CAS-Vacuum for Particle Accelerators

Fundamental of Vacuum Technology

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7th June 2017
Glumslov, Sweden

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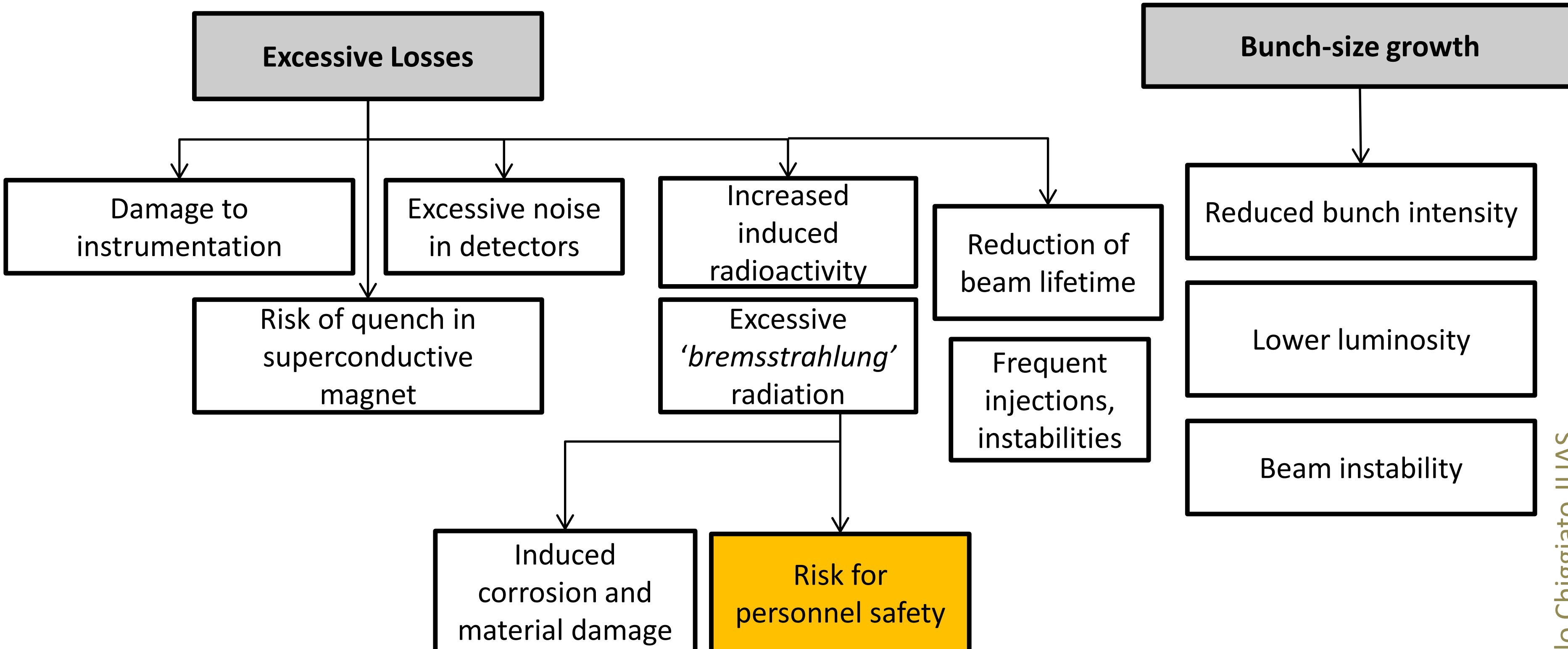
- Why do we need vacuum in particle accelerators?
- What is vacuum and vacuum ranges?
- Ideal gas law.
- Gas flow, conductance and pumping speed.
- Brief introduction to the gas sources in accelerators.
- Gas removal in accelerators: pumping mechanisms in UHV

Why do we need vacuum in accelerators?

Collisions between gas molecules and particles have to be minimized, otherwise:

Particle energy is reduced and trajectories are modified, so that:



Vacuum is also necessary:

- to avoid electrical discharge in high-voltage.
- To thermally isolate cryogenic devices.
- To avoid contamination of optics.

Courtesy: Paolo Chiggiato JUAS

What is vacuum and vacuum ranges

What is vacuum?

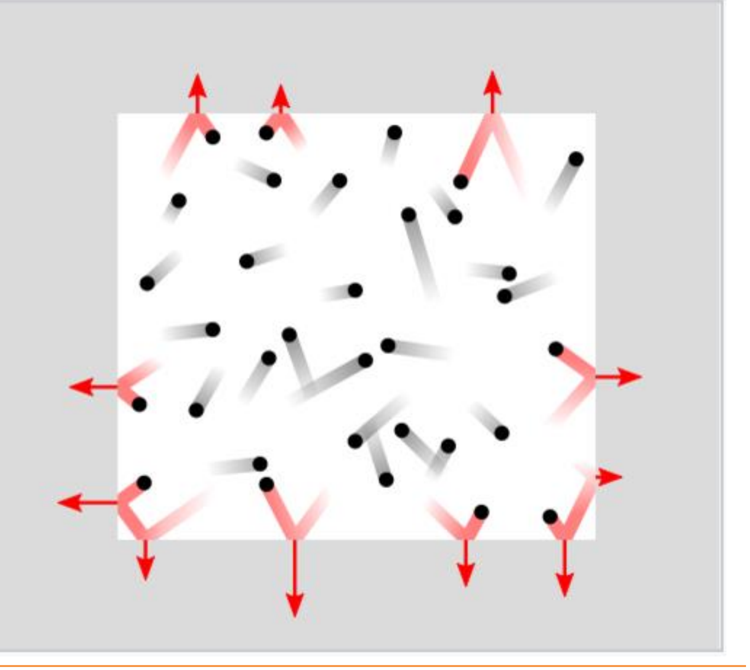
- Vacuum:
  - ISO 3529/1: a dilute gas or the corresponding state at which the pressure or density is lower than that in the surrounding atmosphere.
  - DIN 28400/1: state where the pressure is smaller than 300 mbar, which is the lowest that may exist on the surface of earth!
- Partial emptiness of space, where some gases have been removed, so there is less gases (lower density) than the surrounding space of the same volume.

What is vacuum?

- A gas in a container exerts a force on the walls of that container.
- Pressure (p) is the ratio of the force (F) exerted perpendicularly to the surface of the wall (A)

$$p = \frac{F}{A}$$

… Pressure is a convenient parameter to characterize vacuum, however, below certain vacuum levels, other physical parameters, like **number density** and **mean free path** can characterize vacuum more precisely.



Pressure units

- The same units as for the pressure (p): force (F) over surface area (A).
  - SI units: $$[p] = \frac{[F]}{[A]} = \frac{N}{m^2} = Pa$$
    - One Pascal (Pa) is the pressure at which a force of 1N ($1 kg.m.s^{-1}$) is exerted perpendicularly to a flat surface of 1 m^2.
    - Pa or bar.
    - 1mbar=100 Pa
  - Commonly used:
    - 1 Torr= 133.3 Pa

Units

- **Units conversion**

	Pa	bar	hPa	μbar	torr	micron	atm	at	mm WC	psi	psf
Pa	1	$1 \cdot 10^{-5}$	$1 \cdot 10^{-2}$	10	$7.5 \cdot 10^{-3}$	7.5	$9.87 \cdot 10^{-6}$	$1.02 \cdot 10^{-5}$	0.102	$1.45 \cdot 10^{-4}$	$2.09 \cdot 10^{-2}$
bar	$1 \cdot 10^{5}$	1	$1 \cdot 10^{-3}$	$1 \cdot 10^{6}$	750	$7.5 \cdot 10^{5}$	0.987	1.02	$1.02 \cdot 10^{4}$	14.5	$2.09 \cdot 10^{3}$
hPa	100	$1 \cdot 10^{-3}$	1	1,000	0.75	750	$9.87 \cdot 10^{-4}$	$1.02 \cdot 10^{-3}$	10.2	$1.45 \cdot 10^{-2}$	2.09
μbar	0.1	$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	$7.5 \cdot 10^{-4}$	0.75	$9.87 \cdot 10^{-7}$	$1.02 \cdot 10^{-6}$	$1.02 \cdot 10^{-2}$	$1.45 \cdot 10^{-5}$	$2.09 \cdot 10^{-3}$
torr	$1.33 \cdot 10^{2}$	$1.33 \cdot 10^{-3}$	1.33	1,330	1	1,000	$1.32 \cdot 10^{-3}$	$1.36 \cdot 10^{-3}$	13.6	$1.93 \cdot 10^{-2}$	2.78
micron	0.133	$1.33 \cdot 10^{-6}$	$1.33 \cdot 10^{-3}$	1.33	$1 \cdot 10^{-3}$	1	$1.32 \cdot 10^{-6}$	$1.36 \cdot 10^{-6}$	$1.36 \cdot 10^{-2}$	$1.93 \cdot 10^{-5}$	$2.78 \cdot 10^{-3}$
atm	$1.01 \cdot 10^{5}$	1.013	1,013	$1.01 \cdot 10^{6}$	760	$7.6 \cdot 10^{5}$	1	1.03	$1.03 \cdot 10^{4}$	14.7	$2.12 \cdot 10^{3}$
at	$9.81 \cdot 10^{4}$	0.981	981	$9.81 \cdot 10^{5}$	735.6	$7.36 \cdot 10^{5}$	0.968	1	$1 \cdot 10^{-4}$	14.2	$2.04 \cdot 10^{3}$
mm WC	9.81	$9.81 \cdot 10^{-5}$	$9.81 \cdot 10^{-2}$	98.1	$7.36 \cdot 10^{-2}$	73.6	$9.68 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	1	$1.42 \cdot 10^{-3}$	0.204
psi	$6.89 \cdot 10^{3}$	$6.89 \cdot 10^{-2}$	68.9	$6.89 \cdot 10^{4}$	51.71	$5.17 \cdot 10^{4}$	$6.8 \cdot 10^{-2}$	$7.02 \cdot 10^{-2}$	702	1	144
psf	47.8	$4.78 \cdot 10^{-4}$	0.478	478	0.359	359	$4.72 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$	4.87	$6.94 \cdot 10^{-3}$	1

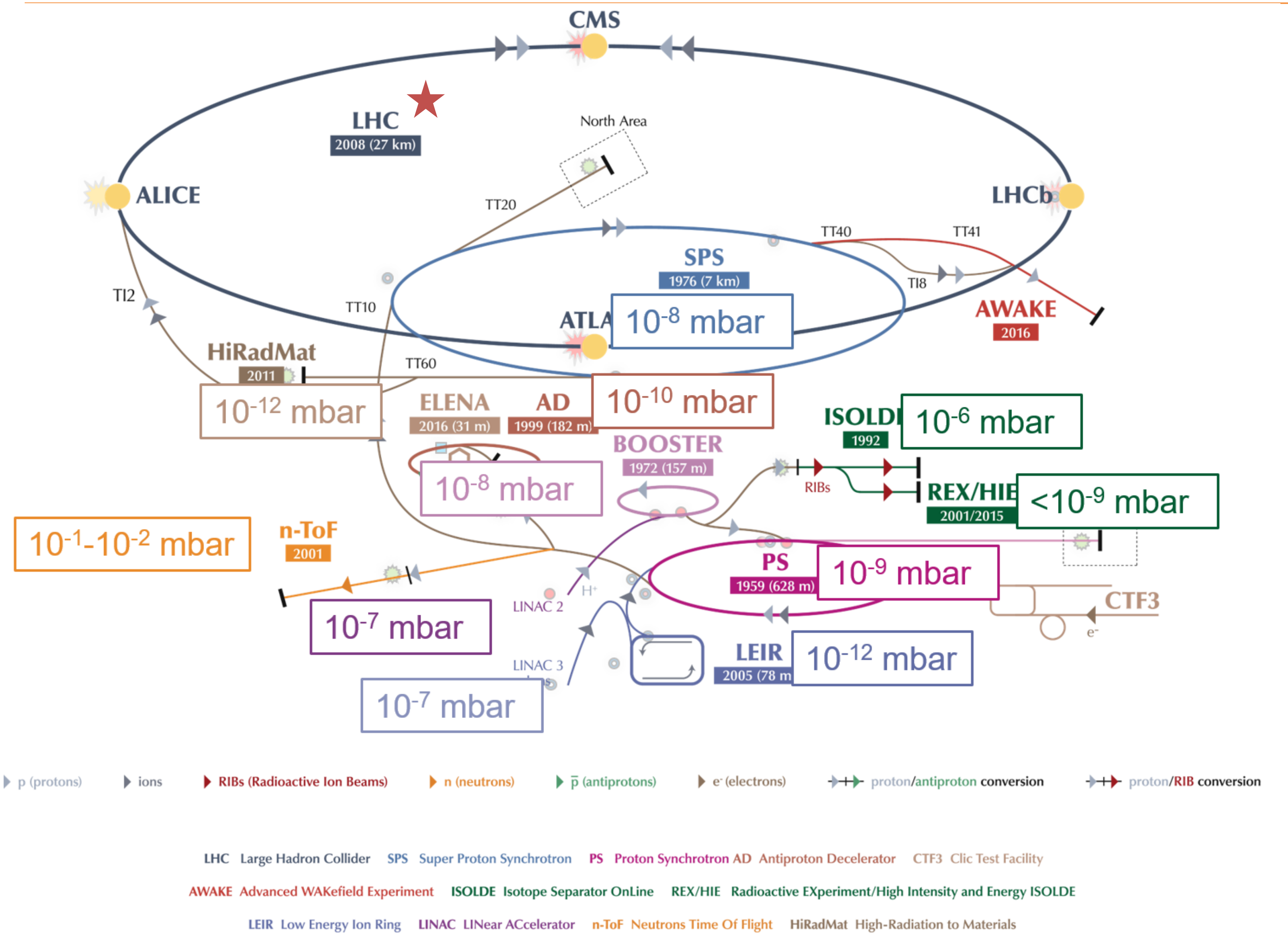
Source: Pfeiffer vacuum-The Vacuum Technology Book Volume II

Vacuum ranges

Vacuum ranges are according to the American vacuum society (AVS) 1980.

Vacuum Range	Pressure Range (mbar)	Typical applications
Low	$33<p<1.0\times10^{3}$	Vacuum cleaner, mechanical handling, vacuum forming,
Medium	$1.0\times10^{-3}<p<33$	Vacuum drying, vacuum freeze (food industries)…etc.
High (HV)	$1.0\times10^{-6}<p<1.0\times10^{-3}$	Production of microwave, light bulbs, vapor deposition.
Very high (VHV)	$1.0\times10^{-9}<p<1.0\times10^{-6}$	Electron microscopes, X-ray and gas discharge tubes, electron beam welding
Ultra-high (UHV)	$1.0\times10^{-12}<p<1.0\times10^{-9}$	Particle accelerators, space simulators, material research, semiconductors,
Extreme ultrahigh (XHV)	$p\leq1.0\times10^{-12}$	Particle accelerators, space simulators, advanced semiconductor devices

Vacuum ranges in particle accelerators



★ For LHC: number density less than 1×10^{15} H_2 equialment $/m^3$ source: Roberto Kersevan·

Status of LHC injectors and experimental areas Jose A. Ferreira Somoza OLAV-V

Basics of vacuum physics

Idea gas law

Assumptions for the ideal gas law

- The volume under discussion has a large number of molecules (e.g. at $1x10^{-9}$ mbar we have $2.5x10^{13}$ molecules).
- The distance between molecules is very large compared to their diameters (e.g. at $1x10^{-9}$ mbar the distance is $3x10^{-5}$m (dia. of molecules ~ $2\text{-}6x10^{-10}$m).
- Molecules are always in motion, in all directions.
- Molecules do not exert forces on each others (unless they collide).

Basic gas properties

- Gases have various properties: pressure (p), Temperature (T), mass (m), particle number (N), and volume (V).

  - Avogadro's constant: $N_A = 6.022142 \times 10^{23}\, mole^{-1}$
  - Mass density [kg.m^{-3}]: $\rho = \frac{m}{V}$
  - Number density [m^{-3}]: $n = \frac{N}{V}$
  - Amount of substance : $\nu = \frac{N}{N_A}$
  - Molar mass [kg.mol^{-1}]: $M = \frac{m}{\nu}$

Gas laws

- For an ideal gas, if gas in state 1 then it can change into state 2 as follow:
- Boyle-Mariotte's law (p vs. V):

$$p_1.V_1 = p_2.V_2 = constant \text{ .... (for fixed: T, N)}$$

- Charles' law (V vs. T):

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = constant \quad \text{.............(for fixed: p, N)}$$

- Gay Lussac's law (p vs. T):

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} = constant \quad \text{.............(for fixed: V, N)}$$

- Avogadro's Law (V vs. N):

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Gas laws

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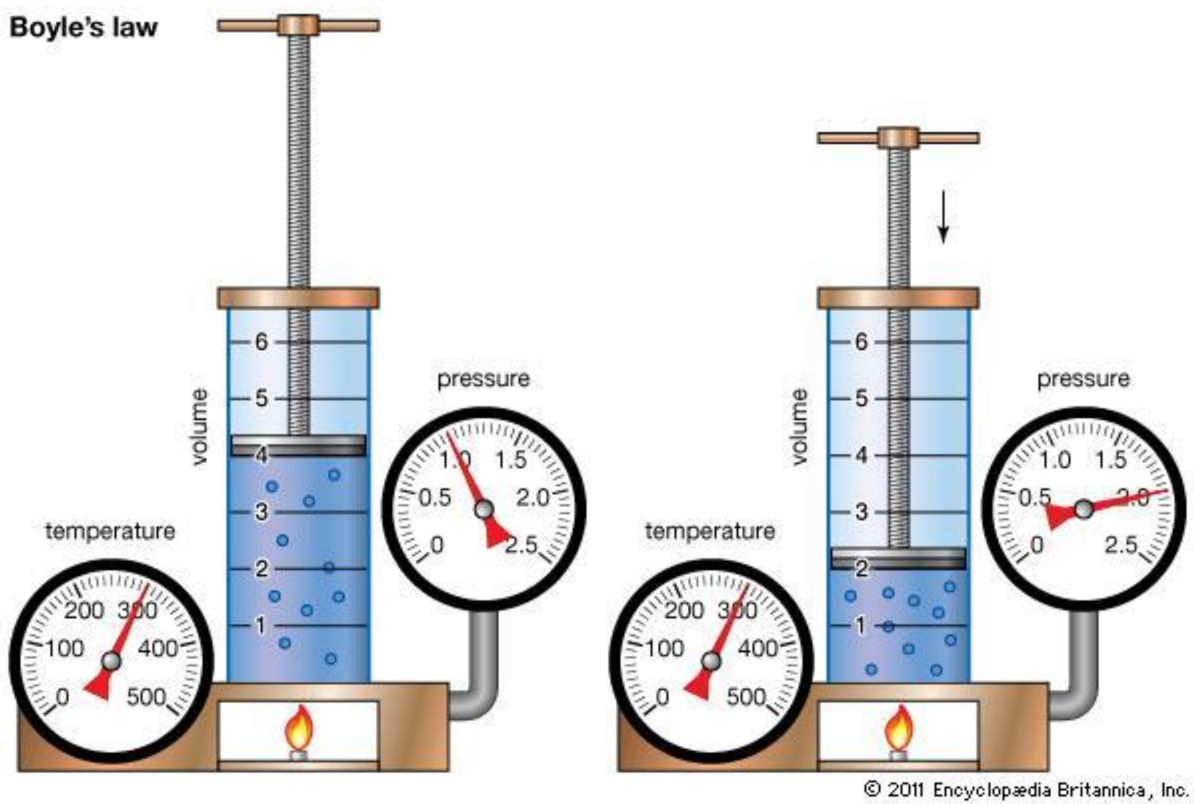
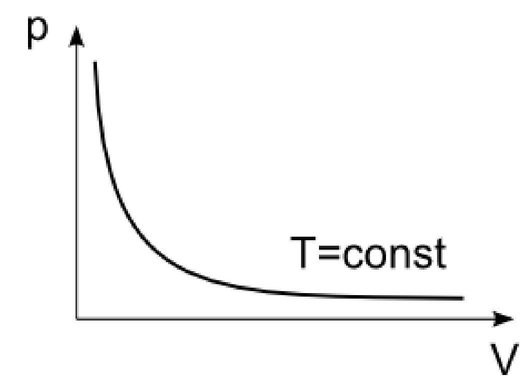
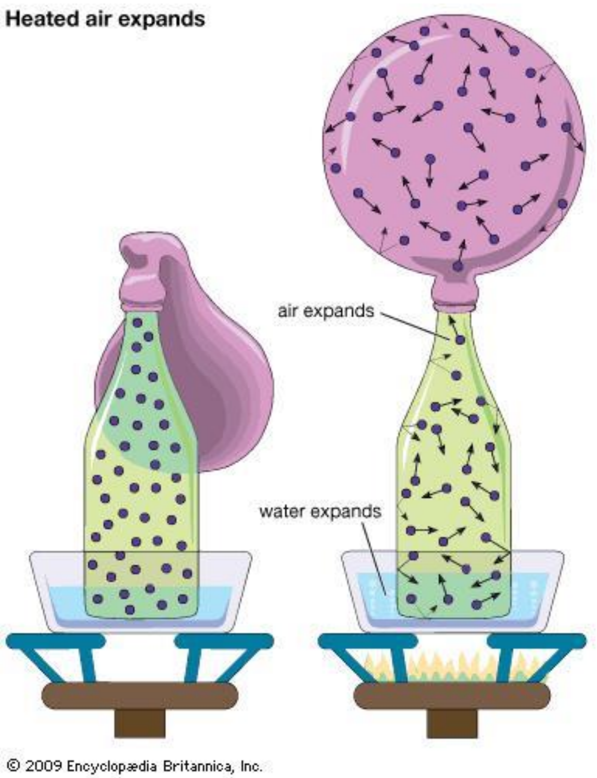


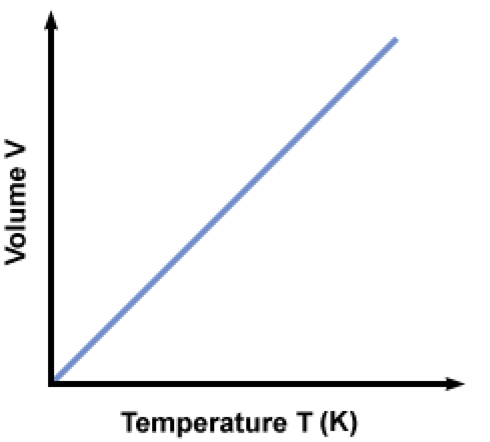


Gas laws

- Charles's law (V vs. T):

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = constant \qquad \text{………….(for fixed: p, N)}$$

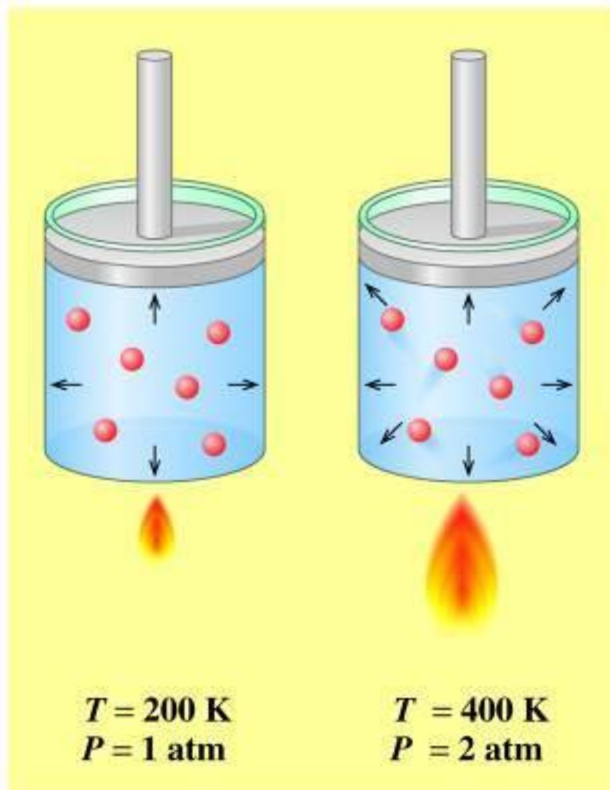


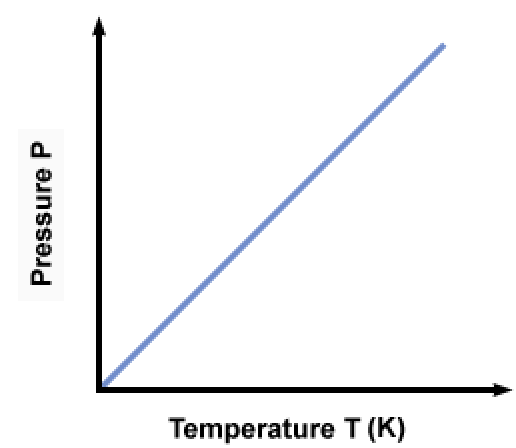


Gas laws

- Gay Lussac's law (p vs. T):

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} = constant$$ ....(for fixed: V, N)

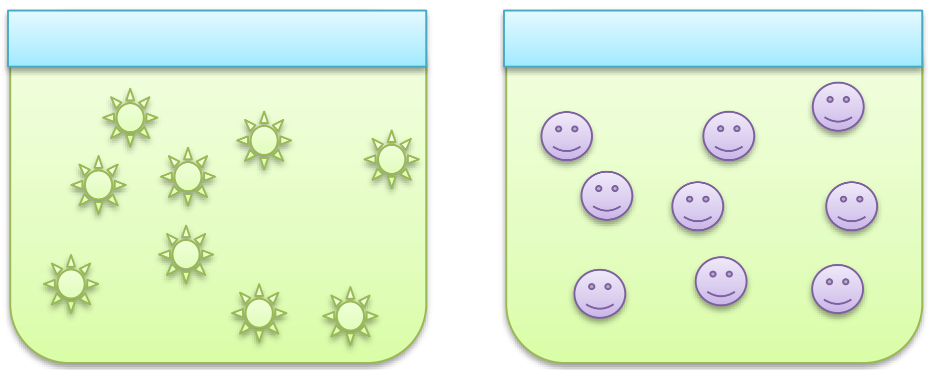




Gas laws

- Avogadro's Law (V vs. N):

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} = constant$$ ....(for fixed: T, p)



Two containers with the same volume at the same temperature and pressure should have the same number of particles.

Gas laws

- Ideal gas law: $$\frac{p.V}{T} = constant$$
- The constant is proportional to the amount of gas:
  - When amount of gas is represented by mass (m):

$$p.V = m.Rs.T \qquad R_s = \frac{R}{M}$$

  - When amount of gas is represented by particle number (N):

$$p.V = N.k.T$$

  - When amount of gas is represented by number density (n):

$$p = n.k.T$$

  - When amount of gas is represented by amount of substance (ν):

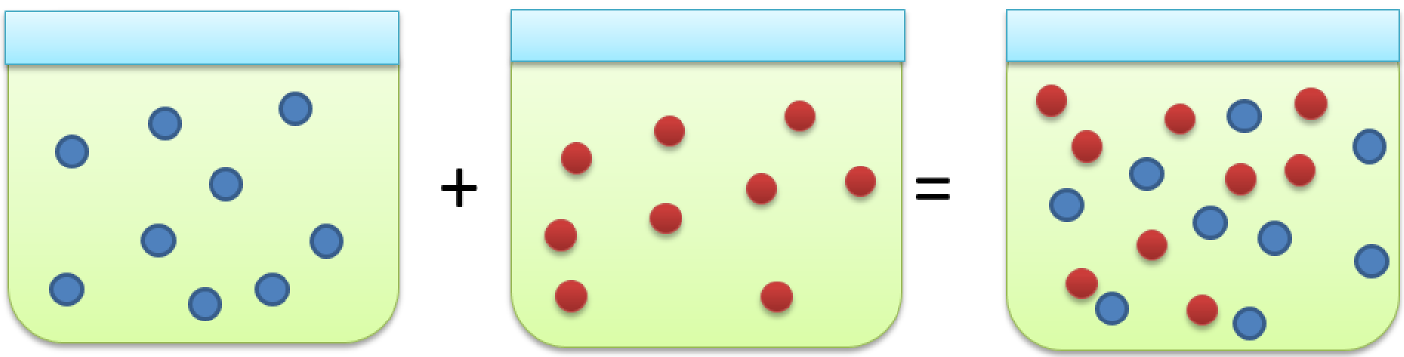
$$p.V = \nu.R.T$$

K=Boltzmann constant [$J.K^{-1}$]	1.3806×10^{-23}
R = Gas constant [$J.K^{-1}.mol^{-1}$]	8.314

Gas laws

- <u>Dalton's Law:</u> total pressure of a gas mixture is the sum of the partial pressure of the individual components:

$$p = p_1 + p_2 + p_3 + \ldots + p_i = \sum p_i$$



Nitrogen at 1 mbar   Oxygen at 2 mbar   Nitrogen and oxygen at 3 mbar

Using ideal gas law:

$$p_{total} = (n_1 + n_2 + \cdots + n_n).\mathrm{k}.\mathrm{T}$$

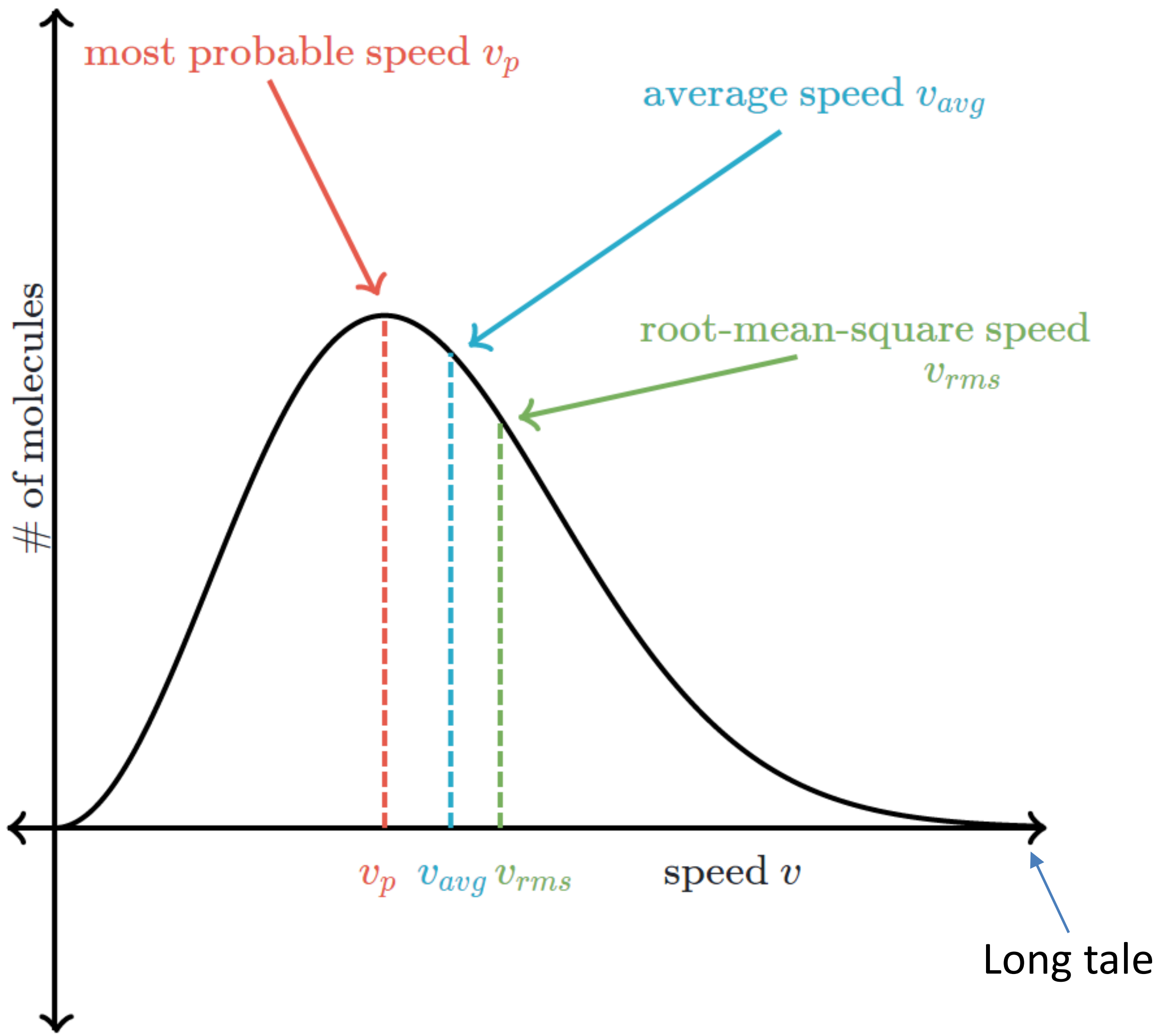
Velocity of gas molecule

- When gas molecules collide with each other or with the wall, their velocity value and direction change.
- Maxwell-Boltzmann velocity distribution:

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

V: velocity of molecules (m/s)
n: number of molecules with v between v and v + dv
N: the total number of molecules
m: mass of molecules (kg)
K: Boltzmann constant, $1.3806503\times10^{-23}\ m^2\ kg\ s^{-2}\ K^{-1}$
T: temperature (K)

Velocity of gas molecule

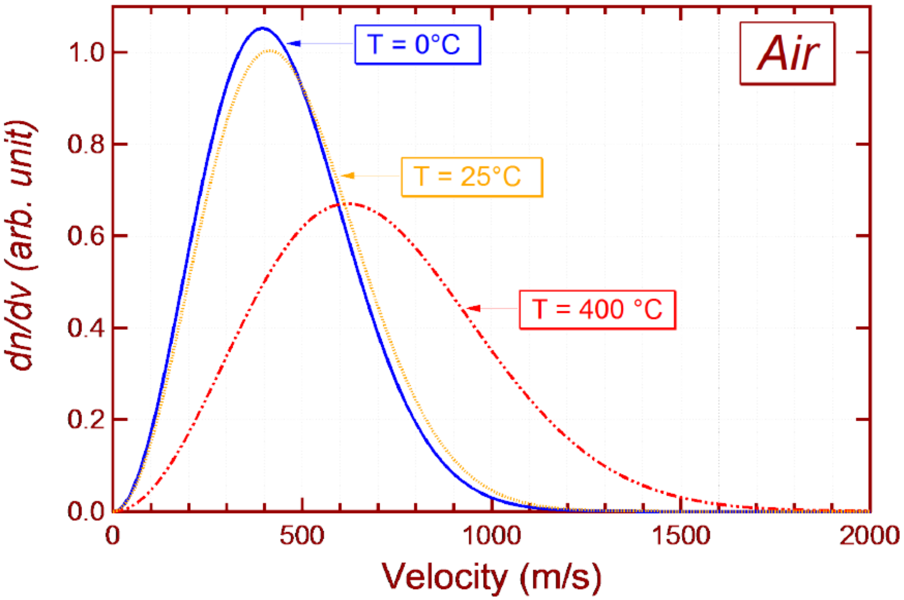


$$v_{max} = \sqrt{\frac{2kT}{m}}$$

$$v_{avg} = \sqrt{\frac{8kT}{\pi m}}$$

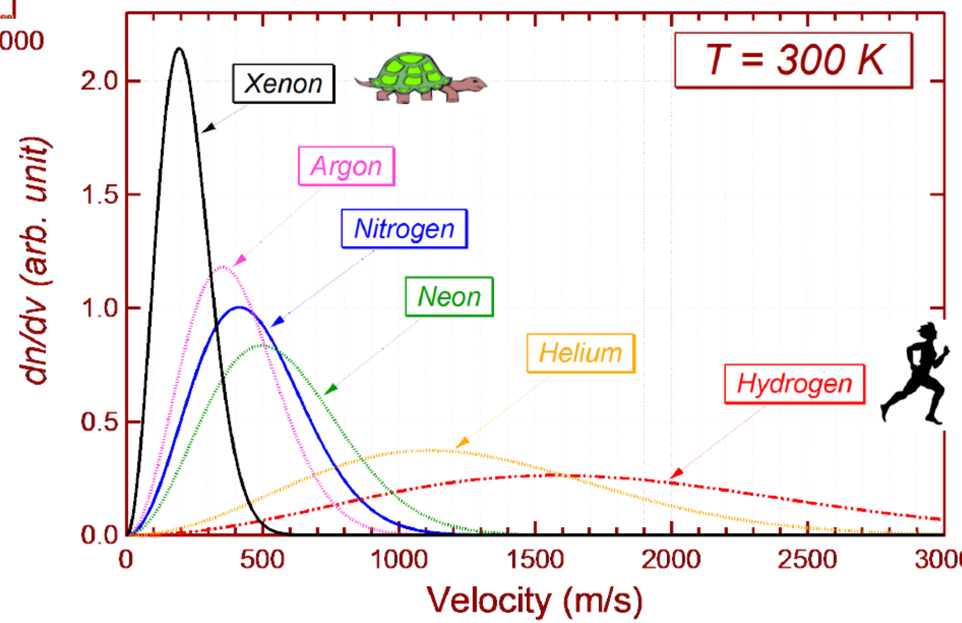
$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

Velocity of gas molecule



Velocity depends on temperature.

Velocity depends on mass

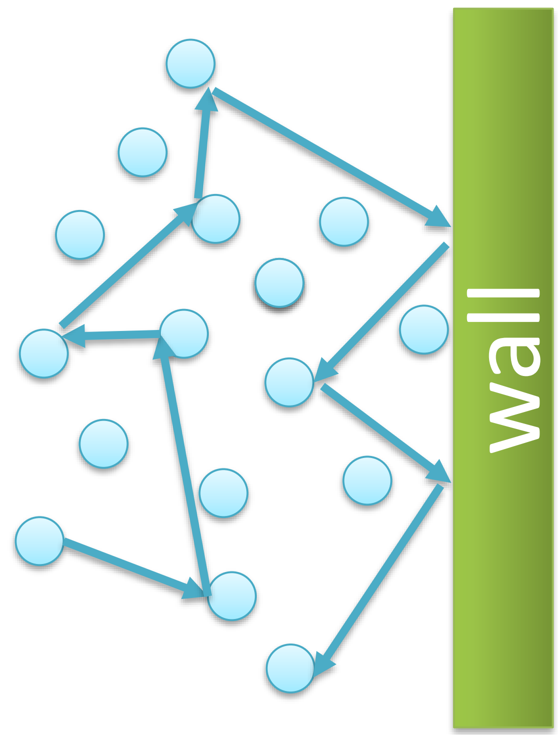


Yulin Li, Cornell University

Mean free path

The mean free path is the average distance that a particle can travel between two successive collisions with other particles or the walls.

$$\lambda = \frac{kT}{\sqrt{2}.\pi d^2.p}$$



- λ :*mean free path (m)*
- *d: diameter of molecule (m)*
- *T - Temperature (K)*
- *P - Pressure (Pascal)*
- *k - Boltzmann constant,* 1.38×10^{-23} m^2 kg s^{-2} K^{-1}

For air at 20°C:

$$\lambda(cm) = \frac{0.007}{p(mbar)}$$

P (mbar)	1.0E+03	1.0E+00	1.0E-03	1.0E-06	1.0E-09
λ (cm)	0.000007	0.007	7	7000	7000000

The impingement rate and time for monolayer formation

- The impingement rate is number of molecules striking unit surface per unit time.

$$Z_A = \frac{2.635 \times 10^{22} . p}{\sqrt{TM}}$$

Z_A - impingement rate (molc/cm^{-2}.s)
p – pressure (mbar)
T – temperature (K)
M – molar mass (g/mol)

- The time for monolayer formation: is the time required for a freshly-formed surface to become covered with a monolayer of gas molecules

$$\tau = \frac{n_{mono}}{Z_A}$$

τ monolayer time formation (s)
n_{mono} number of molecules per unit area (around 10^{19} molec/m^2)

p	Pa	100	0.1	10^{-5}	10^{-7}	10^{-9}
	mbar	1	10^{-3}	10^{-7}	10^{-9}	10^{-11}
t_{mono} (air)		$3.6 \cdot 10^{-6}$ s	$3.6 \cdot 10^{-3}$ s	36 s	1 h	100 h
t_{mono} (H_2O)		$2.8 \cdot 10^{-6}$ s	$2.8 \cdot 10^{-3}$ s	28 s	47 min	78 h
t_{mono} (H_2)		$9.3 \cdot 10^{-7}$ s	$9.3 \cdot 10^{-4}$ s	9.3 s	16 min	26 h

for air at room temperture:

$$\tau = \frac{3.2 \times 10^{-6}}{p}$$

Properties summary

	Pressure				
	10^5 Pa 10^3 mbar	10^2 Pa 10^0 mbar	10^{-1} Pa 10^{-3} mbar	10^{-4} Pa 10^{-6} mbar	10^{-7} Pa 10^{-9} mbar
Particle Density, n (cm^{-3})	10^{19}	10^{16}	10^{13}	10^{10}	10^7
Mean Free Path, λ (cm)	10^{-5}	10^{-2}	10	10^4	10^7 (≈ 100 km)
Impingement Rate, Z_A (s^{-1} cm^{-2})	10^{23}	10^{20}	10^{17}	10^{14}	10^{11}
Collision Rate, Z_V (s^{-1} cm^{-3})	10^{29}	10^{23}	10^{17}	10^{11}	10^5
Monolayer Time, τ	10 ns	10 µs	10 ms	10 s	3 h

Gas flow, conductance and pumping speed

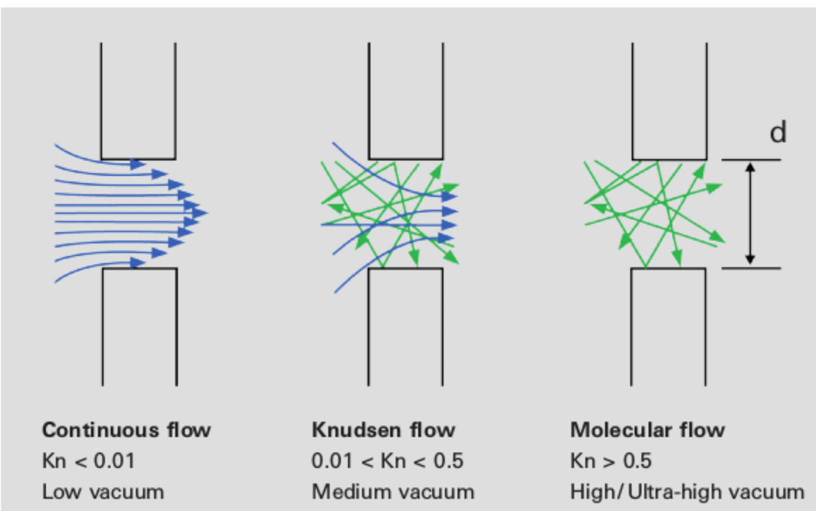
Gas flow

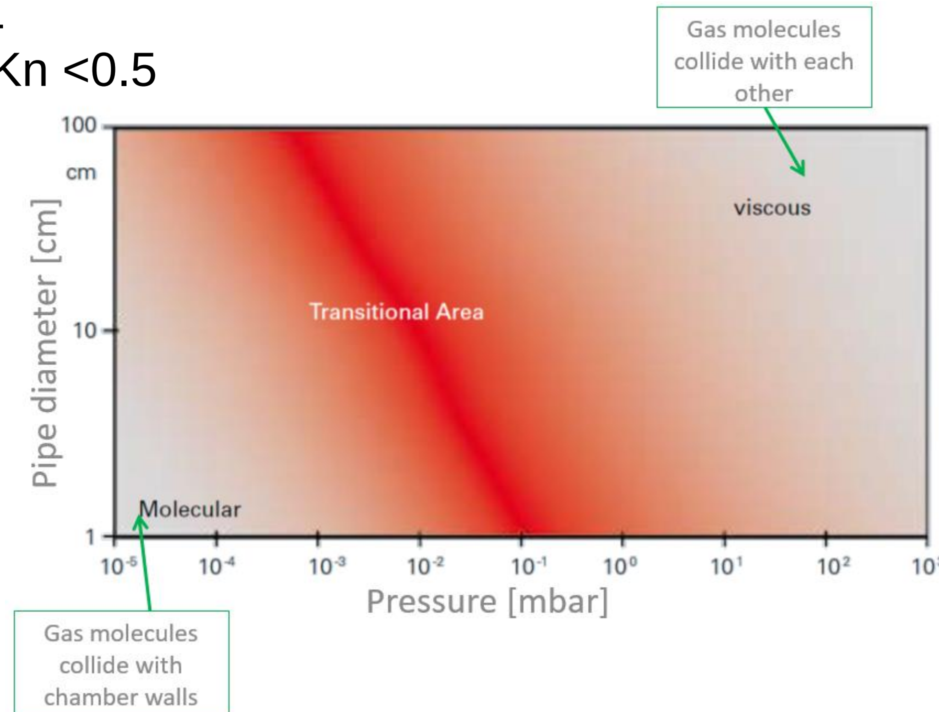
- Knudsen number characterizes the type of gas flow:

$$Kn = \frac{\lambda}{d}$$

d: is the characteristics of the vessel (e.g. chamber diameter))

- Three flow regime:
  - Viscous (continuous) : Kn <0.01
  - Intermediate (Knudsen): 0.01< Kn <0.5
  - Molecular: kn>0.5





Vacuum Technology Know how by Pfeiffer Vacuum GmbH

Gas flow

The flow rate of gas is defined as the transported gas per unit time, the amount of gas can be described as follow:

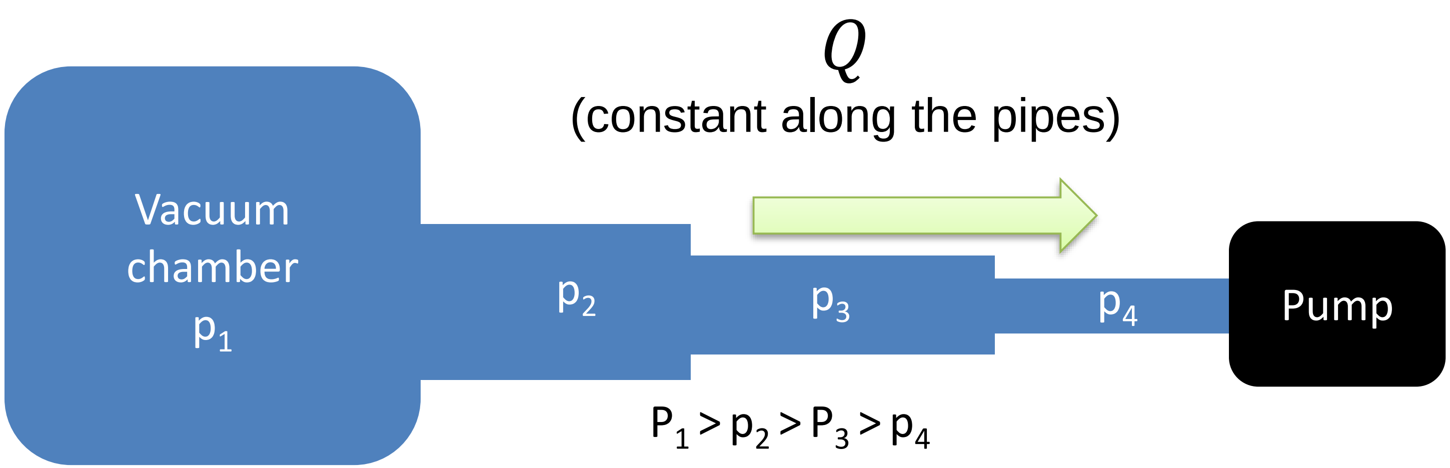
- Volume flow rate: $q_V = \frac{\Delta V}{\Delta t} = \dot{V}$ $[q_V] =$m$^3\cdot$s^{-1}
- Mass flow rate: $q_m = \frac{\Delta m}{\Delta t} = \dot{m}$ $[q_m] =$kg.s^{-1}
- Molar flow rate: $q_\nu = \frac{\Delta \nu}{\Delta t} = \dot{\nu}$ $[q_\nu] =$mol.s^{-1}
- Particle flow rate: $q_N = \frac{\Delta N}{\Delta t} = \dot{N}$ $[q_N] =$s^{-1}

Throughput (Q)

- The flow rate as defined earlier could change along the tube, for example at the exit of the flow rate is higher than the beginning as the pressure drops along the tube end.
- Throughput or pV flow:

$$Q = q_{pV} = p.\dot{V}$$

$$[Q] = \text{mbar.}\,\text{l}\cdot\text{s}^{-1}$$



Pumping speed (S)

- Pumping speed (S): the gas volume flowing through the pump inlet per unit time.

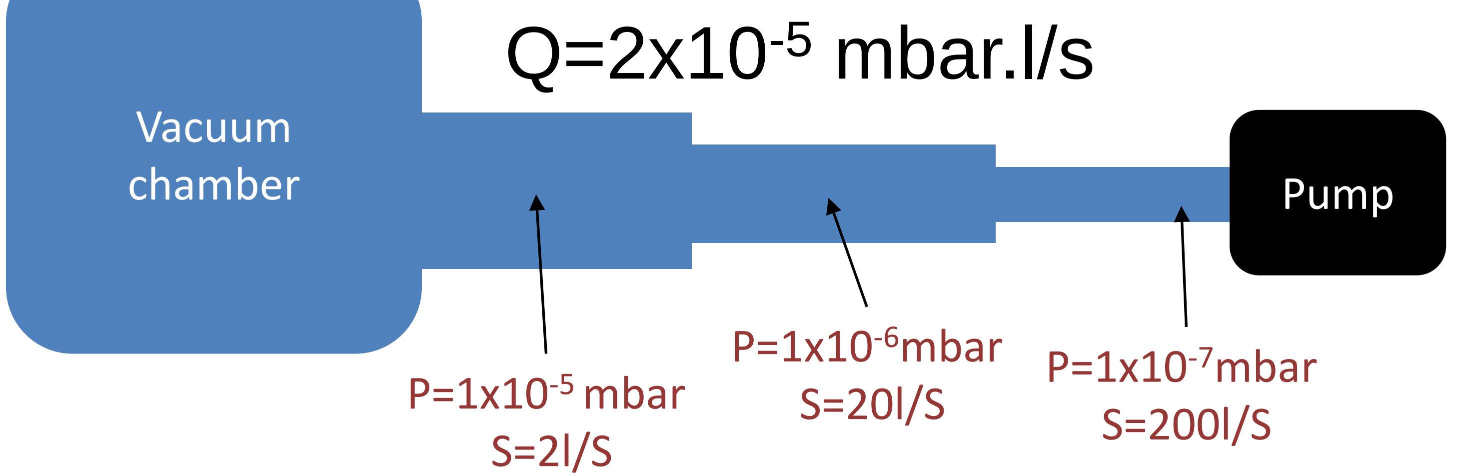
$$S = \dot{V}_{inlet} = q_{V,inlet} \qquad [S]=l/s$$

- The pumping speed relation with the throughput at the entrance of the pump is:

$$\boxed{Q = p.S}$$

Example:

S : varies along the pipes

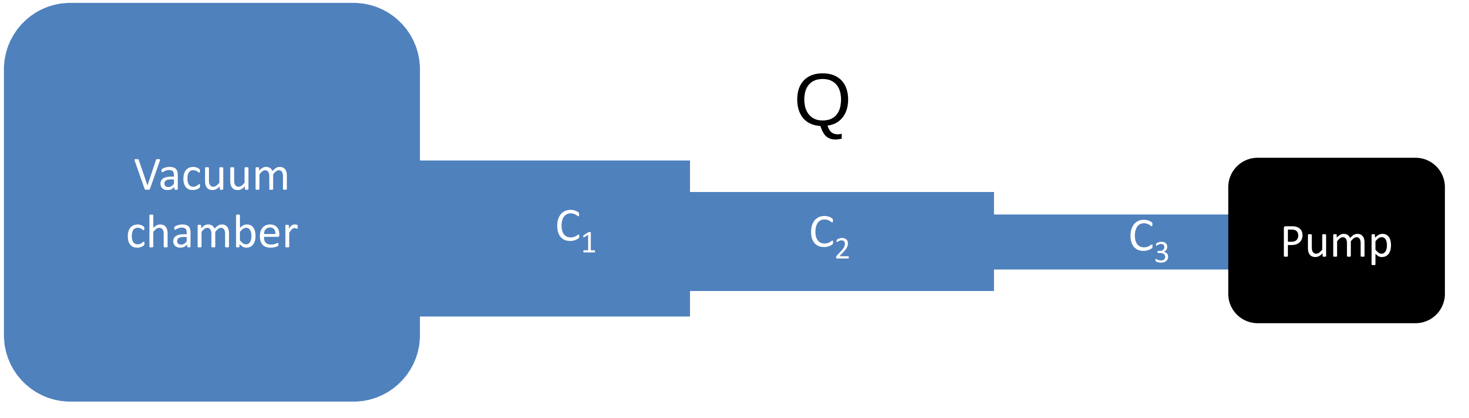


Conductance (C)

- Impedance (Z): the gas flow through a pipe with resistance know as impedance (Z).
- The reciprocal of the impedance is the conductance C [l/s].

$$Q = \frac{(p_1 - p_2)}{Z} = \frac{\Delta p}{Z} = C.\Delta p$$

- C depends on the temperature, molecules, geometry and pressure (in the viscous regime).



Total conductance

- **<u>In series:</u>**

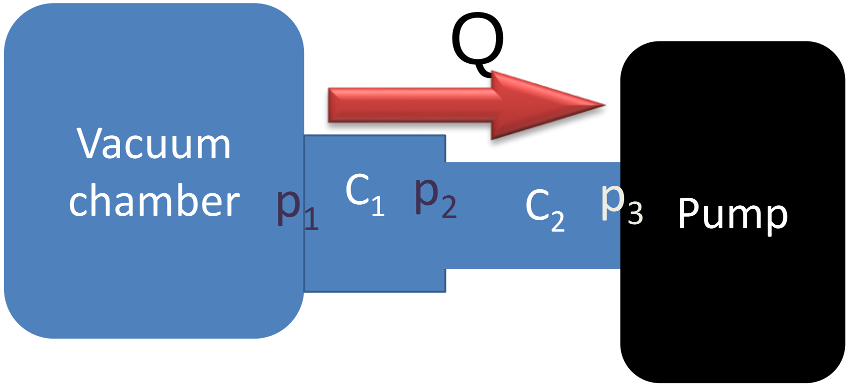
$$Q_1 = C_1.(p_1 - p_2)$$

$$Q_2 = C_2.(p_2 - p_3)$$

$$Q_1 = Q_2 = Q = C_{total}(p_1 - p_3)$$

$$p_1 - p_2 = \frac{Q}{C_1} \quad and \quad p_2 - p_3 = \frac{Q}{C_2}$$

$$p_1 - p_3 = \frac{Q}{C_{total}} = \frac{Q}{C_1} + p_2 + \frac{Q}{C_2} - p_2 = Q\left(\frac{1}{C_1} + \frac{1}{C_2}\right)$$

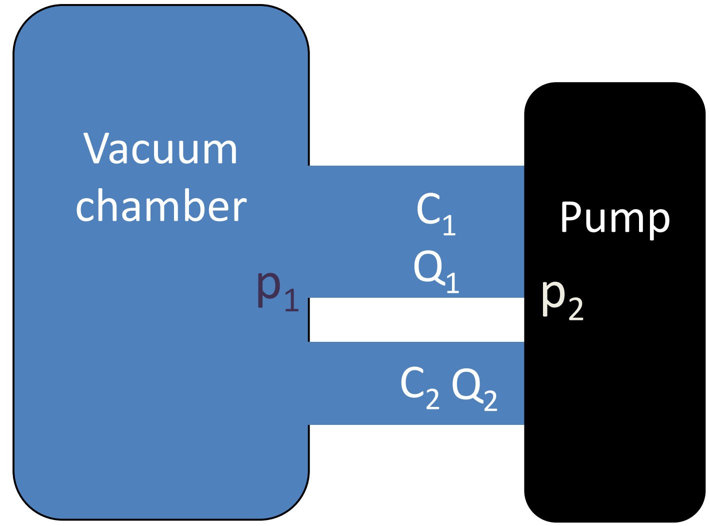


$$\boxed{\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} = \sum_{i}^{N} \frac{1}{C_i}}$$

Conductance in molecular flow

Total conductance

- <u>In parallel</u>
- $Q_1 = C_1 . (p_1 - p_2)$
- $Q_2 = C_2 . (p_1 - p_2)$



- $Q_{total} = Q_1 + Q_2 = C_{total}\ (p_1 - p_2)$
- $Q_{total} = C_{total}\ (p_1 - p_2) = C_1 . (p_1 - p_2) + C_2 . (p_1 - p_2)$

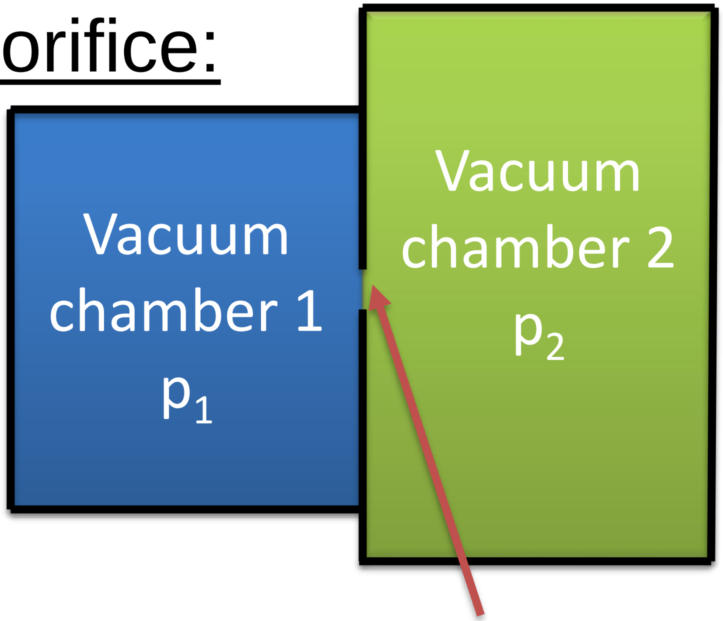
$$\boxed{\boldsymbol{C_{total} = C_1 + C_2 = \sum_{i}^{N} C_i}}$$

Examples of conductance (molecular flow)

Conductance of a thin orifice:

$$C = 3.64 \times A \times \sqrt{\frac{T}{M}}$$

[T]= K, M= molecular weight



Small thin orifice, cross section A

- For air at 20°C:

$$C = 11.6 \times A$$

Where:

[C]=l/s

[A]=cm^2

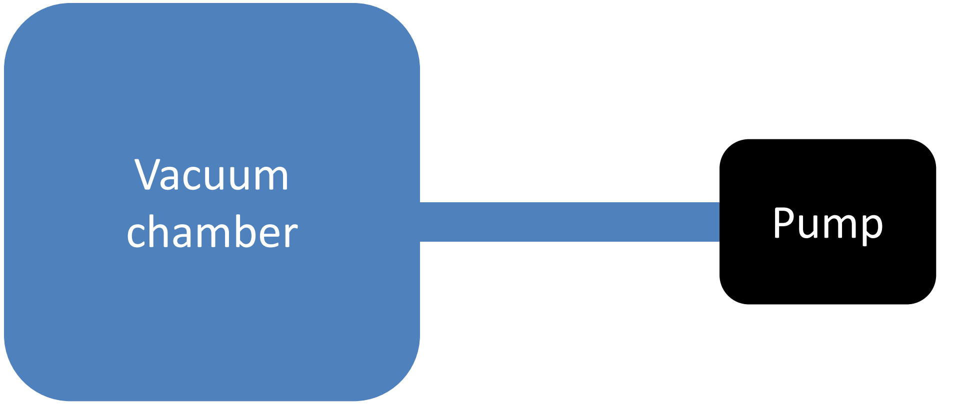
- If the thickness is not negligible, the conductance is

$$C = 11.6 \times A \times \alpha$$

Where α is the transmission factor

Conductance of long circular tube:

$$C = 3.81 \times \frac{d^3}{L}\sqrt{\frac{T}{M}}$$



- Where:

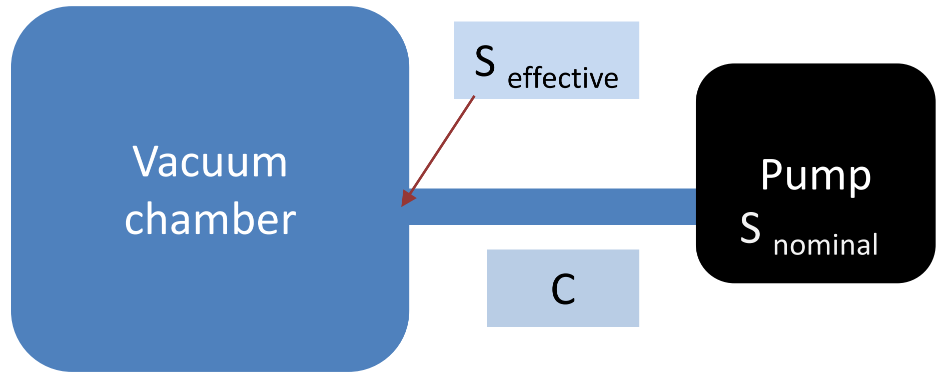
  [C]=l/s
  [d]=cm
  length [L]=cm

- For air at 20˚C:

$$C = 12.1 \times \frac{d^3}{L}$$

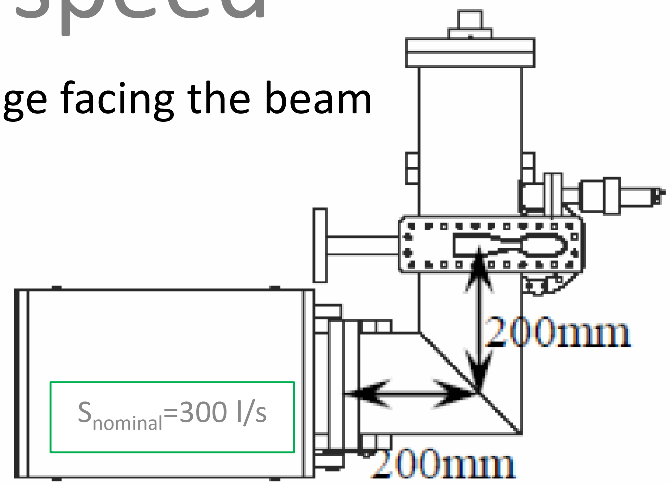
Effective pumping speed

The pumping speed at any given point is not larger than the smallest conductance between that point and the pump



$$\frac{1}{S_{effective}} = \frac{1}{C} + \frac{1}{S_{\ nominl}}$$

Effective pumping speed



What is the effective pumping speed for the pump at the flange facing the beam path.

Input:

$S_{nominal}$ for nitrogen=300l/s

CF150 elbow of ID=15.4 cm and length of 20x20 cm

Answer:

conductance of an orifice for nitrogen at room temp:

$$C = 11.8 \times A \times \alpha$$

$A = \pi . r^2 = \pi . 7.7^2 = 186 cm^2$ (assuming entrance is also circular)

Determine the transmission probability for a circular elbow:

$$\frac{b}{r} = \frac{a}{r} = \frac{20}{7.7} = 2.6 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \alpha \sim 0.3$$

$C = 11.8 \times A \times \alpha$=659l/s

$$\frac{1}{S_{effective}} = \frac{1}{C} + \frac{1}{S_{\ nominl}} = \frac{1}{659} + \frac{1}{300}$$

$$S_{effective} = 206\ l/S$$

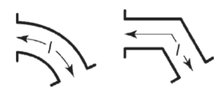


Figure 4.40 Axis length in a tube bend and a tube elbow.

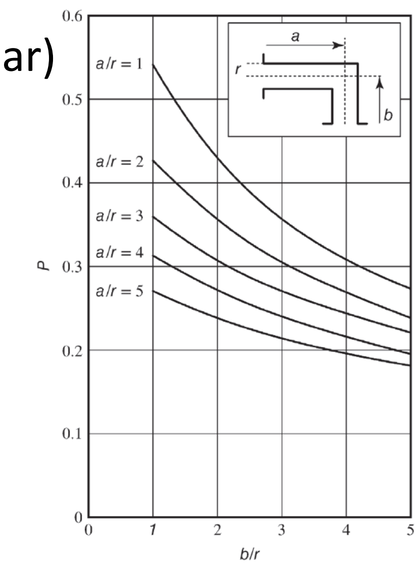


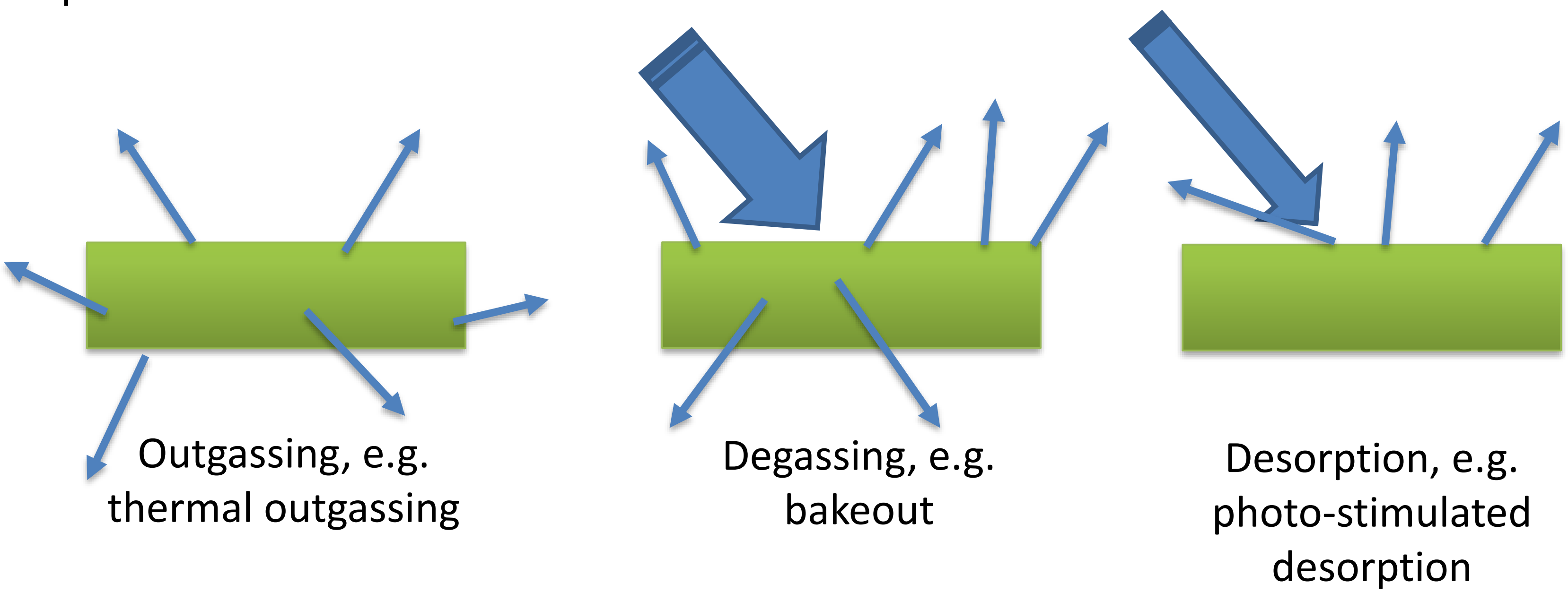
Figure 4.41 Transmission probabilities of 90° tube elbows with circular cross sections and selected dimensions. As in the previous figures, the transmission probabilities apply to a mounting position between two chambers but not to a position between tubes.

Handbook of Vacuum Technology, Karl Jousten

Introduction to the gas sources in accelerators.

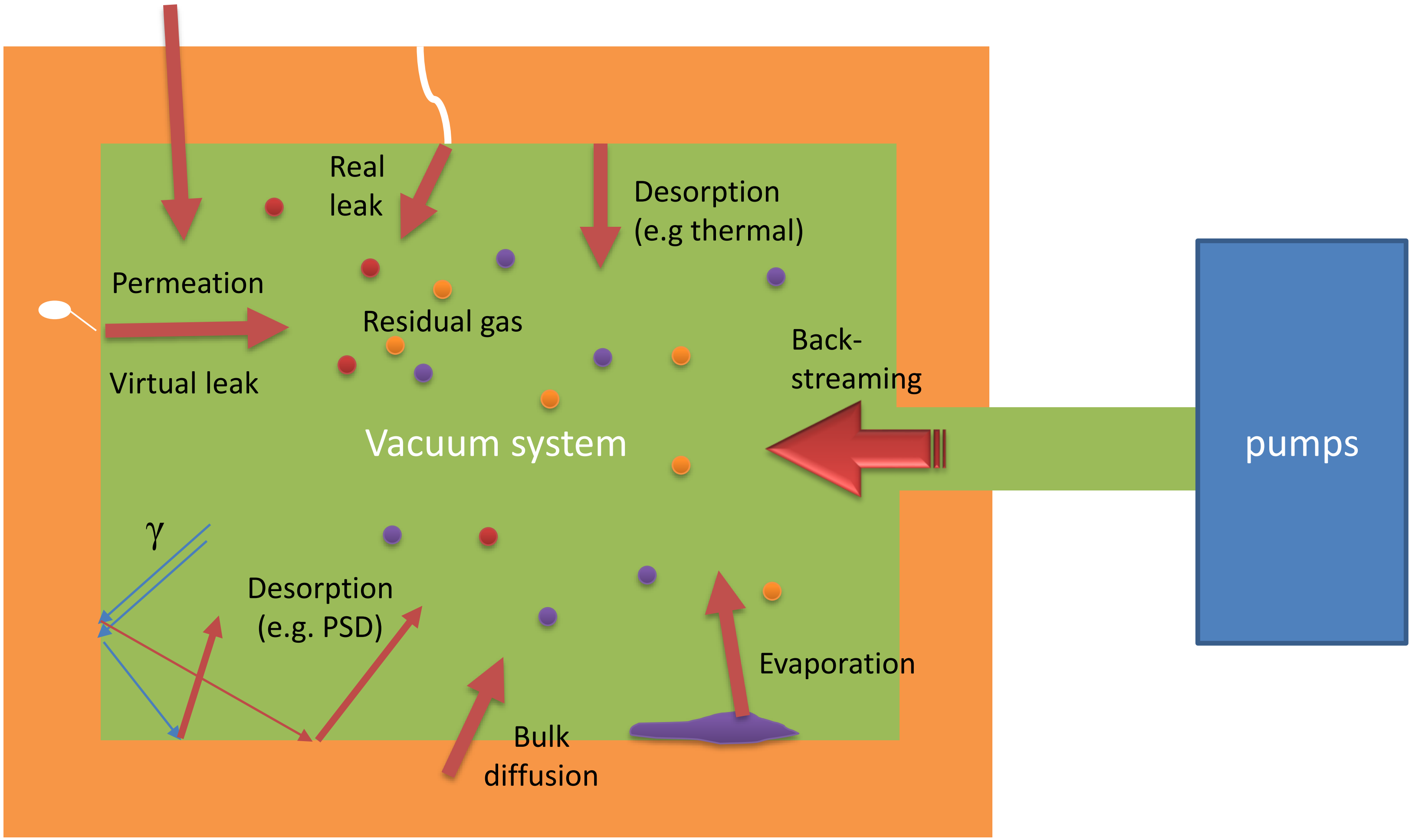
Gas sources

- Definitions:
  - Outgassing: spontaneous release of the gas from solid or liquid
  - Degassing: deliberate removal of the gas from solid or liquid
  - Desorption: release of adsorbed species from the surface of a solid or liquid.



Courtesy: Paolo Chiggiato JUAS

Gas sources

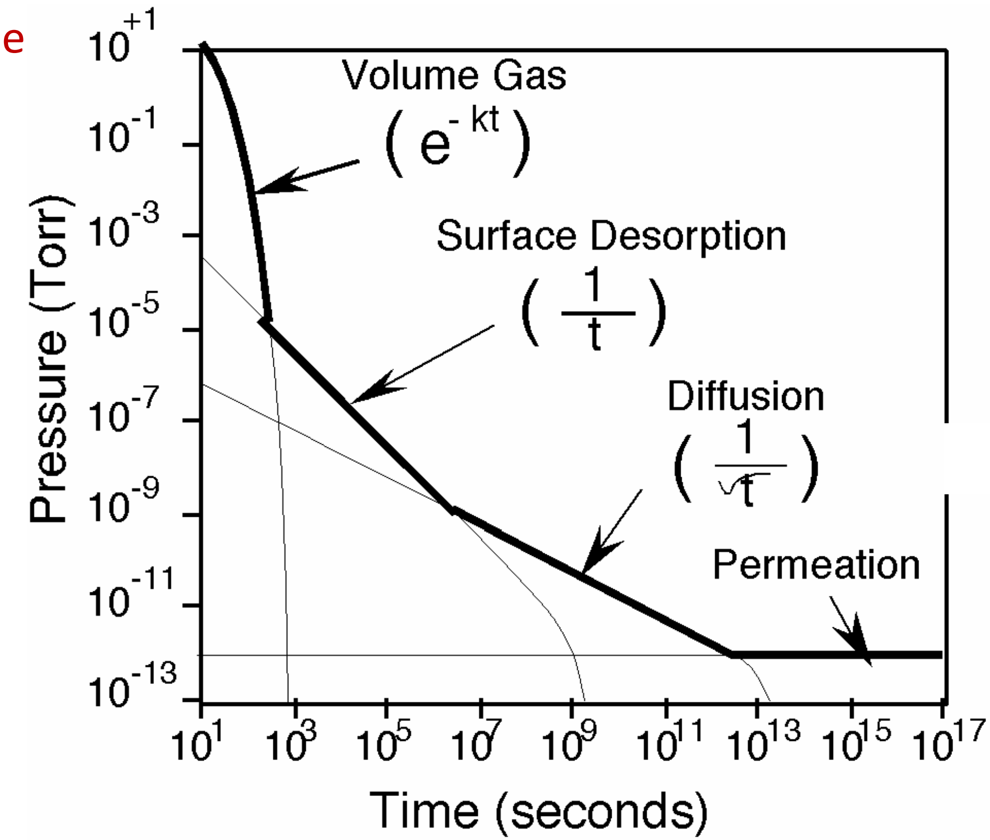


Permeation
Real leak
Desorption (e.g thermal)
Residual gas
Back-streaming
Virtual leak
Vacuum system
pumps
γ
Desorption (e.g. PSD)
Evaporation
Bulk diffusion

The ultimate pressure (p_u) is defined by the total outgassing (Q_{tot}) and the effective pumping speed (S_{eff}).

$$p_u = \frac{Q_{tot}}{S_{eff}}$$

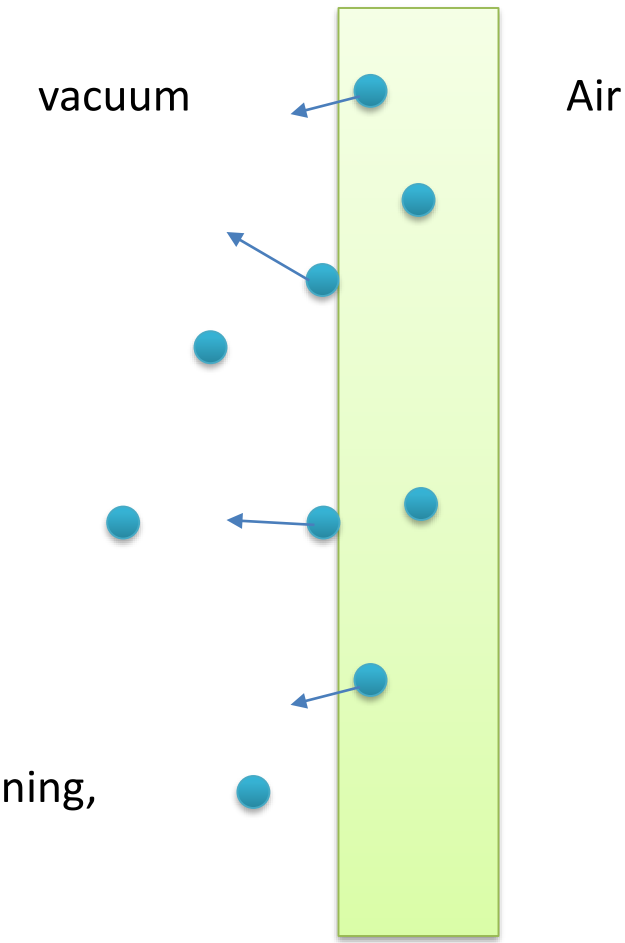
What process defines the pressure over time?



Gas sources in accelerators

Thermal outgassing occurs when:

- Molecules diffusing through the bulk material of a vacuum chamber, entering the surface and desorbing from it.
- Molecules which have been adsorbed previously, usually during venting of the vacuum chamber, that desorb again, when the chamber is pumped to vacuum



- Thermal outgassing depends on: material, cleaning, history, treatments, pump down time,… etc

Challenges in Vacuum Design of Particle Accelerators Oleg Malyshev

Gas sources in accelerators

Thermal outgassing: example of outgassing rates after one hour in vacuum at room temperature:

Material	K_1 (mbar l s^{-1} cm^{-2})
Aluminium (fresh)	9×10^{-9}
Aluminium (20 h at 100 ^{0}C)	5×10^{-14}
Stainless steel (304)	2×10^{-8}
Stainless steel (304, electropolished)	6×10^{-9}
Stainless steel (304, mechanically polished)	2×10^{-9}
Stainless steel (304, electropolished, 30 h at 250 ^{0}C)	4×10^{-12}
Perbunan	5×10^{-6}
Pyrex	1×10^{-8}
Teflon	8×10^{-8}
Viton A (fresh)	2×10^{-6}

Gas sources in accelerators

Beam induced desorption (BID): outgassing stimulated by photons, ion or electrons created by high energy, high intensity beams.

Beam stimulated desorption is characterised by η - the desorption yield:

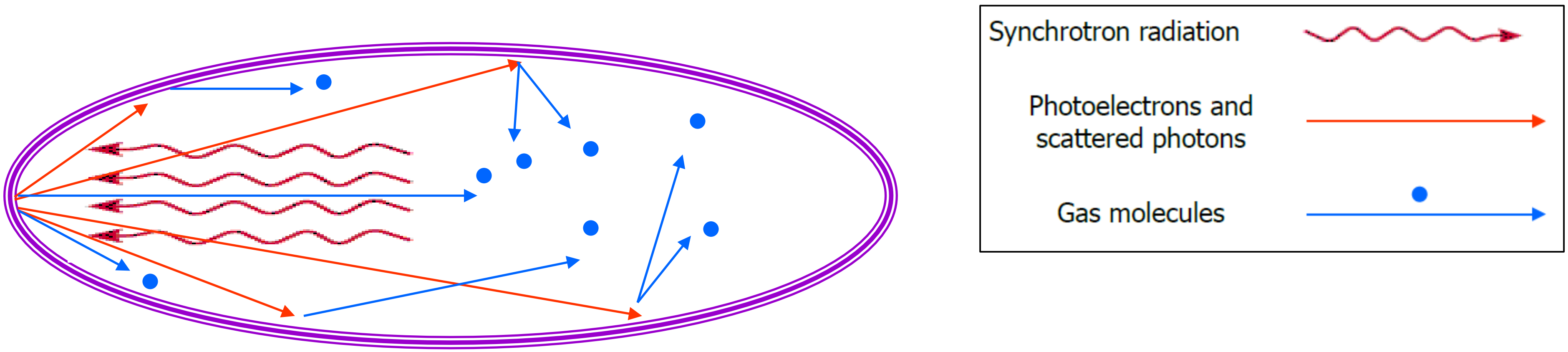
$$\eta = \frac{number\ of\ desorbed\ molecules}{number\ of\ particle\ impinging\ the\ surface}$$

η – depends on many parameters:

- incident particle: type and energy,
- material,
- surface roughness,
- cleanliness of the surface,
- history of the material.
- Temperature.
- Integrated dose
- Particle flux.

Gas sources in accelerators

Photon-stimulated desorption (PSD)



When photoelectrons arrive or leave the surface, they desorb the gases from the surface.

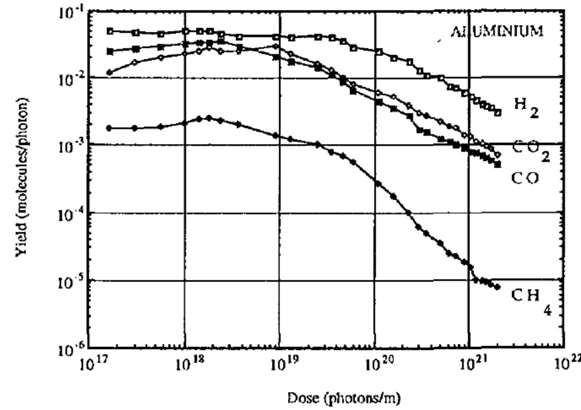
Photon-stimulated desorption (PSD)

Conditioning is the process of which reduction of the BID yield (η) with the accumulated dose (D_i) of the particles:

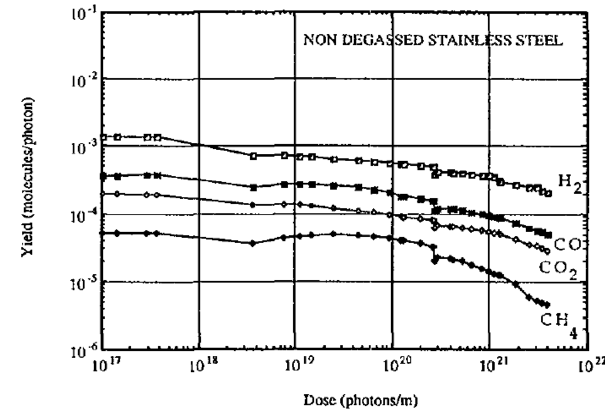
$$\eta = \eta_o D_i^{-\alpha}$$

Photon-stimulated desorption (PSD)

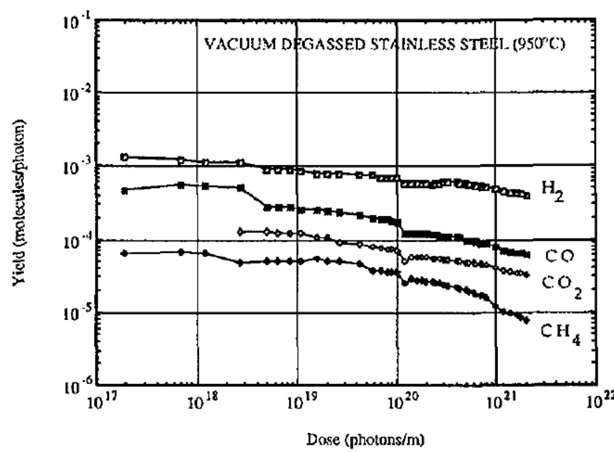
- Experiments were performed to measure the PSD yield and its evolution with the beam dose for various material, incident angle, beam energy...



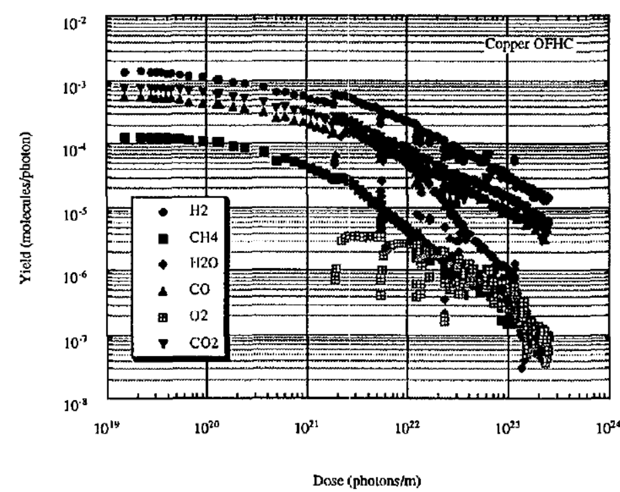
PSD yield vs. dose for Al after bakeout.



PSD yield vs. dose for st. steel after bakeout.



PSD yield vs. dose for fired st. steel



PSD yield vs. dose for OFHC copper after bakeout

C. Herbeaux et. al., J. Vac. Sci. Technology. 1999.

Type equation here.Photon-stimulated desorption (PSD)

Total photon flux $\dot{\Gamma}$ [photons/s] around electron storage ring:

$$\dot{\Gamma} = = 8.08.10^{17}.I.E$$

I – machine current [mA]

E – energy [GeV]

Outgassing (Q_{PSD}) due to PSD:

$$q_{PSD} = \eta\dot{\Gamma} \quad \text{->} \ \frac{molecules}{s}$$

$$Q_{PSD} = K\eta\dot{\Gamma} \quad \text{->} \ \frac{mbar\ l}{s}$$

K – converts number of molecules to pressure units 4.04x10^{-20} [mbar*l/molecule]

η – desorption yield

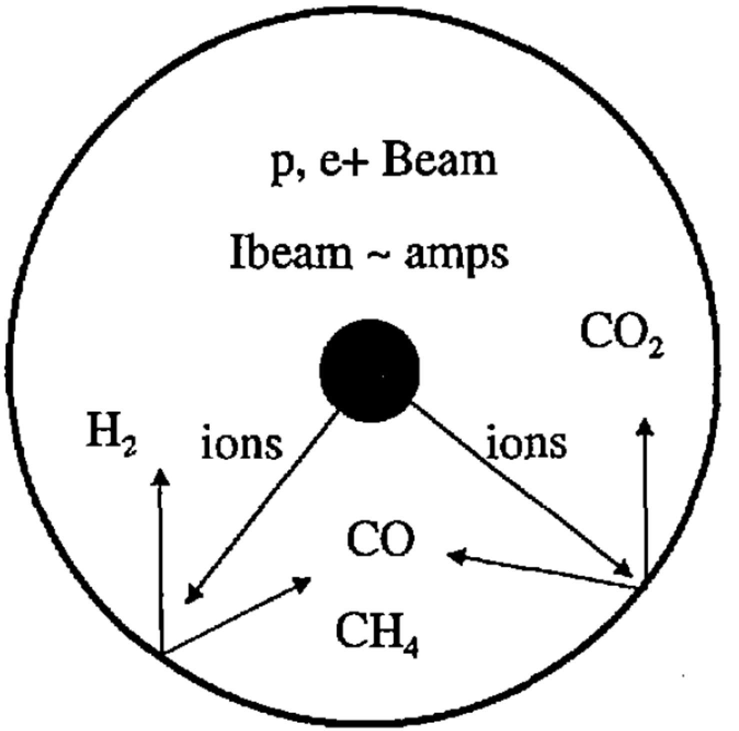
Knowing the gas load (outgassing) due to PSD (Q_{PSD}), thermal outgasing ($Q_{thermal}$) and the target pressure (P) the effective pumping speed S_{eff} can be calculated.

$$S_{eff} = \frac{Q_{PSD} + Q_{thermal}}{P}$$

Ion induced desorption:

In positively charged rings, the created ions from the residual gas are repelled from the positive beam to the walls.
Ions can gain energies which are effective in desorbing the molecules bounded to the chamber walls, as there is more gas more ionization occurs, resulting a continues increase in the pressure.

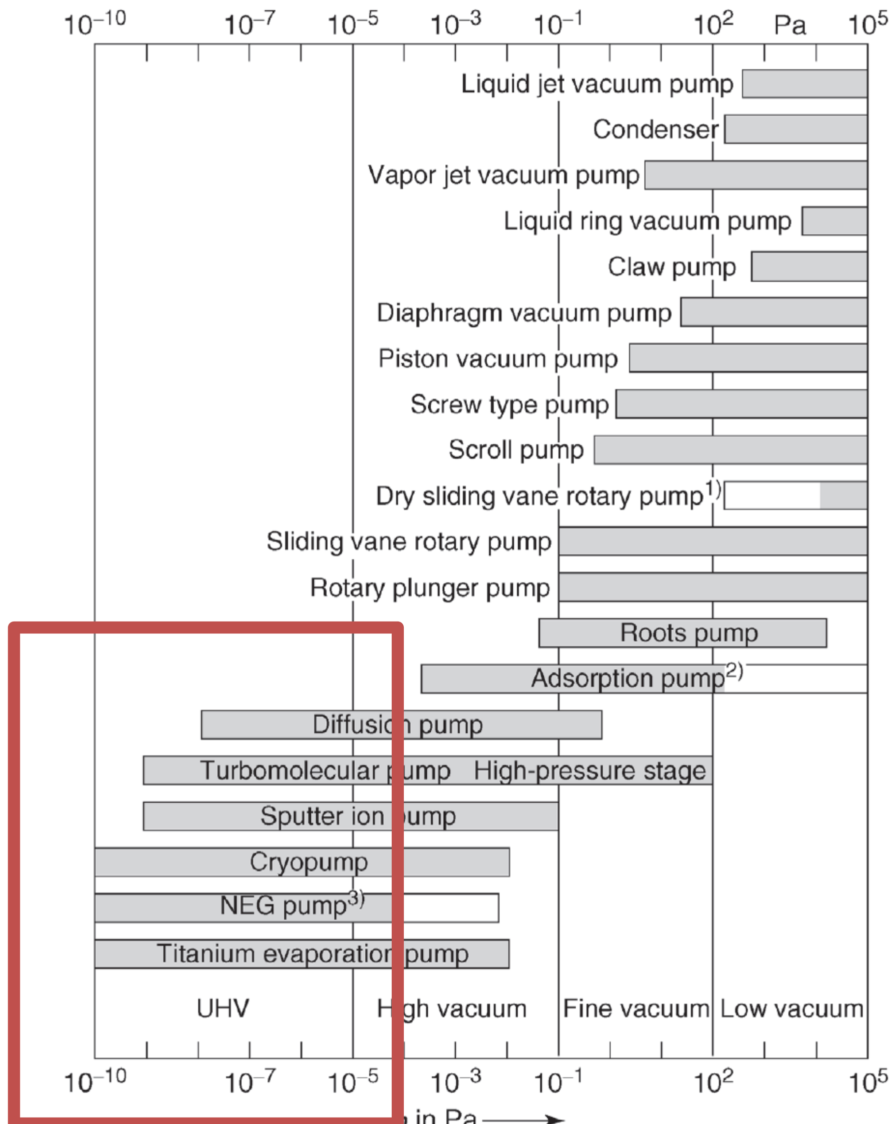
$$Q = \eta\sigma p\frac{I}{e} + Q_{thermal}$$



- η: the molecular desorption yield (molecules/ion).
- σ the ionization cross section of the residual gas molecules
- p: pressure
- I: average beam current
- e: the unit charge.
- $Q_{thermal}$: thermal outgassing

Gas removal in accelerators: pumping mechanisms in UHV

Gas removal in UHV



Handbook of Vacuum Technology *Karl Jousten*

Gas removal in UHV

Vacuum Pumps (molecular regime)

Momentum transfer pumps

Capture pumps

Example: Turbomolecular Pump

Gas is transmitted as momentum is transferred to the gas molecules thereby achieving a directed movement.

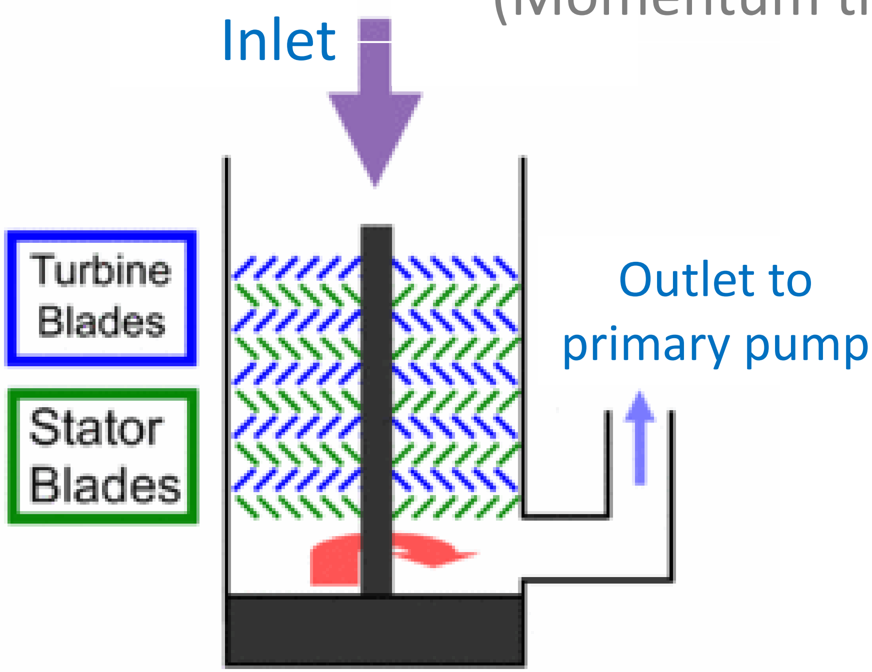
The momentum transfer take place through a quickly turning blades of a turning rotor.

Example: Sputter Ion Pump, Getter pump, Cryo pump

Principle: gas molecules are fixed to a surface inside the wall of the pump.

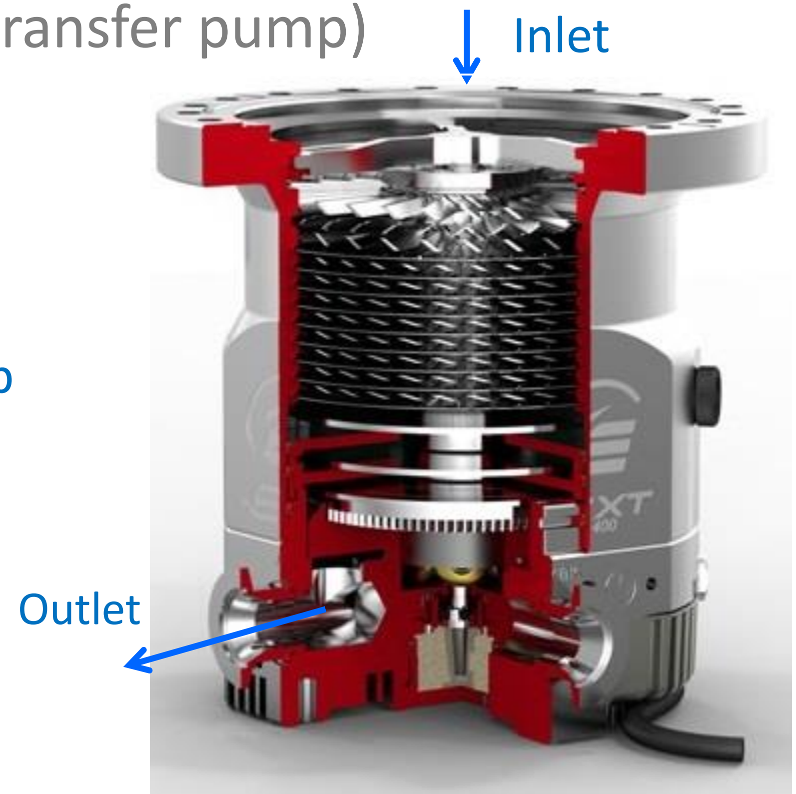
Turbomolecular Pump

(Momentum transfer pump)



Blade rotational speed 1000 – 1500 Hz

Pressure range: 10^{-1} till 10^{-10} mbar,
(with backing pump connected in series).
Usual operational pressure < 10^{-5} mbar.



S (pumping speed) does not depend significantly on the mass of the molecule.

(compression ratio)

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

depends exponentially on the wall speed and square root of the gas molecule mass.

'Fundamentals of vacuum technology' (Leybold)

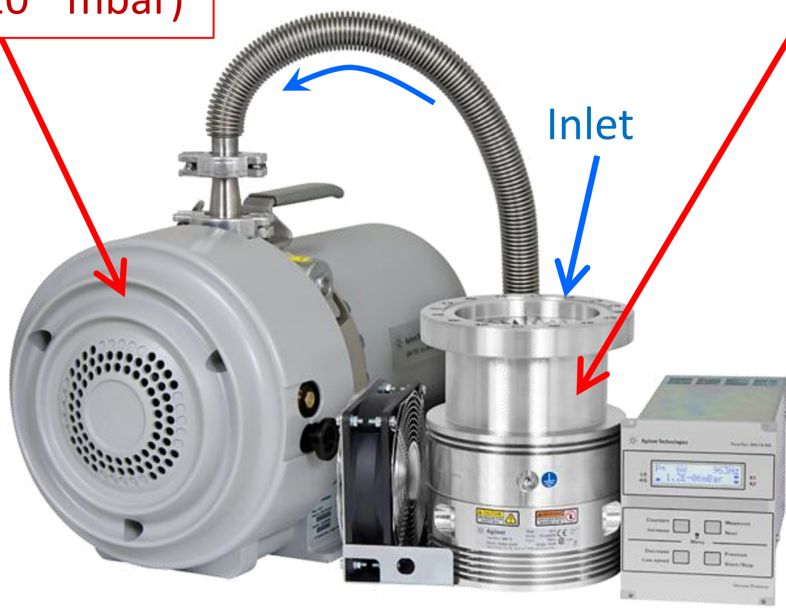
Turbomolecular Pump

Roughing pump (operating range: 1 bar to 10^{-3} mbar)

Outlet to primary pump

Turbo Molecular Pump (range: 10^{-1} to 10^{-10} mbar)

Inlet



Turbo molecular and roughing pump connected in series: from 1 bar (atmospheric pressure) until ~10^{-10} mbar

Turbomolecular pumping speeds: 10 l/s - 25,000 l/s.

Turbomolecular pumps are widely used in particle accelerators for:

- evacuating vacuum systems from atmospheric to ultra high vacuum,
- Testing (leak tests),
- Conditioning (bakeouts),
- High gas loads,
- For accelerator operation with beam capture pumps take over,

'Fundamentals of vacuum technology' (Leybold)

Capture pumps: getters

Capture pumps are vacuum pump in which the molecules are retained by sorption; chemical combination or condensation on internal surfaces within the pump. store gases that are pumped

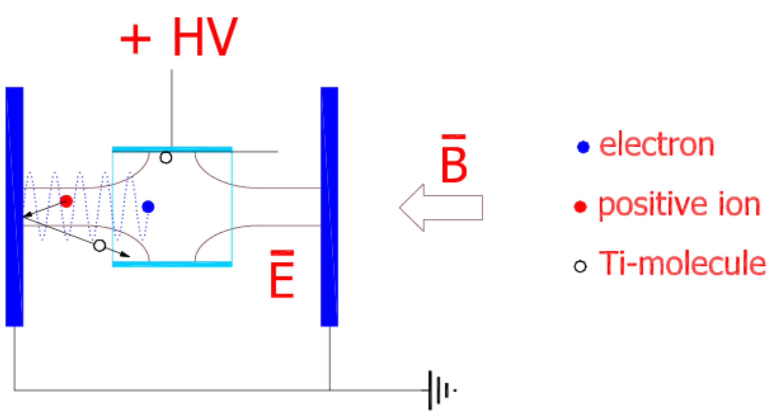
- Sputter ion pumps.
- sublimating the reactive metal *in situ:* evaporable getters or sublimation pumps,

- dissolving the surface contamination into the bulk of the getter material by heating: non-evaporable getters (NEG); the dissolution process is called activation.

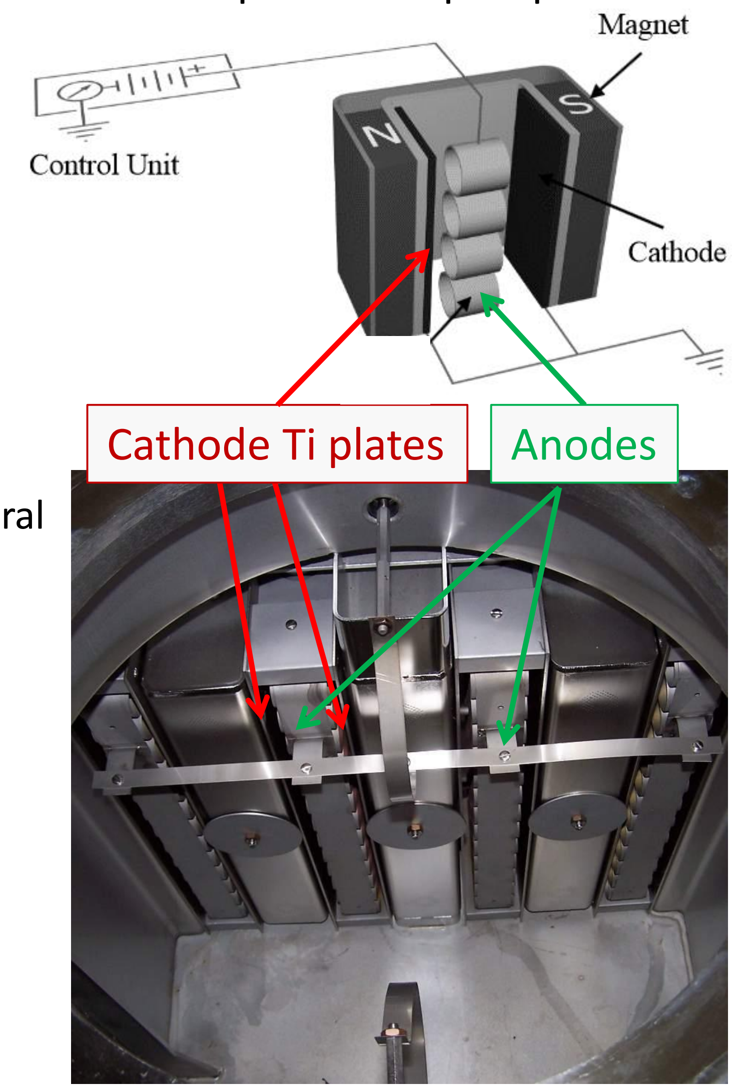
Paolo Chiggiato, Vacuum Technology for particle accelerators, 2013

Capture pumps: sputter ion pumps (SIP)

Penning cell



Sputter ion pump



- The high magnetic field cause the electrons to go into spiral paths (preventing them from reaching to the anode).
- While this the electrons strike the molecules and ionize them.
- Ions forced toward the cathode at high velocity.
- Ions strike the cathode and impact case sputtering of the cathode material.
- The cathode material will cover the internal walls of the pump.
- The ions are chemically and physically reacts with the cathode material.

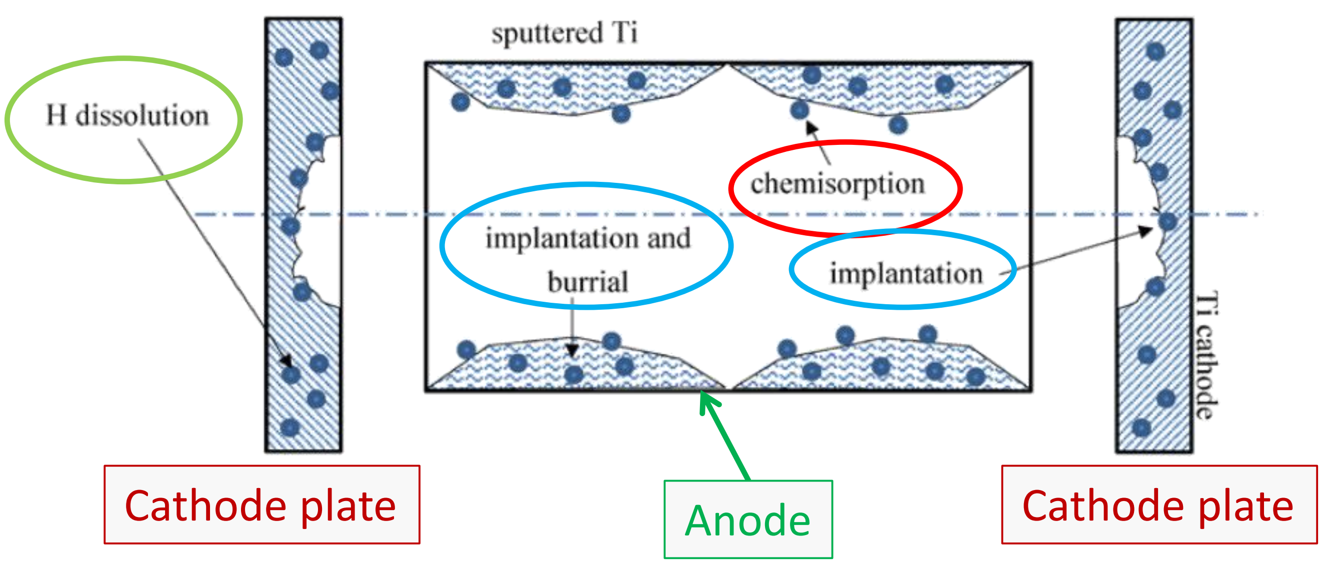
L. Schulz, Sputter ion pumps, CAS 1999 proceedings

Sputter ion pumps

Sputter ion pumps has three pumping mechanisms:

- **Chemical adsorption onto the reactive metal layer (Ti) deposited on anode** and subsequent burial by additional metallic atoms of gas molecules: all gases except rare gases,
- **Implantation of gas ions in the cathode** (not permanent), and of energetic neutrals bounced back from the cathode in **the deposited film**: only mechanism of pumping for rare (noble) gases,
- **Diffusion** into the cathode and the deposited film: only H_2

Diode configuration (cell cross-section)



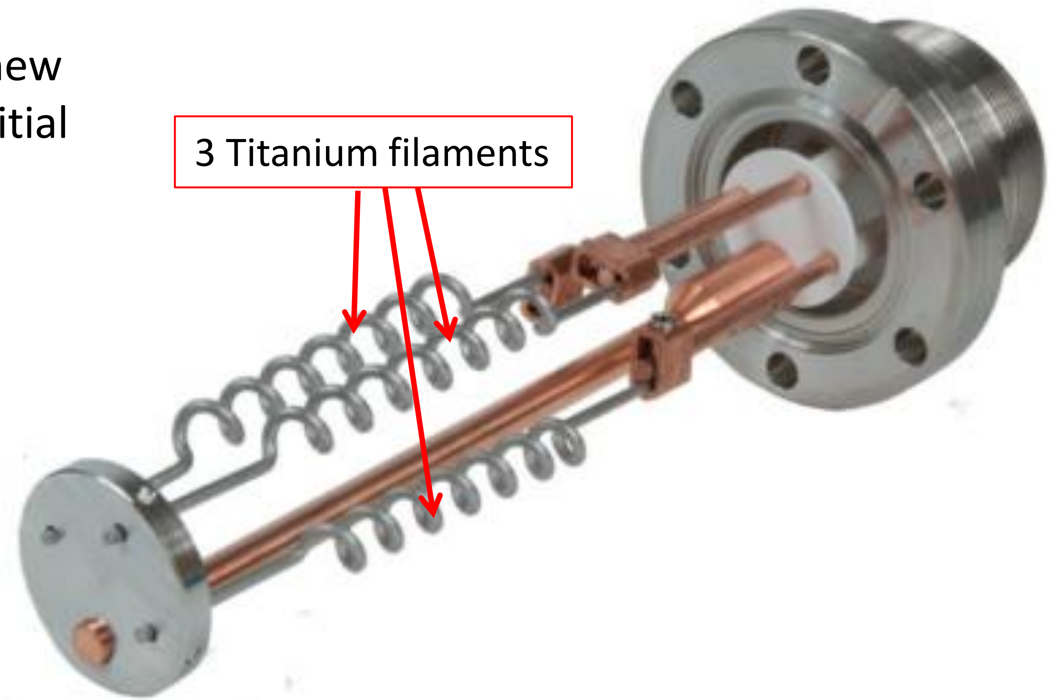
Paolo Chiggiato, Vacuum Technology for Ion Sources, CAS 2012 proceedings

Evaporable Getters

Evaporable getters: TSP – Titanium Sublimation Pump

Ti is the **sublimated** metal. Ti filaments are heated up to 1500°C reaching Ti vapor pressure which is deposited on the surrounding surfaces creating a chemically active surface where gas molecules are captured.

When the deposited film is saturated, new sublimation is needed to recover the initial pumping speed.



Sticking probablities:

$H_2: 0.01 \leq \alpha \leq 0.1$

$CO: \ 0.5 \ \ \leq \alpha \leq 1$

Film capacity:

- For CO, one monolayer adsorbed,
- For of O_2 several monolayers,
- For N_2 fraction of monolayer

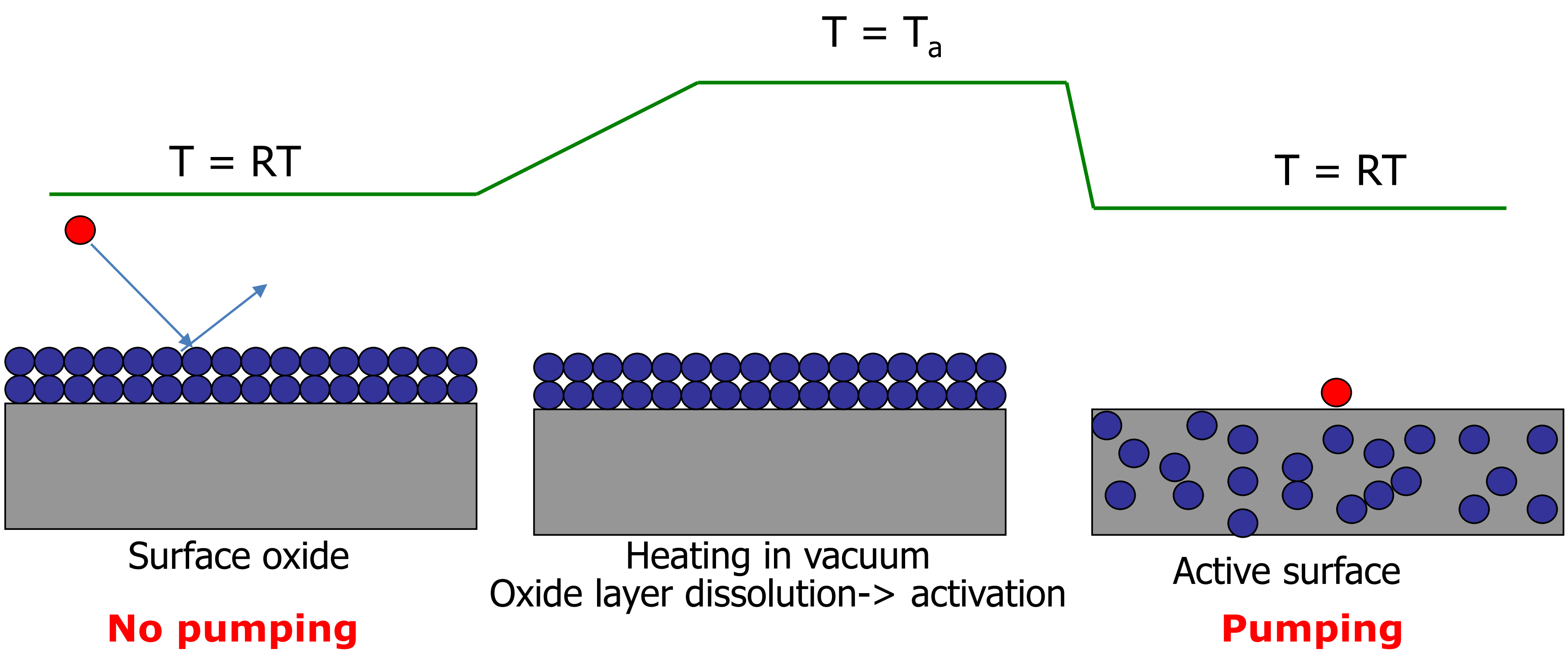
Hydrogen diffuses in the Ti film → much higher capacity

Non-Evaporable Getters (NEG)

- NEG pumps sorb gases by a chemical reaction. They use very reactive alloys, generally made of Ti, Zr, which are configured in a high efficiency getter cartridge structure.
- Pumping of the different gases:
  - Active gases, like O_2, N_2, H_2O, CO, CO_2 impinging on the cartridge surface are dissociated and permanently trapped, in the form of stable chemical compounds.
  - Hydrogen is very effectively pumped by the NEG. hydrogen atoms diffuse inside the getter bulk and dissolve as a solid solution.
  - Noble gases (and CH_4 at room temperature) are not pumped

Courtesy of SAES getters

Non-Evaporable Getters (NEG)



Courtesy of Paolo Chiggiato JUAS

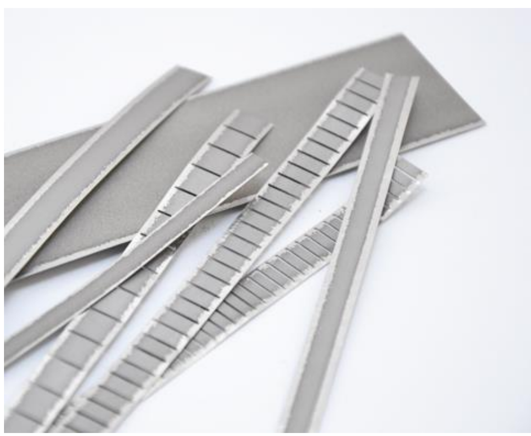
On activation the oxide layer at the surface of NEG is diffused to the bulk of the material creating clean, chemically active surface where gas molecules are captured.

Non-Evaporable Getters (NEG)

NEG materials are produced industrially by powder technology. The powder is sintered to form discs or strips.

A typical alloy produced by SAES Getter is **St707 made of Zr (70%), V (25%), Fe (5%)**.

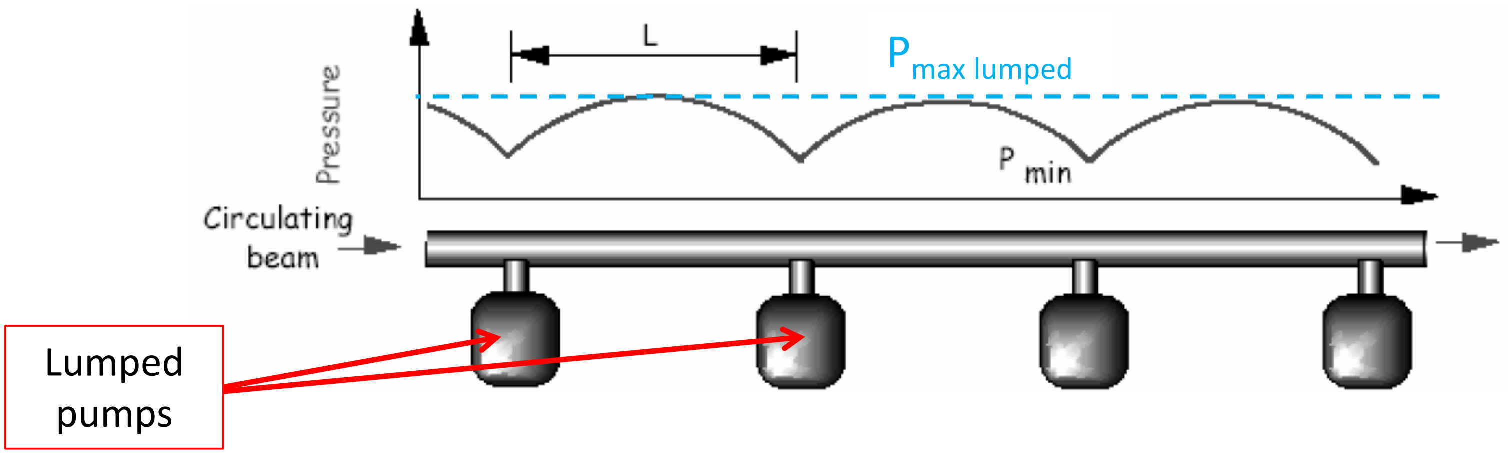
The **high porosity of NEG materials** allows pumping of relatively high quantities of gas without reactivation. After 40 venting cycles (with nitrogen) and reactivation 80% pumping speed is conserved.



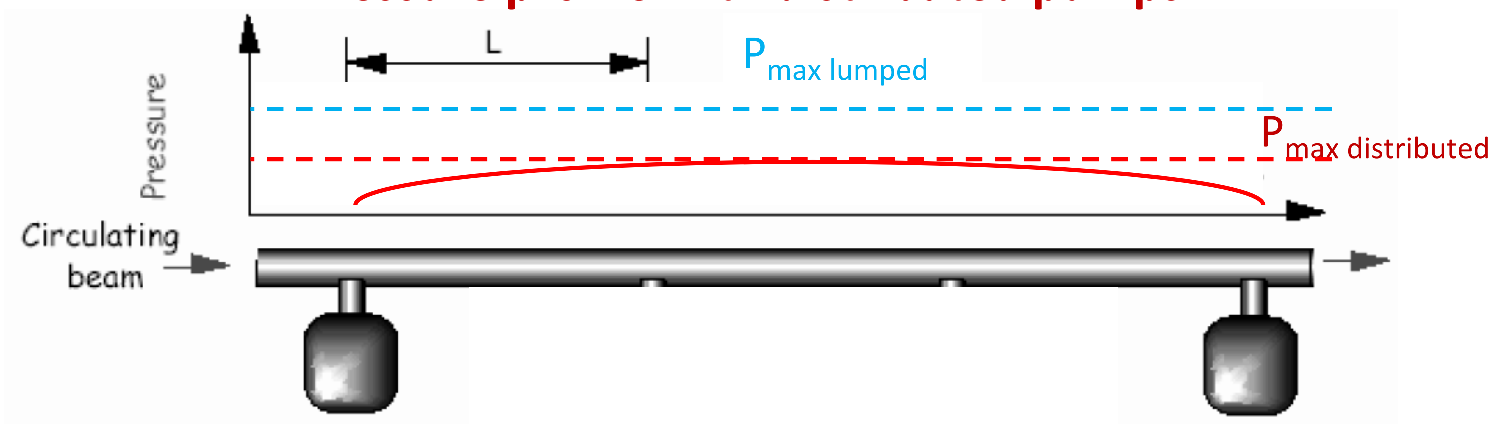
Courtesy: Paolo Chiggiato, Vacuum Technology for particle accelerators, 2013
SAES getter

Distributed pumping

Pressure profile with lumped pumps



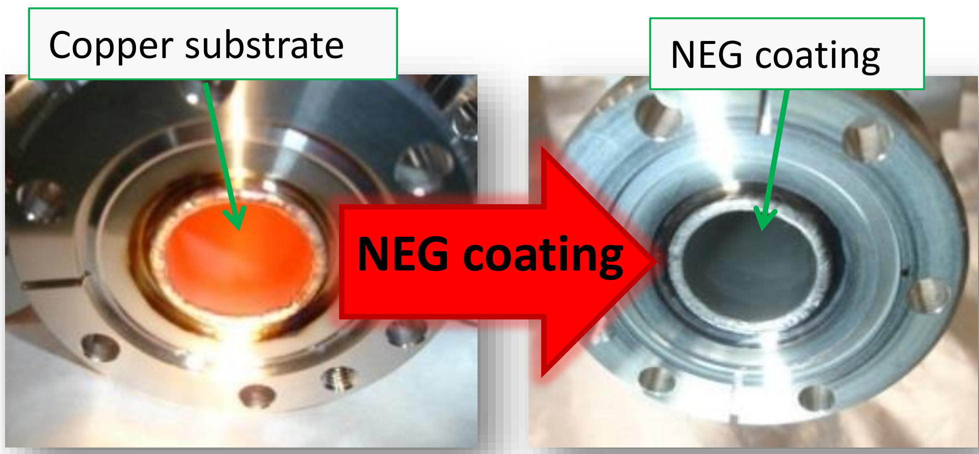
Pressure profile with distributed pumps



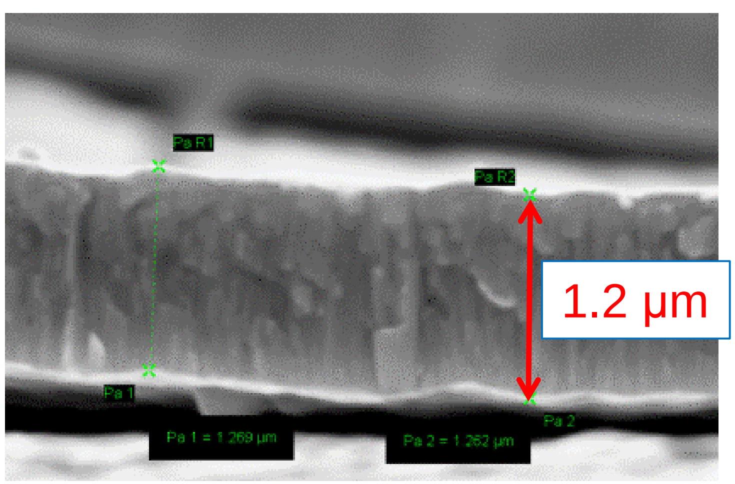
F. Mazzolini, 'The use of NEG pumps and coatings in large vacuum systems: experience and limitations', CAS 2006 Vacuum in accelerators

NEG coatings

NEG-coating transforms a vacuum chamber from a gas source to a vacuum pump.



The technology of coating vacuum chambers by magnetron sputtering was developed at CERN for the warm sections of LHC. Nowadays it is also widely applied in synchrotron radiation sources.



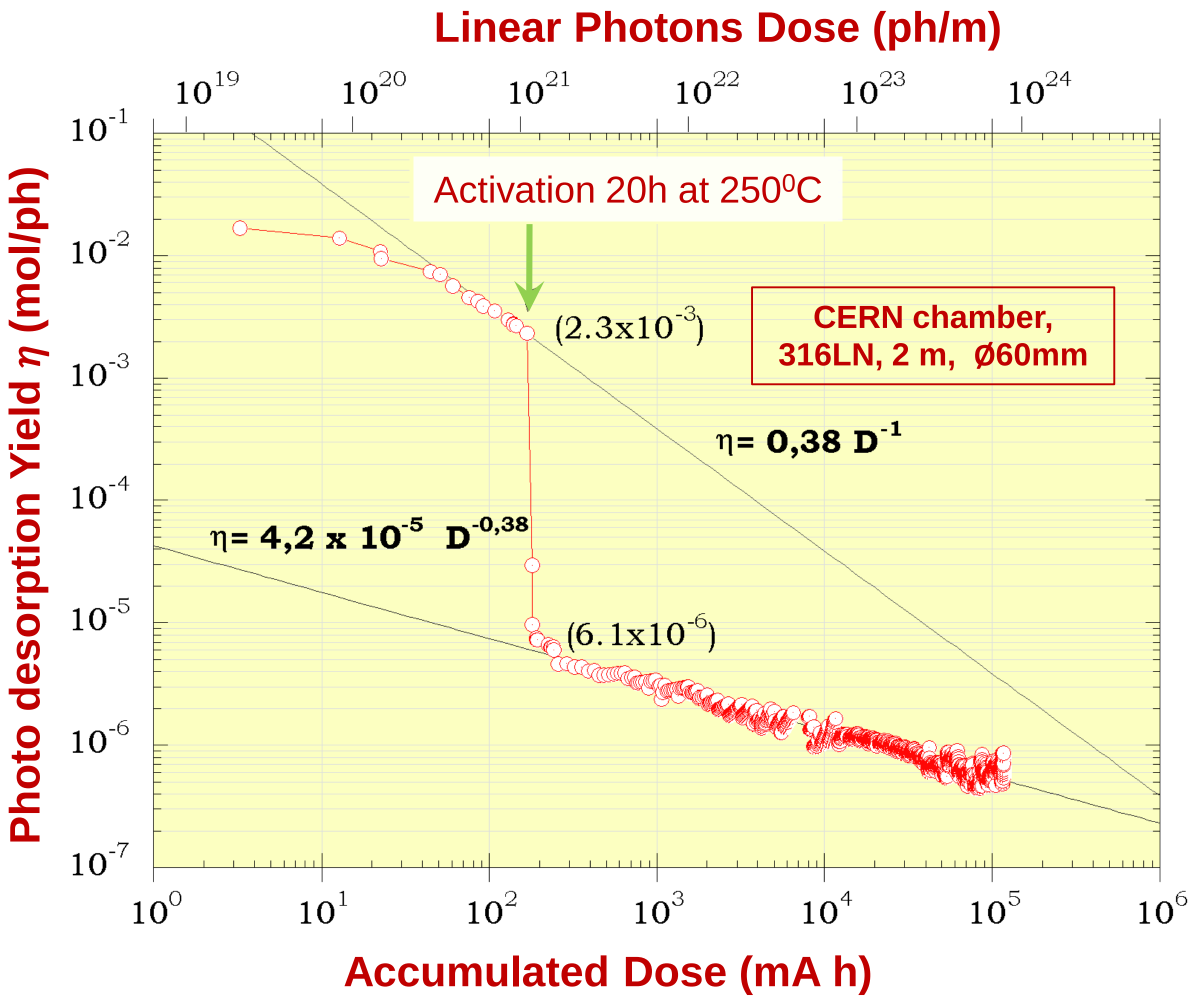
NEG film characteristics:

- Film composition: Ti (30%), Zr (40%), V (30%).
- Thickness ~1 um,
- Activation temperature 200^0C for 24 h,
- Low PSD (Photon stimulated desorption),
- Sticking probability similar to TSP.

Disadvantage of NEG: has limited capacity and activation cycles.

NEG coatings

Photon stimulated desorption (PSD) measurements at ESRF (beamline D31).



'Synchrotron Radiation-Induced Desorption from a NEG-Coated Vacuum Chamber', P. Chiggiato, R. Kersevan

closing

- You may not need to deal with the vacuum fundamentals in your daily work, however, you still need to know how the different parameters in your system will affect your vacuum.
- Gas sources are important part which need to be under our control at all stages, in order to achieve the required pressure.
- Relating outgassing, pressure, conductance and pumping speed together, will allow you to design a vacuum system.
- I gave you the fundamentals but as you know, ¨the devil is in the details¨ and this is what my colleagues will give you in the coming days.

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Thank you for your attention
&
Wish you great time here!