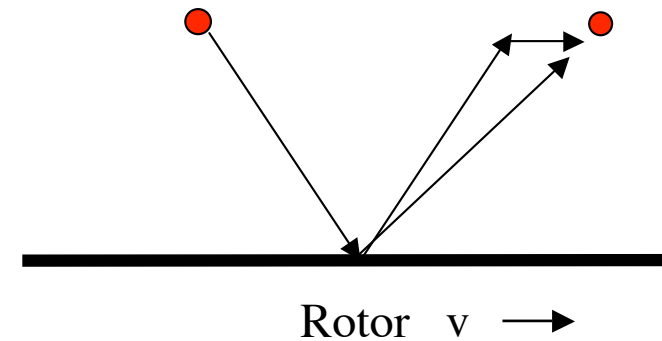
$v$  rotational speed, typically at least >40000 rpm

$A$ : pump geometry, large entrance flange

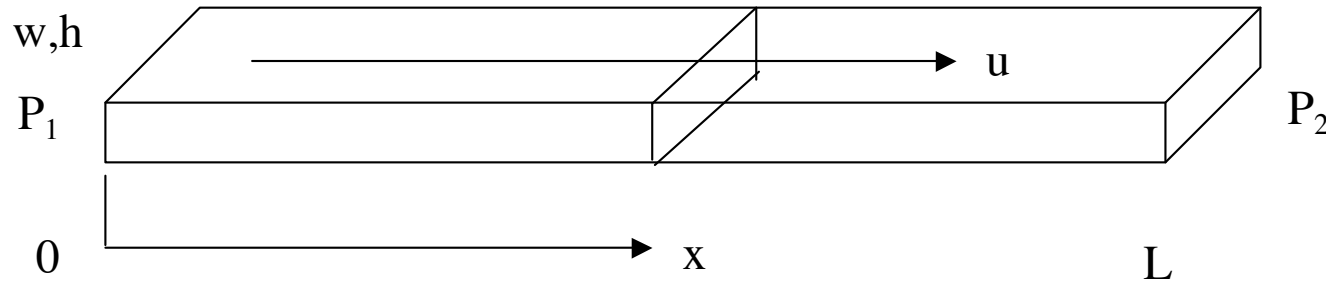
Compression ratio of the pump is defined as  $K = \frac{P_{outlet}}{P_{inlet}}$

$K$  is an exponential function of the molecular weight and of the rotational speed ( $10^3$  for  $H_2$  to  $10^9$  for  $N_2$ )

Hence the compression ratio is large for heavy molecules -> 'clean vacuum' without heavy hydrocarbon molecules. Oil contamination from primary pump can be avoided.



## The Molecular Pump Principle



The molecular conductance of a rectangular duct, with the perimeter  $H = 2(w + h)$  and the section  $A = w \cdot h$  is given by  $\square$

$$c = \frac{4}{3} \frac{\bar{v}}{x} \frac{H}{A^2} dl = \frac{2}{3} \bar{v} \frac{h^2 w^2}{x(h+w)}.$$

In molecular flow  $\square$   $\frac{dP}{dx} = \frac{Q}{c}$ .

Assuming that one surface is moving with the speed  $u$ , the gas flow which traverses a given cross section corresponds to  $\square$   $Q = PV = P \frac{u}{2} A$ .

Thus  $\frac{dP}{dx} = \frac{u}{2c} AP$ .

Integrating this equation over the length of the duct

$$\int_{P_1}^{P_2} \frac{dP}{P} = \frac{u}{2c} A \int_0^L dx$$

one obtains the result

$$K = \frac{P_2}{P_1} = e^{\frac{u}{2c} AL}.$$

K defines the compression ratio of a pump i.e. the ratio between input and output pressures.

K increases exponentially with the molecular weight, and with the rotational speed of the pump.

Typical values of commercial pumps :      for hydrogen  $\sim 2 \cdot 10^3$

for nitrogen  $\sim 10^8$  !

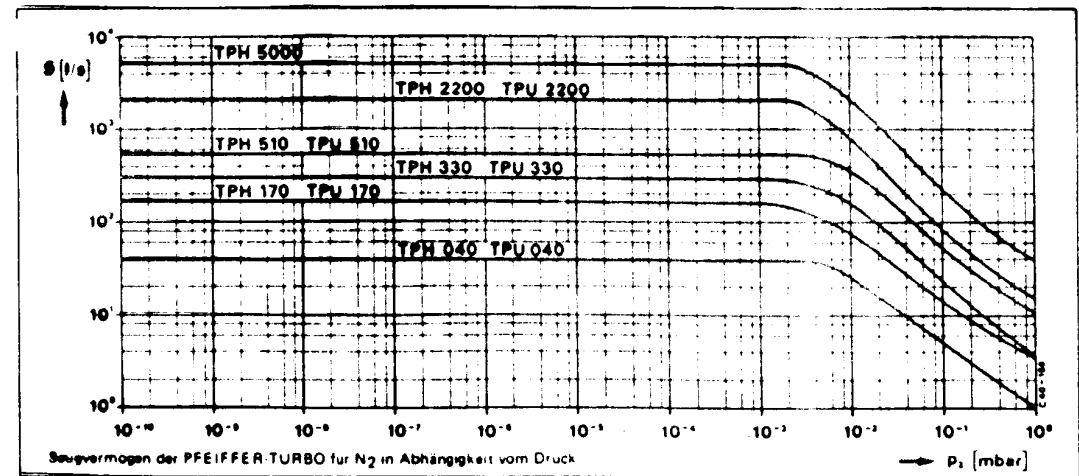
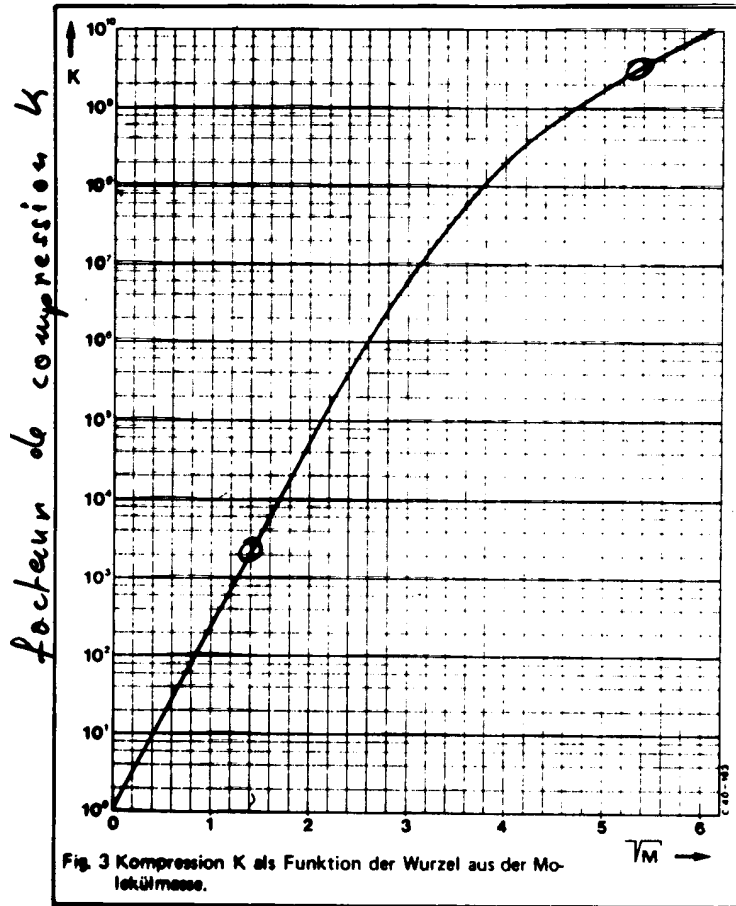
A large compression ratio for heavy molecules results in a 'clean vacuum' without hydrocarbon (C-H) contamination.

The pumping speed S is proportional to the rotational speed and depends on the geometry of the pump.

S does not depend on the molecular weight M.

## Turbomolecular pumps

Compression factor and pumping speed curves of commercial turbomolecular pumps

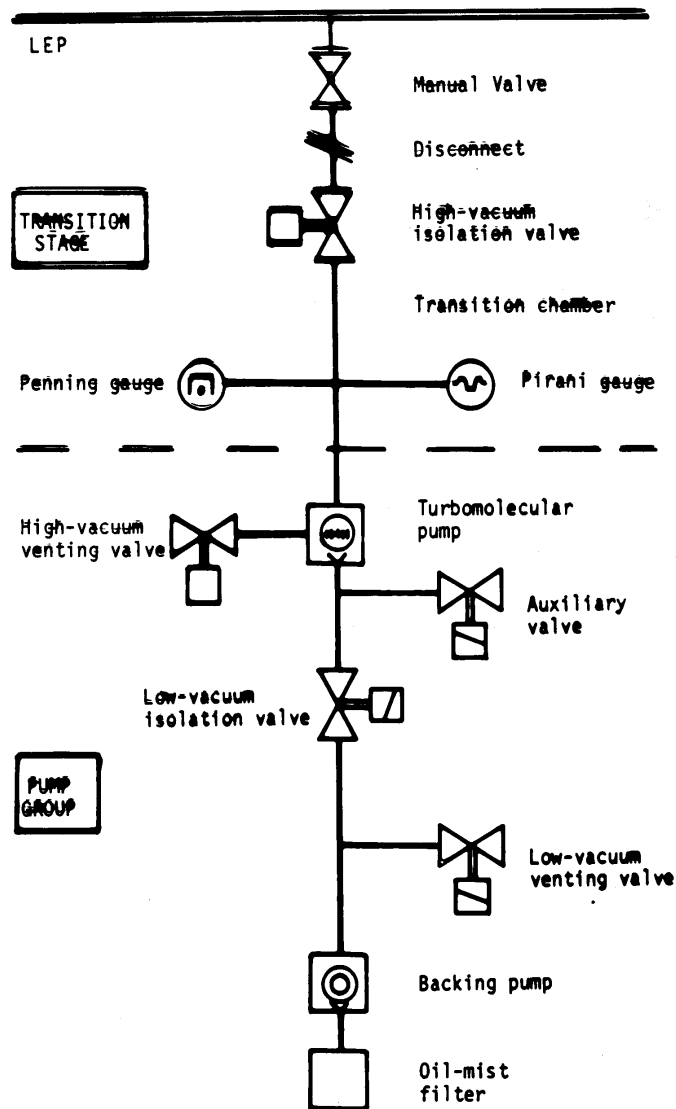


## Pumping station for LEP

Schematic layout:

Pumps required for the initial pump down only.

During operation of the accelerator, the separation valve is closed. The mobile pumps can be removed from the tunnel.



## Sputter-Ion-Pump

Configuration of a parallel electric and magnetic field produces a self-maintained discharge plasma.

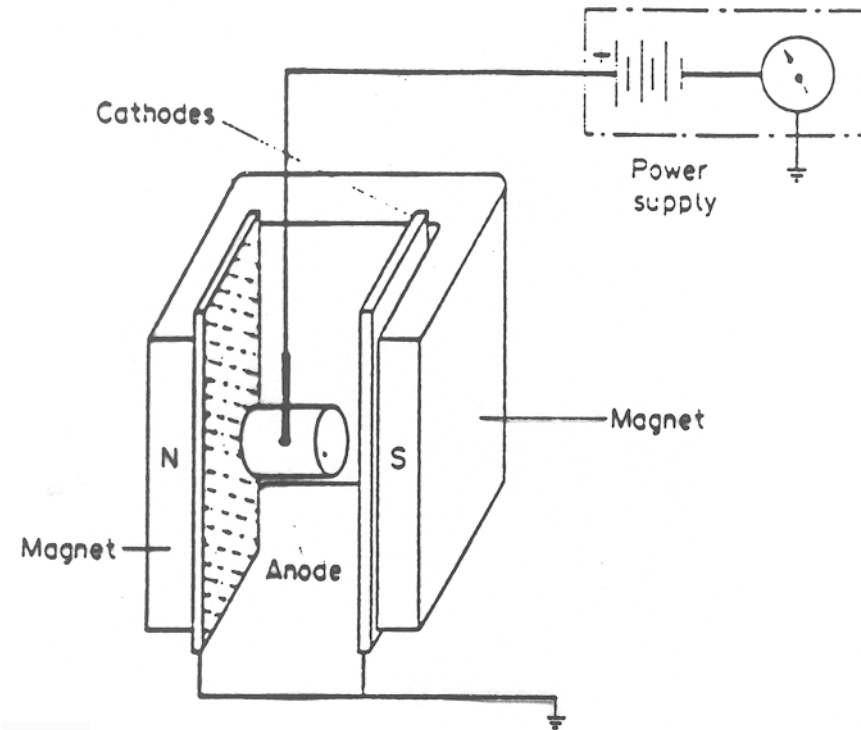
-> Penning configuration

Ionised residual gas molecules are accelerated towards the Ti cathode and 'trapped' and removed from the gas phase.

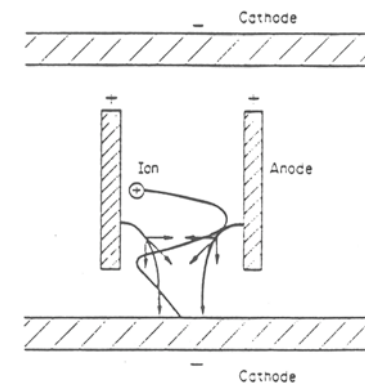
Sputtering of Ti from cathode produces a clean gettering film.

In a particle accelerator, the magnetic field is provided by bending magnets. --> integrated, linear ion-pumps.

To increase the pumping speed, arrays of cells are used



Basic configuration of a sputter-ion pump.



## Pumping mechanisms

**Gettering** -> chemisorption of active species  $H_2$ ,  $CO$ ,  $N_2$ ,  $O_2$ ,  $CO_2$

**Diffusion** of  $H_2$  into the Ti- cathode (re-diffusion!)

**Cracking** of inert hydrocarbons into C, H, O which can be pumped (chemisorbed) separately

**Nobel gases:** energetic ions of He, Ne, Ar by implantation into the cathode: “ion burial” of energetic ions. -> Argon instability after pumping of air.

To increase the discharge intensity and thus the pumping speed it is desirable to increase the sputtering rate of the titanium cathode

→ Triode Sputter-Ion pump with grazing incidence of ions on a grid cathode

Note:

Molecules are not removed from the vacuum system. Therefore, memory effect of previously pumped gas (Argon).



## Surface Pumping

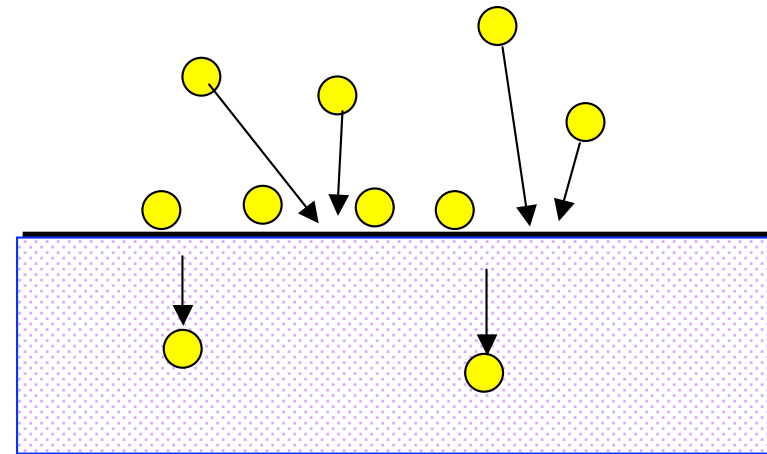
### Getters (chemisorption $E \sim eV$ )

Evaporable getter pumps (Ti sublimators)

Non Evaporable Getters (NEG)

Ti, Zr, V

Surface pumping  $\rightarrow S = \frac{1}{4} \bar{v} n F$



Gettering surface achieved by sublimation from a Ti-filament.

Or by surface activation (heating  $\rightarrow$  reduction of surface oxide layer and diffusion of O into the bulk)

### Cryo-pumps (physisorption $E \sim meV$ )

Sorption (capacity  $\sim$  monolayer)

Condensation (vapour pressure)

## Monolayer Capacity

To illustrate the significance of a monolayer of gas, let us assume an evacuated sphere which has one monolayer molecules adsorbed on the inner surface.

$$N_{ads} = 4\pi r^2 \sigma$$

In case this gas is desorbed it would correspond to a volume density

$$n = \frac{N_{ads}}{V} = \frac{3\sigma}{r}$$

Taking, e.g.  $1 \text{ m}^3$  as the volume and  $p \approx 3 \cdot 10^{19} \text{ m}^{-3}$  the pressure at room temperature would increase to typically

$$p = n kT \approx 0.4 \text{ Pa}$$

Hence:

To reach uhv conditions, the ‘surface gas’ is extremely important.

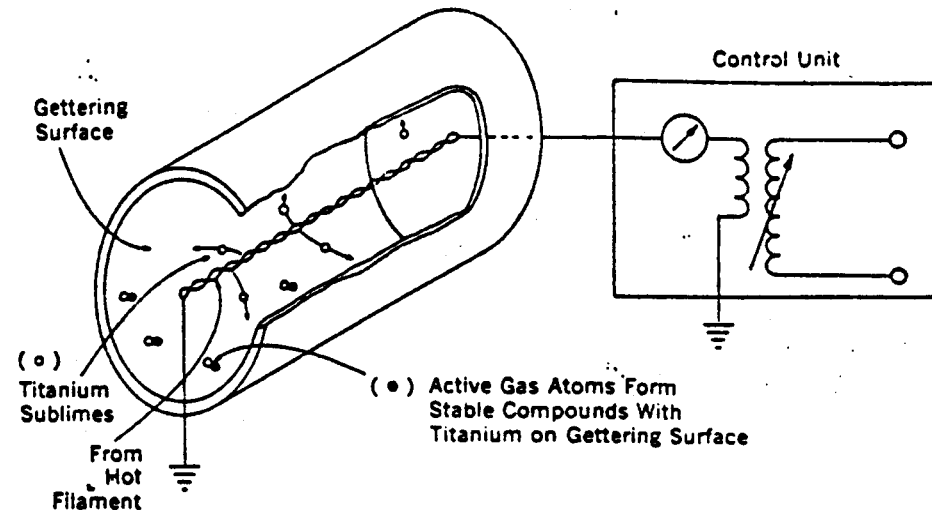
Inversely, adsorbing molecules permanently on an ‘active’ surface (getters or cryo-pumps) is an extremely efficient pumping principle.

## Getter Pumps

### Evaporable getters:

### Titanium sublimation pump

Configuration □



Deposition of a thin film of fresh Ti on the inner surface of the vacuum chamber

Filament temperature  $\sim 1300$  deg C

To increase the lifetime of the pump one uses pump holders with several filaments (3 – 6)

Depending on the amount of gas pumped, the film has to be regenerated (e.g. typically at  $10^{-6}$  Pa after one hour)

The pumping speed increases with the surface of the pump and can be very substantial.

Note : only chemically active molecules can be pumped.

## **Non-Evaporable Getters or Bulk getters (NEG) :**

Getter material ( e.g. Ti, Zr, V) produced in the form of an alloy e.g. with Al and used as a bulk material.

For LEP : metal ribbon coated with a thin layer of getter powder has been used.

Clean, active gettering surface is produced by heating under vacuum. Gas adsorbed on the surface diffuses into the bulk and a 'clean' surface can be obtained.

Activation requires heating from 350 °C up to 700°C for one hour depending on the specific getter.

A new development consisting of a combination of evaporable getters and of bulk getters is under development at CERN ->

**sputter deposited getter films** (few  $\mu\text{m}$  only) coated directly onto the inner surface of vacuum chambers. First use in insertion chambers (ESRF) and for LHC vacuum (CERN).

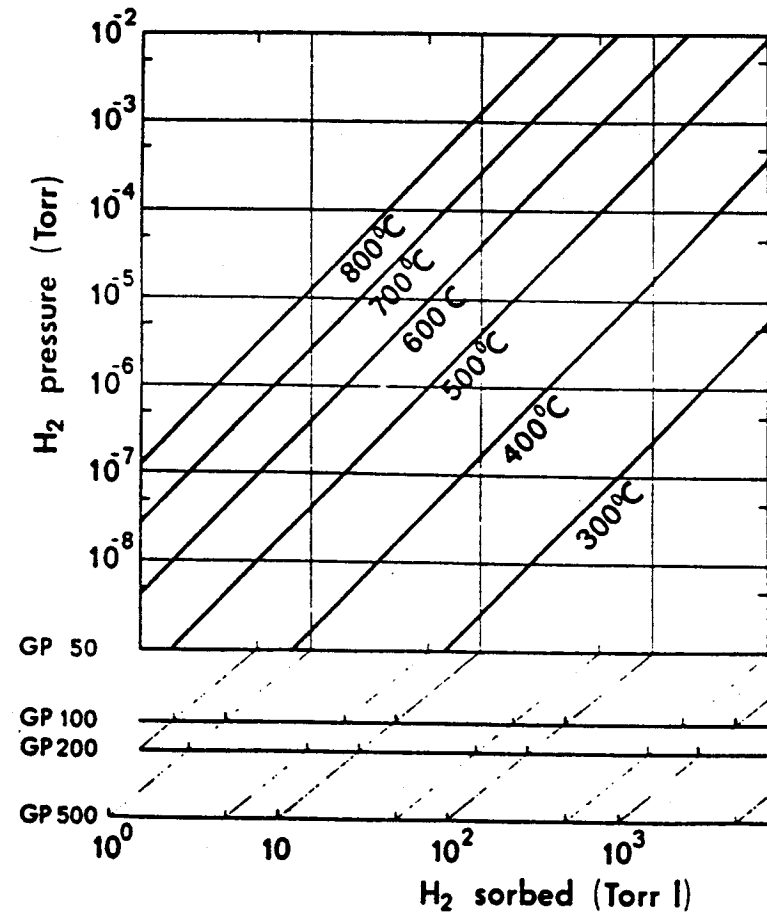
Note: Getters have a limited total pumping capacity and a memory effect of the gas previously pumped.

Getters pump only chemically active gas i.e. noble gases and hydrocarbons (methane, ...) are NOT pumped. Combination with ion pumps is required.

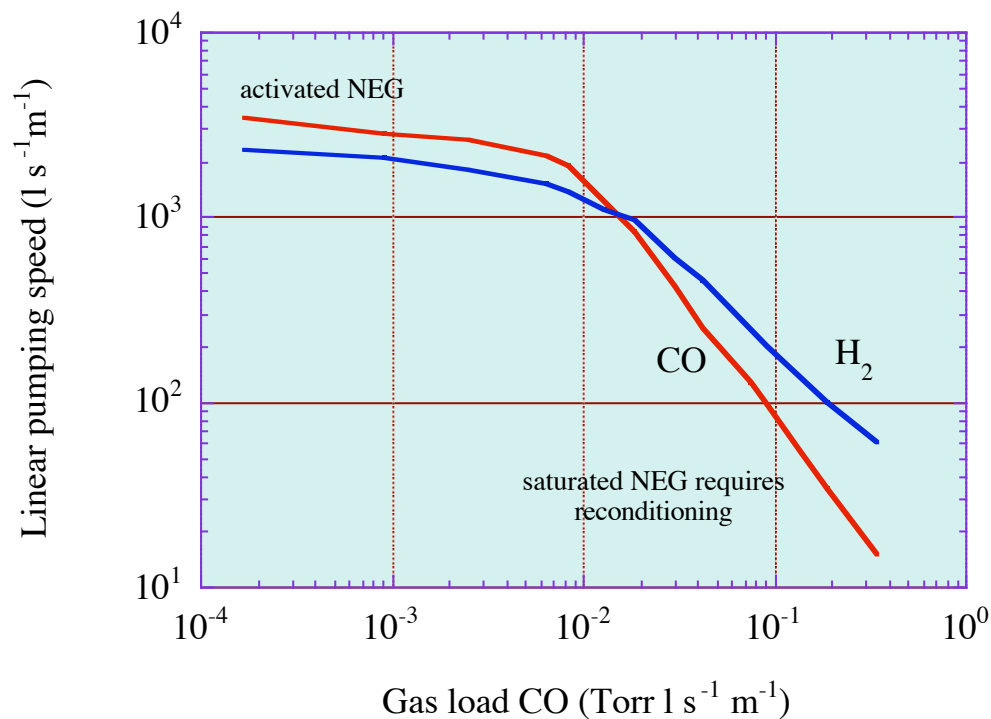
## Reversible pumping of hydrogen by the NEG st101.

The equilibrium pressure of hydrogen is a function of the concentration of  $H_2$  in the bulk,  $q$  ( $\text{Pa m}^3\text{g}^{-1}$ ) and of the temperature,  $T$  (K)  $\square$

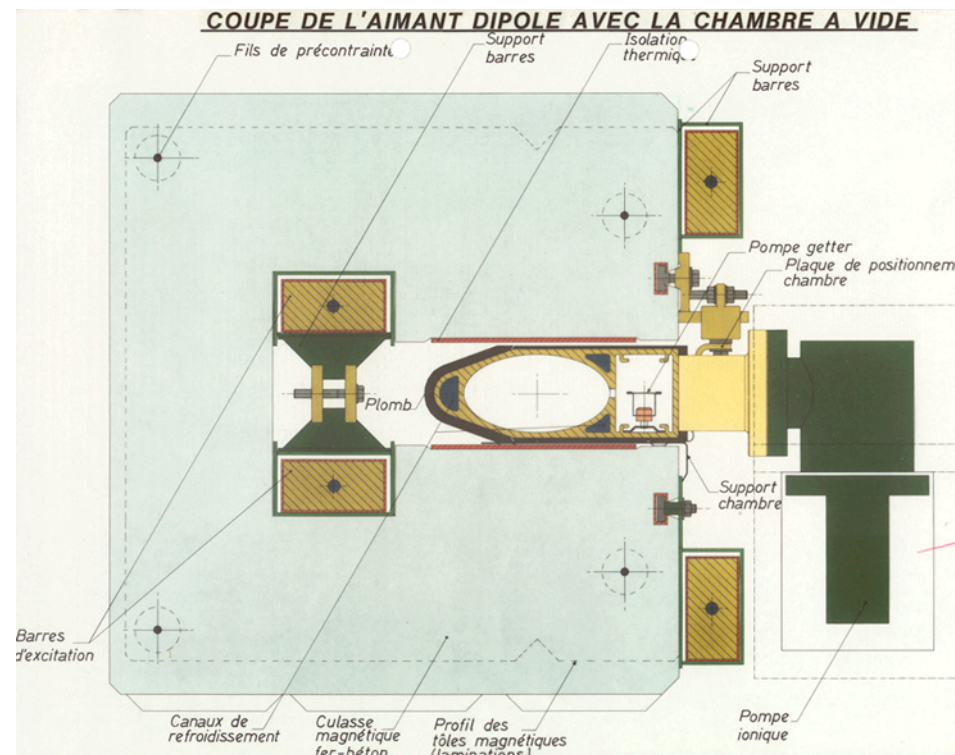
$$\ln P_{equ} = 8.275 + \ln q^2 - \frac{7000}{T}$$



## Pumping speed of a St101 getter

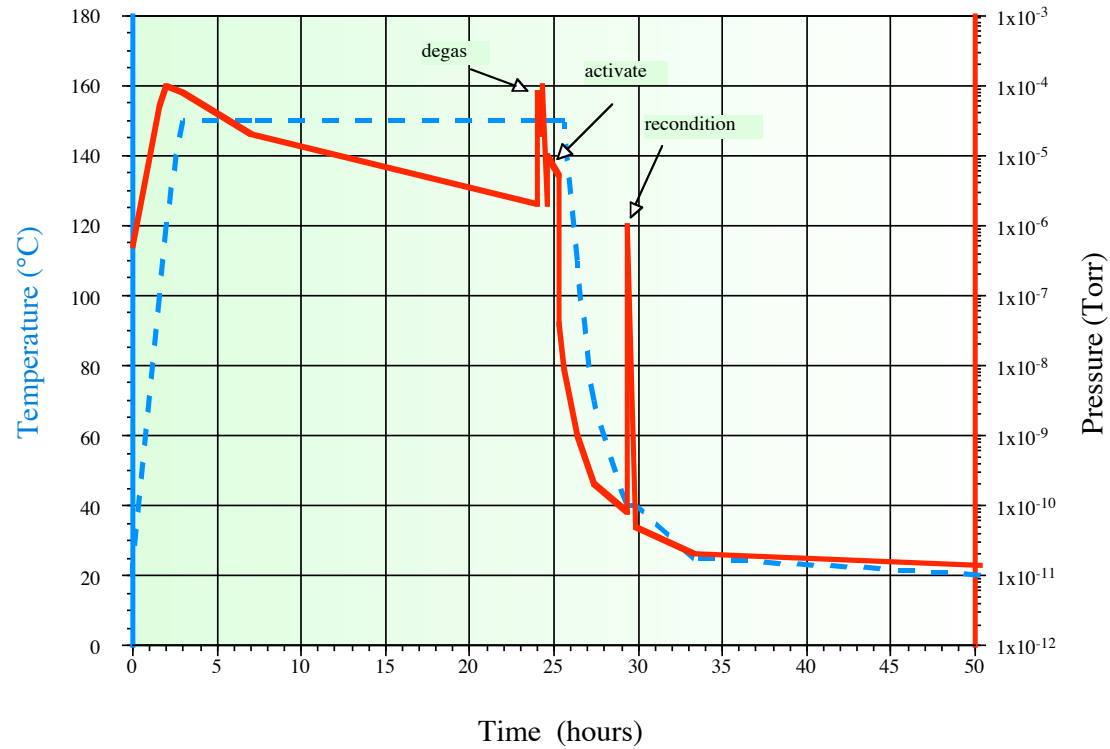


Reduction of the pumping speed due to the gradual saturation of the surface by adsorbed molecules. During **re-activation**, molecules diffuse into the bulk. A fresh surface is obtained for the next pumping cycle.



## Preparation of LEP vacuum system with NEG pumps

Typical bakeout cycle with NEG



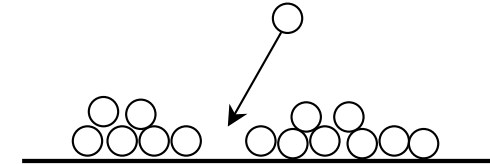
Within less than 12 hours after the bakeout uHV conditions can be achieved.

## Cryo-Pumping

Adsorption of molecules at low temperature -> e.g. at liquid helium temperature

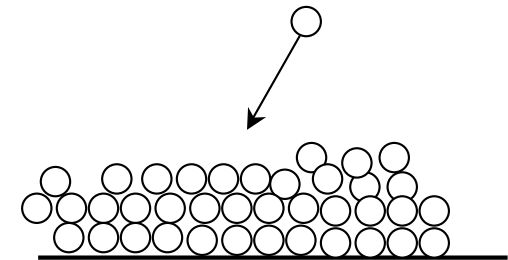
### A) Sorption

Adsorption of gas molecules with low surface coverage, to avoid the effect of the vapour pressure of the condensate. Increasing the effective surface area by a coating with a large specific surface area e.g. charcoal. -> Adsorption isotherms.



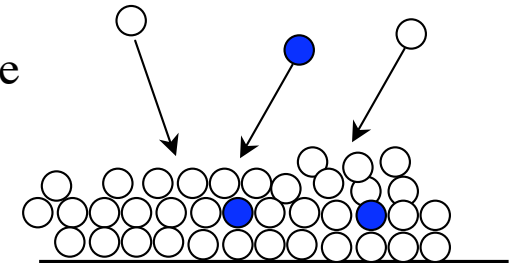
### B) Condensation

adsorption in multi-layers -> limitation due to the vapour pressure of the condensed gas.



### C) Cryo-trapping

Cryo-sorption of a gas e.g.  $H_2$  or  $He$  with a **high** vapour pressure in the presence of an easily condensable carrier gas e.g.  $Ar$ .





## Characteristics of cryo-pumping :

### Large pumping speed

Low limit pressure  $\square$  -> limitation occurs only by the vapour pressure of the condensed gas

Large capacity -> **Attention**  $\square$ ! hazardous over-pressure may build-up during warming up of a cryo-pumped system. ! -> a safety valve required  $\square$

-> 'clean' vacuum -> absence of heavy hydro-carbon molecules.

-> in combination with superconducting magnets or accelerating cavities, very effective **integrated cryo-pumping** can be obtained -> e.g. LHC vacuum system.

-> the walls of the vacuum system act as pumps (LHC).

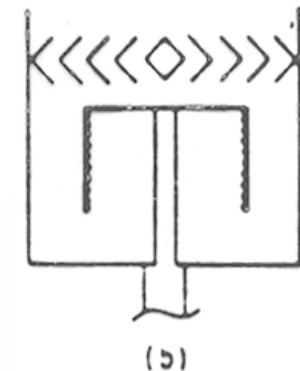
The saturated vapour pressure limits the total quantity of gas which can be cryosorbed at low pressure.

Increase of the specific surface area of a cryo pump by using special cryo-sorbing materials with a large specific surface -> e.g. activated charcoal.

Design of a commercial cryo-pump with a cryo-panel :

Baffle is needed to intercept thermal radiation.

Risk of overpressure during warm-up when too large amount of gas has been condensed.



## Cryopumps in accelerator vacuum systems

In combination with superconducting magnets or accelerating cavities, at little (or no) extra cost very effective **integrated cryo-pumps** can be obtained in an otherwise conductance limited vacuum systems.

Large freedom in the design of cryopumps : since the cold walls of the vacuum system act as pumps (LHC).

The limitations of cryopumps due to the exposure to environmental room temperature radiation and to the bombardment by beam induced energetic particles (photons, electrons, ions) must be taken into account.

Imposes -> LN<sub>2</sub> cooled baffles and the LHC beam screen. This requirement arises not only for heat load reasons but mainly to avoid re-desorption of molecules.



## Vapour pressure of common gases and of Hydrogen

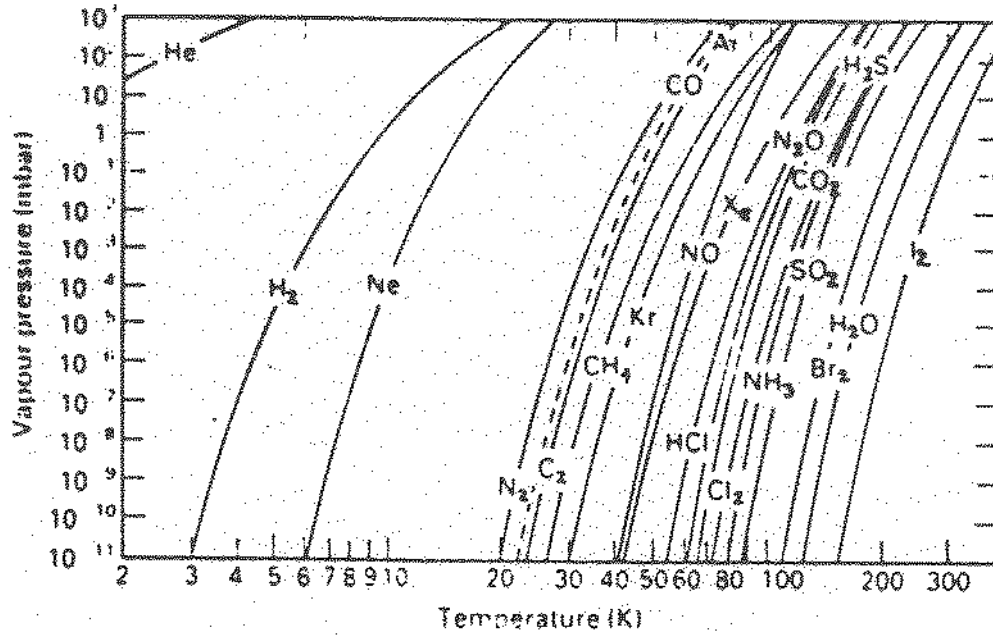


Figure 2. Vapour pressures of some common gases (from Bentley<sup>9</sup>).

