

UHV - Technology

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CERN LHC-VAC

- 1) Introduction and some basics
- 2) Building blocks of a vacuum system
- 3) How to get clean ultra high vacuum
- 4) Desorption phenomena
- 5) Practical examples

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Literature

Books

The Physical Basis of Ultrahigh Vacuum,
P.A. Redhead, J.P. Hobson, E.V. Kornelsen,
American Vacuum Society Classics,
American Institute of Physics, 1993

Foundations of Vacuum Science and Technology,
Edited J.M. Lafferty, John Wiley & Sons, 1998

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Chao, M. Tigner, World Scientific, 1998

CAS CERN Accelerator School : Vacuum Technology,
Edited : S. Turner. CERN 99-05, 19 August 1999

Handbuch Vakuumtechnik, M. Wutz et. al, Vieweg,
Braunschweig/Wiesbaden, 2000

Journals:

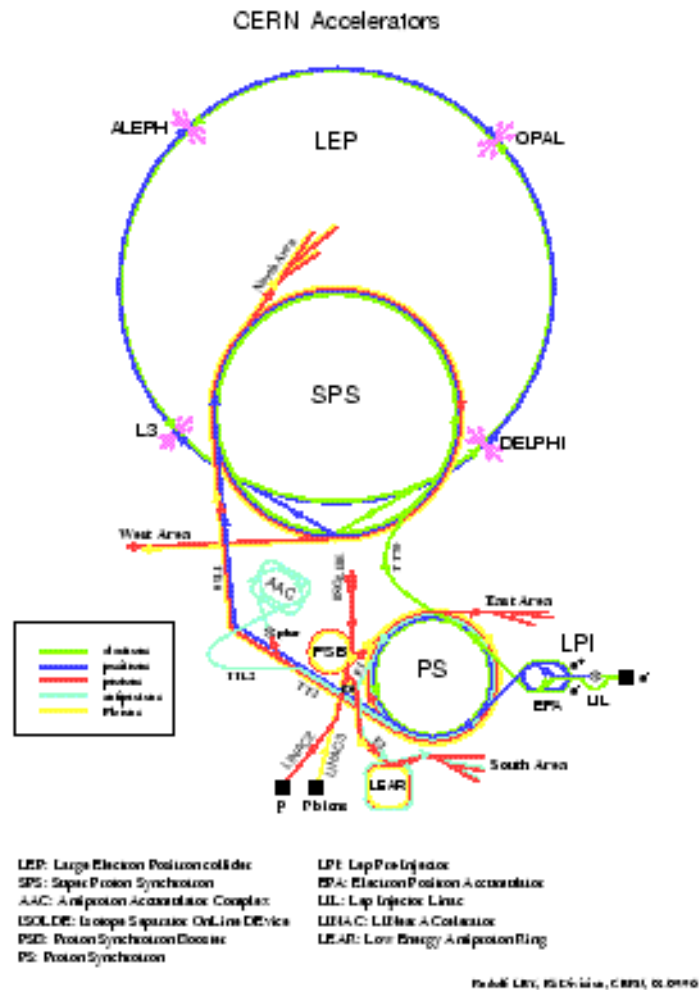
VACUUM

Journal of Vacuum Science and Technology (A)

Nuclear Instruments and Methods (Section A)

Accelerators at CERN

Historical map from 1996



Nearly all CERN accelerators require ultrahigh vacuum

Total length of vacuum systems over 60 km

LEP to be replaced by LHC (cryogenic vacuum system)

Pressure and Molecular Density

Ideal gas law: $P V = \frac{N}{N_0} R T$

with P pressure, V volume, T temperature
 N number of molecules
 R gas constant = 8.31 kJ kmol⁻¹ K⁻¹,
 $N_0 = 6.02 \cdot 10^{26}$ molecules kmol⁻¹

Molecular density $n = N/V$

Pressure : $P = n k T$

Boltzmann constant $k = 1.38 \cdot 10^{-23}$ J/K

Note : $R = N_0 k$

In nearly all cases, it is the gas density rather than the pressure which matters.

Units :

Pressure : Pa (N/m²)
 mbar = 100 Pa
 Torr = 133 Pa

Gas load : Pa m³ = 7.5 Torr l
 mbar l ~ 2.4 · 10¹⁹ molecules at RT

Specific outgassing rate :

Gas release from the walls
 Pa m³/s/m² ~ 7.5 · 10⁻⁴ Torr l/s/cm²

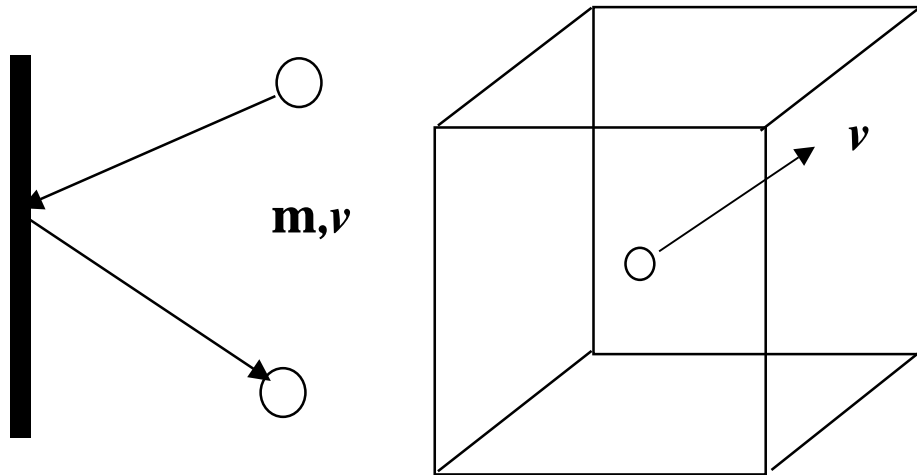
Leak rate : Pa m³/s or W
 mbar l/s or Torr l/s

Wall collisions

Frequency of wall collisions

$$\nu = \frac{1}{4} n \bar{v}$$

proportional to the number density n and to the average molecular velocity \bar{v} .



Momentum transfer to the walls is $2 m \bar{v}$, hence the pressure is proportional to $m \nu \bar{v}$

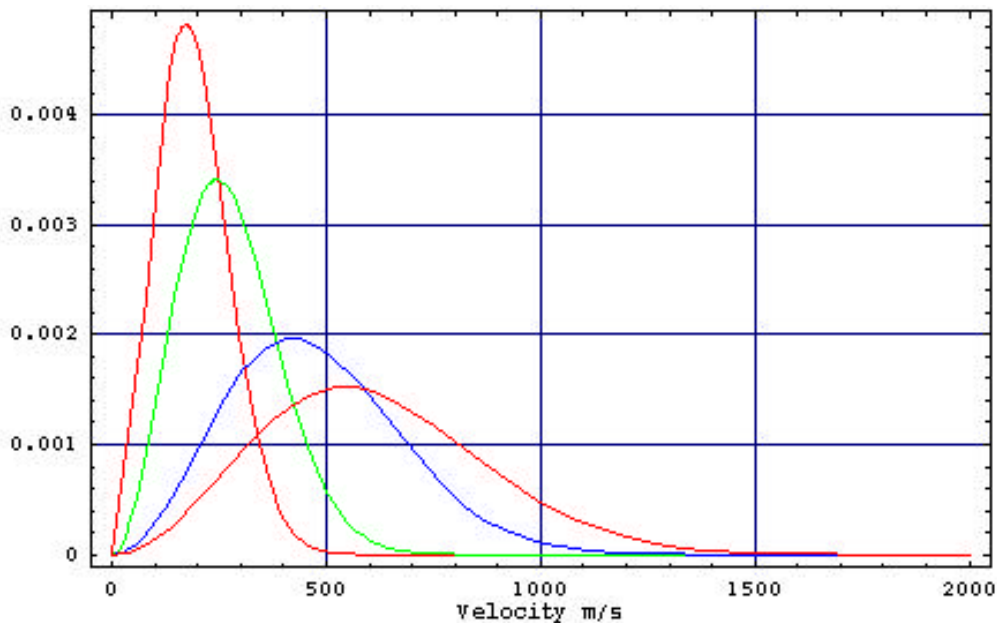
Distribution of Molecular Velocities

Maxwell-Boltzmann distribution of molecular velocities at the temperature T

$$\frac{1}{N} \frac{dN}{dv} = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2kT} \right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}$$

The average velocity is given by ($m = M m_o$)

$$\bar{v} = \sqrt{\frac{8kT}{\pi M m_o}}, \text{ numerically } \sim 146 \sqrt{\frac{T}{M}} \text{ (m s}^{-1}\text{)}$$



Molecular velocities for N₂ at 50, 100, 300 and 500K.

Mean molecular velocities at 20°C (m/s)

H ₂	N ₂	Air	A	Kr
1754	470	464	393	272

Mean Kinetic Energy

The kinetic energy :

$$E_{kin} = \frac{1}{2} m \bar{v}^2 = \frac{1}{2} M m_o \frac{8kT}{\pi M m_o} = \frac{4}{\pi} k T$$

M molecular weight

$$m_o = 1.66 \cdot 10^{-27} \text{ kg}$$

does not depend on the molecular mass, M , but only on temperature T .

In thermal equilibrium heavy molecules move sufficiently slowly and light molecules move sufficiently fast to carry on average the same kinetic energy.

Total and Partial Pressures

For each gas component n_1, n_2, n_3, \dots
the individual contribution to the total pressure :

$$P_i = n_i kT$$

The total pressure is therefore the sum of the partial pressures:

$$P = \sum_i P_i = kT \sum_i n_i$$

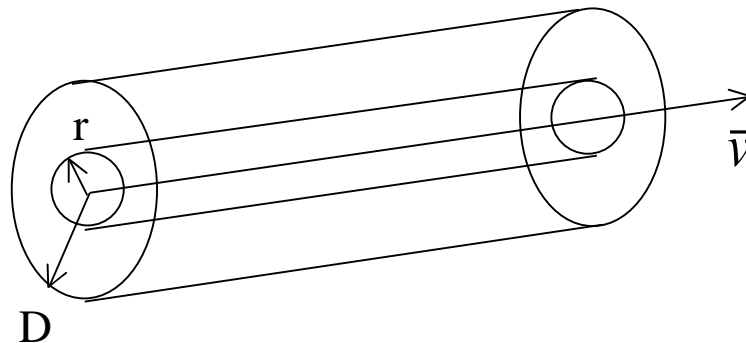
Mean Free Path

$$l = \frac{l}{\sqrt{2} \pi D^2 n}$$

D molecular diameter ($\sim 3 \cdot 10^{-8}$ m)

The product $n l = \text{const}$

For air, $n l \sim 2.5 \cdot 10^{14} \text{ m}^{-2}$. For N_2 at RT and 1 Pa $l \sim 0.9$ mm



Volume traversed by a molecule per second : $\pi D^2 \bar{v}$
 Molecule collides with all other molecules contained within the cylinder of radius D .

Number of collisions: $Z = \pi D^2 \bar{v} n$.

The mean free path is defined as

$$l = \frac{\bar{v}}{Z} = \frac{l}{\sqrt{2} \pi D^2 n}$$

It also follows that $n l = P l = \text{const}$.

Note: $\sqrt{2}$ accounts for the fact that molecules in the cylinder are not stationary.

Molecular Flow Conditions

Mean free path \gg relevant dimensions of system

Knudsen relation: gas flow $Q \propto \Delta P$.

$$\text{Molecular flow conductance } c = \frac{4}{3} \frac{\bar{v}}{L} \frac{H}{A^2} dl \quad (\text{m}^3/\text{s})$$

L length of the element (L \gg transverse dimensions).
 H perimeter, A cross section of the element.

The conductance is proportional to the mean molecular velocity, i.e. to $\sqrt{\frac{T}{M}}$.

A cylindrical duct with uniform section and radius r :

$$c = \frac{4}{3} \bar{v} \frac{r^3}{L} \sim 306 \frac{r^3}{L} \sqrt{\frac{T}{M}}.$$

An orifice (pumping orifice, L \sim 0) :

$$c = \frac{1}{4} \bar{v} A \sim 36.5 A \sqrt{\frac{T}{M}}.$$

Vacuum characteristics

gas : Nitrogen, N₂, 20°C, M = 28

Pressure	P Pa	n m ⁻³	kg m ⁻³	v m ⁻² s ⁻¹	l m
atm	10 ⁵	2.5 10 ²⁵	1.16	2.9 10 ²⁷	9 10 ⁻⁸
primary vacuum	1 10 ⁻¹	2.5 10 ²⁰ 2.5 10 ¹⁹	1.16 10 ⁻⁵ 1.16 10 ⁻⁶	2.9 10 ²² 2.9 10 ²¹	9 10 ⁻³ 9 10 ⁻²
high vacuum	10 ⁻⁴ 10 ⁻⁷	2.5 10 ¹⁶ 2.5 10 ¹³	1.16 10 ⁻⁹ 1.16 10 ⁻¹²	2.9 10 ¹⁸ 2.9 10 ¹⁵	9 10 ¹ 9 10 ⁴
uhv	10 ⁻¹⁰	2.5 10 ¹⁰	1.16 10 ⁻¹⁵	2.9 10 ¹²	9 10 ⁷
xhv	<10 ⁻¹¹				

$$n = \frac{P}{kT} \quad kT = 4.04 \cdot 10^{-21} \text{ Joule}$$

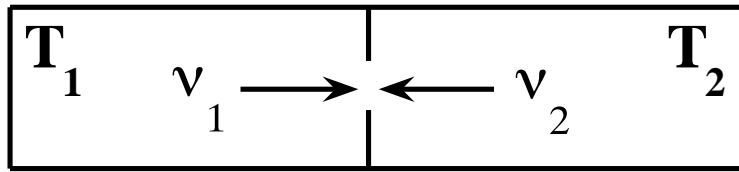
$$= M m_0 n$$

$$M m_0 = 4.65 \cdot 10^{-26} \text{ kg}, \quad m_0 = 1.66 \cdot 10^{-27} \text{ kg}$$

$$v = \frac{l}{4} n \bar{v} \quad \bar{v} = 146 \sqrt{\frac{T}{M}}$$

$$l = \frac{l}{\sqrt{2}\pi D^2 n} \quad D(\text{N}_2) = 3.15 \cdot 10^{-10} \text{ m}$$

Thermal transpiration



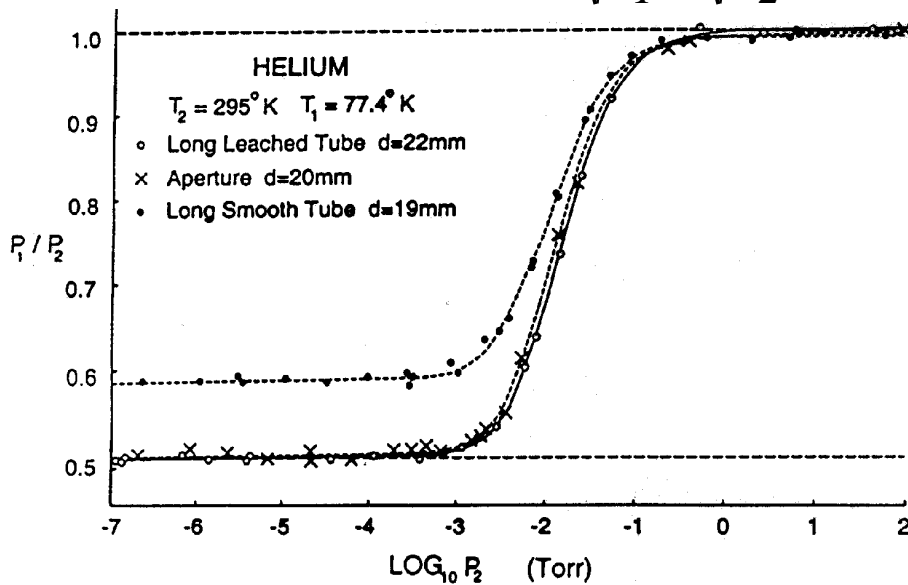
At high pressure, the pressures on both sides are equal.

In molecular flow, the net number of molecules traversing the separating wall should be zero.

$$v_1 = v_2$$

Since $v = \frac{1}{4} \bar{v} n$ and $\bar{v} = \sqrt{\frac{8kT}{\pi m}}$ one obtains

$$n_1 \sqrt{T_1} = n_2 \sqrt{T_2} \quad \text{or} \quad \frac{P_1}{\sqrt{T_1}} = \frac{P_2}{\sqrt{T_2}}$$



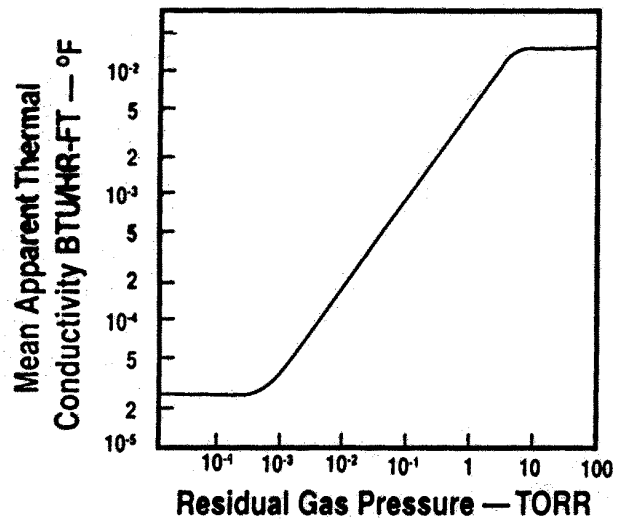
Thermal Conductivity

Thermal conductivity of a gas is independent of the pressure when the pressure is well above the molecular flow regime.

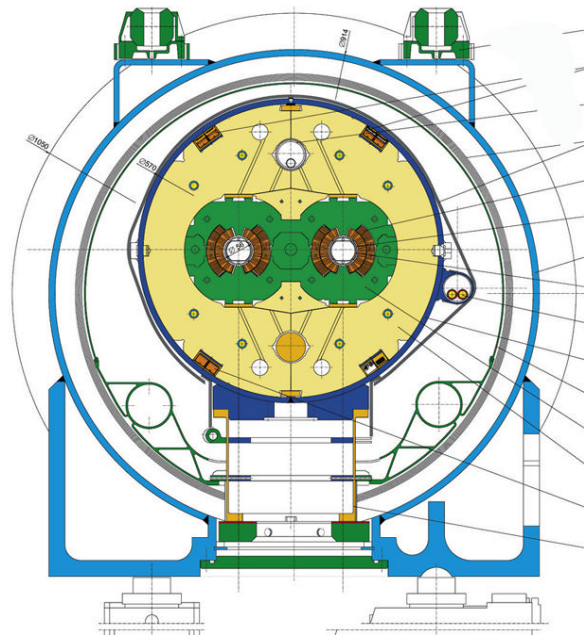
In the transition regime, the heat transfer is proportional to the pressure and to the temperature difference.

(Pressure measurement by Pirani gauge)

$$10^{-3} \text{ Torr} < P < 10 \text{ Torr}$$

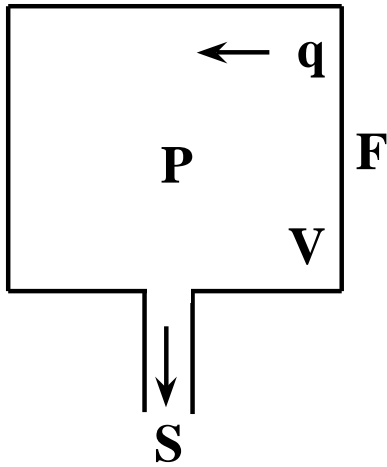


At very low pressures, the heat transfer by conduction is negligible -> vacuum for thermal insulation.



LHC Cryodipole

Basic Vacuum System



V	volume	(m ³)
F	surface	(m ²)
P	pressure	(Pa)
S	pumping speed	(m ³ /s)
q	specific outgassing rate	(Pa m/s)

Stationary conditions (independent of volume)

$$P = \frac{q F}{S}$$

Dynamic conditions

$$V \frac{\partial P}{\partial t} = q F - S P$$

Solution (constant K depends on initial conditions)

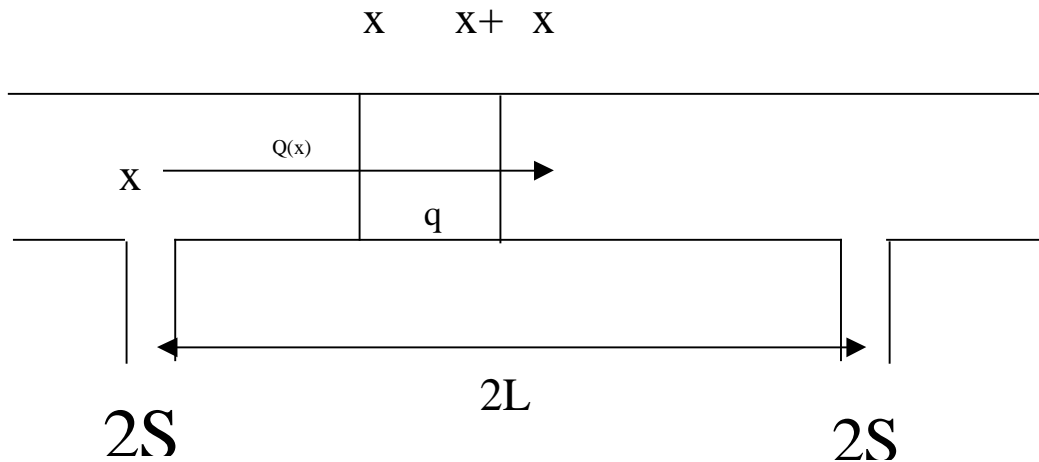
$$P(t) = K e^{-\frac{S}{V} t} + \frac{q F}{S}$$

The time constant of the system: $\frac{S}{V}$

To obtain a low pressure :

- 1) Low outgassing rate of the surface, **No leaks !**
- 2) Large pumping speed

Linear Vacuum System (Accelerators)



Gas flow:	$Q(x)$	$[\text{Pa m}^3 \text{ s}^{-1}]$
Specific outgassing rate:	$q(x)$	$[\text{Pa m s}^{-1}]$
Specific surface area per unit length:	A	$[\text{m}]$
Molecular conductance per unit length of the tube:	c	$[\text{m}^4 \text{ s}^{-1}]$

$$\frac{dQ}{dx} = A q \quad \text{et} \quad Q(x) = -c \frac{dP}{dx}$$

$$c \frac{d^2 P}{dx^2} = -A q$$

Boundary conditions for this configuration :

By symmetry $\frac{dP}{dx} \Big|_{x=\pm L} = 0$ and the pressure at $x = 0$

$$P(x=0) = \frac{Q(x=0)}{2S}$$

$$Q(0) = 2 A q L$$

One obtains a parabolic pressure distribution :

$$P(x) = A q \frac{2 L x - x^2}{2 c} + \frac{L}{S}$$

The average pressure, relevant for the beam :

$$P_{av} = \frac{1}{2L} \int_0^{2L} P(x) dx = A q \frac{L^2}{3c} + \frac{L}{S}$$

Note : the pressure is limited by the molecular conductance of the system.

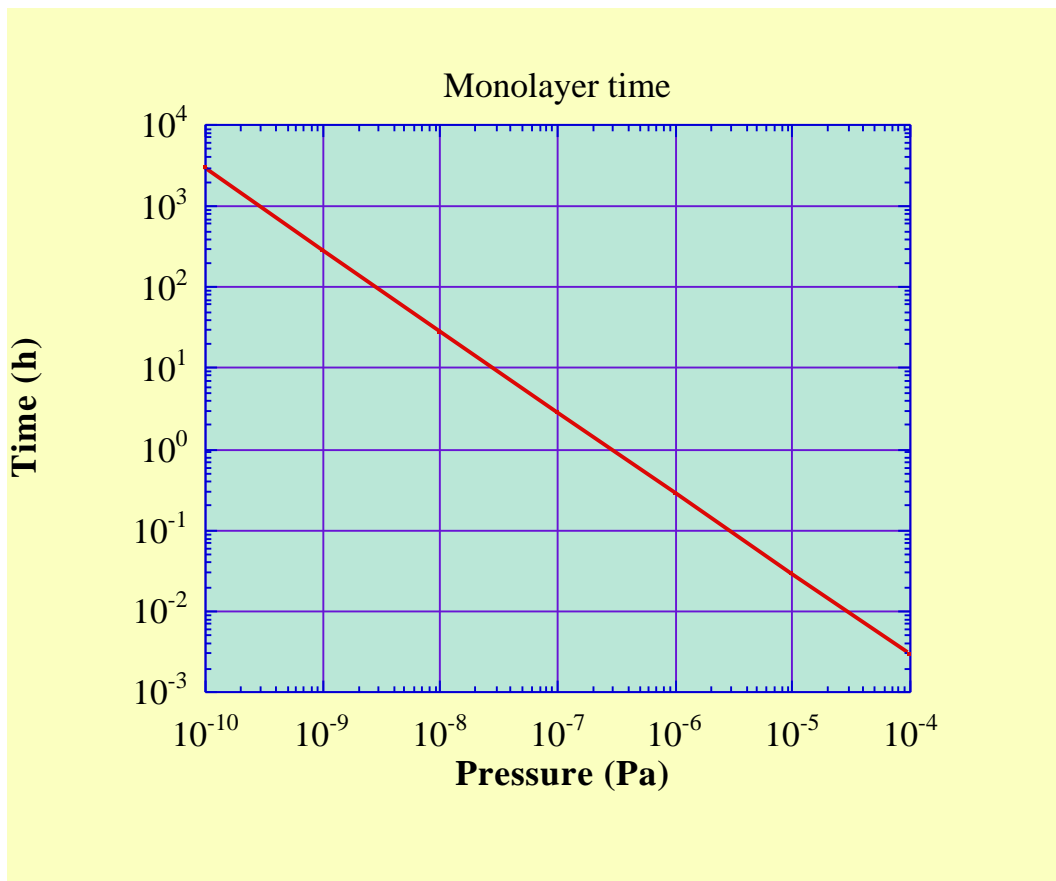
Inspite of an increase of the pumping speed S , the average pressure is limited to the value :

$$P_{av \min} = \frac{A q L^2}{3 c}$$

Note requirements :

Large diameter of the vacuum chamber

close spacing of pumps



$$t = \frac{\Theta}{\frac{1}{4} \bar{v} s n}$$

monolayer coverage Θ ($\sim 3 \cdot 10^{19}$ molecules m^{-2})

molecular velocity \bar{v} (m s^{-1})

gas density n (molecules m^{-3})

sticking probability $s = 1$

Note: Area occupied per molecule $\sim A \sim 2\sqrt{3}r^2$

Beam Lifetime due to Vacuum

(see lectures by O. Brüning)

At injection energy (450 GeV), multiple Coulomb scattering dominates

At the design energy of 7 TeV the beam-gas lifetime is dominated by nuclear scattering.

$$\frac{1}{\tau} = \sigma c n$$

lifetime (s)

c velocity of light (m/s)

n gas density molecules/m³)

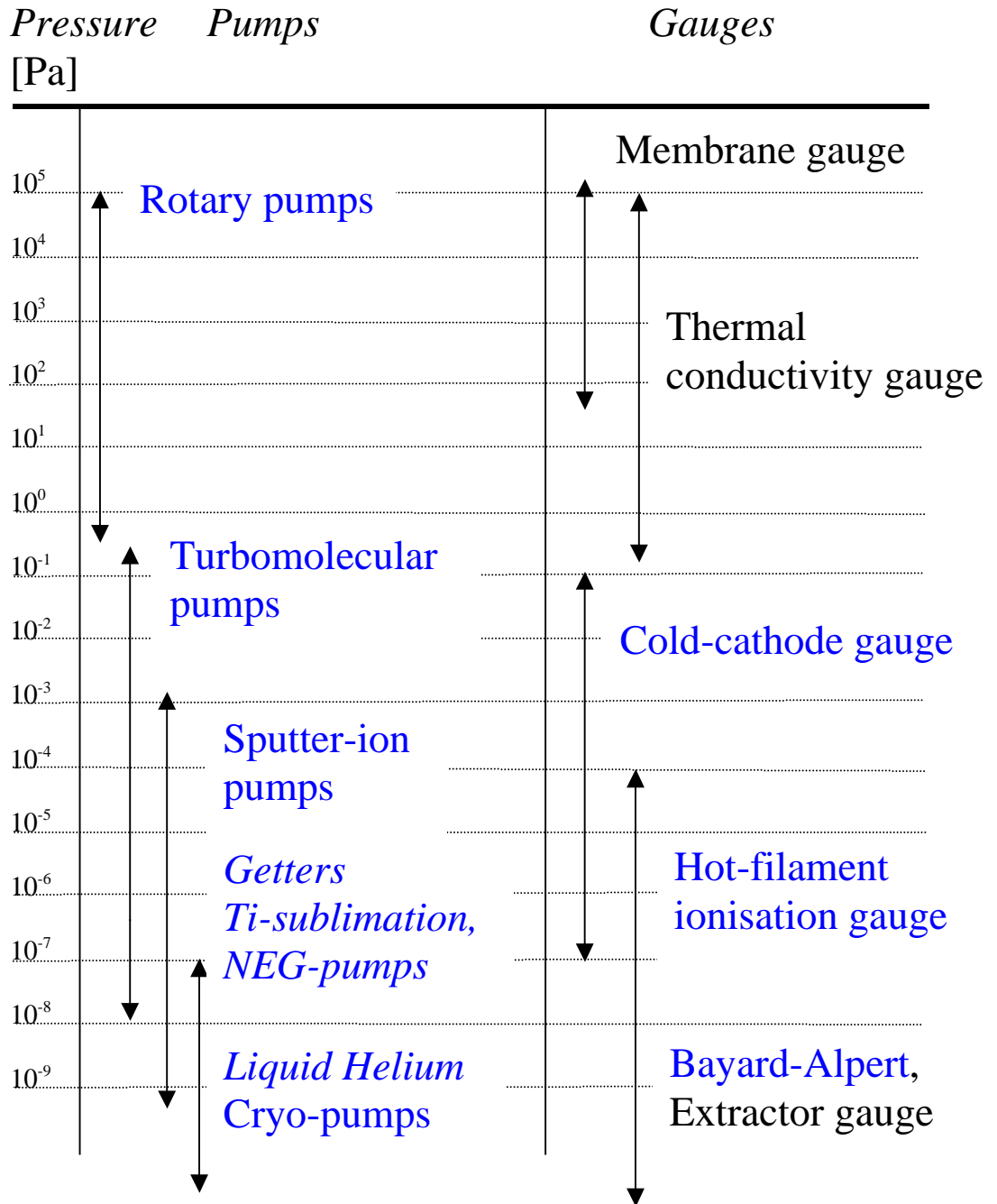
nuclear scattering cross section (m²)

$$\tau(h) = \frac{9.26 \cdot 10^{10}}{\frac{\sigma_{gas}}{\sigma_{H2}} n(atoms/cm^3)}$$

Gas	$\frac{\sigma_{gas}}{\sigma_{H2}}$	n (= 24 h)
H ₂	1	3.9 10 ⁹
He	1.26	3.1 10 ⁹
CH ₄	5.4	7.1 10 ⁸
H ₂ O	5.4	7.1 10 ⁸
CO	7.8	4.9 10 ⁸
CO ₂	12.2	3.2 10 ⁸

10⁹ molecules/cm³ ~ 10⁻⁹ Torr at 10 K

Vacuum pumps and vacuum gauges used in large accelerator systems



Rotary Pumps

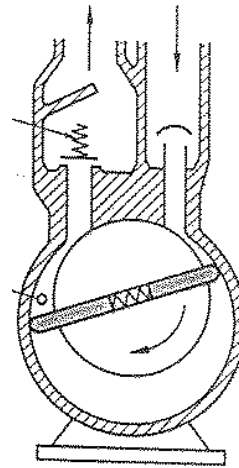
Single stage and double stage pumps

Oil sealed

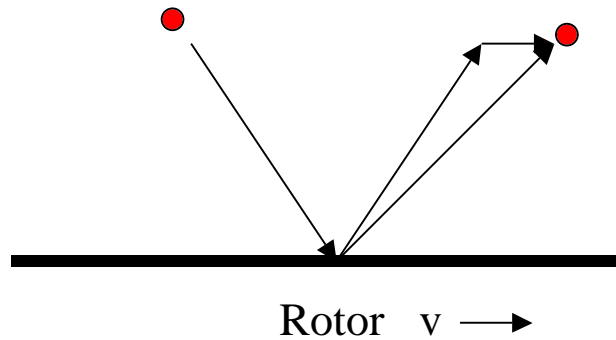
Typical end pressures :
 10^{-2} to $\sim 10^{-3}$ mbar

Typical pumping speeds :
4 to ~ 40 m³/h
(used for systems with small volume)

Filter for oil vapour is required.



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

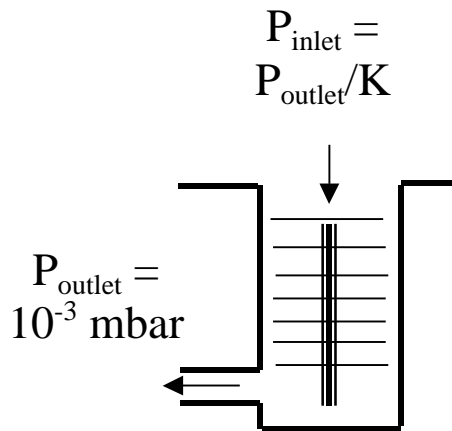
A pump geometry, large entrance flange

Compression ratio of the pump is defined as

$$K = \frac{P_{outlet}}{P_{inlet}}$$

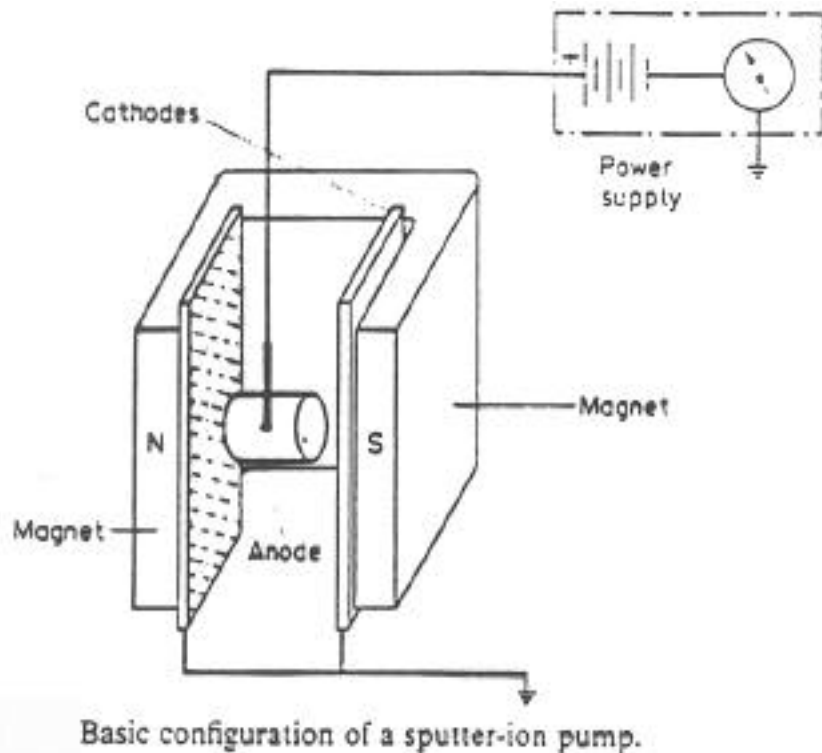
K is an exponential function of the molecular weight and of the rotational

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 (no contamination by oil vapour from a primary pump) can be obtained

Sputter-Ion-Pump



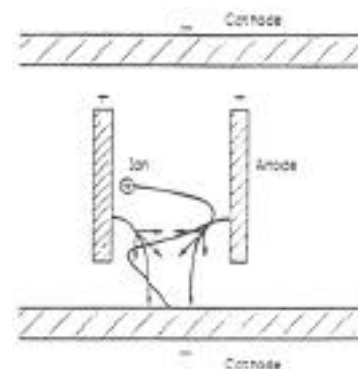
Configuration of a parallel electric and magnetic field produces a self-maintained discharge plasma.

-> 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 can be provided by bending magnets. --> integrated, linear ion-pumps.



To increase the pumping speed arrays of cells are used

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.

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.

Surface Pumping

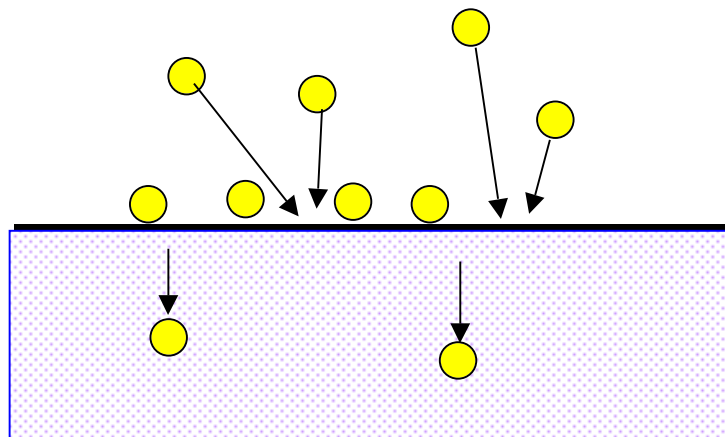
Getters (chemisorption E~eV)

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 (Ti-filament)
by surface activation (heating \rightarrow reduction of surface
oxide layer and diffusion of O into the bulk)

Cryo-pumps (physisorption E~ meV)

Sorption (capacity ~ 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.

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

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

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

Taking, e.g. 1 m^3 as the volume and $\Theta = 3 \cdot 10^{19} \text{ m}^{-2}$ the pressure at room temperature would increase to typically

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

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 film deposited by sublimation from a Ti-filament. The substrate can be the vacuum chamber walls directly. The fresh film has adsorption sites available -> pumping action.

Saturation of the getter film : ~ 1 h at 10^{-6} Pa

Non-Evaporable Getters (NEG) :

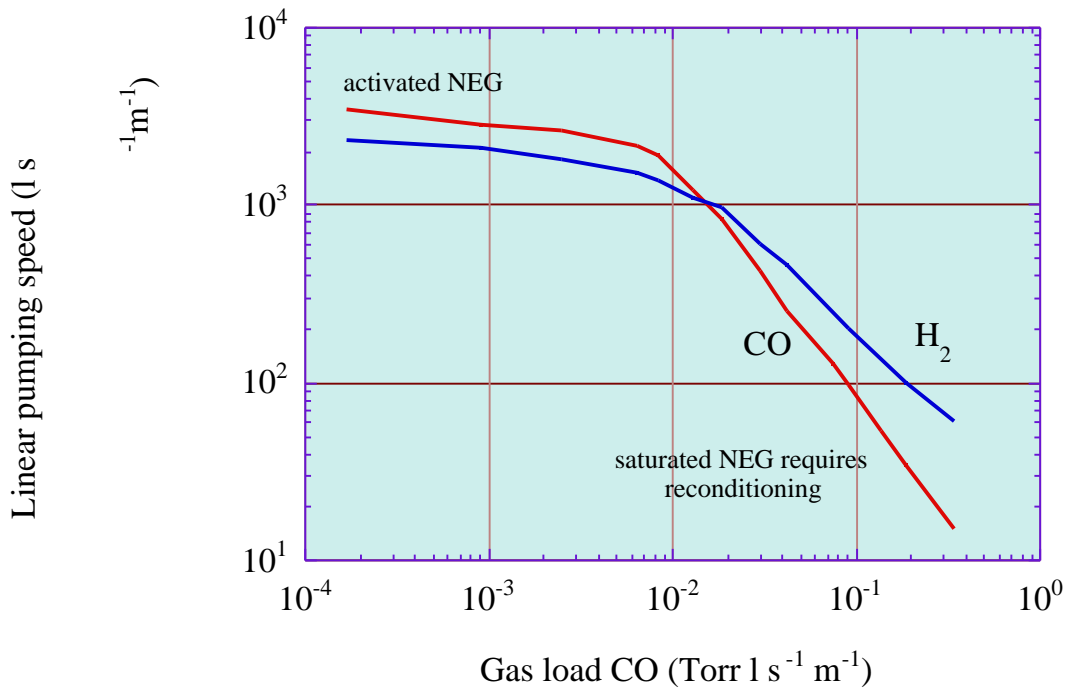
Getter material (e.g. Ti, Zr, V) produced in the form of an alloy e.g. with Al and used as a bulk material. For LEP : metal ribbon coated with a thin layer of getter powder has been used.

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.

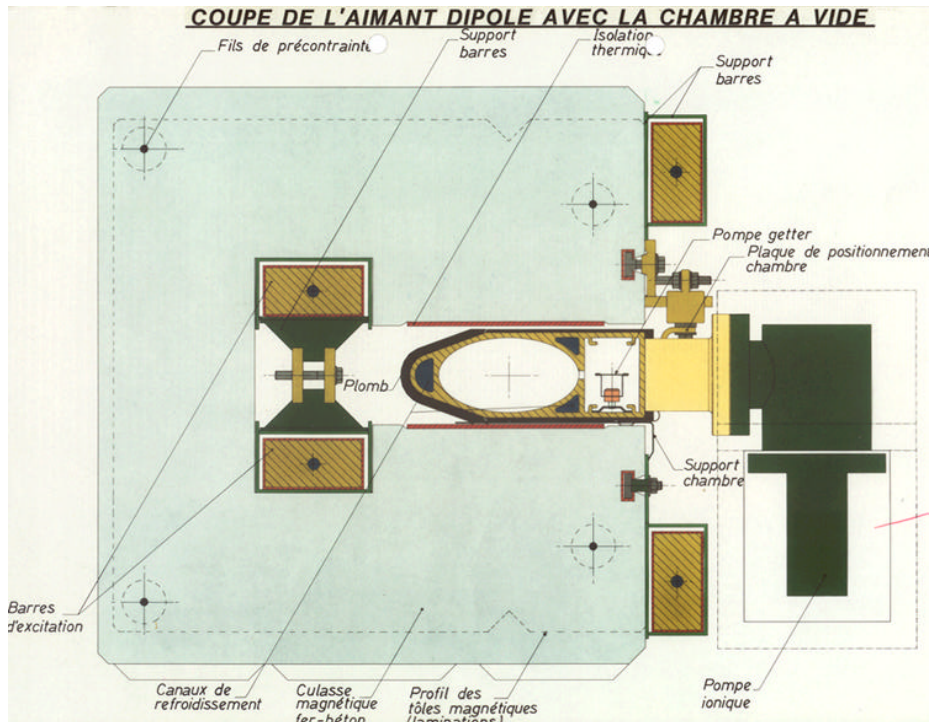
A combination of evaporable getters and of bulk getters is under development at CERN -> [sputter deposited getter films](#) (few μm) coated directly onto the inner surface of vacuum chambers.

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

Pumping speed of a St101 getter

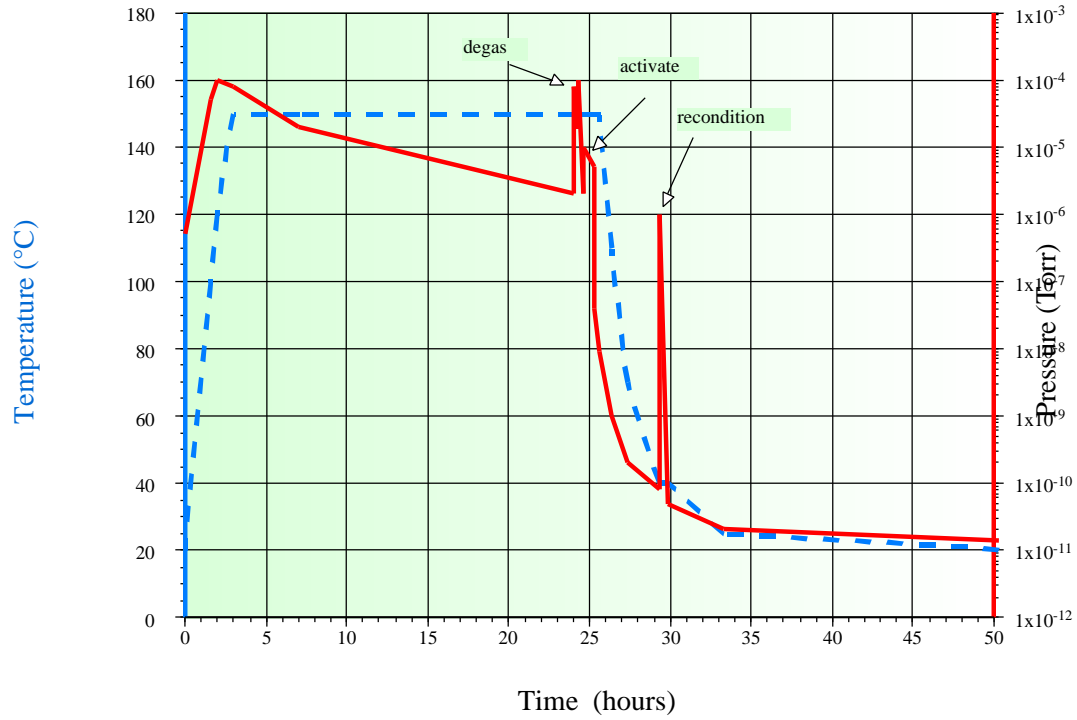


Reduction of the pumping speed due to the gradual saturation of the surface by adsorbed molecules. During **re-activation**, molecules diffuse into the bulk. A fresh surface is obtained for the next pumping cycle.



LEP vacuum system with NEG pumping

Typical bakeout cycle with NEG

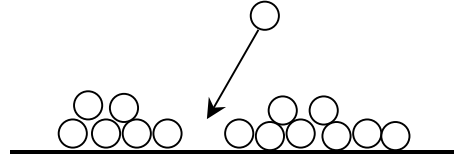


Within less than 12 hours after the bakeout uhv conditions can be achieved.

Cryo-Pumping

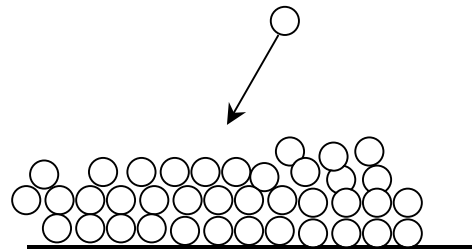
Adsorption of molecules at low temperature -> e.g. at liquid helium temperature

A) Sorption



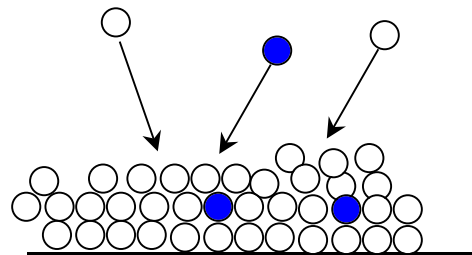
Adsorption of gas molecules with low surface coverage, to avoid the effect of the vapour pressure of the condensate. Increasing the effective surface area by a coating with a large specific surface area e.g. charcoal. -> Adsorption isotherms.

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 : -> limitation occurs only by the vapour pressure of the condensed gas

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

-> '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.

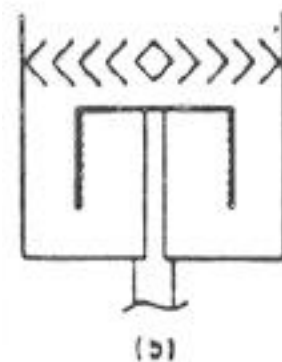
Increase of the specific surface area of a cryo pump by using special cryo-sorbing materials with a large specific surface -> charcoal.

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

Baffle to intercept thermal radiation.

Risk of overpressure during warm-up

when too large amount of gas has been condensed.



Vapour pressure

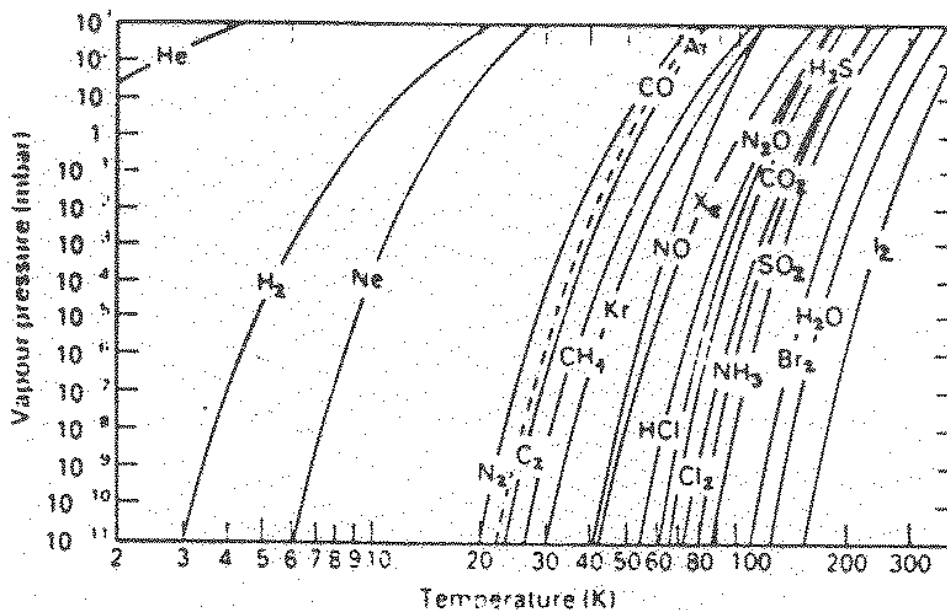
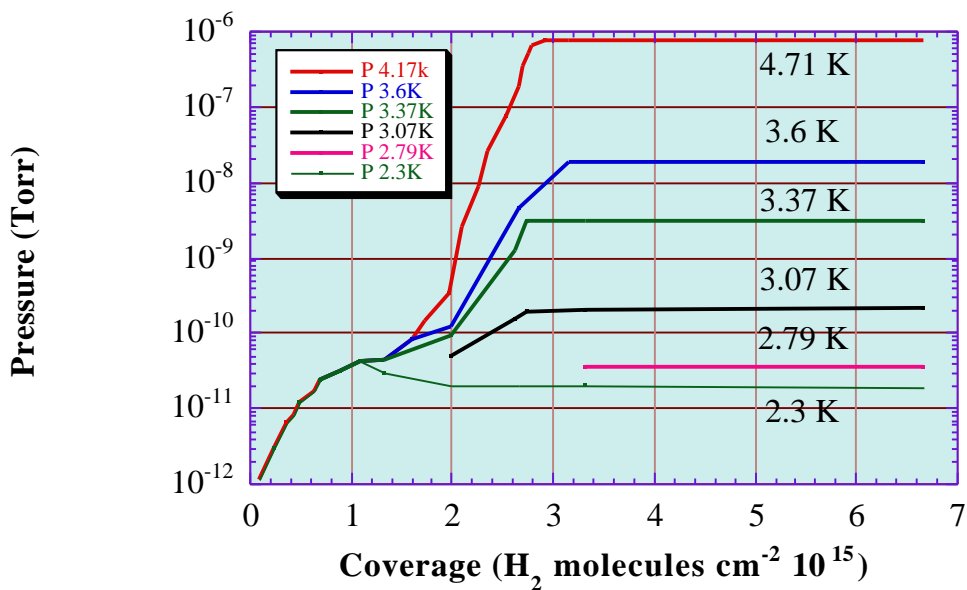


Figure 2. Vapour pressures of some common gases (from Bentley⁹).

Hydrogen Vapour Pressure



Pirani Gauge

Change of the thermal conductivity with pressure

Reliable and simple system.

Pressure range : atmospheric pressure to < 0.1 Pa

A resistor with a large temperature coefficient is mounted inside the vacuum. This resistor is heated to a constant temperature and the required heating current is a measure of the pressure.

The electronic circuitry (Wheatstone-bridge) provides temperature compensation and linearisation of the pressure reading.

Cold Cathode Ionisation Gauge

Penning Gauge

Based on the operating principle of an ion pump.

Ratio of pressure and pump current ~ constant.

Useful pressure range : 10^{-2} to 10^{-7} Pa

Limitations:

At high pressure the discharge is unstable (arcing)

At low pressure the discharge extinguishes -> zero
pressure reading

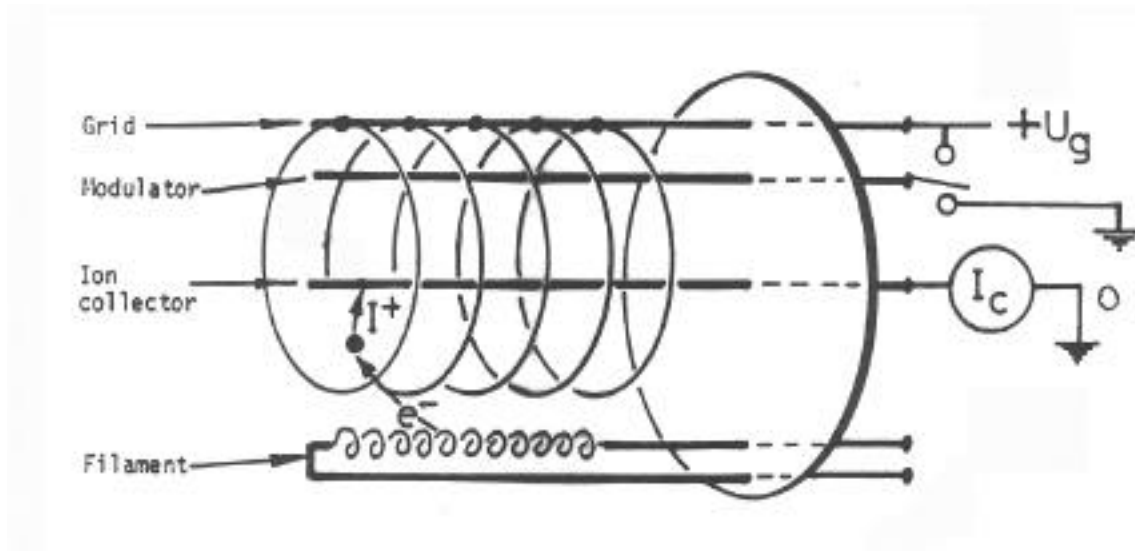
Leakage current in the cables and in the gauge can
simulate a higher pressure

Contamination of the gauge may change the calibration.

Extended operation at very high pressure can contaminate
the gauge -> required demounting and cleaning.

Ionisation Gauge

Hot Filament Gauge



Operating principle :

Residual gas molecules are ionised by the electrons emitted from a hot filament.

Ions are collected by a "collector electrode". This ion current is proportional to the gas density, n , and hence the pressure, P .

The ionisation probability P_i (number of ion–electron pairs produced per m and per Pa) depends on the type of molecule and on the kinetic energy of the electrons.

Ion collector current :

$$I^+ = I_e P_i L P$$

Where :

I_e emission current of the filament

L path length of the electrons

P pressure

Gauge Sensitivity

$$S = P_l L \quad [\text{Pa}^{-1}]$$

Obtained by calibration with a known pressure (N_2)

-> Nitrogen equivalent pressure N_2 .

-> To measure a pressure for another gas, the relative gauge sensitivity for this particular gas with respect to nitrogen must be known.

S_i/S_{N_2} must be known for different gas species.

For H_2 , one finds typically $S_{\text{H}_2}/S_{\text{N}_2} \sim 0.38$

“Outgassing” of an Ionisation Gauge

Electrons emitted from the filament, reach the grid electrode with an energy of approximately $\sim 150\text{eV}$ and may heat-up the grid and desorb gas molecules.

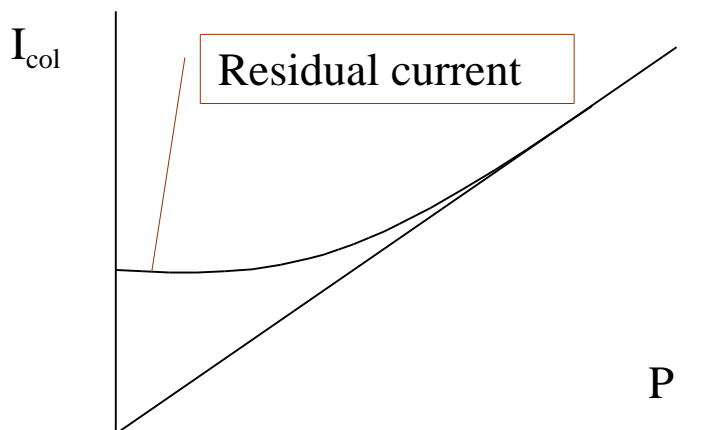
-> pressure increase which disturbs the measurement.

-> To suppress the effect, the grid and all other electrodes must be cleaned.

A common method to avoid this disturbance:

the emission current is increased to heat the grid electrode temporarily to a very high temperature. -> Outgassing.

Pressure limitation : residual current -> limit pressure



X-Ray Limit of an Ionisation Gauge

Electrons which hit the grid produce soft photons (x-rays) due to Bremsstrahlung.

A small fraction of these photons can reach the collector electrode and liberate photo-electrons which return to the grid -> this current is equivalent to a positive, "x-ray current" I_x , which is independent of the pressure. The correction of this effect can be done by the « modulation » method

‘Modulated Bayard-Alpert’ gauge

Modulator electrode	
measurement (1), + U_{grille} ,	$I_1 = I^+ + I_x$
measurement (2), 0 V,	$I_2 = \alpha I^+ + I_x$
Corrected collector current	$I^+ = \frac{I_1 - I_2}{1 - \alpha}$

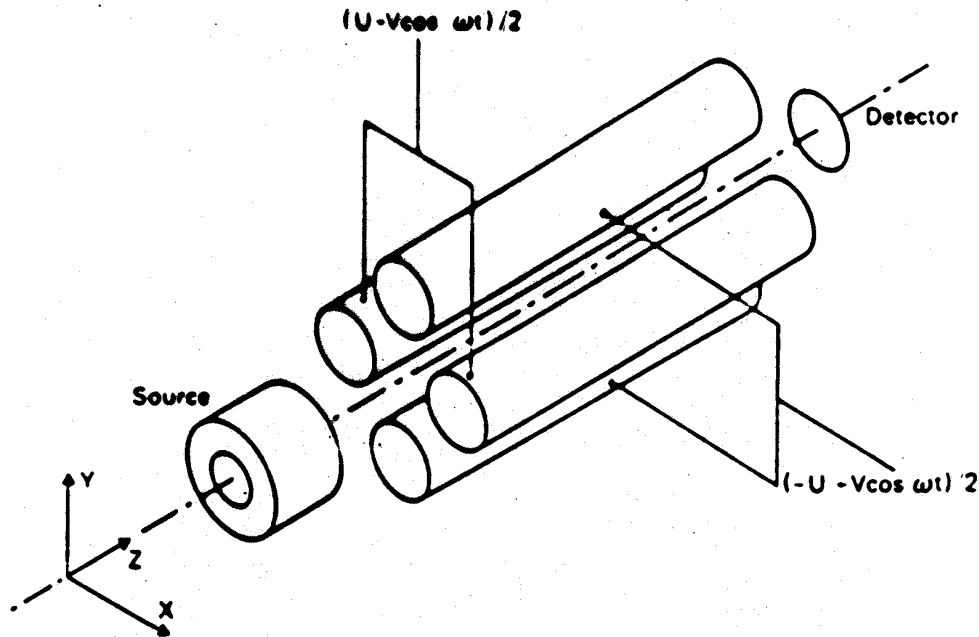
The modulation factor : $1-\alpha$
 can be determined easily by an independent measurement at high pressure where $I^+ \gg I_x$.

Alternative design of an ionisation gauge:

Ions are 'extracted' from the grid volume to a collector which is optically screened from the photons of the grid.

-> Extractor gauge

Partial Pressure Measurement



Combination of an ion source with a mass spectrometer.

- 1) Ion source
- 2) Quadrupole mass filter
- 3) Ion collector, Faraday-cup or secondary electron multiplier

Operating principle of a quadrupole mass filter :

Ions with different mass to charge ratio are injected into the quadrupole structure. As they traverse the structure, ions are subjected to a periodically varying transverse electric field which excites transverse oscillations.

Ions with an incorrect charge to mass ratio have unstable orbits, are lost and do not reach the collector.

The ion trajectories are described by the equations :

$$\ddot{x} + \left(\frac{e}{m} r_o^2\right) x = 0$$

$$\ddot{y} - \left(\frac{e}{m} r_o^2\right) y = 0 \quad \text{and} \quad \ddot{z} = 0$$

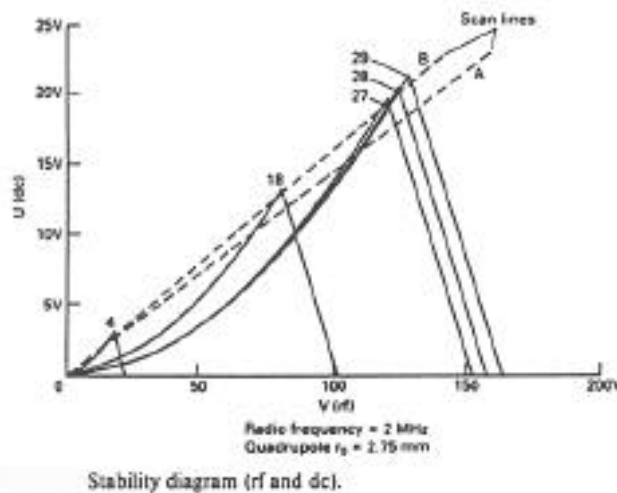
r_o is the radius of the structure and V the potential:
 $V = U - V \cos(\omega t)$.

With $a = 4 \frac{e}{m} \frac{U}{\omega^2 r_o^2}$ and $q = 2 \frac{e}{m} \frac{V}{\omega^2 r_o^2}$ -> Mathieu equation

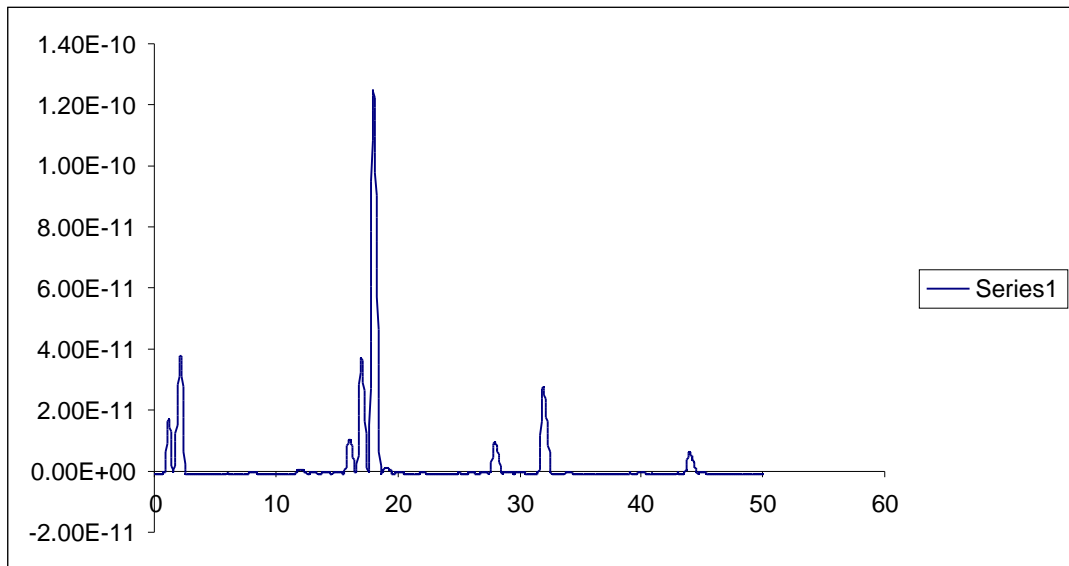
$$\frac{d^2 u}{ds^2} + \{a - 2q \cos(2s)\} u = 0$$

Solutions define regions with stable and unstable motion.
 Only the ions (e/m) with stable trajectories through
 the quadrupole mass filter are measured.

Stability Diagram



Residual gas spectrum



Ion current (A) corresponding to a particular molecular species (e/m)

Total (N_2 -equivalent) pressure is obtained with a gauge.

Qualitative analysis relatively straightforward, e.g. :
 H_2 , H_2O , CO/N_2 , O_2 , CO_2

Distinction between CO/N_2 requires knowledge of the “cracking pattern” of the two molecular species.

Quantitative analysis requires a perfectly calibrated system for each residual gas component.

Typical cracking patterns of common molecules

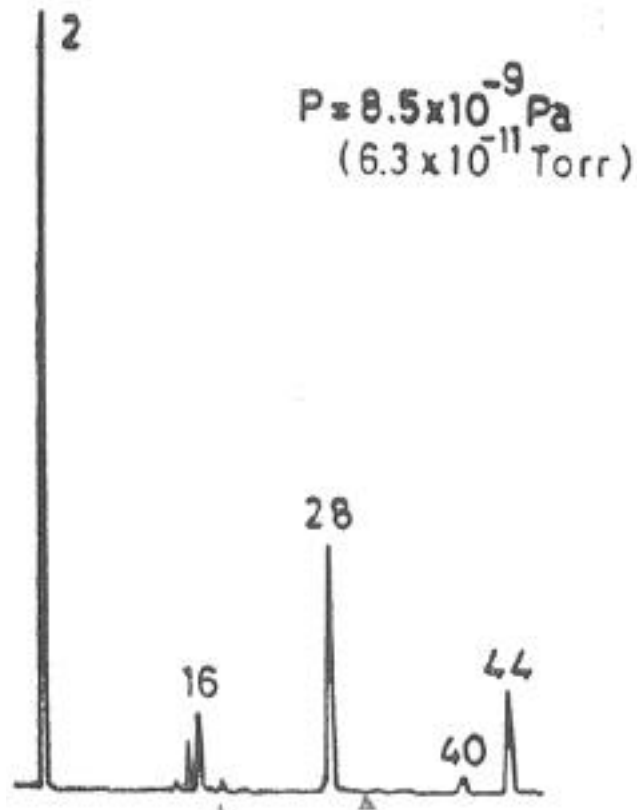
peak	2	14	15	16	17	18	20	27	28	32	40	44
H ₂	100											
CH ₄	2.4	10.7	85	100								
H ₂ O				1.8	27	100						
N ₂		6.2							100			
CO		0.9							100			
O ₂				18						100		
A							13				100	
CO ₂				7.5					18.5			100

Principal peak is normalised to 100%.

Residual gas spectrum of a baked, 'clean' uhv system

Absence of peaks
17,18 : H₂O has
been removed
during the bakeout.

Absence of peaks
due to hydrocarbons:
small trace of CH₄



Chemical solvent pre-cleaning procedure

- 1) Removal of gross contamination and machining oils using the appropriate solvents
- 2) Perchloroethylene (C_2Cl_4) vapour degreasing at ($121^\circ C$) today no longer applicable
- 3) Ultrasonic cleaning in alkaline detergent ($pH = 11$)
- 4) Rinsing in cold demineralised water (conductivity $< 5 \mu S cm^{-1}$)
- 5) Drying in a hot air oven at $150^\circ C$
- 6) Wrapping in clean Al-foil or paper

Cleaning method will depend on the material (stainless steel, aluminium, copper)

Important:

Any subsequent handling must be done with **clean gloves**. Contamination by any residues in the air must be avoided.

No car exhaust gases, No smoking!!

Thermal Desorption

Specific desorption rate : q [$\text{Pa m}^3 \text{s}^{-1} \text{m}^{-2}$]

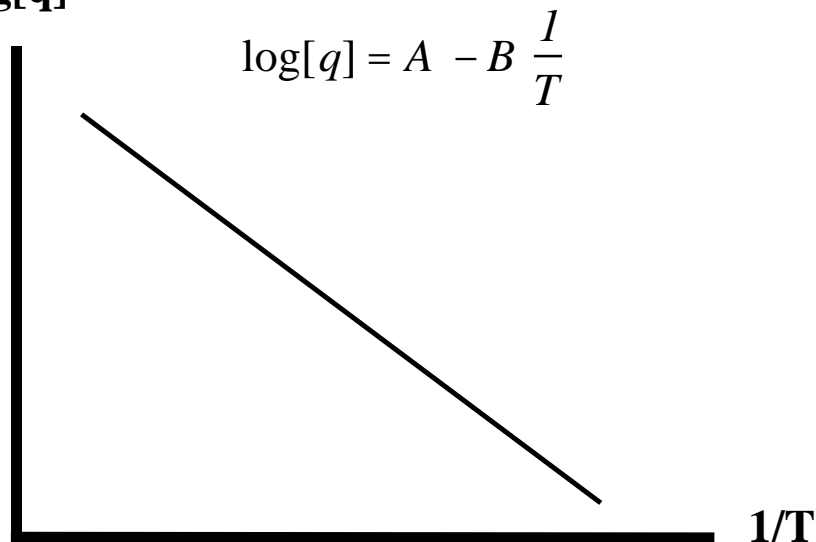
$$q = \text{Const} e^{-\frac{E}{kT}}$$

molecular residence time $\tau = \frac{1}{\nu_o} e^{\frac{E}{kT}}$

E activation energy for desorption,

$\nu_o \sim 10^{13} \text{ s}^{-1}$ vibration frequency in the surface potential

Log[q]



Physisorbed molecules $E < 40 \text{ kJ/mole}$ (0.4 eV)

Chemisorbed molecules $E > 80 \text{ kJ/mole}$ (0.8 eV)

Bakeout between $150 - 300^\circ\text{C}$: reduced residence time.

Reduction for H_2O , CO , CO_2 (by factors of 10^{-2} to 10^{-4})

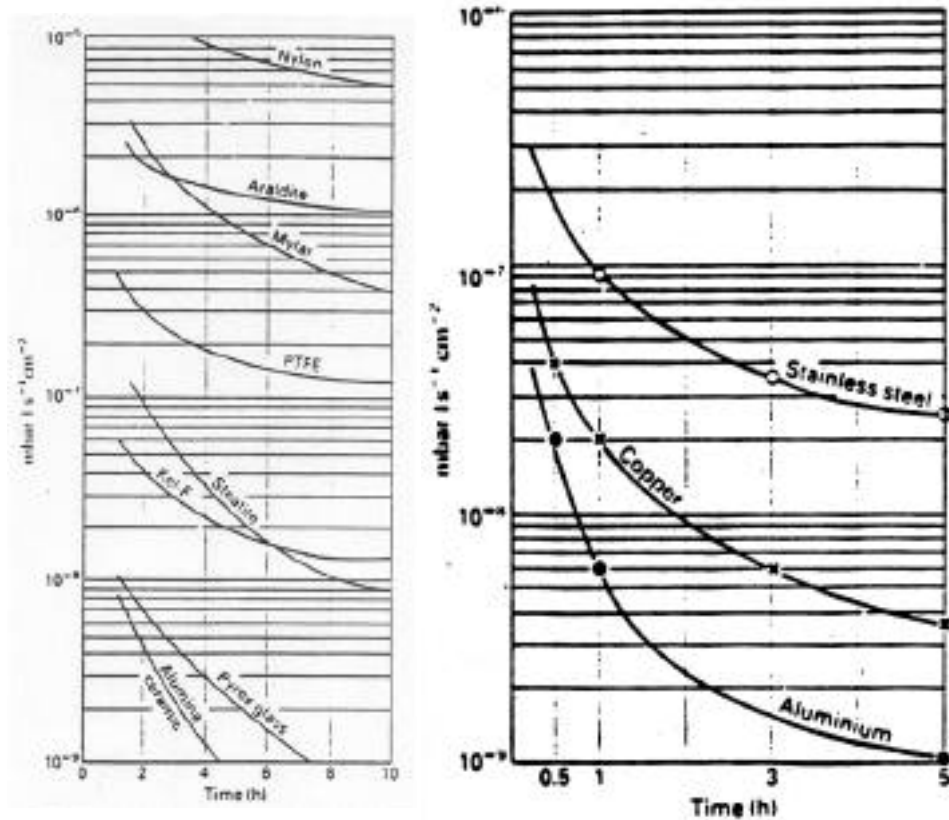
At higher temperature $> 400-500^\circ\text{C}$ -> cracking of hydrocarbon molecules (C-H)

Note: Reduced thermal desorption at cryogenic temperatures

Thermal outgassing Rates

Comparison of organic materials and of metals

Unbaked samples (usually H₂O dominates)



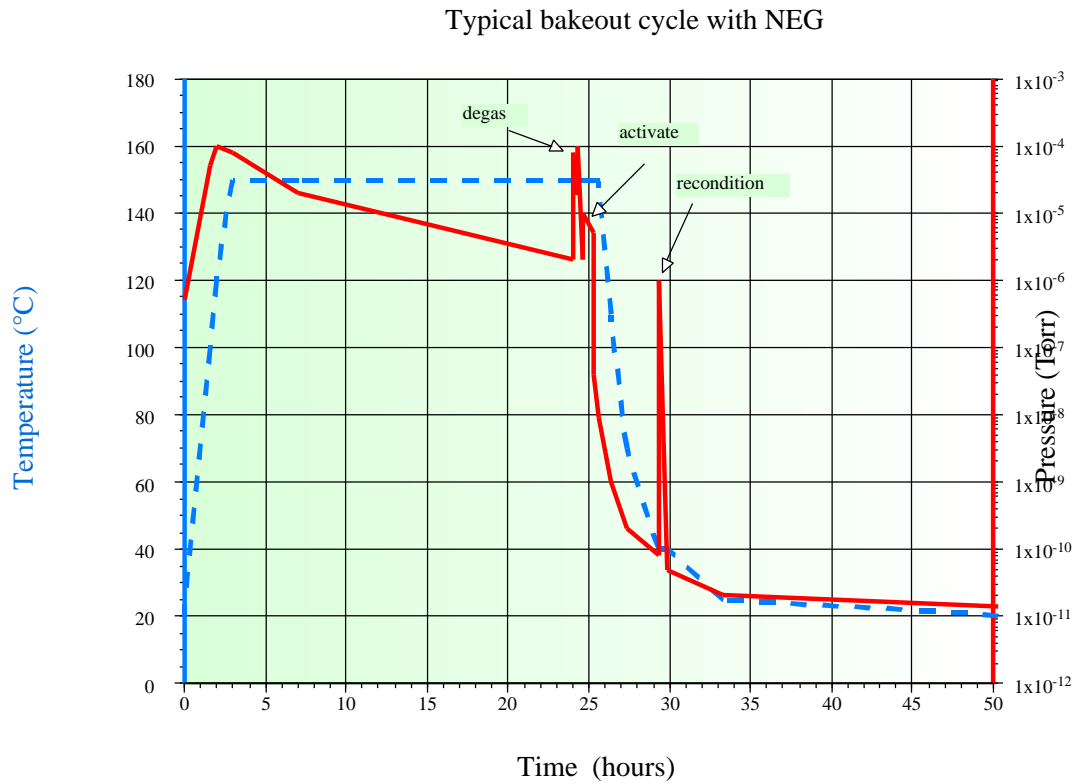
Baked samples (24 hours at 150°C to 300 °C)

Typical values after 50 hours of pumping :

(units : Torr l s⁻¹ cm⁻²)

Gas	Al, Stainless steel
H ₂	5 10 ⁻¹³
CH ₄	5 10 ⁻¹⁵
CO	1 10 ⁻¹⁴
CO ₂	1 10 ⁻¹⁴

Bakeout of the LEP Vacuum System with NEG



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

Criteria influencing the Choice of Materials

Low outgassing rate

Low vapour pressure

Temperature resistant -> bakeout

Thermal and electrical conductivity -> beam interaction

Corrosion resistance -> leaks

Low induced radioactivity -> handling

High mechanical strength -> 1dN/cm² external pressure!

Machining, welding

Low cost

Common choices :

Stainless steel

Aluminium

Copper

Ceramics for electric insulation

Low porosity -> leaks

Brazing to metal -> leaks

For particular applications

Organic materials(e.g. as composite materials (carbon-fibers & epoxy), polymers to be used in small quantities

Synchrotron Radiation Induced Desorption

$$\text{Radiated power (W)} : P_{\gamma} = 88.6 \frac{E^4 I}{\rho}$$

E , beam energy of electrons (GeV)

I , beam current (mA)

ρ , bending radius (m),

$$\text{Critical energy of the spectrum (eV)} \varepsilon_c = 2.2 \cdot 10^3 \frac{E^3}{\rho}$$

$$\text{Photon flux (s}^{-1}\text{)} \quad \Gamma = 8.08 \cdot 10^{17} I E$$

$$\text{Linear photon flux (m}^{-1}\text{ s}^{-1}\text{)} \quad \frac{d\Gamma}{ds} = 1.28 \cdot 10^{17} \frac{I E}{\rho}$$

Gas desorption occurs in two steps :

-> photons -> produce photo-electrons

-> photo-electrons -> excite molecules which subsequently will desorb thermally

Gas flow : $Q = \eta \Gamma$

$Q = K \eta I E + Q_o$ with Q_o , the thermal desorption.

η , molecular desorption yield (molecules per photon).

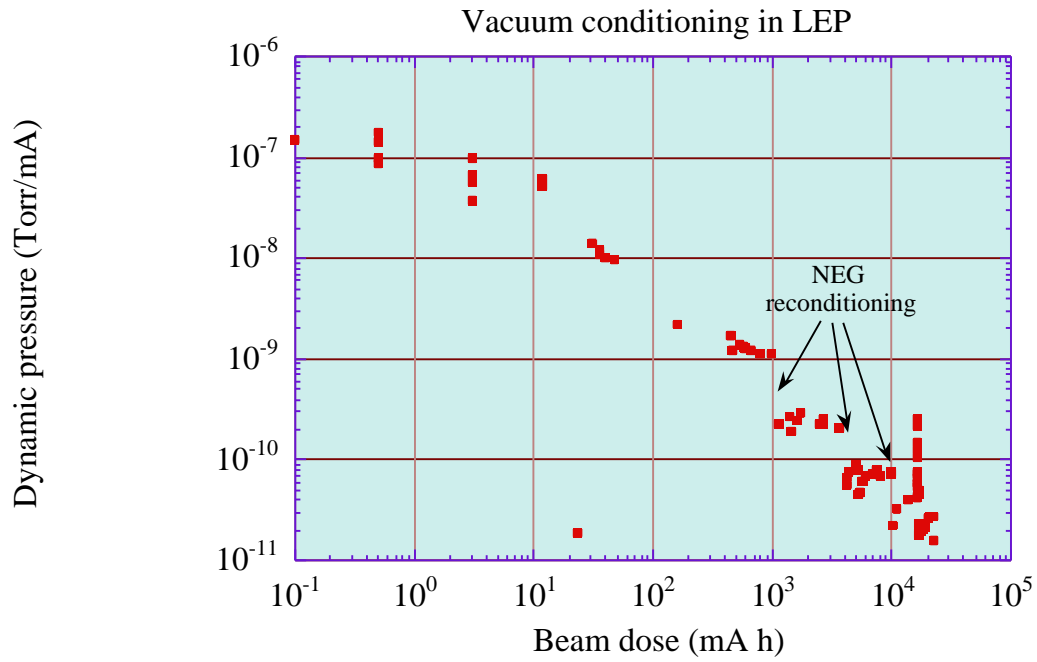
The **dynamic pressure** : $P_{dyn} = \frac{Q}{S}$.

The dynamic pressure increases proportionally with the

beam intensity : $\frac{\Delta P}{I}$ (Pa/mA).

‘**Beam cleaning**’ (scrubbing) of the vacuum system.

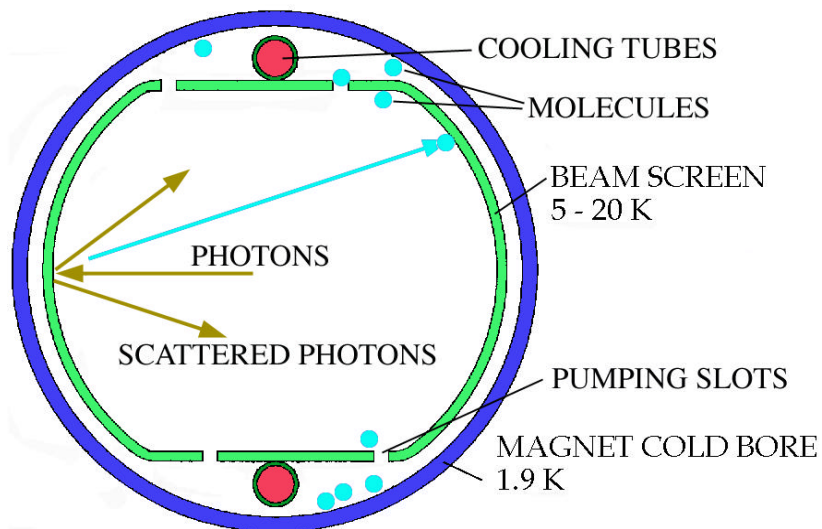
Beam cleaning of the LEP vacuum system



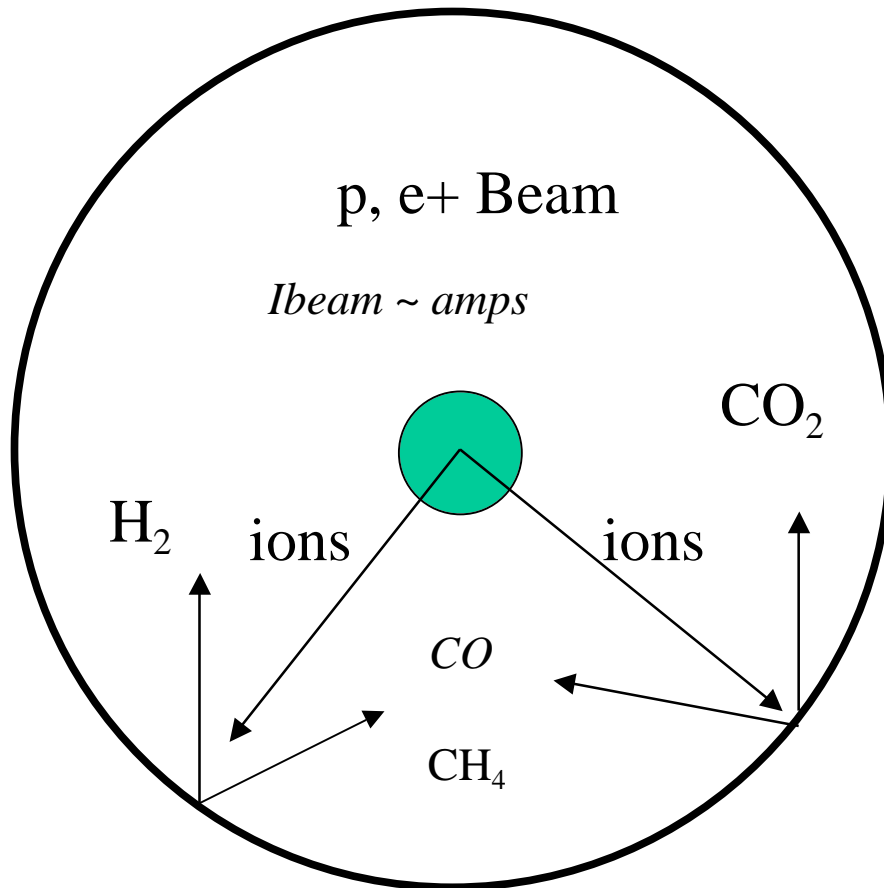
Dose scale may be given in terms of accumulated photons/m or in Ah.

Synchrotron Radiation in LHC

Imposes the use of a **beam screen** ($\sim 200 \text{ mW/m}$)
Critical photon energy 45 eV is sufficient to desorb gas.
Molecules will be cryosorbed on the 1.9 K cold-bore of the cryomagnets



Beam Induced Pressure Instability



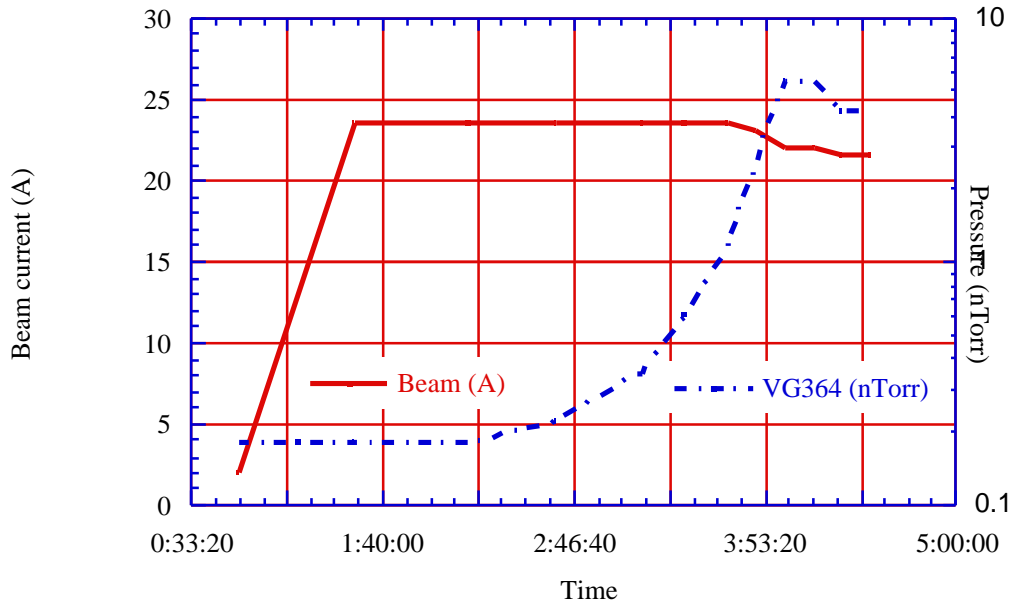
Ionisation of the residual gas molecules by proton beam:
 Molecular desorption yield (molecules/ion)
 unit charge e, ionisation cross section

Critical current (I_{crit}) defines the stable pressure range

$$P(I) = \frac{P_o}{1 - \frac{\eta I}{e/\sigma S_{eff}}}$$

S_{eff} is the effective pumping speed of the system.
 For the LHC the pumping is provided by the pumping holes or by external pumps and by getters.

Ion induced pressure rise in the Intersecting Storage Rings (ISR)



Development of a pressure bump in the ISR vacuum system at room temperature during a coasting beam run.

The slow build-up of the pressure can be attributed to the adsorption and re-desorption of molecules on the vacuum chamber wall.

Ion induced pressure instability is an important problem for high intensity proton (positron) storage rings.