Vacuum in Accelerators

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General introduction
  Surface pumping
    Getters, Cryopumping
Dynamic vacuum effects
    SR desorption
    Ion desorption induced pressure instability
    BIM electron cloud effect

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Literature

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VACUUM Journal

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Nuclear Instruments and Methods (Section A)

Pressure and molecular density

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

with 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 : $R = No\ k$

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

Beam lifetime for a process with cross section σ: $1/\tau = \sigma\, v\, n$

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

Distribution of molecular velocities

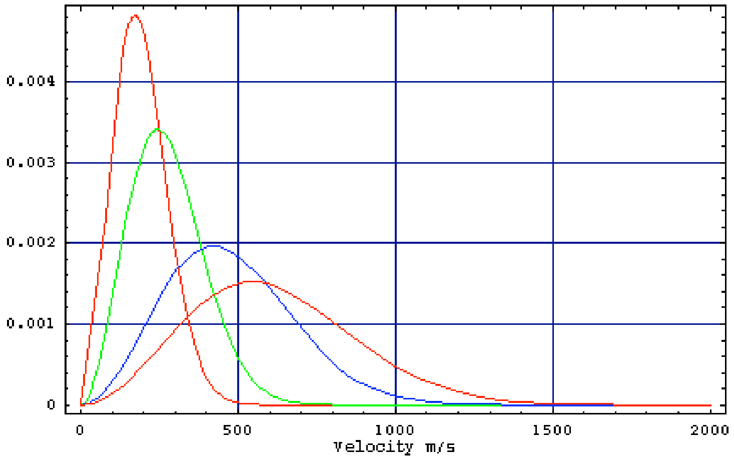
Maxwell-Boltzmann distribution of molecular velocities at the temperature T

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

Average velocity ($m = M\,m_o$) :

$$\bar{v} = \sqrt{\frac{8kT}{\pi M m_o}}$$

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

Wall collisions

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

Number density n and the average molecular velocity $\bar{v}$.

Mean free path of molecules

D molecular diameter (~3 10^{-8} m) $l = \frac{1}{\sqrt{2}\,\pi D^2 n}$

The product $n\,l \approx const$

For air, $n\,l \sim 2.5\ 10^{14}\ \mathrm{m}^{-2}$. At RT and for 1 Pa : $l \sim 0.9$ mm

Molecular conductance -> Knudsen relation: gas flow $Q = c\,\Delta P$.

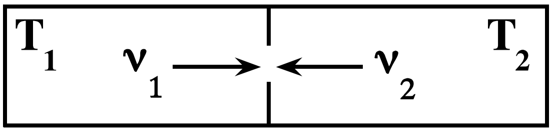
Conductance with l >> dimensions of the system. $c = \frac{4}{3} \frac{\bar{v}}{\int_0^L \frac{H}{A^2} dl}$ (m^3/s)

L length of the element (L >> transverse dimensions).

H perimeter, A cross section of the element. Proportional to $\sqrt{T/M}$.

Uniform cylindrical duct with radius r : $c = \frac{4}{3} \bar{v} \left(\frac{r^3}{L}\right) \sim 306 \cdot \left(\frac{r^3}{L}\right) \sqrt{\frac{T}{M}}$.

Thermal transpiration

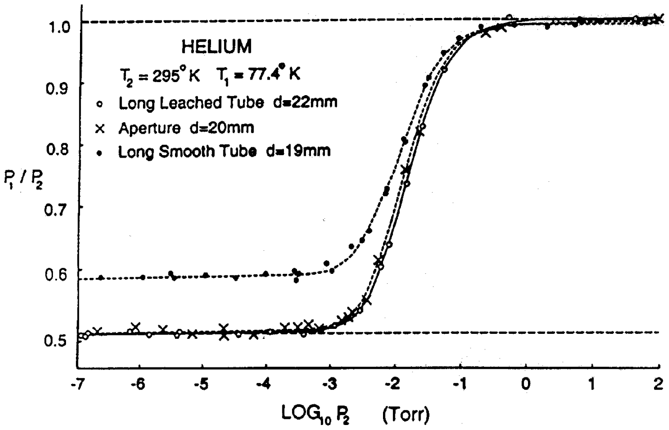


At high pressure, the pressures on both sides are equal.
In molecular flow, the net number of molecules traversing the orifice in the separating wall must be zero : $\nu_1 = \nu_2$

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

one obtains $n_1 \sqrt{T_1} = n_2 \sqrt{T_2}$

or $\frac{P_1}{\sqrt{T_1}} = \frac{P_2}{\sqrt{T_2}}$



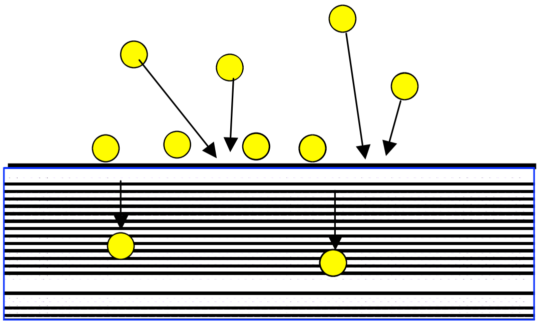
Surface pumping

Getters (chemisorption E~eV)

Evaporable getter pumps (Ti sublimators)

Non Evaporable Getters (NEG) ->Ti, Zr, V

Surface pumping -> $S \propto \frac{1}{4}\bar{v}\, n\, F$



Surface area : *F*

Getter surface by sublimation (Ti-film)

New developments: thin film sputtering: Ti Zr V

Surface activation :

heating -> reduction of surface oxide layer

and diffusion of O into the bulk)

Lowering of ctivation temperature: 750C -> 250C larger choice of materials (st.steel, Al alloy)

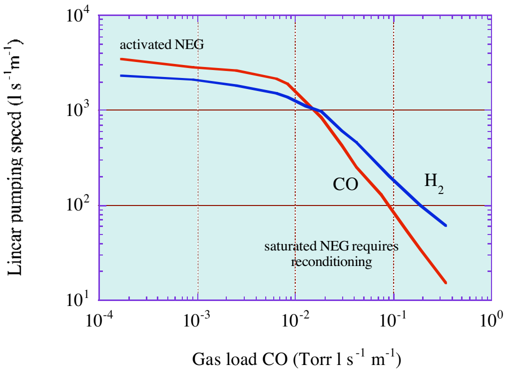
Cryo-pumps (physisorption E~ meV)

Sorption (capacity ~ monolayer)

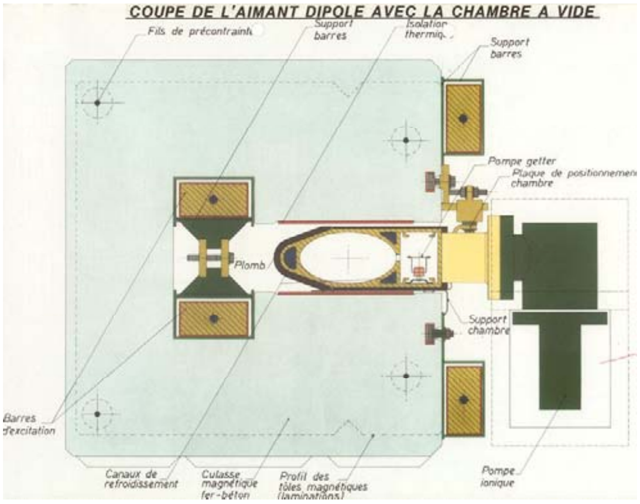
Condensation (vapour pressure)

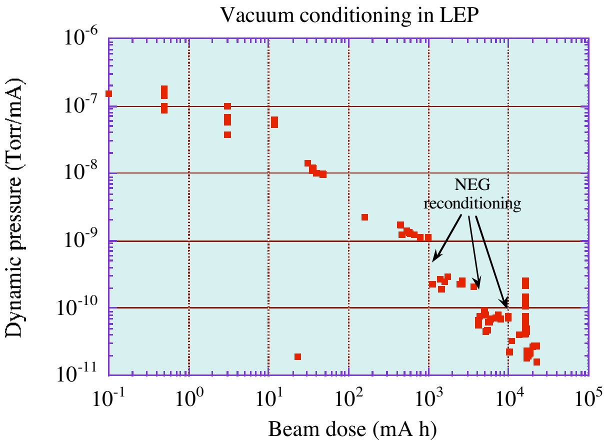
NEG pumps

Non-evaporable getters used as main pumping system in LEP : Al+Zr alloy coating on a metal ribbon. Initial pumping speed decreases with the quantity of gas pumped. Periodic reactivation required.



Section of the LEP vacuum system in a dipole magnet





Dynamic pressure rise by synchrotron radiation

The pressure in an electron/positron storage ring increases due to photon induced desorption from the walls of the vacuum chamber:

$$\Delta P = const \frac{d^2 N_\gamma}{dsdt} \frac{\eta}{S}$$

$$\frac{d^2 N_\gamma}{dsdt} = const \frac{IE}{\rho}$$

$$\frac{\Delta P}{I} = const \frac{1}{\rho} \frac{\eta E}{S}$$

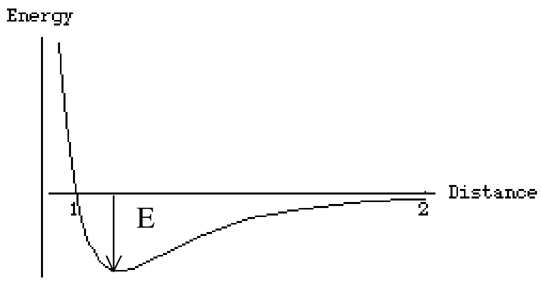
A simplified model of the molecular desorption as a 2-step process:
-> molecules near the surface are excited and photo- or secondary electrons are produced
-> excited molecules accumulate and recombine on the surface and desorb spontaneously (thermal desorption)

A close correlation between desorbed molecular flux and the photo-electron current can be observed
-> the desorption yield is found to increase at low photon energies (LHC) and to decrease at high photon energies (LEP).

Thermal desorption

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

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



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

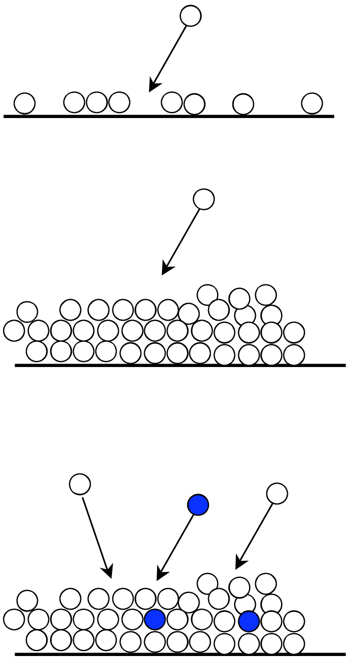
E Binding energy, activation energy for desorption
$\nu_o \sim 10^{13}$ s^{-1} vibration frequency in the surface potential

Physisorbed molecules E < 30 kJ/mole (0.3 eV)
Chemisorbed molecules E > 80 kJ/mole (0.8 eV)
Residence time for physisorbed molecules at R.T. ~ 10^{-7} s
at 80 K ~ 50 y

Bakeout between 150 – 300°C : reduced residence time.
Reduction for H_2O, CO, CO_2 (by factors of 10^{-2} to 10^{-4})

Above 400-500°C-> cracking of hydrocarbon molecules.
Important : Thermal desorption strongly reduced at cryogenic temperatures.

Cryo-pumping



A) Sorption

Adsorption of molecules on a substrate at low surface coverage. To increase the pumping capacity, the effective surface area of the cryosorber may be increased with a coating with a large specific surface area e.g. activated charcoal or molecular sieve.

B) Condensation

Adsorption in multi-layers -> limitation due to the vapour pressure of the condensed gas.
Below 20 K only Ne, H_2 and He have a significant saturated vapour pressure

C) Cryo-trapping

Cryo-sorption of a gas mixture, 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 proportional to the surface, *F* as long as the saturated vapour pressure of the adsorbed gas layer is low compared to the system pressure.

$$S = S_o\left(1 - \frac{p}{p_s}\right)$$

Pumping speed S_o can be close to the theoretical limit, s~1.
Limit pressure : -> vapour pressure of the adsorbed gas.

At 20 K all gases with the exception of He, H_2 and Ne can be condensed in large quantities at uhv pressures.
At 4.5 K pumping of large quantities of H_2 requires cryosorbing materials with large specific surface area, to stay well away from the saturated vapour pressure.
Pumping of He is difficult
-> avoid helium leaks!

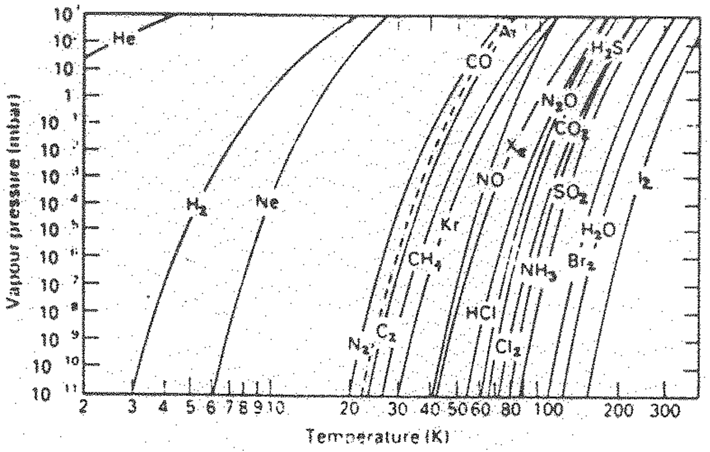
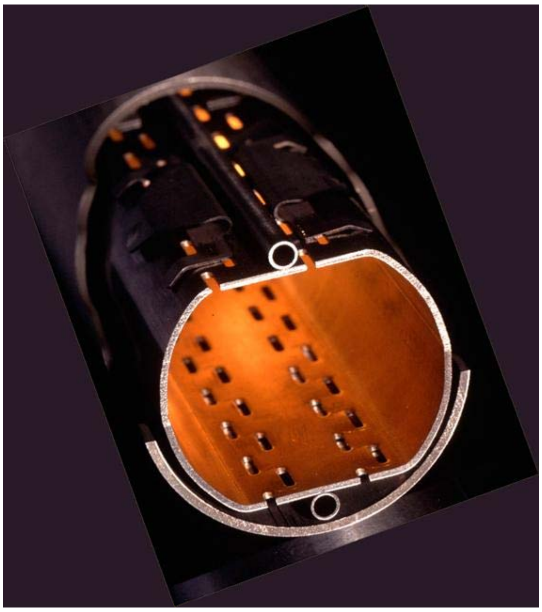


Figure 2. Vapour pressures of some common gases (from Bentley[9]).

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).

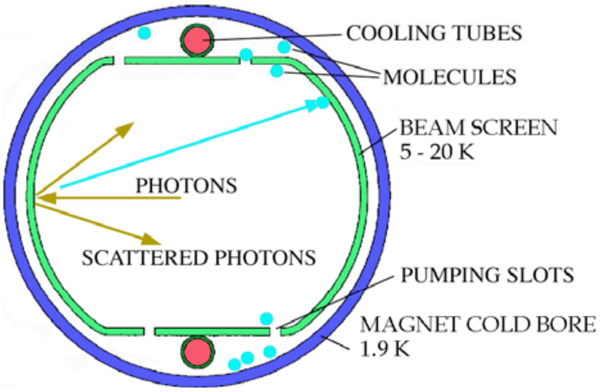


The limitations of cryopumps due to the exposure to environmental room temperature radiation and to the bombardment by beam induced energetic particles (photons, electrons, ions) must be taken into account.

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.

Synchrotron radiation in LHC

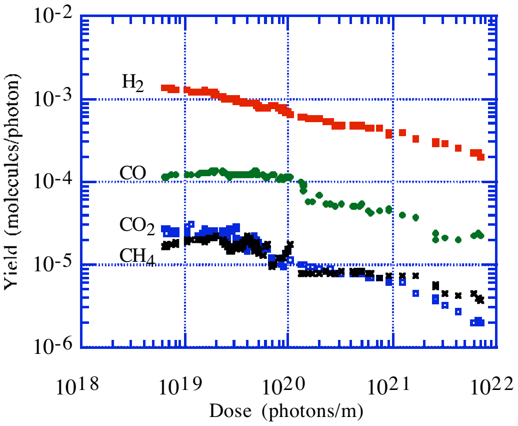
The LHC beam screen has been proposed initially for cryogenic reasons (S.R. power ~ 200 mW/m).
However : Critical photon energy of 45 eV is sufficient to desorb large amounts of gas.
In a first stage molecules are cryosorbed on the 20 K surface of the beam screen.



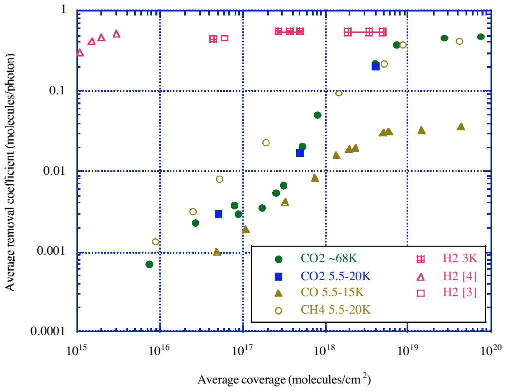
Scattered/reflected photons re-desorb (‘*recycle*’) molecules at a rate increasing with coverage, leading to an increasing gas density. More and more molecules escape through the pumping holes and are permanently adsorbed on the 1.9 K cold bore.
This effect stabilises the gas density in the beam pipe at a safe value i.e. to 10^{15} molecules/m^3.
This H_2 density ~ 5 10^{-9} mbar N_2 equivalent gauge reading at R.T.

Primary desorption yield & recycling coefficient

Photons produce molecules from strongly bound surface layers (chemisorbed mol.)
The clean-up of the vacuum chamber wall with photon dose improves the vacuum conditions during operation.
About one order of magnitude reduction will be required to operate the LHC with ultimate beam currents.



Recycling of physisorbed, weakly bound molecules increases with surfac coverage.
Hydrogen is most important species since its value is close to unity at a monolayer.



Dynamic pressure in LHC

The dynamic pressure in a beam screen with pumping holes, *f(%)*, is described by the equations

$$V \frac{dn}{dt} = q - a\ n + b\ \theta$$

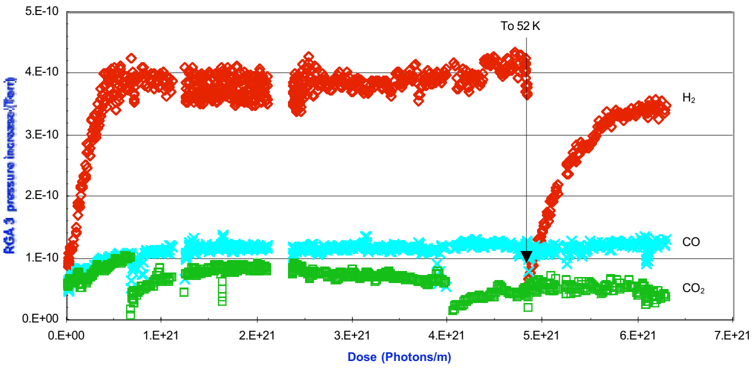
$$F \frac{d\theta}{dt} = c\,n - b\,\theta$$

Equilibrium solutions for volume and surface gas densities

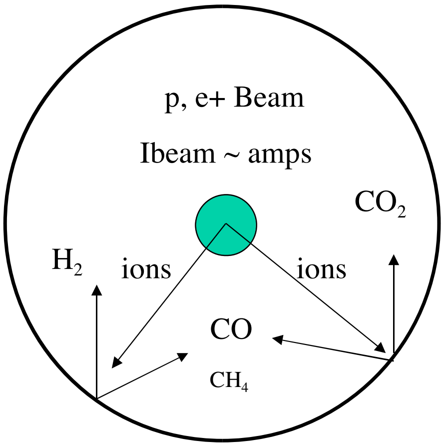
$$\boxed{\theta_{equ} = \frac{c}{b}\ n = \frac{\frac{1}{4}\ \bar{v}\ s\ F}{F \nu_o\, e^{-E/kT} + \kappa\ \Gamma}\ n}$$

$$\boxed{n_{equ} = \frac{q}{a - c} = \frac{\eta \Gamma}{\frac{1}{4}\ v F\ f}}$$

Volume density depends only on the desorption yield and on the pumping through the holes.
The surface coverage, i.e. the total pumping capacity of the beam screen, is reduced due to the recycling effect.
The recycling effect determines the time response of the system.



Beam Induced Pressure Instability



p, e+ Beam

Ibeam ~ amps

CO_2

H_2 ions ions

CO

CH_4

Molecular desorption yield η (molecules/ion)
unit charge e, ionisation cross section σ

Critical current $(\eta I)_{crit}$ defines the stable pressure range

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

S_{eff} is the effective pumping speed of the system.
For the LHC with a beam screen the minimum pumping is provided by the pumping holes

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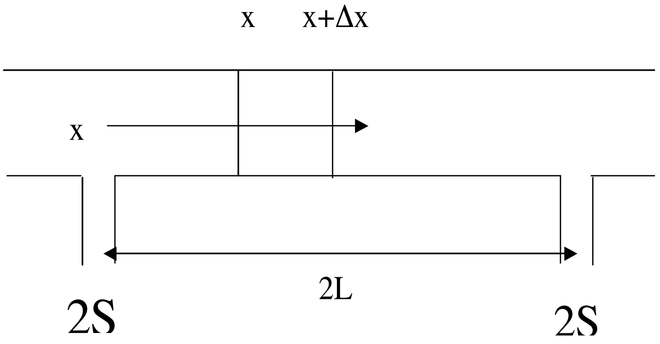
Linear Vacuum System with Ion Induced Desorption



Gas flow:	$Q(x)$	[Pa m^3 s^{-1}]
Specific linear outgassing rate:	$q(x)$	[Pa m^2 s^{-1}]
Specific molecular conductance of the tube:	c	[m^4 s^{-1}]
Pumping speed	S	[m^3 s^{-1}]
Ion induced desorption	b	[m^2 s^{-1}]

Where $b = \sigma \eta \frac{I}{e}$ with :

I beam current, e electron charge, σ the ionisation cross section and η the molecular desorption yield.
In stationary conditions, the pressure is given by

$$c \frac{d^2 P}{dx^2} + b\,P + q = 0$$

Boundary conditions for a uniform, periodic vacuum system with pumps at regular distance $2L$:

$$c \left[\frac{dP}{dx}\right]_{x=\pm L} = \mp S\,P[\pm L] \,.$$

For $b = 0$, one obtains a parabolic pressure distribution :

$$P(x) = q\left(\frac{2L\,x - x^2}{2\,c} + \frac{L}{S}\right) \quad \text{and} \quad P_{av} = AqL\left(\frac{L}{3\,c} + \frac{1}{S}\right)$$ -> “conductance limited” for very large S

For $b > 0$, the solution has the form

$$P[x]=\frac{q}{b}\left[\frac{\cos[\sqrt{b/c}\;x]}{\cos[\sqrt{b/c}\;L]-\frac{\sqrt{bc}}{S}\sin[\sqrt{b/c}\;L]}-1\right]$$

A finite solution exists for :

$$\cos[\sqrt{b/c}\;L]-\frac{\sqrt{bc}}{S}\sin[\sqrt{b/c}\;L]>0\,.$$

The limit of stability, i.e. the largest stable value for the parameter *b* corresponds to the first root of the transcendental equation

$$L\sqrt{b/c}\;\tan[L\sqrt{b/c}\,]=\frac{SL}{c}.$$

There exists an upper limit for b when the vacuum system is conductance limited (S very large), which is

$$b_{\lim}=\frac{\pi^2}{4}\frac{c}{L^2}.$$

The critical beam current for this condition is

$$(\eta I)_{crit}=\frac{\pi^2}{4}\frac{e\,c}{\sigma L^2}.$$

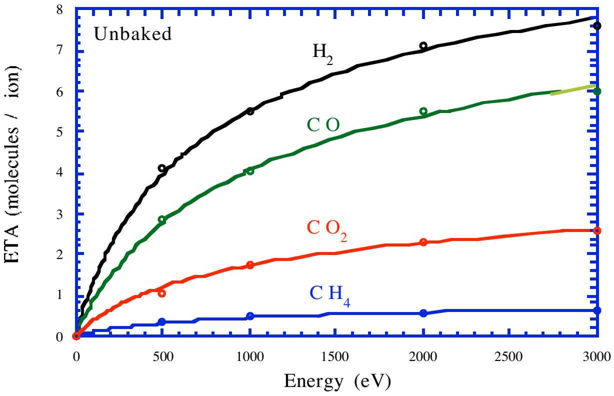
For any practical situation, the critical current will be lower.

For $b < 0$, the pressure decreases since the beam acts like an ion-pump -> **beam pumping**. This situation gives always a stable pressure. -> beam pumping speed $S_{beam}=\frac{\sigma\kappa}{e}I$ (m^2s^{-1})

where κ represents the probability that the incident ion is captured in the wall, e.g. for a typical ion pump κ~0.1.

Since the residual gas is a mixture of different molecular species:

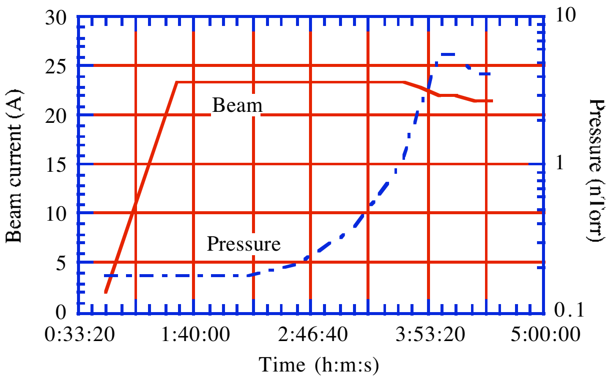
Heavy molecules e.g. CO are more critical than H_2.
Desorption yield is not a single number but a desorption matrix.
Set of linear coupled differential equations has to be solved.
Stability limit will be lower than for a single gas system.



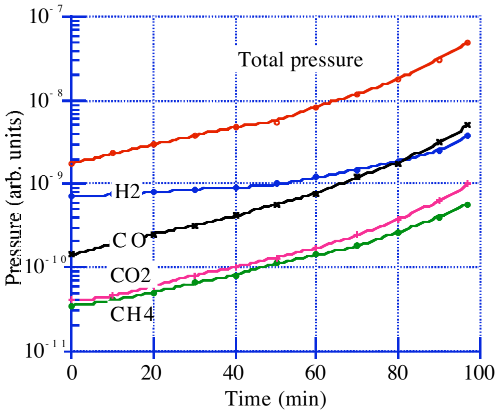
Molecular desorption yields as a function of the ion energy for unbaked stainless steel.

Pressure instability in the ISR with a proton beam

Note : slow development of the pressure rise over many hours. Molecules are re-adsorbed on the wall before they are pumped out from the system.
Same effect as in the cold LHC vacuum system.



Change of the residual gas composition during the instability growth.



Vacuum stability in a cryogenic vacuum system

Molecules are cryopumped with high efficiency directly onto the cold bore.

The pumping speed per unit length is $S_{eff} = \frac{1}{4}\bar{v}\, s\, F$

with the mean molecular velocity, s the sticking probability of molecules on the wall and F the surface area per unit length.

With the LHC beam pipe radius r_p, the stability limit is

$$(\eta I)_{crit} = \frac{\pi}{2}\bar{v}\, s\, r_p\, \frac{e}{\sigma}$$

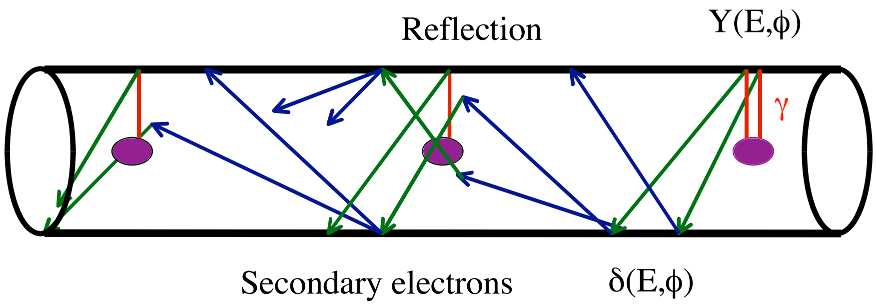
and for s~1 the critical current will be of the order of kA.

However, this large stability limit is offset by two factors:

Firstly, the sticking probability can be much less than unity

Secondly, the molecular desorption yield η for thick layers of condensed gas, specifically for H_2, which accumulates on the cold bore can become very large, up to 10^4 molecules per ion.

Electron cloud and beam induced multipacting (BIM)



Key parameters
Synchrotron radiation intensity,
Y(E,ϕ) photoelectric yield
δ(E,ϕ) secondary electron yield, E_{max}, δ_{max}
Energy distribution of secondary electrons
Photon reflectivity (magnetic field)
Beam screen shape and diameter
Bunch intensity and spacing
External fields (magnetic, electric, space charge)

Outgassing:
k converts molecules to pressure
<Ecloud> average energy
η_e molecular desorption yield
P_{lin} *(W/m)* linear power deposition

$$Q_{cloud} = k \frac{\eta_e P_{lin}}{< E_{cloud} >}$$

Secondary electrons and beam induced multipacting (BIM)

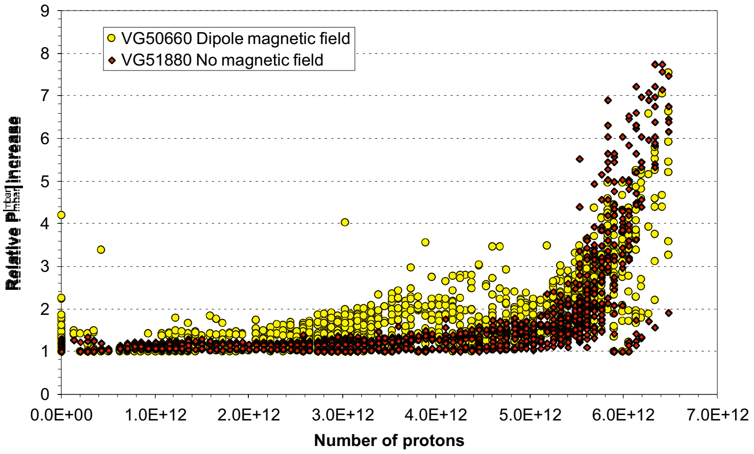
BIM produced by photoelectrons and low energy secondary electrons bouncing back and forth between opposite walls of the vacuum chamber during successive proton bunches.

Transit time condition: $N_b = \frac{r_p^2}{r_e L_{bb}}$, (r_e the classical electron radius),

In the LHC the beam screen radius r_p = 22 mm and the bunch spacing L_{bb} = 7.5 m such that the wall-to-wall BIM threshold is reached at about 1/4 of the nominal intensity of 1.1 10^{11} protons/bunch.

Power -> up to few W/m !
Important additional gas load.

BIM in the SPS with LHC-type beam. (by M. Jimenez)



Summary

Surface pumping with getters or on a cold surface are preferred solutions for a conductance limited accelerator vacuum system -> LHC arcs and long straight sections

Dynamic vacuum due to the presence of the beam :
Stable, finite increase of pressure by synchrotron radiation induced desorption

Pressure instability and pressure run-away due to ion induced desorption when the beam current exceeds a critical value

Beam pumping in case the net desorption coefficient is less unity

Electron stimulated desorption by BIM.