Vacuum for Accelerators

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1) Introduction and some basics
2) Pumps used in accelerators
3) Desorption phenomena
4) 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, Ed. J.M. Lafferty, John Wiley & Sons, 1998

Handbook of Accelerator Physics and Engineering, A. W. Chao, M. Tigner, World Scientific, 1998

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

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

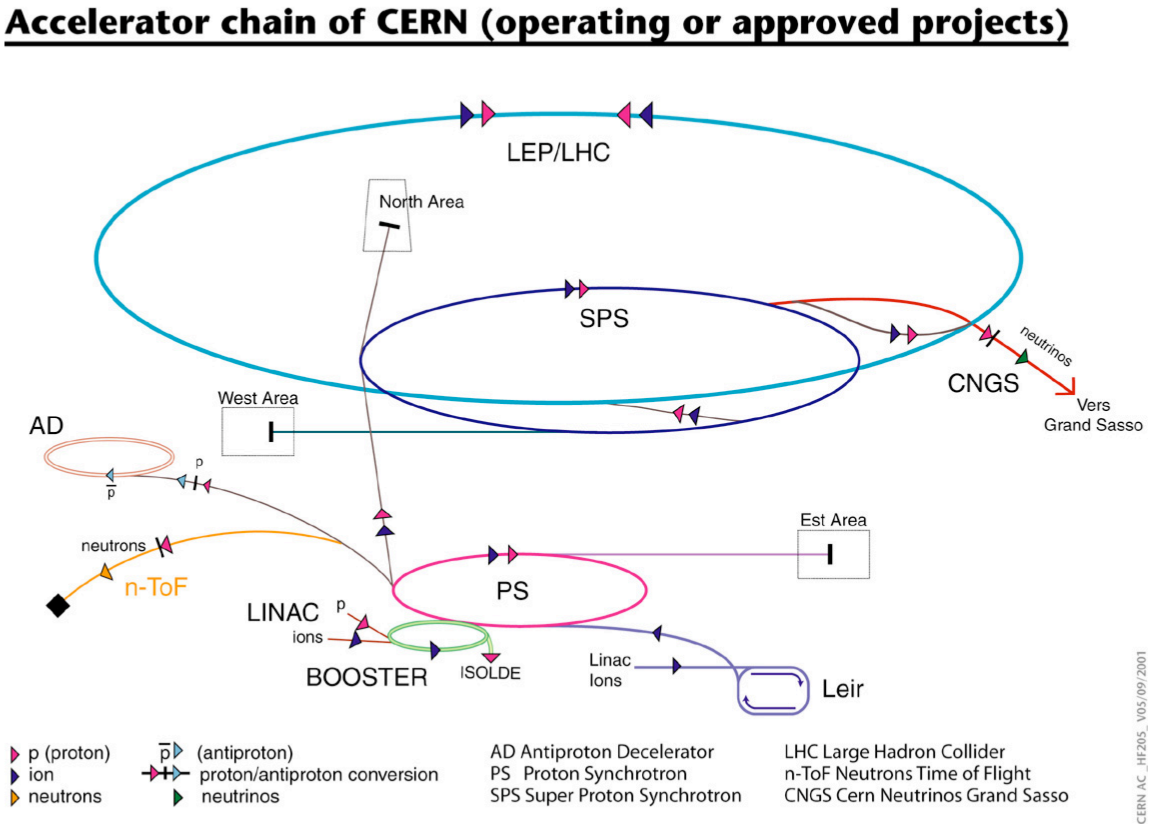
Journals:

VACUUM

Journal of Vacuum Science and Technology (A)

Nuclear Instruments and Methods (Section A)

Accelerators at CERN


Accelerator chain of CERN (operating or approved projects)

Nearly all CERN accelerators require ultrahigh vacuum

Total length of vacuum systems over 60 km

LEP is replaced by LHC (cryogenic vacuum system)

Pressure and Molecular Density

Ideal gas law: $P\ V = \frac{N}{No} R\,T$

P pressure, V volume, T temperature
N number of molecules
R gas constant = 8.31 kJ kmol^{-1} K^{-1},
No = 6.02 10^{26} molecules kmol^{-1}

Molecular density $n = N/V$

Pressure : $P = n\ k\,T$

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

Note : $R = No\ k$

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

Units :

Pressure : Pa (N/m^2), mbar = 100 Pa, Torr = 133 Pa
Gas load : Pa m^3 = 7.5 Torr l, mbar l ~ 2.4 10^{19} molecules at RT
Specific outgassing rate : Gas release from the walls
Pa m^3/s/m^2 ~ 7.5 10^{-4} Torr l/s/cm^2
Leak rate : Pa m^3/s or W, mbar l/s or Torr l/s

Wall collisions

Frequency of wall collisions $\nu = \frac{1}{4} n \bar{v}$

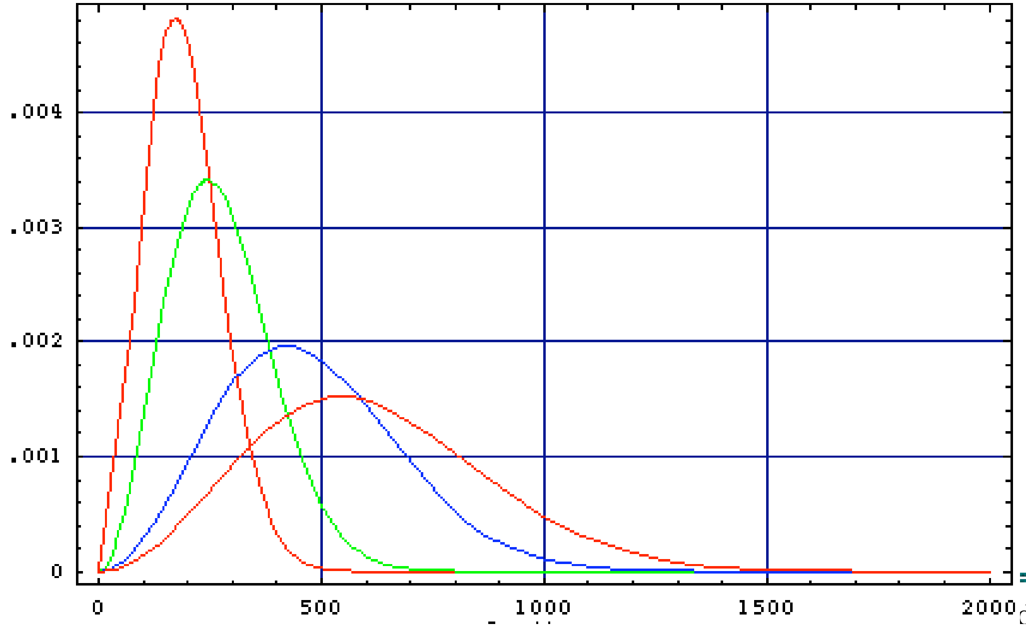
Proportional to the number density n and to the average molecular velocity $\bar{v}$.

Distribution of Molecular Velocities

Maxwell-Boltzmann distribution of molecular velocities at the temperature T

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

Average velocity is given by ($m = M m_o$): $\bar{v} = \sqrt{\frac{8kT}{\pi M m_o}}$, numerically $\sim 146\sqrt{\frac{T}{M}}$ (m s^{-1})



Molecular velocities for N_2 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 : $$E_{kin} = \frac{1}{2} m \bar{v}^2 = \frac{1}{2} M m_o \left(\frac{8kT}{\pi M m_o} \right) = \frac{4}{\pi} k T$$

M molecular weight, $m_o = 1.66\ 10^{-27}$ kg

E_{kin} 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

Each gas component $n_1, n_2, n_3, \ldots$ contributes to the total pressure : $P_i = n_i\, kT$

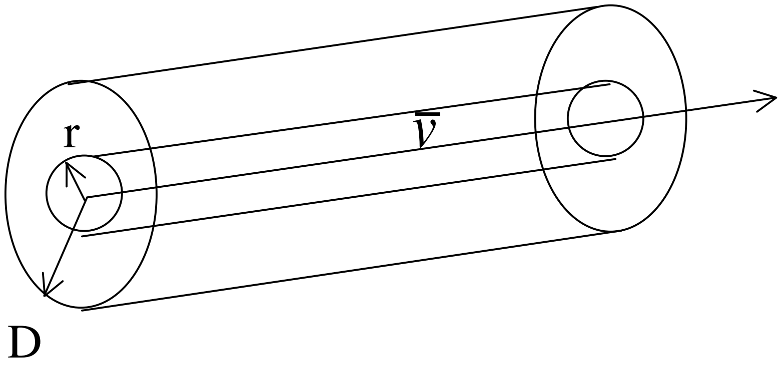
The total pressure is therefore the sum of the partial pressures: $P = \sum_i P_i = k\,T \sum_i n_i$

Partial pressures for atmospheric air

Gas	%	Pi (Pa)
N_2	78.1	$7.9\ 10^{4}$
O_2	20.5	$2.8\ 10^{3}$
Ar	0.93	$1.2\ 10^{2}$
CO_2	0.0033	4.4
Ne	$1.8\ 10^{-3}$	$2.4\ 10^{-1}$
He	$5.2\ 10^{-4}$	$7\ 10^{-2}$

Mean Free Path

D molecular diameter (~3 10^{-8} m)



Volume traversed by a molecule per second : $\pi D^2 \overline{v}$

Molecule collides with all other molecules contained within the cylinder of radius *D*.

Number of collisions: $Z \approx \pi D^2 \overline{v}\, n.$ The mean free path $l = \frac{\overline{v}}{Z} = \frac{1}{\sqrt{2}\,\pi D^2 n}$

It also follows that $n\,l \quad P\,l \approx const.$

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

For air the product $n\,l \approx$ 2.5 10^{14} m^{-2} .

For N_2 at 20°C and at 1 Pa -> l ~ 9 mm

Molecular Flow Conditions

Knudsen relation: gas flow $Q \propto \Delta P$ applies if the mean free path >> relevant dimensions of system

Molecular flow conductance $$c = \frac{4}{3}\frac{\bar{v}}{\int_0^L \frac{H}{A^2}\,dl} \qquad (\mathrm{m^3/s})$$

L length of the element (L >> 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: $$c = \frac{4}{3}\bar{v}\left(\frac{r^3}{L}\right) \sim 306 \cdot \left(\frac{r^3}{L}\right)\sqrt{\frac{T}{M}}.$$

An orifice (pumping orifice, L~0) : $$c = \frac{1}{4}\bar{v}\,A \sim 36.5 \cdot A\sqrt{\frac{T}{M}}.$$

Conductance of elements in series or in parallel add the same as for electric circuits

Series : $\frac{1}{c} = \frac{1}{c_1} + \frac{1}{c_2}$ and parallel: $c = c_1 + c_2$

For complicated geometries it is often necessary to use Monte Carlo calculations for the molecular flow.

Vacuum characteristics

gas : Nitrogen, N_2, 20°C, M = 28

Summary expressions:

$$n = \frac{P}{kT}$$

kT = 4.04 10^{-21} Joule

$$\rho = M\, m_O\, n$$

$M\, m_O$ = 4.65 10^{-26} kg

m_O = 1.66 10^{-27} kg

$$\nu = \frac{1}{4}\, n\, \bar{v} \quad \text{and} \quad \bar{v} = 146\sqrt{\frac{T}{M}}$$

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

D (N_2) = 3.15 10^{-10} m

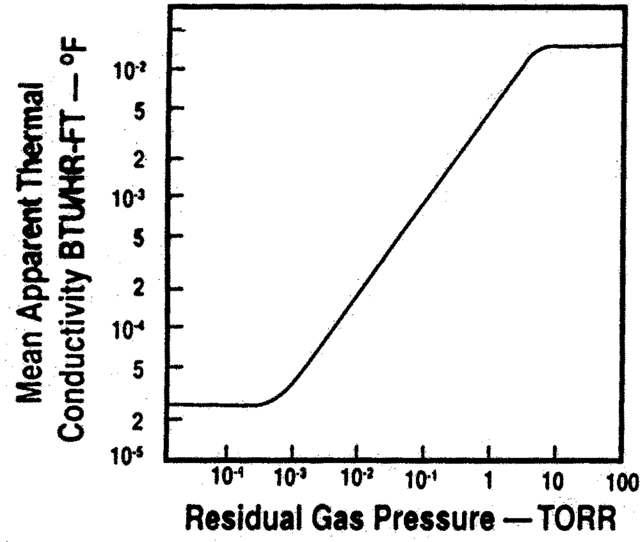
Pressure	P Pa	n m^{-3}	ρ kg m^{-3}	ν $m^{-2}s^{-1}$	l m
atm	10^5	2.5 10^{25}	1.16	2.9 10^{27}	9 10^{-8}
primary	1	2.5 10^{20}	1.16 10^{-5}	2.9 10^{22}	9 10^{-3}
vacuum	10^{-1}	2.5 10^{19}	1.16 10^{-6}	2.9 10^{21}	9 10^{-2}
high	10^{-4}	2.5 10^{16}	1.16 10^{-9}	2.9 10^{18}	9 10^{1}
vacuum	10^{-7}	2.5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

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. Principle of pressure measurement with a Pirani gauge.

10^{-3} Torr < P < 10 Torr



At very low pressures, the heat transfer by conduction is negligible : vacuum for thermal insulation in cryogenics.

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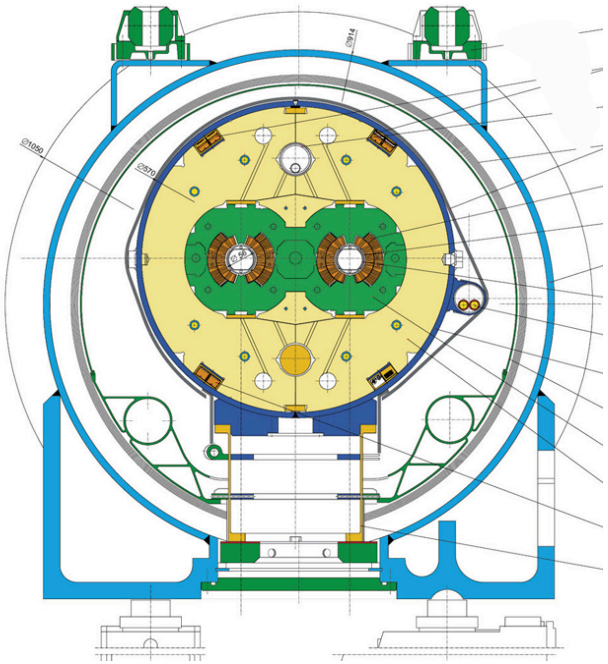
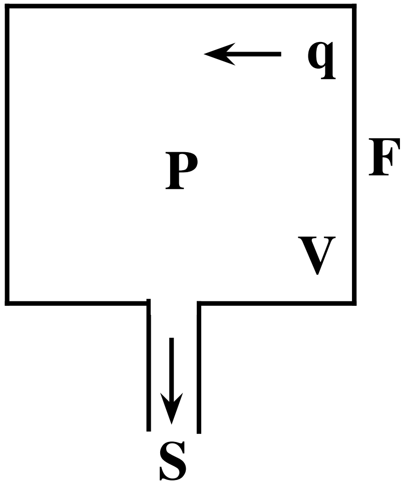


LHC Cryodipole

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 $m^3/s/m^2$)

Stationary conditions (P is independent of volume) $P = \frac{q\,F}{S}$

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

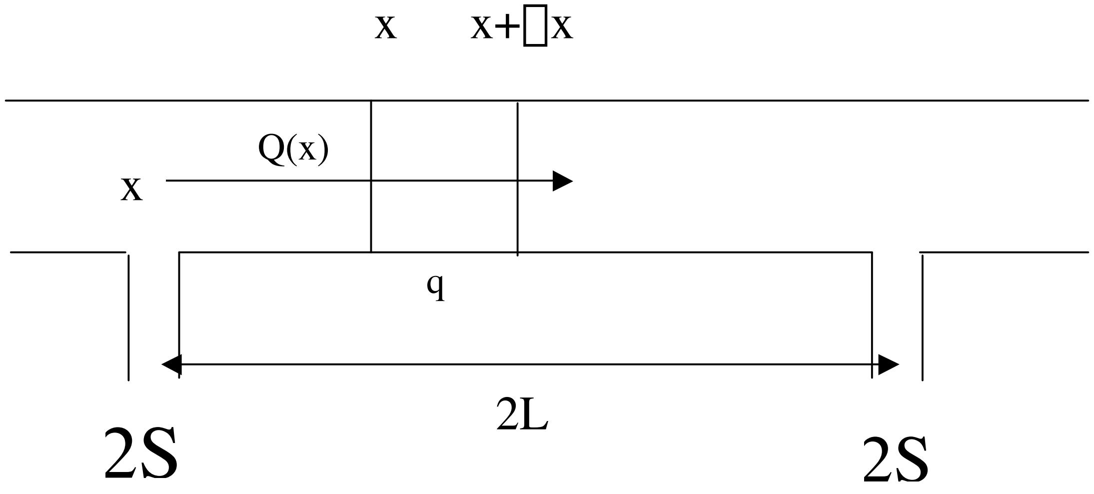
Solution (constant K depends on initial conditions) $P(t) = K\,e^{-\frac{S}{V}t} + \frac{q\,F}{S}$

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

To obtain a low pressure : Low outgassing rate of the surface, No leaks!

Large pumping speed

Linear Vacuum System (Accelerators)



Gas flow: Q(x) [Pa m^3 s^{-1}], specific outgassing rate: q(x)) [Pa m s^{-1}]

Specific surface area per unit length: A[m], molecular conductance per unit length: c [m^4 s^{-1}]

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

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

Boundary conditions for this configuration:

By symmetry $\left(\frac{dP}{dx}\right)_{x=\pm L} = 0$ 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: $P(x) = A\,q\left(\frac{2Lx - x^2}{2c} + \frac{L}{S}\right)$

The average pressure, relevant for the beam: $P_{av} = \frac{1}{2L}\int_0^{2L} P(x)\,dx = A\,q\left(\frac{L^2}{3c} + \frac{L}{S}\right)$

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

In spite of an increase of the pumping speed *S*, the average pressure is limited to the value:

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

Two important requirements : Large diameter of the vacuum chamber

Close spacing of pumps

Beam Lifetime due to Vacuum

Beam loss by Bremsstrahlung : $-\frac{dE}{dx} = \frac{E}{X_o}$

Lifetime $\frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt} = \frac{c\beta\rho}{X_o}W$

X_o radiation length, cβ speed of the particles and the gas density $\rho = \frac{m_0 M}{kT}P$

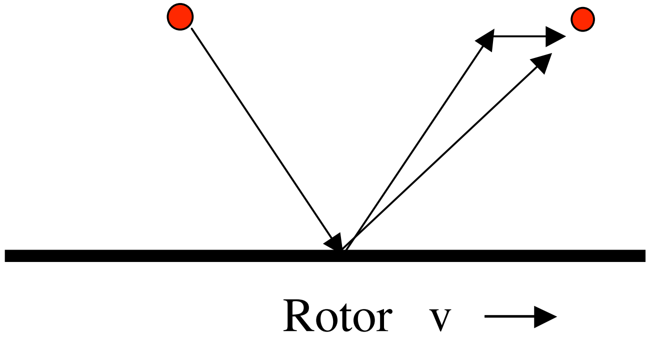
W is the probability per radiation length to emit a photon with an energy larger than the energy acceptance of the machine so that the particle will be lost.

The lifetime $\tau = \frac{X_o}{c\beta\rho W} \propto \frac{X_o}{P}$

For nitrogen or CO one finds typically $\tau P = 3.4 \times 10^{-8}$ (Torr hours)

Consequence : UHV is required for storage rings.
Heavy molecules with short radiation length must be avoided.

Turbomolecular Pump



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

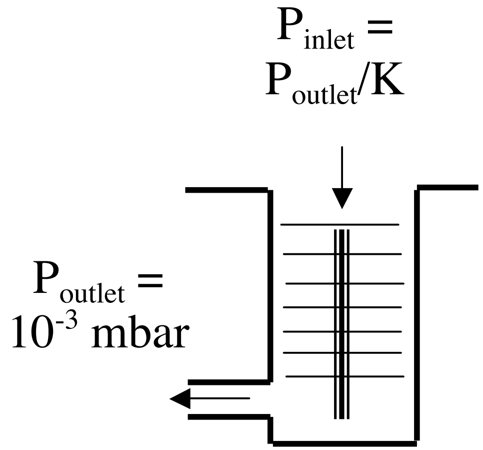
Pumping speed of a turbomolecular pump $S \quad v\ A$

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



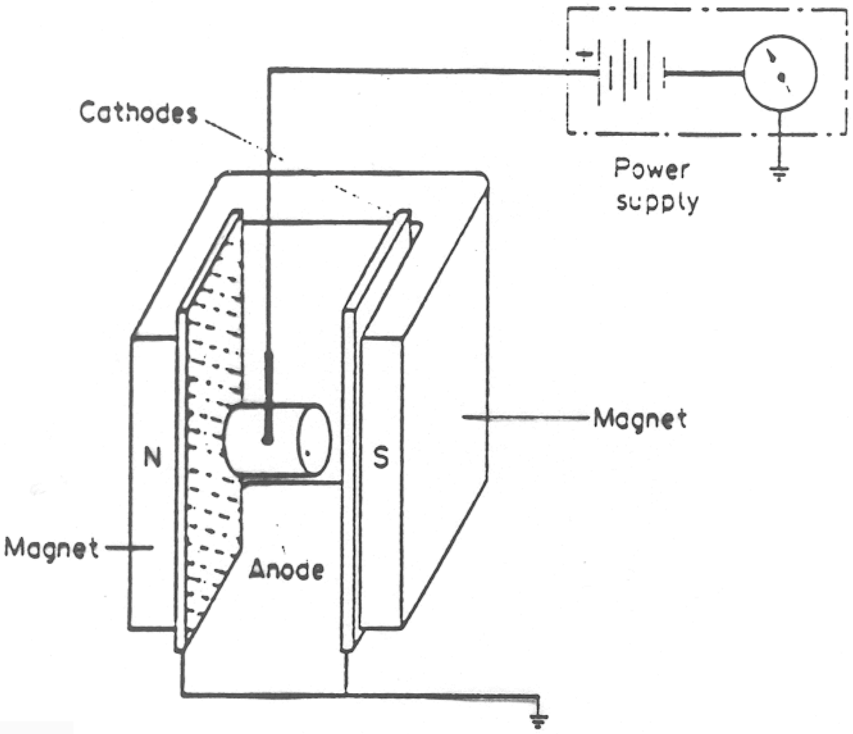
K is an exponential function of the molecular weight and of the rotational speed (10^3 for H_2 to 10^9 for N_2)

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

Sputter-Ion-Pump

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

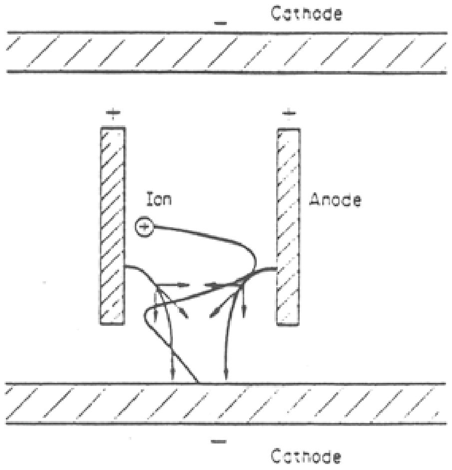
Ionised residual gas molecules are accelerated towards the Ti cathode and ‘trapped’ i.e. removed from the gas phase.



Basic configuration of a sputter-ion pump.

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

To increase the pumping speed, arrays of many cells are used



Pumping mechanisms

Gettering -> chemisorption of active species on sputtered Ti film: 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

Nobel gases: energetic ions of He, Ne, A by implantation into the cathode: “ion burial” of energetic ions. -> Argon instability due to pumping of large quantities 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, important memory effect of previously pumped gas (Argon).

Discharge current is proportional to pressure -> useful pressure measurement.

Surface Pumping

Surface pumping speed -> $S \quad \frac{1}{4}\bar{v}\,nF$

Getters (chemisorption E~eV)

Evaporable getter pumps (Ti sublimators, Ba getters used in vacuum tubes)

Non Evaporable Getters (NEG) Ti, Zr, V

Gettering surface achieved by sublimation from a Ti-filament.

Surface activation (heating -> reduction of surface oxide layer and diffusion of O into the bulk)

Sputter deposited getter film has been a new development for LHC, ESRF and other machines

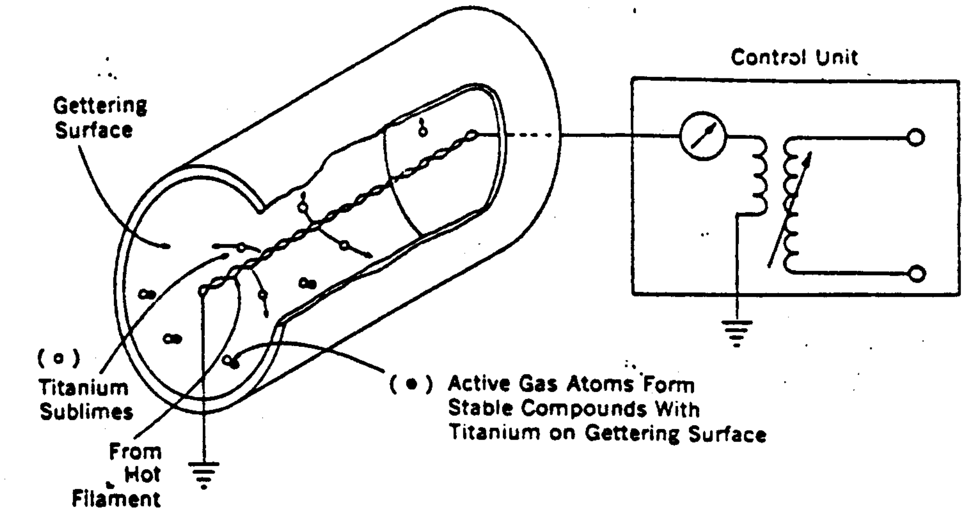
Cryo-pumps (physisorption E~ meV) requires cold pumping surface

Sorption (capacity ~ monolayer)

Condensation (vapour pressure)

Titanium sublimation pump

Configuration



Deposition of a thin film of fresh Ti on the inner surface of the vacuum chamber
Filament temperature ~ 1300 deg C
To increase the lifetime pumps have 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 has been developed at CERN -> sputter deposited getter film
few μm coated directly onto the inner surface of vacuum chambers.

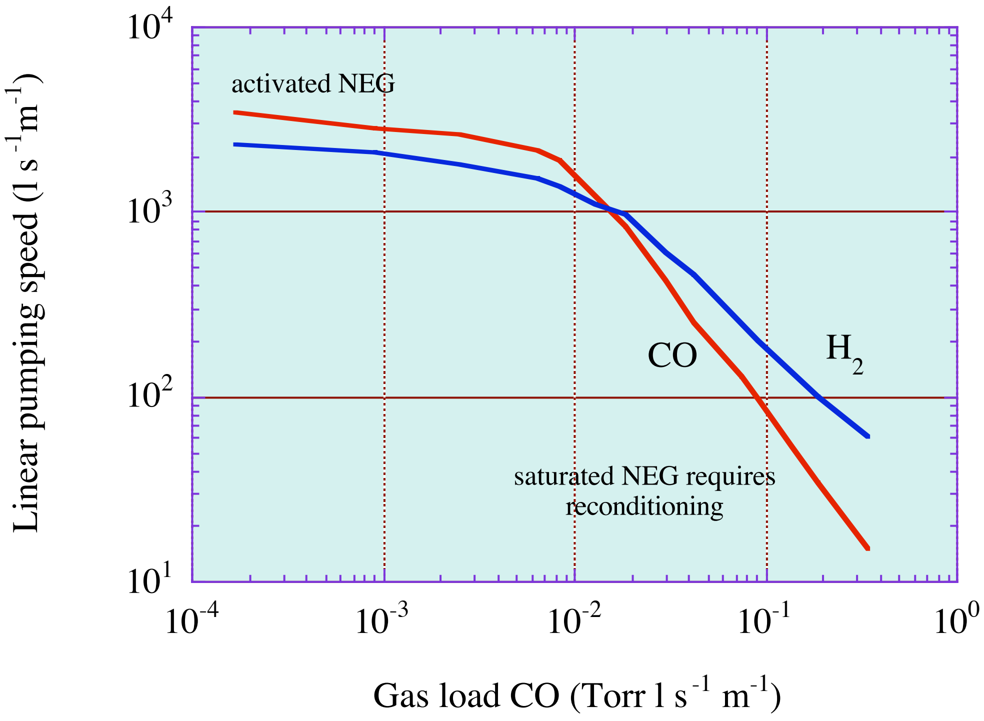
Double advantage : large pumping speed without conductance limitation
low outgassing rate.

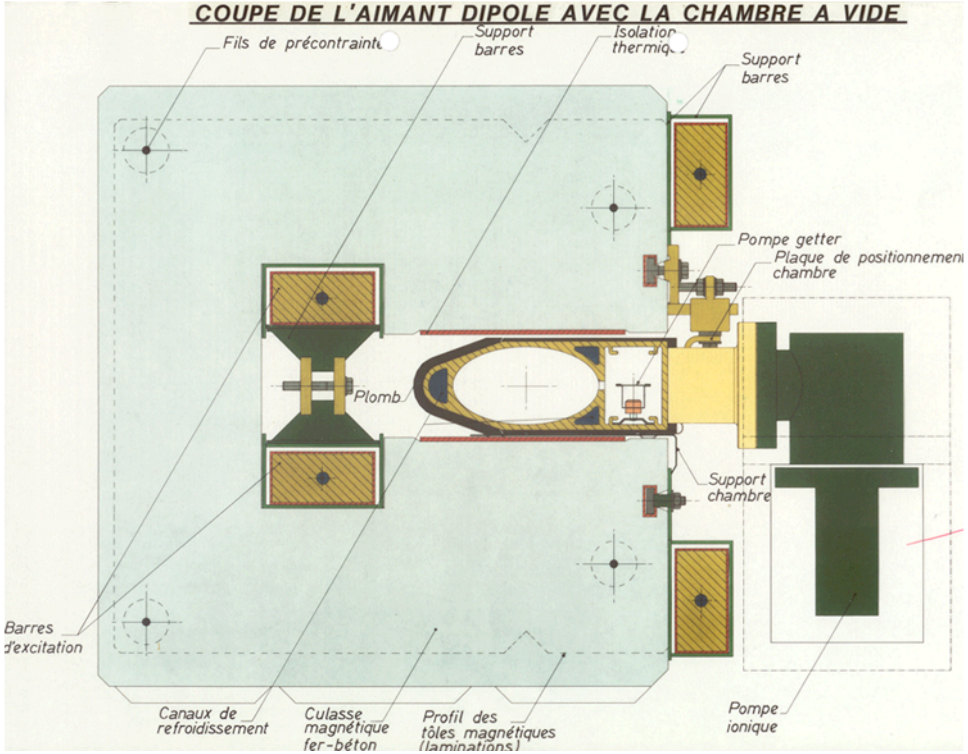
Note: Getters have a limited total pumping capacity and a memory effect of the gas previously pumped.
Getters pump only chemically active gas i.e. nobel gases and hydrocarbons (methane, …) are NOT pumped. Combination with ion pumps is required.

Pumping speed of a St101 getter

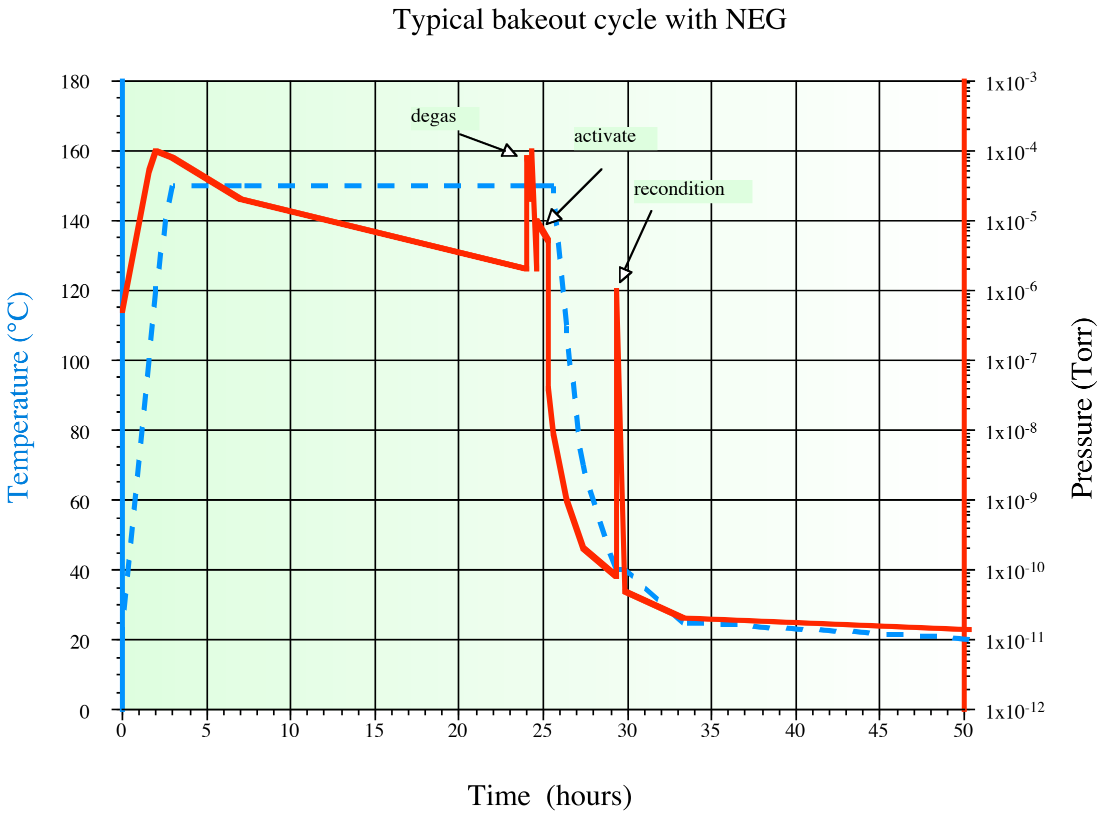
Reduction of the pumping speed due to the gradual saturation of the surface by adsorbed molecules.

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

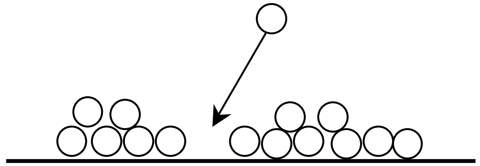


Within less than 12 hours after the bakeout uhv conditions can be achieved.

Cryo-Pumpimg

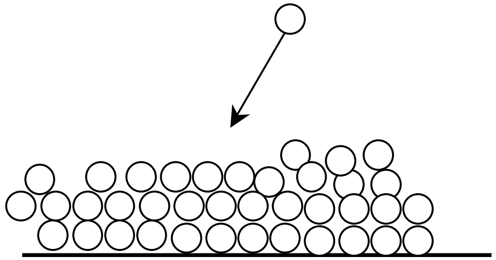
Adsorption of molecules at low temperature -> e.g. at liquid helium temperature

A) Sorption



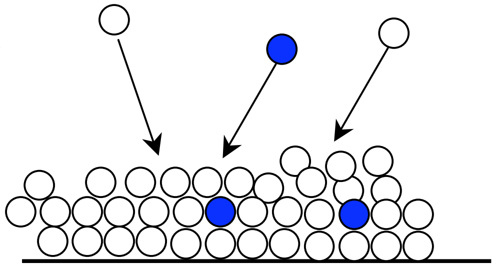
Adsorption of gas molecules with low surface coverage, to avoid the effect of the vapour pressure of the condensate. Increasing the effective surface area by a coating with a large specific surface area e.g. charcoal. -> Adsorption isotherms.

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 :

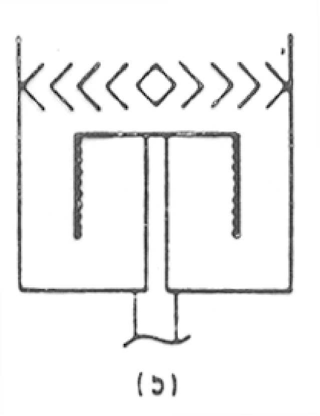
Large pumping speed and low limit pressure

limitation occurs due to 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. in LHC -> 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.

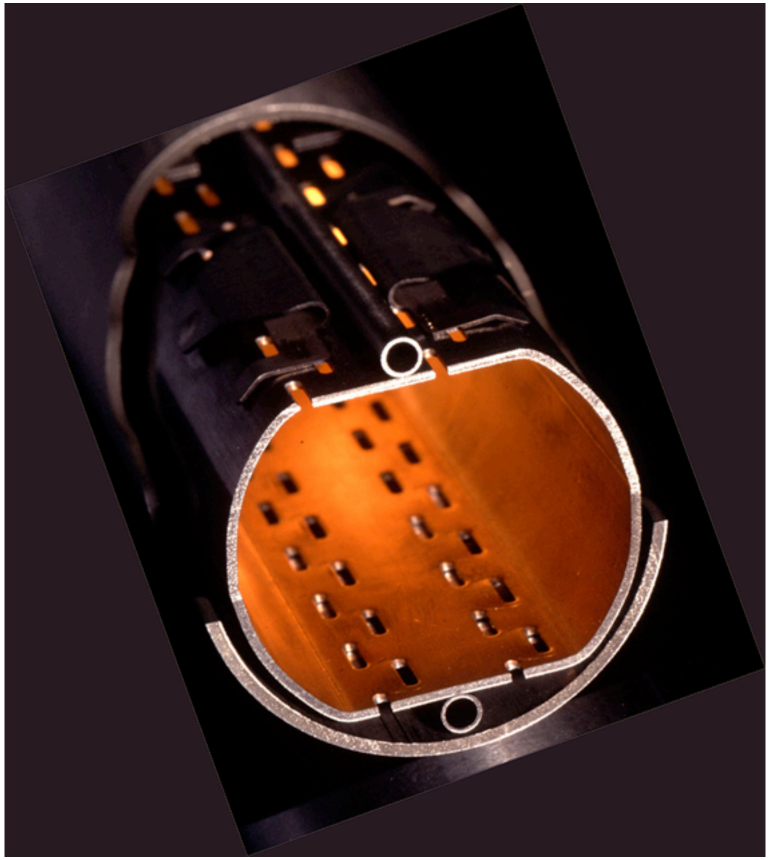
Commercial cryp-pump with a cryo-pannel :
Baffel is needed to intercept thermal radiation.
Risk of overpressure during warm-up if a too large amount of gas has been condensed.



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_2 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

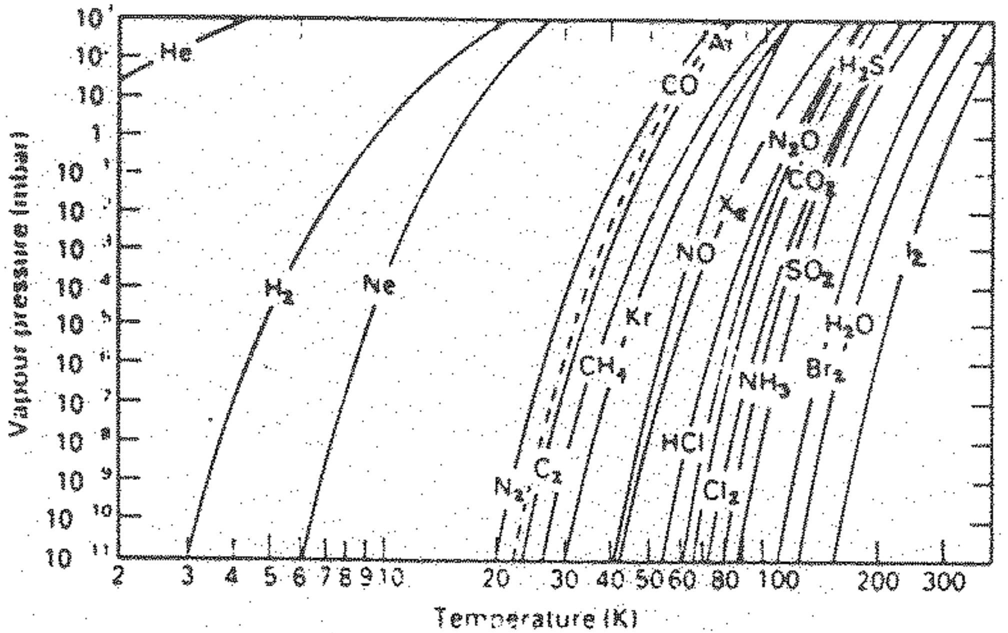
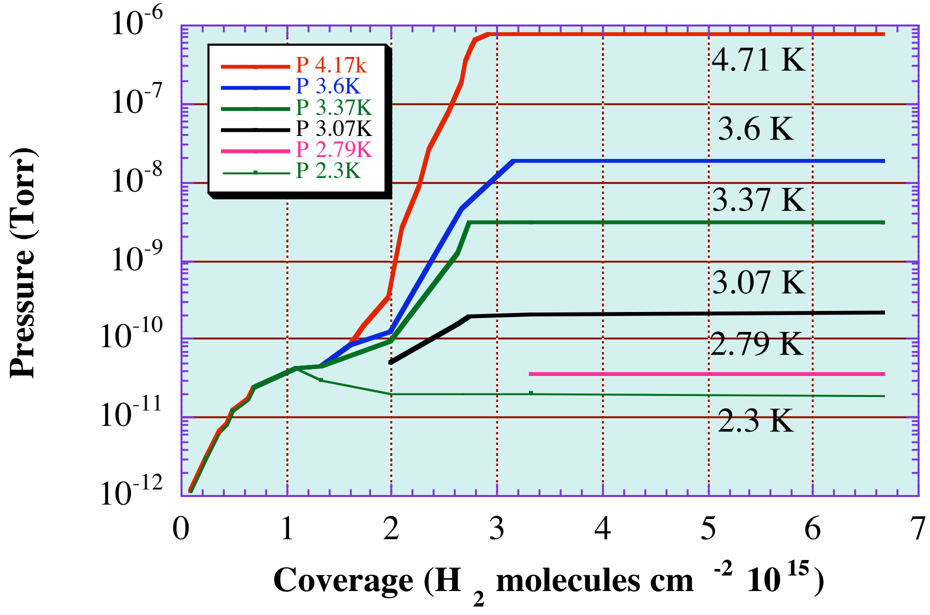


Figure 2. Vapour pressures of some common gases (from Bentley[9]).

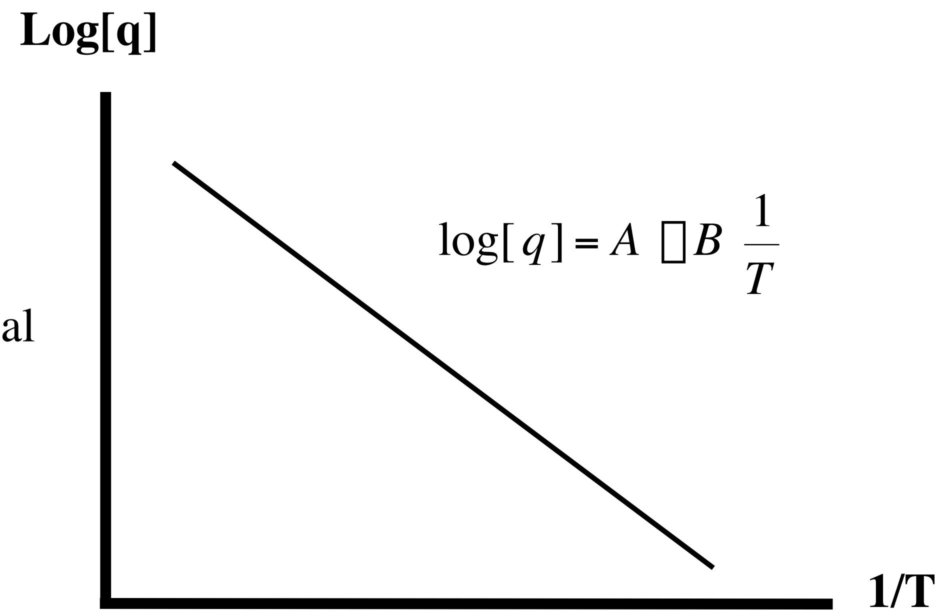


Thermal Desorption

Specific desorption rate : q [Pa m^3 s^{-1} m^{-2}] $q = Const \cdot e^{-\frac{E}{kT}}$

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

E activation energy for desorption,



$$\log[q] = A - B\,\frac{1}{T}$$

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

Physisorbed molecules E < 40 kJ/mole (0.4 eV)
Chemisorbed molecules E > 80 kJ/mole (0.8 eV)

Bakeout between 150 – 300°C : reduced residence time.
Reduction for H_2O, CO, CO_2 (by factors of 10^{-2} to 10^{-4})
At higher temperature > 400-500°C -> cracking of hydrocarbon molecules (C-H)

Note: Strongly reduced thermal desorption at cryogenic temperatures

Thermal outgassing rates of some materials

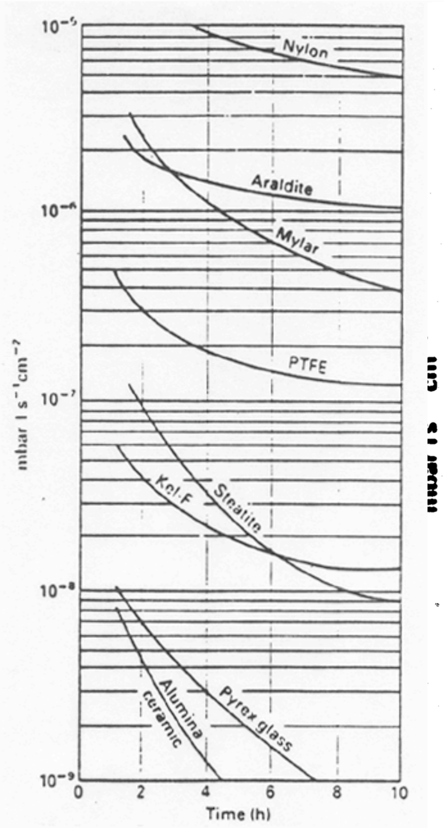
Comparison of organic materials and of metals

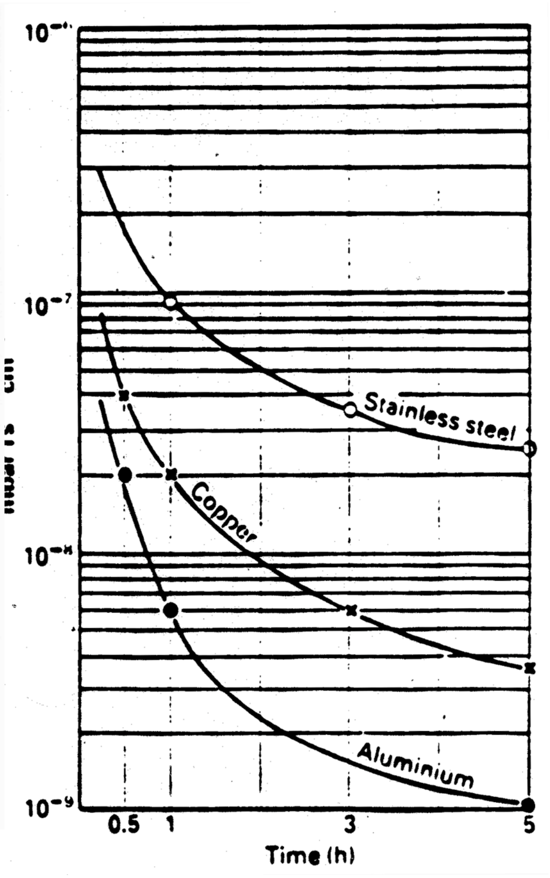
Unbaked samples (usually H_2O dominates)

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	$1\ 10^{-14}$





Synchrotron Radiation Induced Desorption

Gas desorption occurs in two steps: 1 -> photons -> produce photo-electrons
2-> photo-electrons -> excite molecules which subsequently can desorb thermally

Gas flow: $Q = \eta \Gamma$, here Γ is the linear photon flux (photons/s/m) $Q \quad \frac{\eta I E}{\rho} + Q_o$

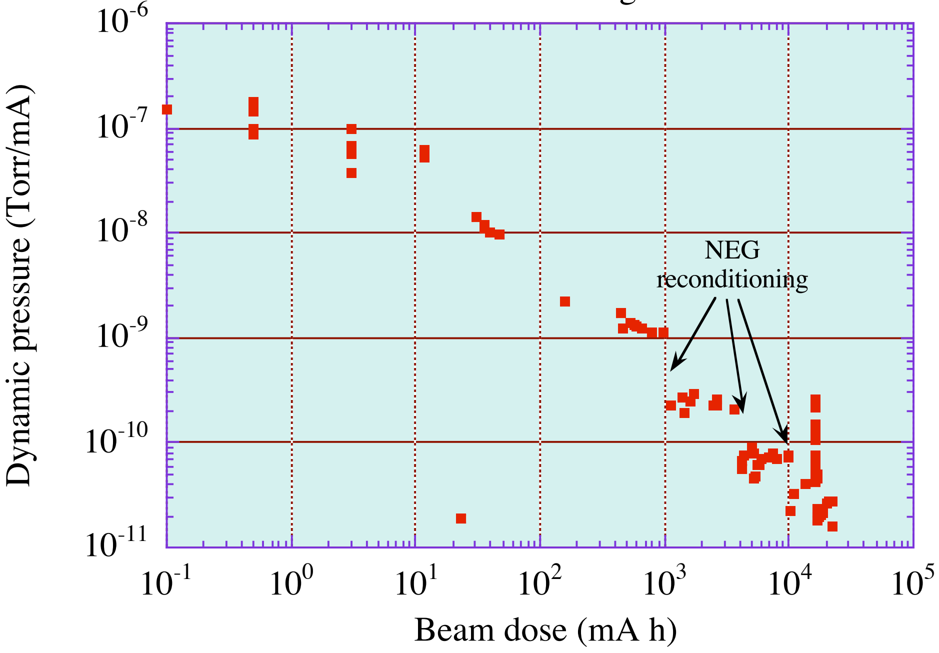
Q_o, thermal desorption rate, η, molecular desorption yield (molecules per photon), ρ, bending radius

Dynamic pressure: $P_{dyn} = \frac{Q}{S}$

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

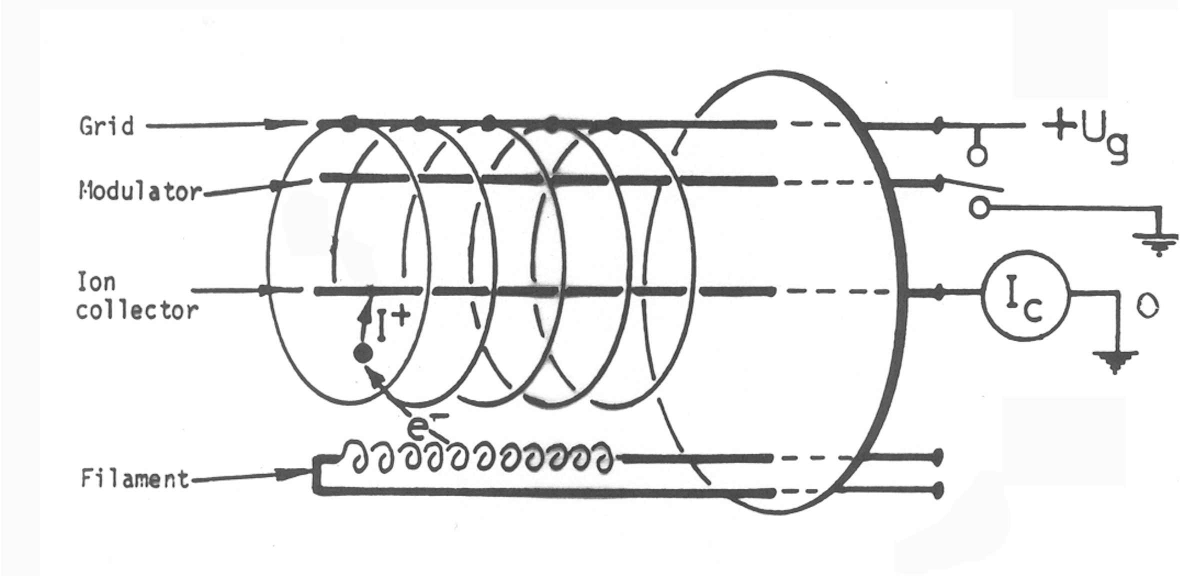
‘Beam cleaning’ (scrubbing) of the vacuum system is an essential procedure in many machines.

Vacuum conditioning in LEP



Hot Filament ionization Gauge

Operating principle⊡
Residual gas molecules are ionized 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 to the total pressure, P.



The ionization probability Pi
(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.

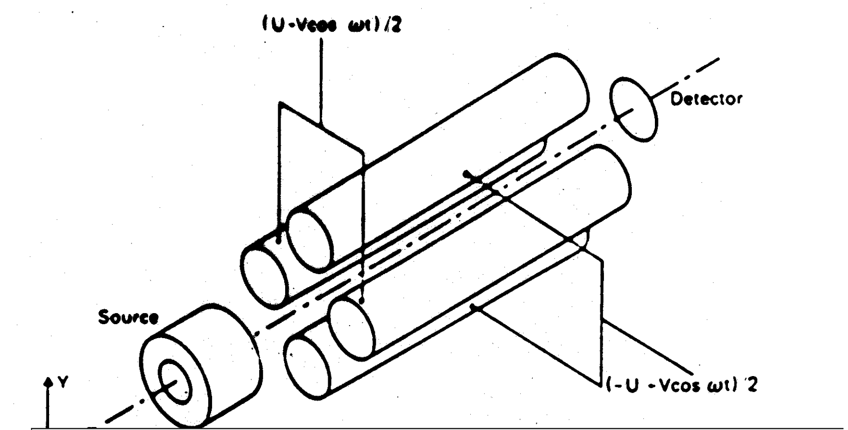
Ion collector current : $I^+ = Ie\ Pi\ L\ P$

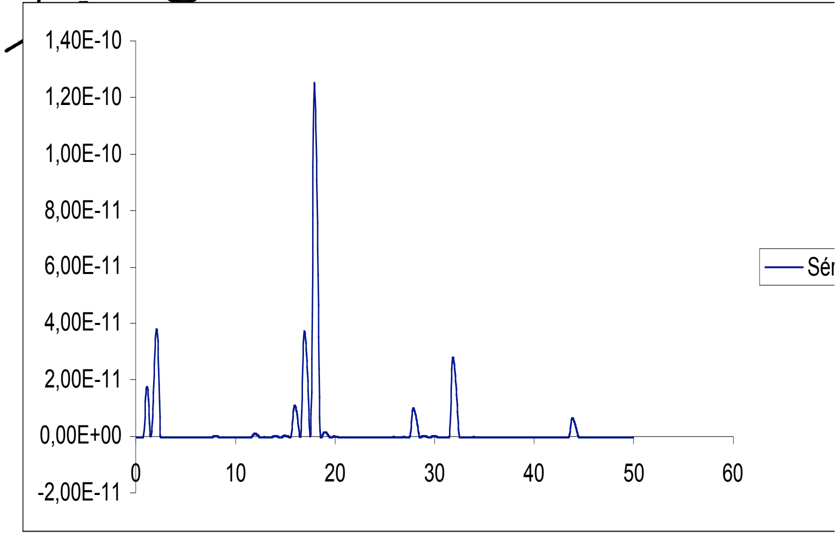
Where⊡ Ie emission current of the filament, L, path length of the electrons, P total pressure
Product Pi L i.e., the gauge sensitivity is obtained by calibration.

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





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.

Qualitative analysis is relatively straightforward, e.g. identification of: H_2, H_2O, CO/N_2, O_2, CO_2
Quantitative analysis requires a perfectly calibrated system and knowledge of ‘cracking pattern’ for each residual gas component.

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/cm^2 external atmospheric 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: Be for detectors for high transparency
Organic materials (e.g. as composite materials (carbon-fibre & epoxy), polymers to be used in small quantities