

School on Synchrotron Radiation

UHV - Technology

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- 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, Ed. J.M. Lafferty, John Wiley & Sons, 1998

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

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Journals:

VACUUM

Journal of Vacuum Science and Technology (A)

Nuclear Instruments and Methods (Section A)

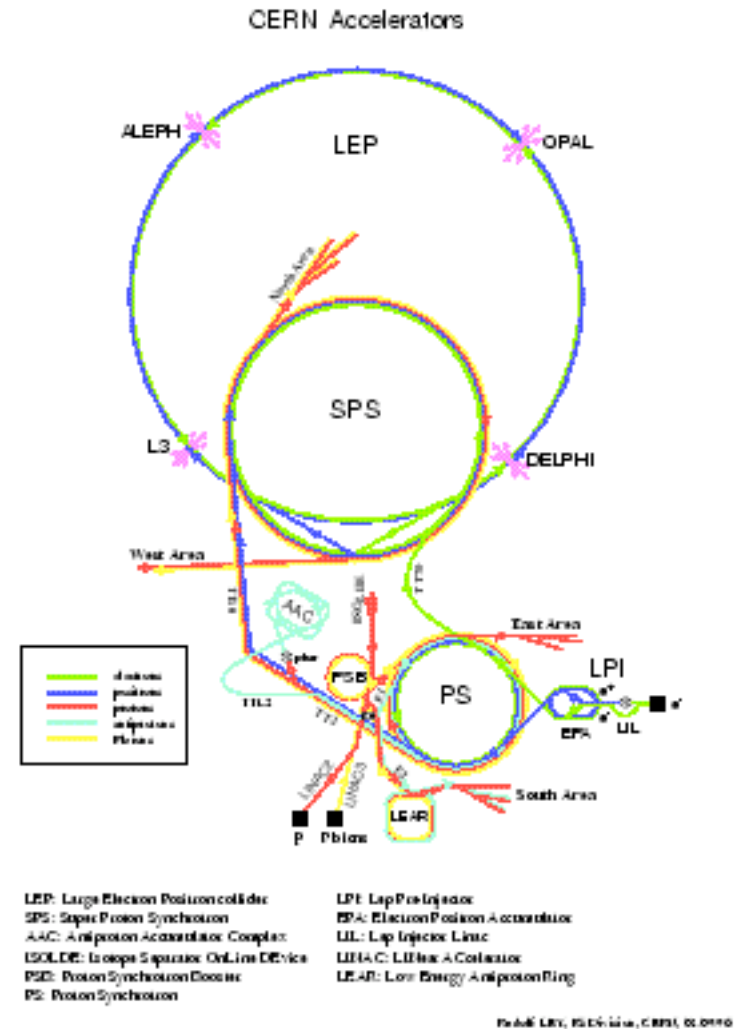
Accelerators at CERN

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

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 : $R = N_0 k$

Note: 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

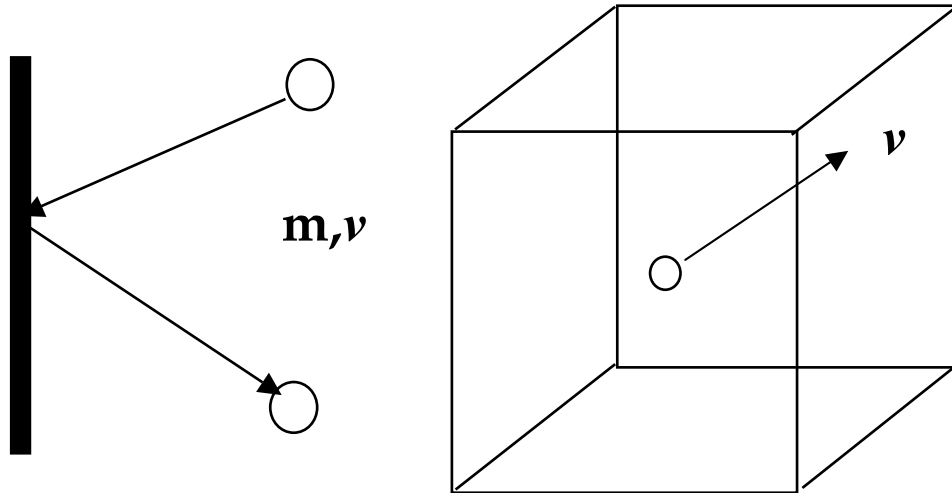
Leak rate : Pa m³/s or W, mbar l/s or Torr l/s

Wall collisions

Frequency of wall collisions

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

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 $m \square \bar{v}$

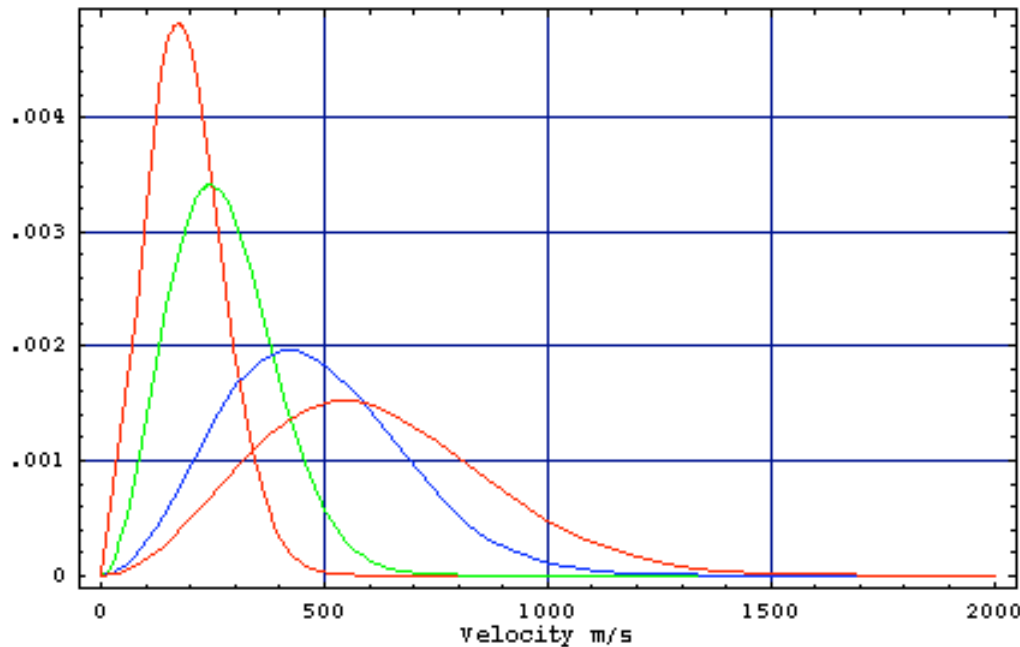
Distribution of Molecular Velocities

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

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

Pressure

$$p = \text{const } m \bar{v} \square$$

m mass of a molecule
 \bar{v} average molecular velocity
 \square // rate of wall collisions

A complete calculation gives $\text{const} = \square/2$

Thus one finds

$$p = \square/2 m \sqrt{\frac{8kT}{\square m}} n \sqrt{\frac{kT}{2\square m}}$$

and the final result

$$p = n kT$$

Considering a molar quantity, $n = \frac{N_o}{V_o}$

One finds again the familiar result
 with the gas constant R

$$pV_o = N_o kT = RT$$

Mean Kinetic Energy

The kinetic energy :
$$E_{kin} = \frac{1}{2} m \bar{v}^2 = \frac{1}{2} M m_o \frac{8kT}{M m_o} = \frac{4}{2} kT$$

M molecular weight, $m_o = 1.66 \cdot 10^{-27}$ 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 contribution to the total pressure : $P_i = n_i kT$

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

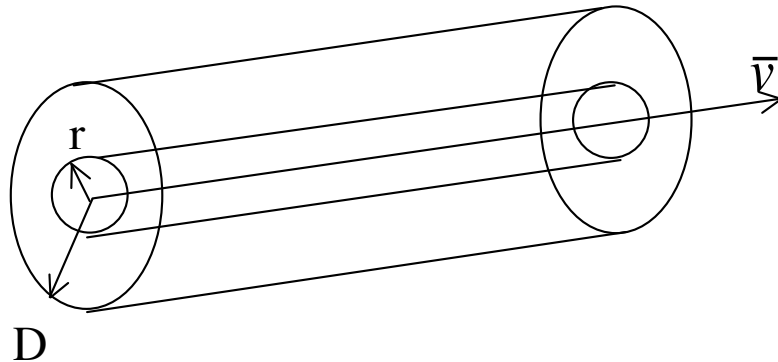
Partial pressures for atmospheric air

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

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

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



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: $Z \pi \pi D^2 \bar{v} n$. The mean free path $l = \frac{\bar{v}}{Z} = \frac{l}{\sqrt{2} \pi D^2 n}$

It also follows that $n l \propto P l \propto const$.

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

For air the product $n l \propto const$ is $\sim 2.5 \cdot 10^{14} \text{ m}^{-2}$.

For N_2 at 20 deg. C and at a pressure of 1 Pa $\rightarrow l \sim 9 \text{ mm}$

Molecular Flow Conditions

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

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

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 :

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

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

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

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

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

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

Molecular conductance of circular tubes

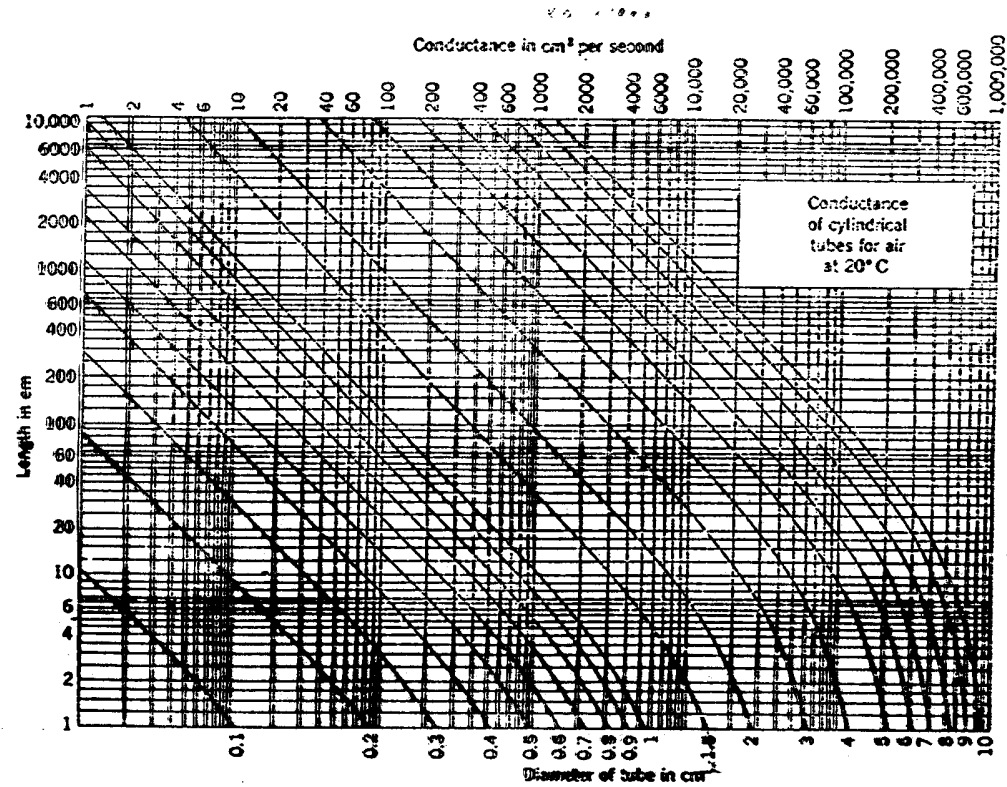


Fig. 2.1. Plots of conductance of cylindrical tubes for air at 20° C calculated according to equation 2.40.

Vacuum characteristics

gas : Nitrogen, N₂, 20°C, M = 28

Summary expressions:

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

$$kT = 4.04 \cdot 10^{-21} \text{ Joule}$$

$$\rho = M m_O n$$

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

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

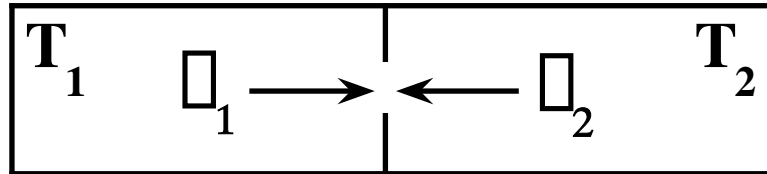
$$\lambda = \frac{l}{4} n \bar{v} \quad \text{and} \quad \bar{v} = 146 \sqrt{\frac{T}{M}}$$

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

$$D (\text{N}_2) = 3.15 \cdot 10^{-10} \text{ m}$$

Pressure	P Pa	n m ⁻³	ρ kg m ⁻³	λ 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				

Thermal transpiration



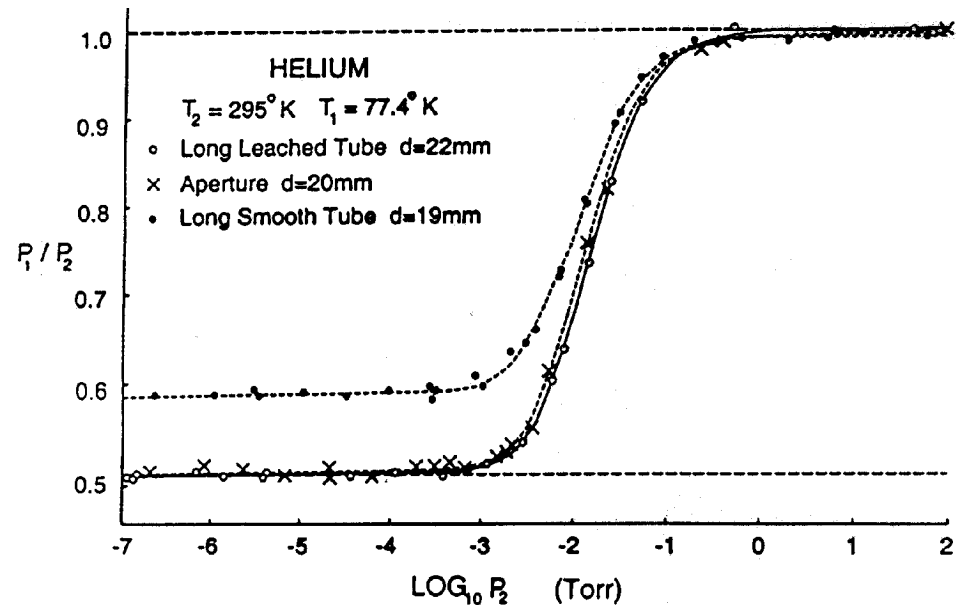
At high pressure, the pressures on both sides are equal.

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

$$\varrho_1 = \varrho_2$$

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

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

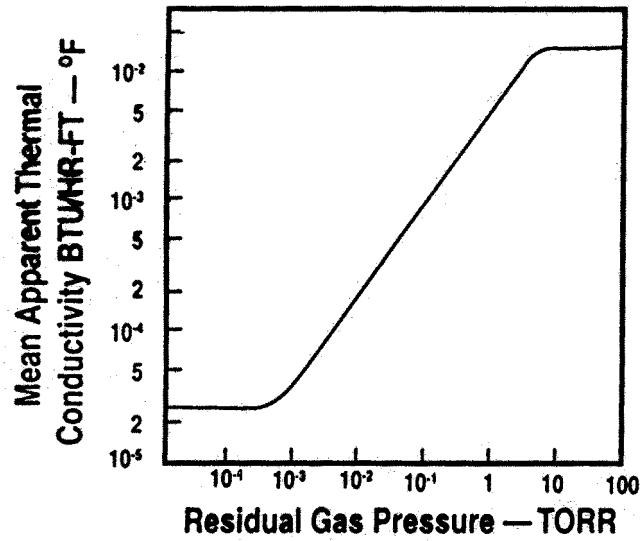


Thermal Conductivity

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

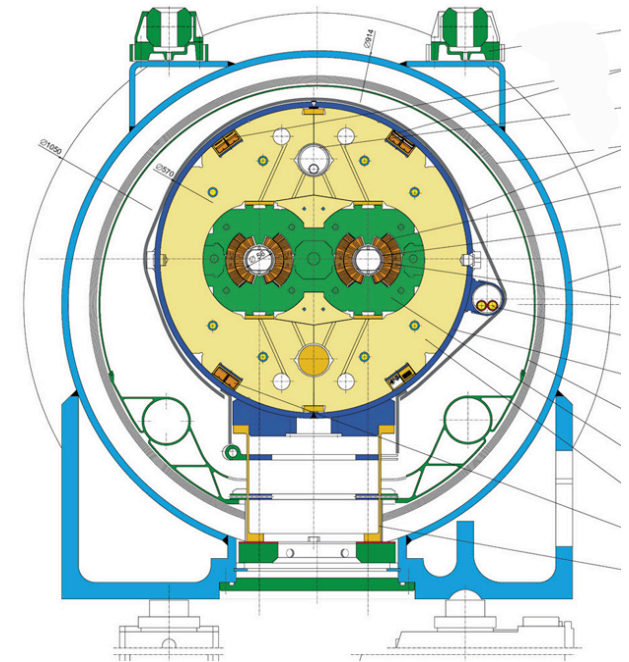
In the transition regime, the heat transfer is proportional to the pressure and to the temperature difference. Principle of pressure measurement with a Pirani gauge.

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



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

is



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 ($\text{Pa m}^3/\text{s/ m}^2$)

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

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

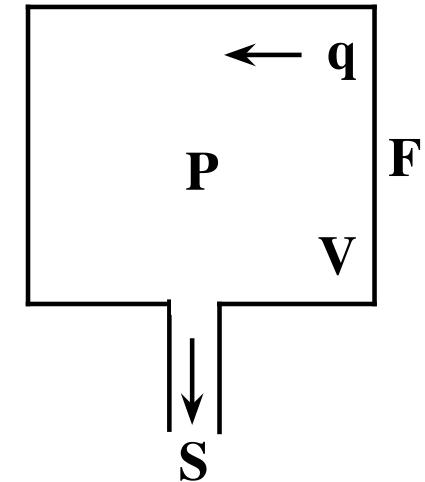
Solution (constant K depends on initial conditions) $P(t) = K e^{-\frac{S}{V}t} + \frac{q F}{S}$

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

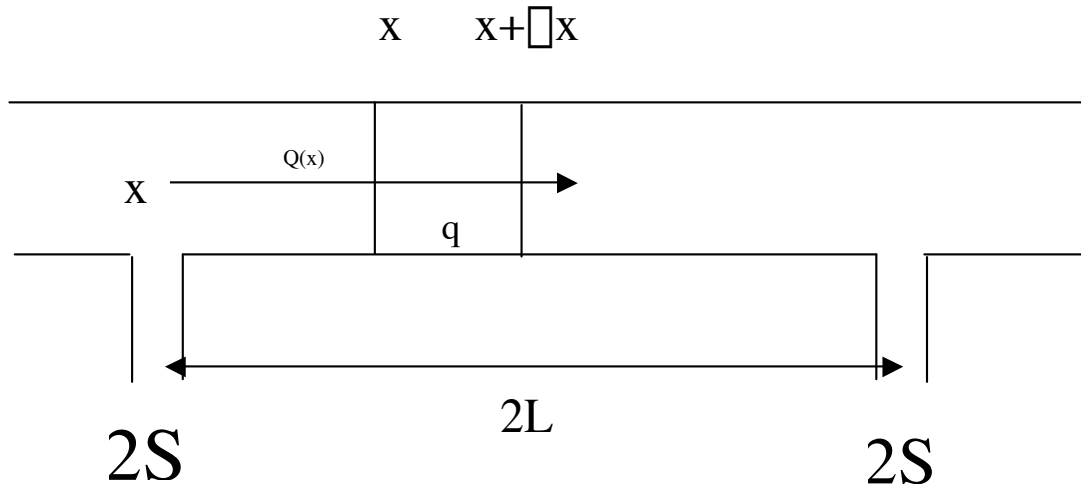
To obtain a low pressure :

Low outgassing rate of the surface, **No leaks**

Large pumping speed



Linear Vacuum System (Accelerators)



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

Specific surface area per unit length: A [m^2], molecular conductance per unit length: c [$\text{m}^4 \text{s}^{-1}$]

$$\frac{dQ}{dx} = Aq \quad \text{and} \quad Q(x) = c \frac{dP}{dx}$$

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

Time to form one monolayer

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

Mono layer coverage:

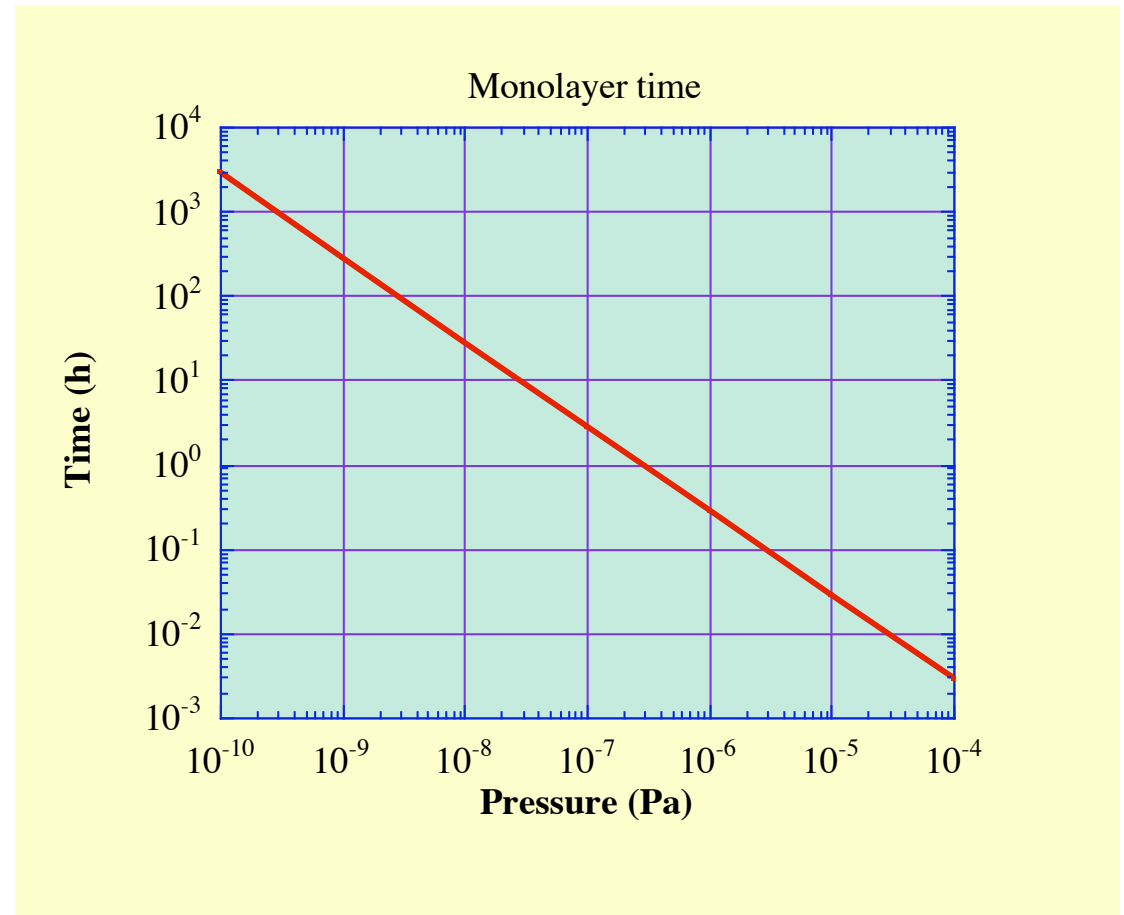
Γ ($\sim 3 \cdot 10^{19}$ molecules m^{-2})

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

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

Sticking probability $s < 1$

UHV becomes indispensable for surface analysis and for thin film technology
 -> Historically the main motivation to develop uhv techniques



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

Beam Lifetime due to Vacuum

Beam loss by Bremsstrahlung : $\square \frac{dE}{dx} = \frac{E}{X_0}$

$$\text{Lifetime } \frac{1}{\square} = \square \frac{1}{N} \frac{dN}{dt} = \frac{c \square}{X_0} W$$

X_0 radiation length, c speed of particles and $\square = \frac{m_0 M}{kT} P$ is the density of the residual gas at the pressure P .

$$\text{Here } W = \log\left(\frac{E}{\square E}\right)$$

Represents 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 $\square = \frac{X_0}{c \square W} \frac{X_0}{P}$

For nitrogen or CO one finds typically $\square P = 3.410 \square^8$ (Torr hours)

Consequence : UHV is required for storage rings.

Heavy molecules with short radiation length must be avoided.