Introduction to vacuum technology

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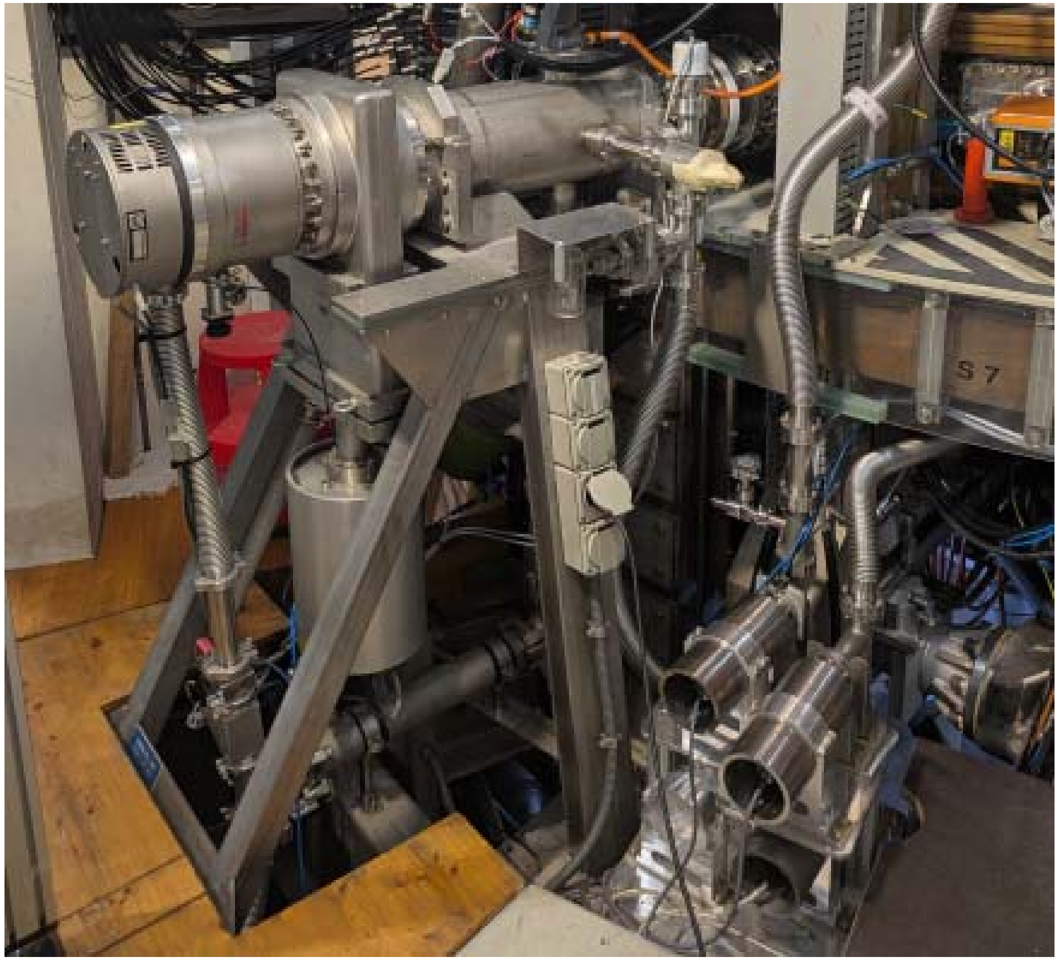

Bibliography

J.F. O'Hanlon, "*A user's guide to vacuum technology*", 3rd Ed. (2003)

Also:

- **A. Roth** "*Vacuum Technology*"
- **A. Chambers, R.K. Fitch, B.S. Halliday** "*Basic Vacuum Technology*"
- **Pfeiffer Vacuum** "*Vacuum Technology*"
- **Oerlikon Leybold Vacuum** "*Fundamentals of Vacuum Technology*"
- **Varian** "*Basic Vacuum Practice*"
- Wikipedia

Outline

1. Introduction - vacuum, pressure, mean free path
2. Vacuum quantities - flow rate, conductance, throughput
3. Pumping speed
4. (Some) vacuum pumps - descriptive
5. Sorption, desorbtion, permeation, degassing, outgassing, leaks, virtual leaks, base pressure, ultimate pressure
6. (Some) vacuum gauges and components - descriptive
7. Practical advice, and leak detection (*if time permits*)

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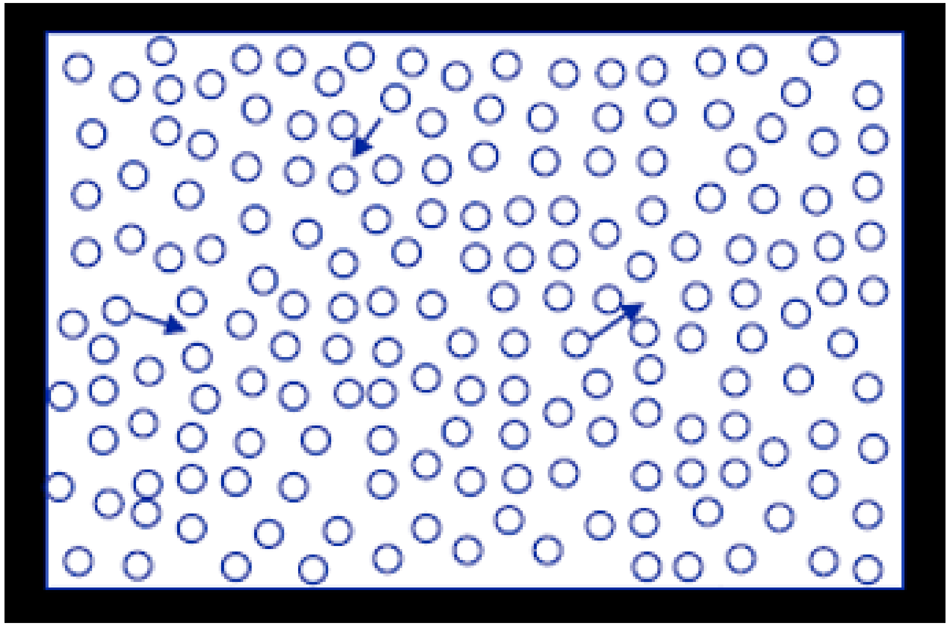
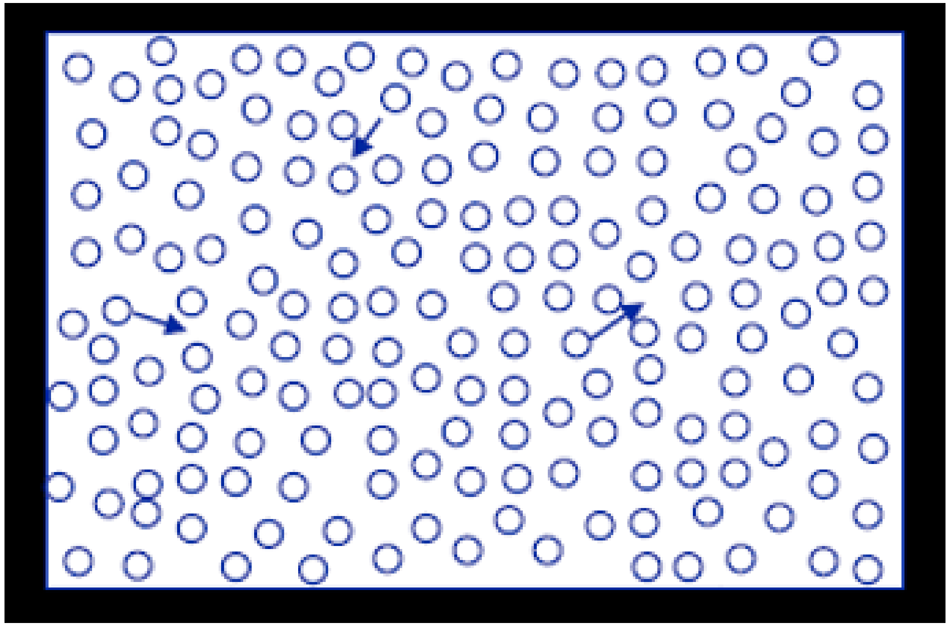
Introduction



Chamber filled with gas

Introduction



p : pressure
V : volume
N : num. particles
T : temperature

k_B: k Boltzmann
$\approx 1.38 \cdot 10^{-23}$ J/K

Ideal gas law states that

$$pV = Nk_BT$$

Introduction

Defining the *particle number density* as $n = N/V$, the ideal gas law becomes

$$p = nk_B T$$

Notice that:

- We have assumed thermal equilibrium of the gas particles **and also** of the gas with the **chamber walls**.
  - The gas particles have velocities following a Maxwellian distribution.
  - The average particle (mass m) speed is then $\langle v \rangle_{\text{th}} = \sqrt{\dfrac{8k_B T}{\pi\, m}}$
- For a gas composed of different species, the total pressure fulfills

$$p = p_{s1} + p_{s2} + \cdots = n_{s1} k_B T + n_{s2} k_B T + \cdots$$

Introduction

Pressure = normal force / area

SI units : $1\ N/m^2 = 1\ Pa$ (Pascal)

$1\ atm = 1.013 \cdot 10^5\ Pa$

$1\ bar = 10^5\ Pa$ by definition. Not an SI unit.

1 mbar =100 Pa. We will use Pa and mbar

Some (few) people still use:

1 Torr = pressure of 1 mm height of mercury

760 Torr = 1 atm

1 Torr = 4/3 mbar (approximately)

Introduction

Question: What particle density do we have in a chamber kept at room temperature and atmospheric pressure?

$$n = \frac{p}{k_B T} = \frac{1.013 \cdot 10^5 \text{ Pa}}{\left(1.38 \cdot 10^{-23} \frac{\text{J}}{\text{K}}\right) \cdot 293 \text{ K}} = 2.5 \cdot 10^{25} \text{ m}^{-3}$$

What about at 10^{-7} mbar?

10^{-7} mbar = 10^{-5} Pa $\quad \Rightarrow n \approx 2.5 \cdot 10^{15} \text{ m}^{-3}$

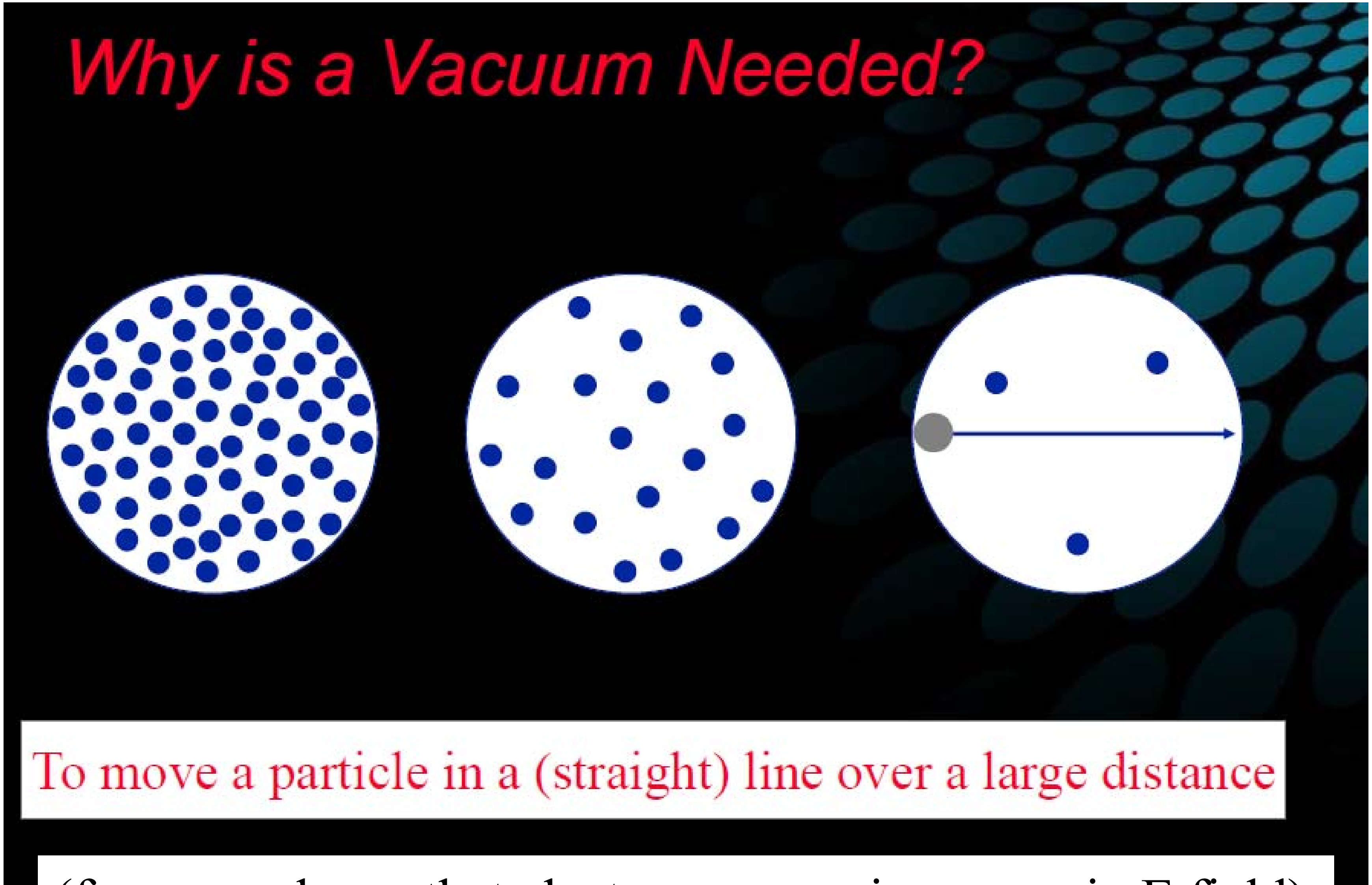
Introduction

The basis of vacuum technology: pressure

Degree of Vacuum

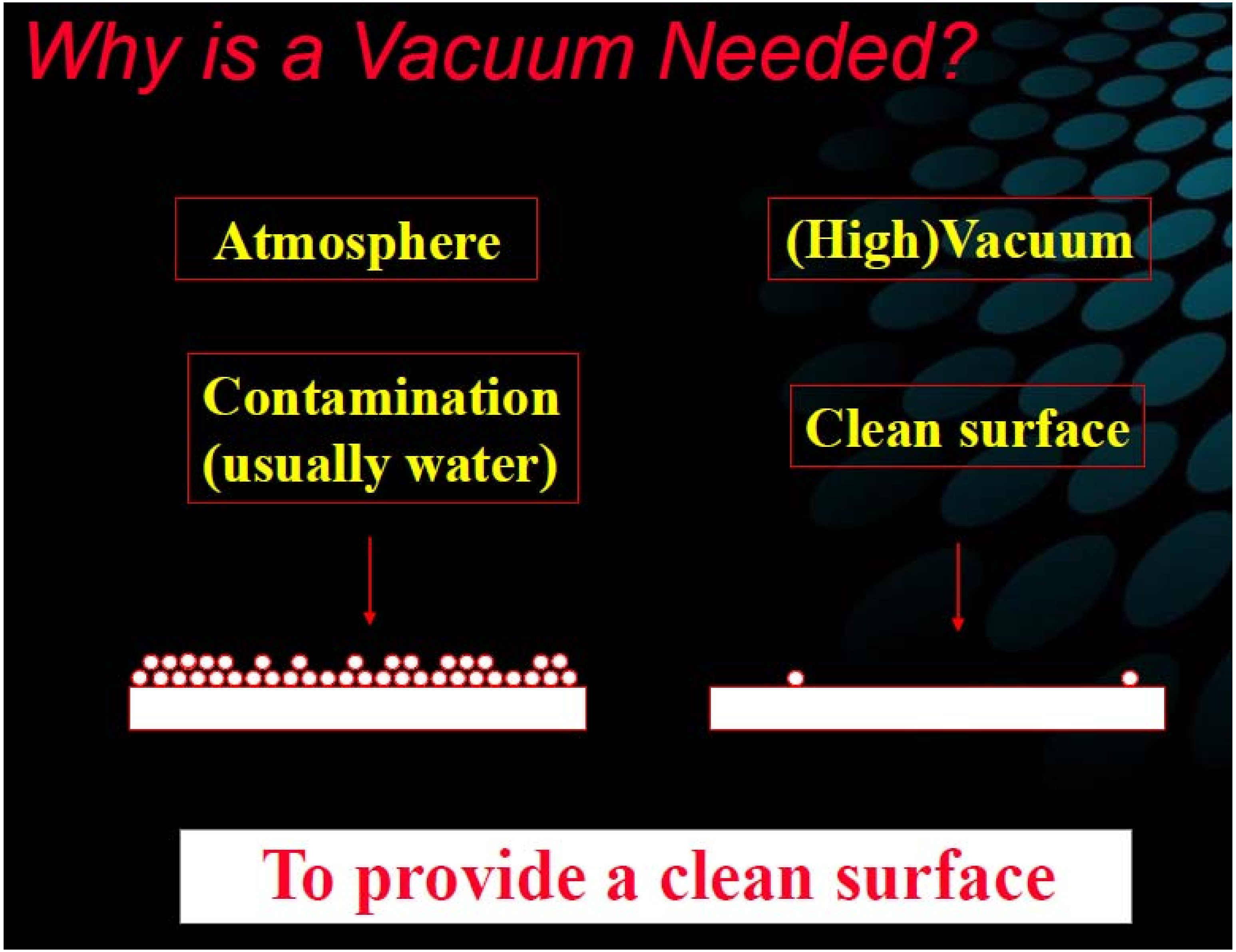
	Pressure boundaries [mbar]	Pressure boundaries [Pa]
Low Vacuum LV	1000-1	10^5-10^2
Medium Vacuum MV	1-10^{-3}	10^2-10^{-1}
High Vacuum HV	10^{-3}-10^{-9}	10^{-1}-10^{-7}
Ultra High vacuum UHV	10^{-9}-10^{-12}	10^{-7}-10^{-10}
Extreme Vacuum XHV	$<10^{-12}$	$<10^{-10}$

Introduction



(for example, so that electrons can gain energy in E field)

Introduction



Introduction

WHY IS A VACUUM NEEDED?

- **To extend (and maintain) molecular Mean-Free-Paths**
  - Electron tubes
  - Early generation particle accelerators
  - Mass spectrometers and vacuum instruments
  - Vacuum coaters
  - High voltage and thermal insulation
- **To obtain (and maintain) clean surfaces and pure process gases**
  - Surface analysis and instrumentation
  - Cleaning prior to film deposition
  - Molecular Beam Epitaxy (MBE) devices
  - Contemporary accelerators and magnetic fusion devices
  - Semiconductor industry, deposition and etching
  - Atomic layer deposition

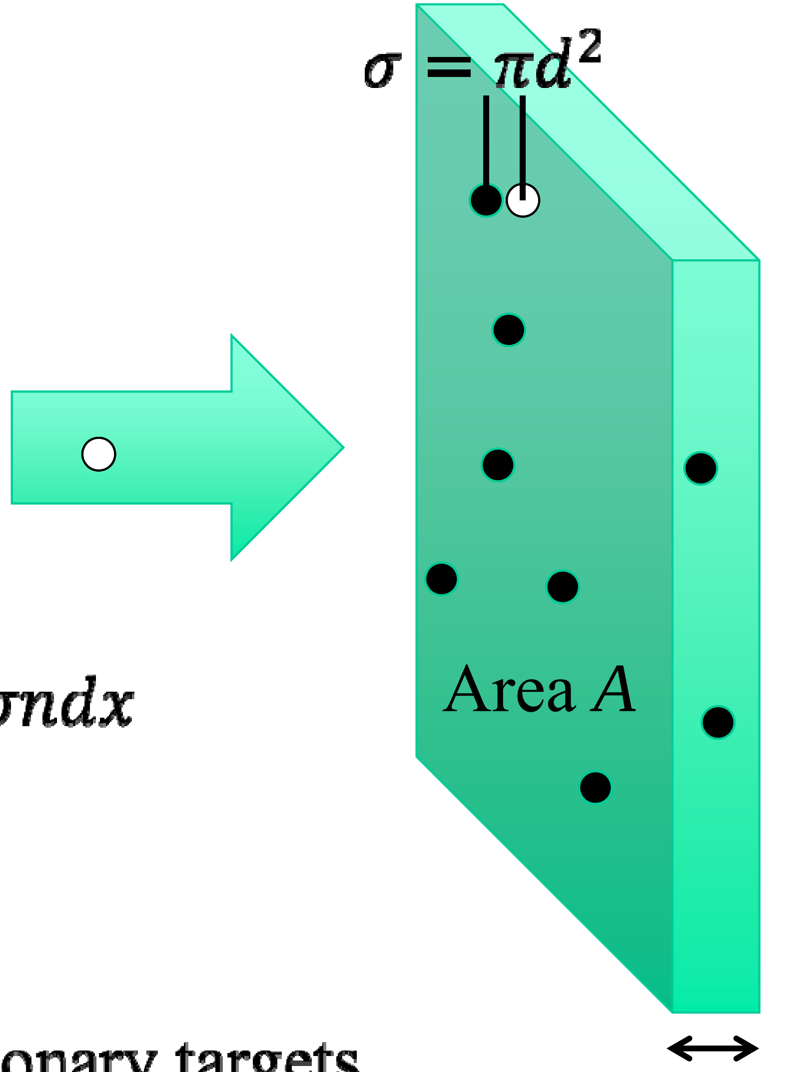
Introduction: Mean free path for collisions

n [molecules m^{-3}]

Cross-section for collision σ [m^2]

Total collision area $dA = \sigma n A dx$

Uniform beam flux $\Gamma = nAv$ [molecules s^{-1}]



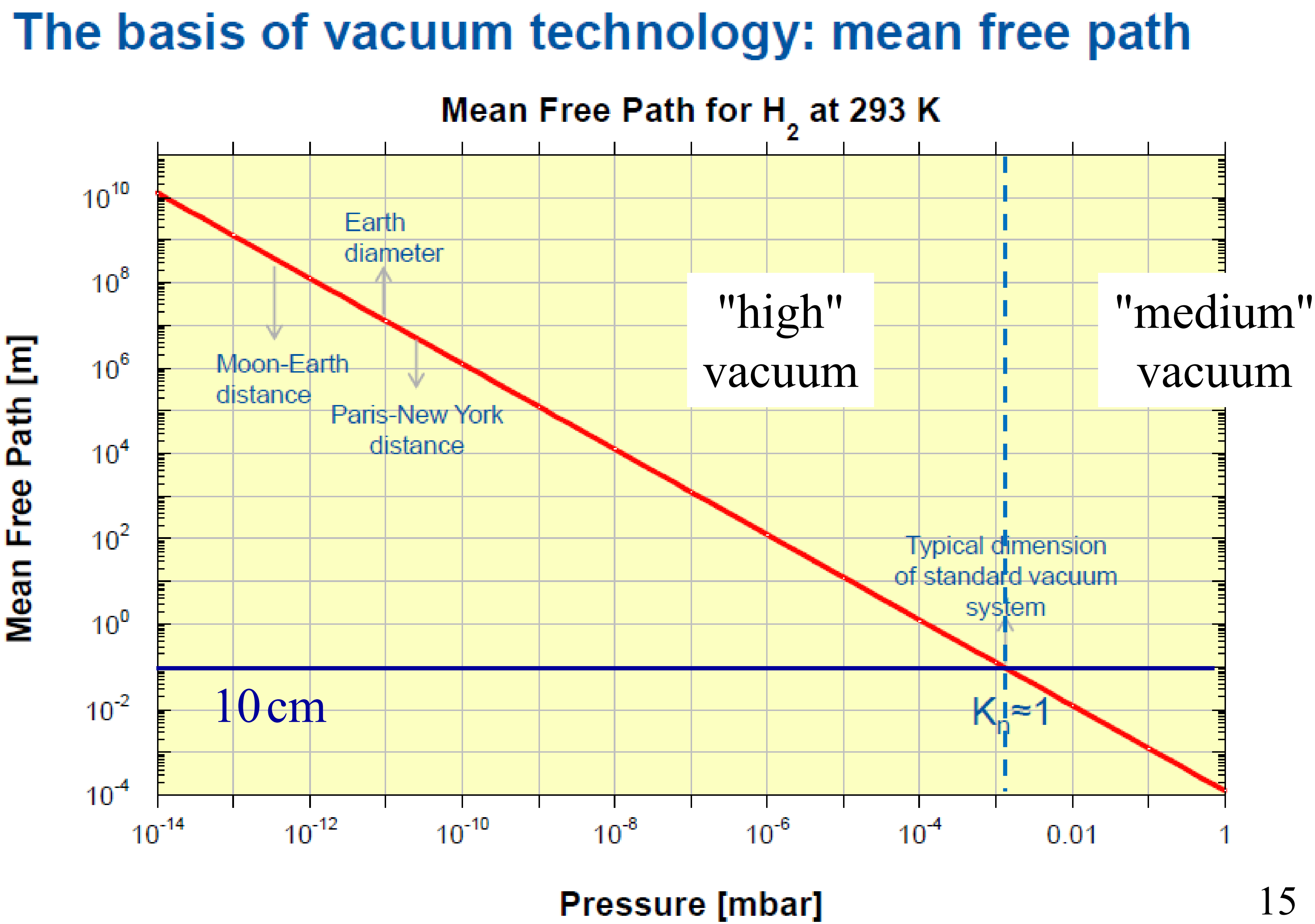
Beam fraction lost by collisions, $\frac{-d\Gamma}{\Gamma} = \frac{dA}{A} = \sigma n dx$

Integrate: $\Gamma(x) = \Gamma_0 e^{-\sigma n x} = \Gamma_0 e^{-\frac{x}{\lambda}}$

where $\boxed{\lambda = \frac{1}{n\sigma}}$ is the mean free path for stationary targets

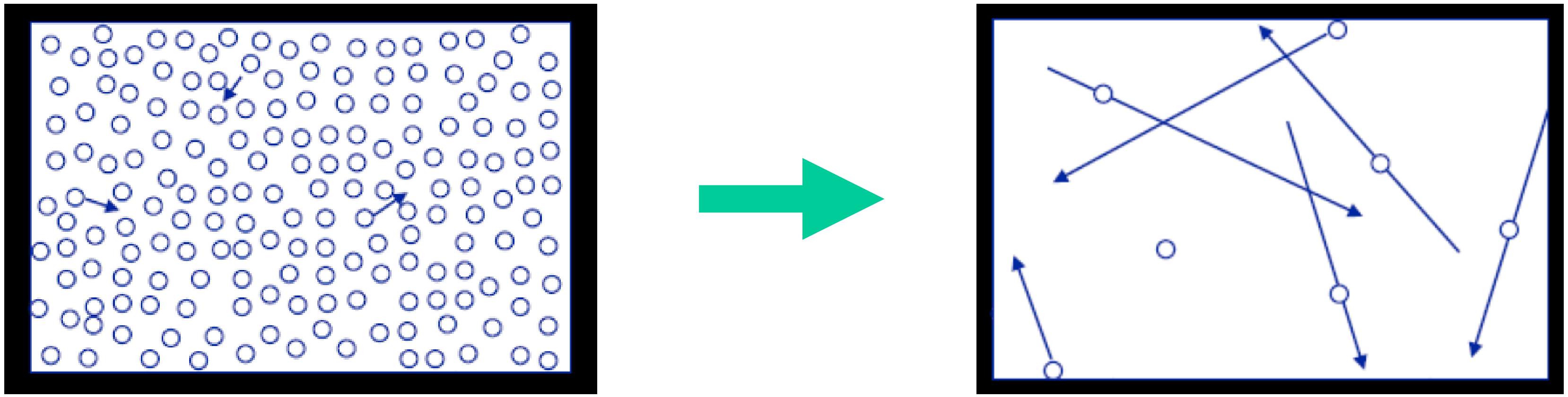
in fact, $\lambda = \frac{1}{n\sqrt{2}\pi d^2} =$ mean free path for Maxwell distribution

Introduction: Mean free path



Introduction

Low pressure

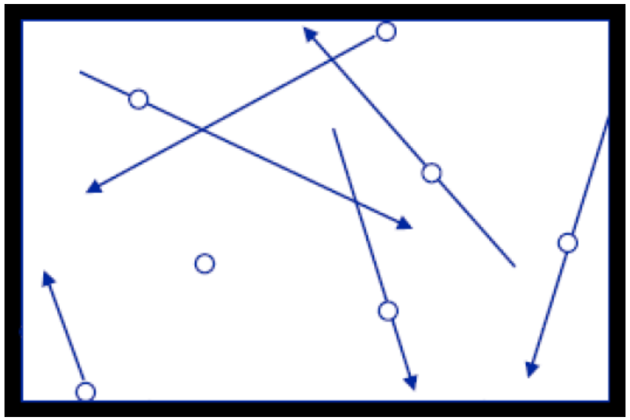


Viscous flow
(momentum transfer between molecules)

Molecular flow
(molecules do not collide with one another)

- Gas-wall collisions predominate
- Concept of viscosity becomes meaningless

Introduction



Molecular flow regime

(gas-wall collisions predominate)

For most wall surfaces, **diffuse reflection** is a good approximation:

- «Each particle arrives, sticks, rattles around in a surface imperfection and is re-emitted in a direction independent of its incident velocity» (O'Hanlon, p. 26).

Introduction

The basis of vacuum technology: Knudsen number

$$K_n = \frac{\lambda}{D}$$

λ is the mean free path and **D** is a characteristic dimension of a vacuum system (p.ex. the diameter of a beam pipe).

K_n range	Regime	Description
$K_n > 0.5$	**Free molecular flow**	The gas dynamic is dominated by molecular collisions with the walls of the system
$K_n < 0.01$	Continuous (viscous) flow	The gas dynamic is dominated by intermolecular collisions
$0.5 < K_n < 0.01$	Transitional flow	Transition between molecular and viscous flow

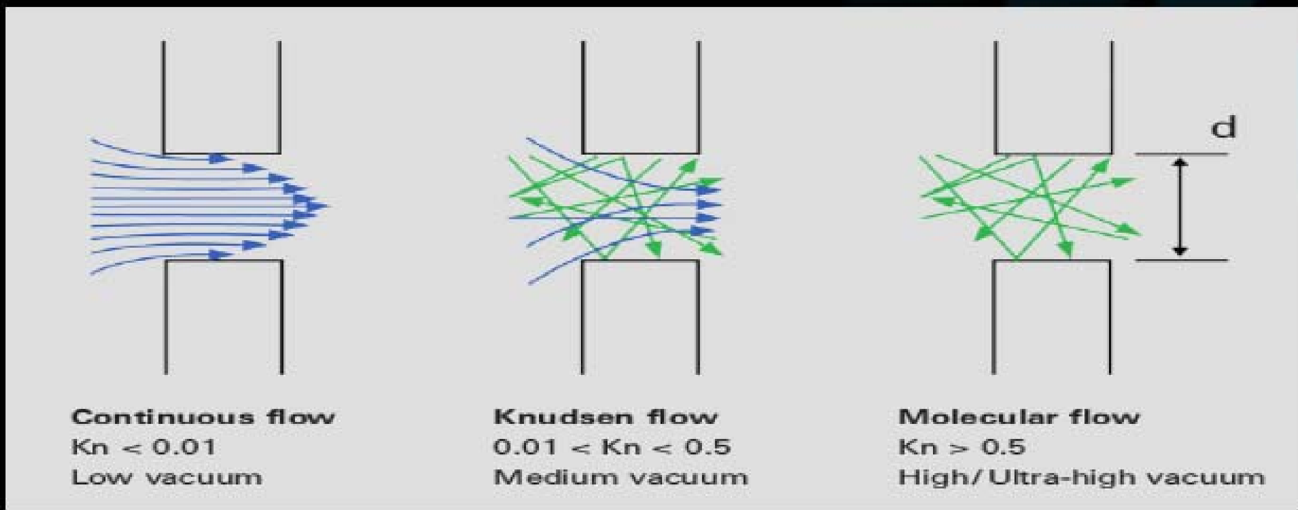
Introduction

FLOW REGIMES

Viscous Flow: $\frac{\text{Mean Free Path}}{\text{Characteristic Dimension}}$ is less than 0.01

Transition Flow: $\frac{\text{Mean Free Path}}{\text{Characteristic Dimension}}$ is between 0.01 and 1

Molecular Flow: $\frac{\text{Mean Free Path}}{\text{Characteristic Dimension}}$ is greater than 1



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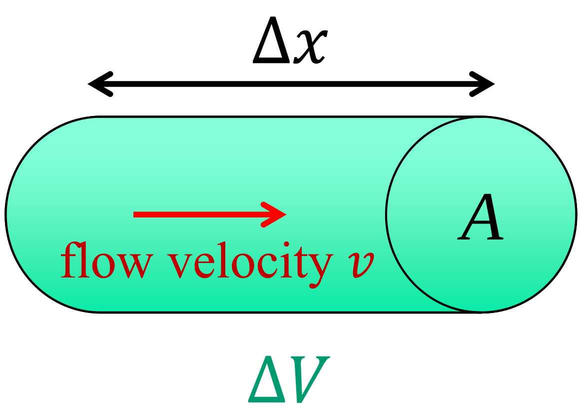
Vacuum quantities: Volumetric rate (S)

The volumetric flow rate S is how large a volume of gas (ΔV) can flow through a cross section of area A during a time interval Δt :

$$S = \frac{\Delta V}{\Delta t}$$



For a uniform flow velocity v,
$\Delta V = A\,\Delta x = A\,v\,\Delta t$ and then

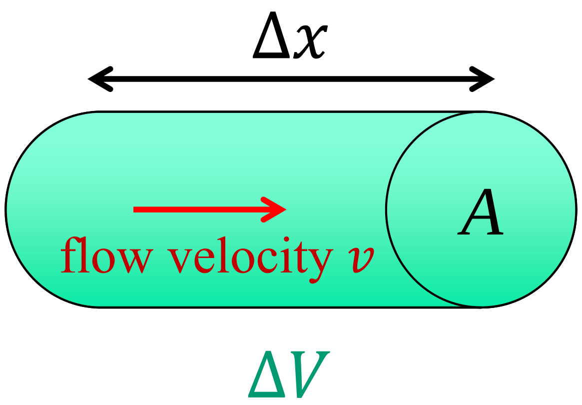
$$S = \frac{\Delta V}{\Delta t} = Av$$

Units: $[S] = \frac{\mathrm{m}^3}{\mathrm{s}} = 10^3\,\frac{l}{\mathrm{s}} = 3600\,\frac{\mathrm{m}^3}{\mathrm{h}}$

Vacuum quantities: Molecular flow (Γ)

Quantifies the number of particles that pass through a cross section of area A per unit time.

For a uniform flow velocity v, $\Delta V = A\Delta x = Av\Delta t$, and then



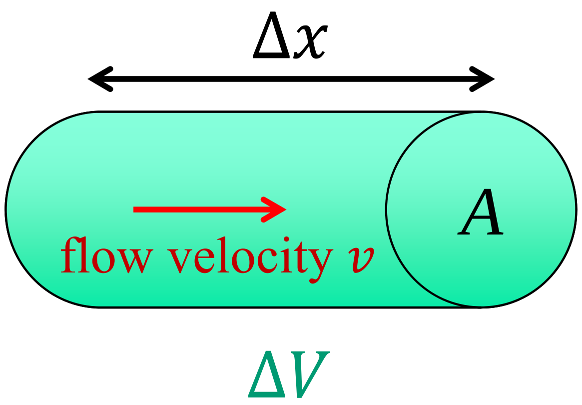
$$\dot{N} \approx \frac{\Delta N}{\Delta t} = n\frac{\Delta V}{\Delta t} = nAv = \Gamma$$

$$= n\,S$$

Units: $[\Gamma] = \frac{1}{s}$

Vacuum quantities: Throughput (Q)

The throughput Q is the energy passing through a cross section of area A per unit time.
This energy is *not the kinetic nor potential energy contained in the gas particles* but the one required to transport the particles across A .

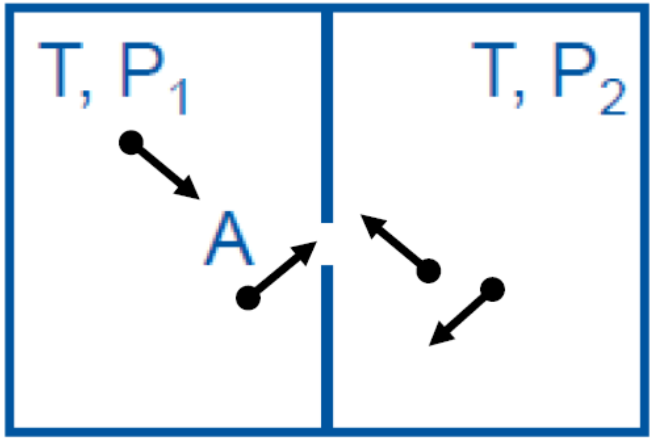


$$Q = \dot{N} k_B T = n\, S\, k_B T$$
$$= (n k_B T)\, S$$
$$= p\, S$$

Units: $[Q] = \mathrm{Pa}\,\frac{\mathrm{m}^3}{\mathrm{s}}$ (SI), but very often one uses $[\mathrm{mbar}\,\frac{l}{\mathrm{s}}]$
or also [sccm] (**s**tandard **c**ubic **c**m per **m**inute; $60\,\mathrm{sccm} = 1\,\mathrm{mbar}\,\frac{l}{\mathrm{s}}$)

Vacuum quantities: Conductance (C)

The simplest example is to consider the *molecular flow* through a small hole of area A and negligible length.



In steady state,

Flow 1 → 2: $\Gamma_{1\to 2} = n_1 A \frac{\langle v \rangle_{th}}{4}$

Flow 2 → 1: $\Gamma_{2\to 1} = n_2 A \frac{\langle v \rangle_{th}}{4}$

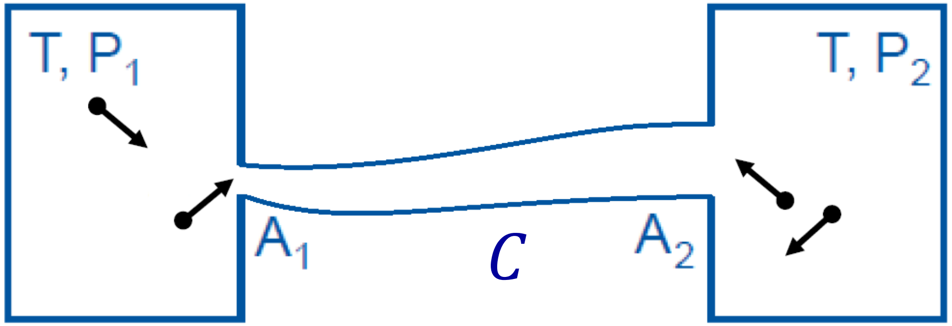
Net flow: $\Gamma = \frac{A}{4} \langle v \rangle_{th} \, (n_1 - n_2)$

$$\Rightarrow \; Q = \frac{A}{4} \langle v \rangle_{th} \, (p_1 - p_2)$$

The conductance C is the proportionality factor between Q and Δp. For the small hole:

$$C = \frac{A}{4} \langle v \rangle_{th} = \frac{A}{4} \sqrt{\frac{8 k_B T}{\pi \, m}} = A \sqrt{\frac{k_B T}{2\pi \, m}}$$

Vacuum quantities: C



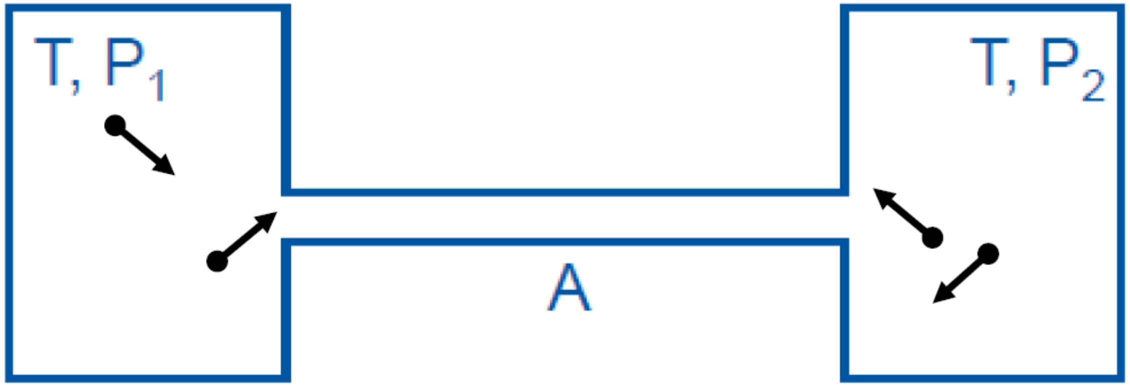
- For more complex situations, one can still model the steady-state net flow and throughput using a conductance:

$$\Gamma = C\ (n_1 - n_2) \quad \text{and} \quad Q = C\ (p_1 - p_2)$$

- The calculation of C will not be as simple because the particles interact with the wall along the way.
- It is useful, though, to think of C in terms of the conductance for a hole *multiplied* by a transmission probability a :

$$C = a\ C_h$$

Vacuum quantities: C



$$C = a\, C_h$$

$$= a\, A \sqrt{\frac{k_B T}{2\pi\, m}}$$

- For a long cylindrical duct of constant cross section: $a \approx \frac{4d}{3l}$ (d: diameter, l: length)
- Values of a for other "easy-going" shapes are tabulated in books (check O'Hanlon).

Vacuum quantities: C

LNLS Laboratório Nacional de Luz Síncrotron

CNPEM

Vacuum basics:

Conductance calculation in molecular regime

For simple geometry the conductance can be calculated by simple eqs.:

For an orifice: $C_{air,20°C} = 11.6\,A$

Conductance C [l/s]
Orifice area A [cm^2]

For exemple, the conductance of an orifice of 4 cm is: **146 l/s**

For a tube: $C_{air,20°C} = 12.1\,\frac{d^3}{L}$

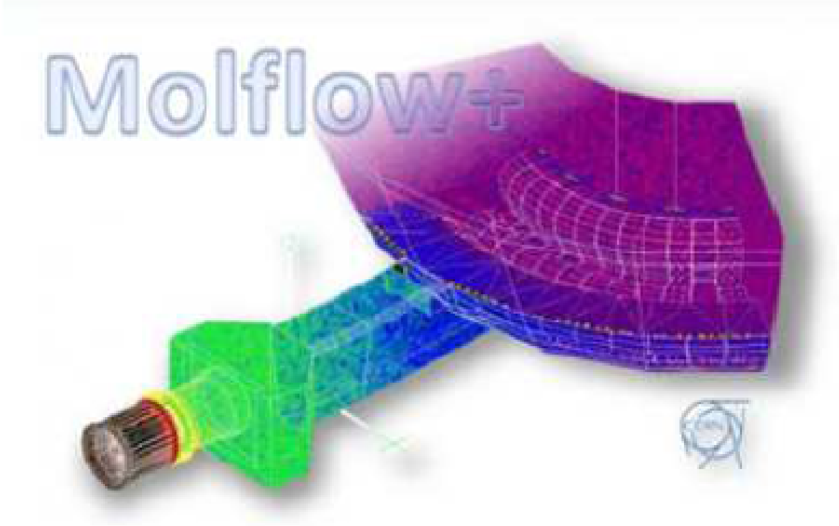
Conductance C [l/s]
Tube diameter d [cm]
Tube length L [cm]

For exemple, the conductance of a tube with diameter of 4 cm and length of 10 cm is: **77.5 l/s**

Vacuum quantities: C

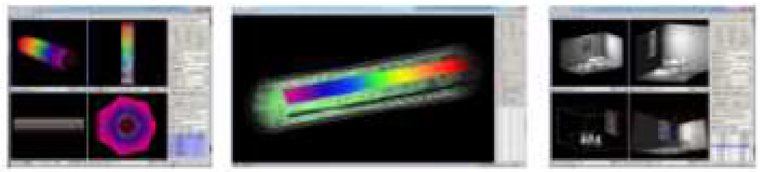
For complex geometry the conductance can be calculated by:

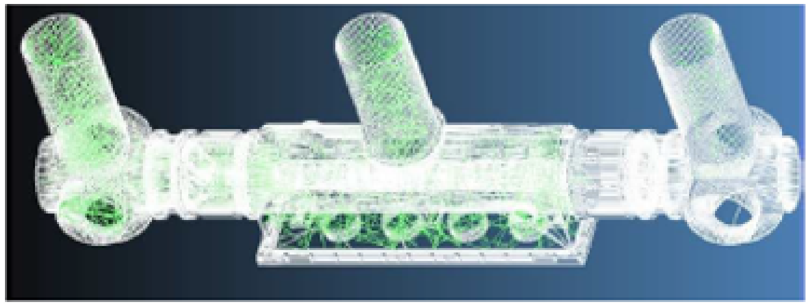
Based on Test-Particle Monte Carlo method (TPMC), which calculates a large number of molecular trajectories to have a picture of a rarefied gas flow.



A test-particle Monte-Carlo simulator for ultra-high-vacuum systems

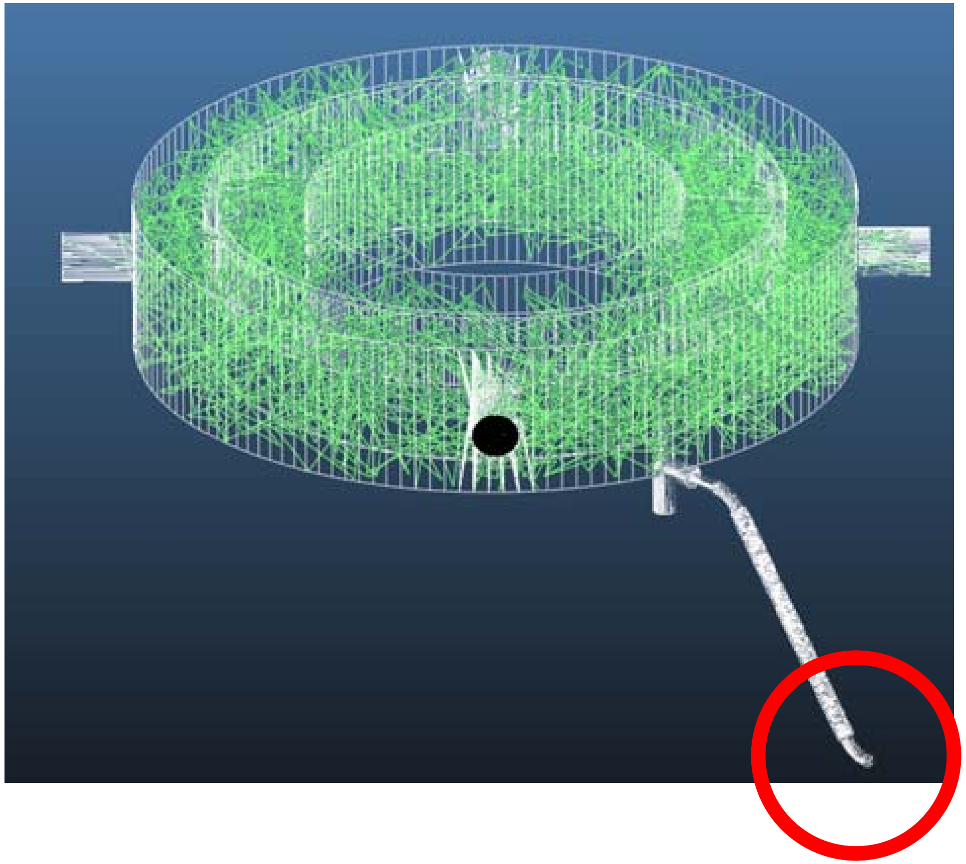
http://cern.ch/test-molflow

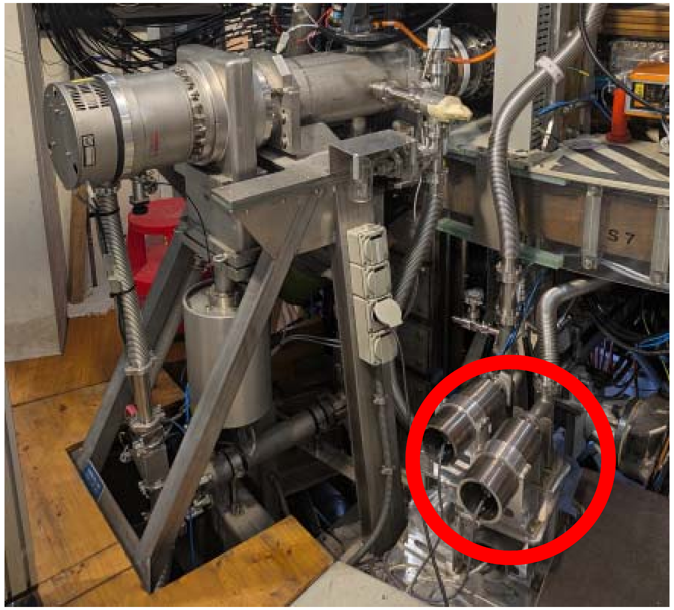


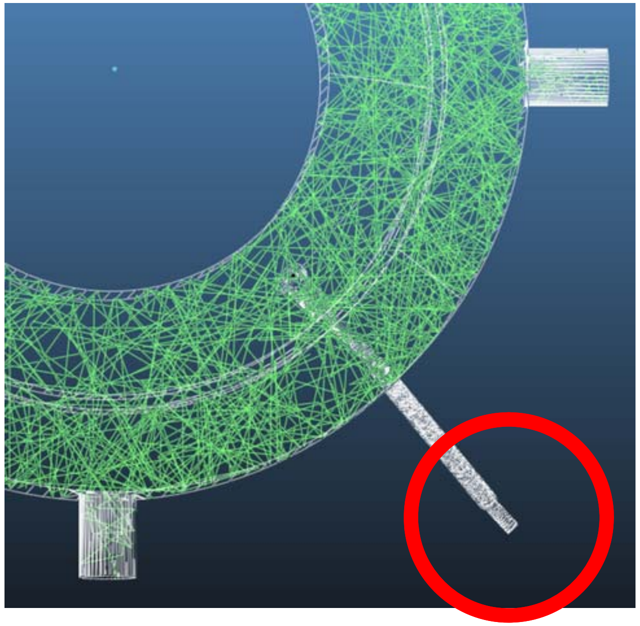


R. Kersevan and J.-L. Pons, JVST A 27(4) 2009, p1017

Vacuum quantities: C



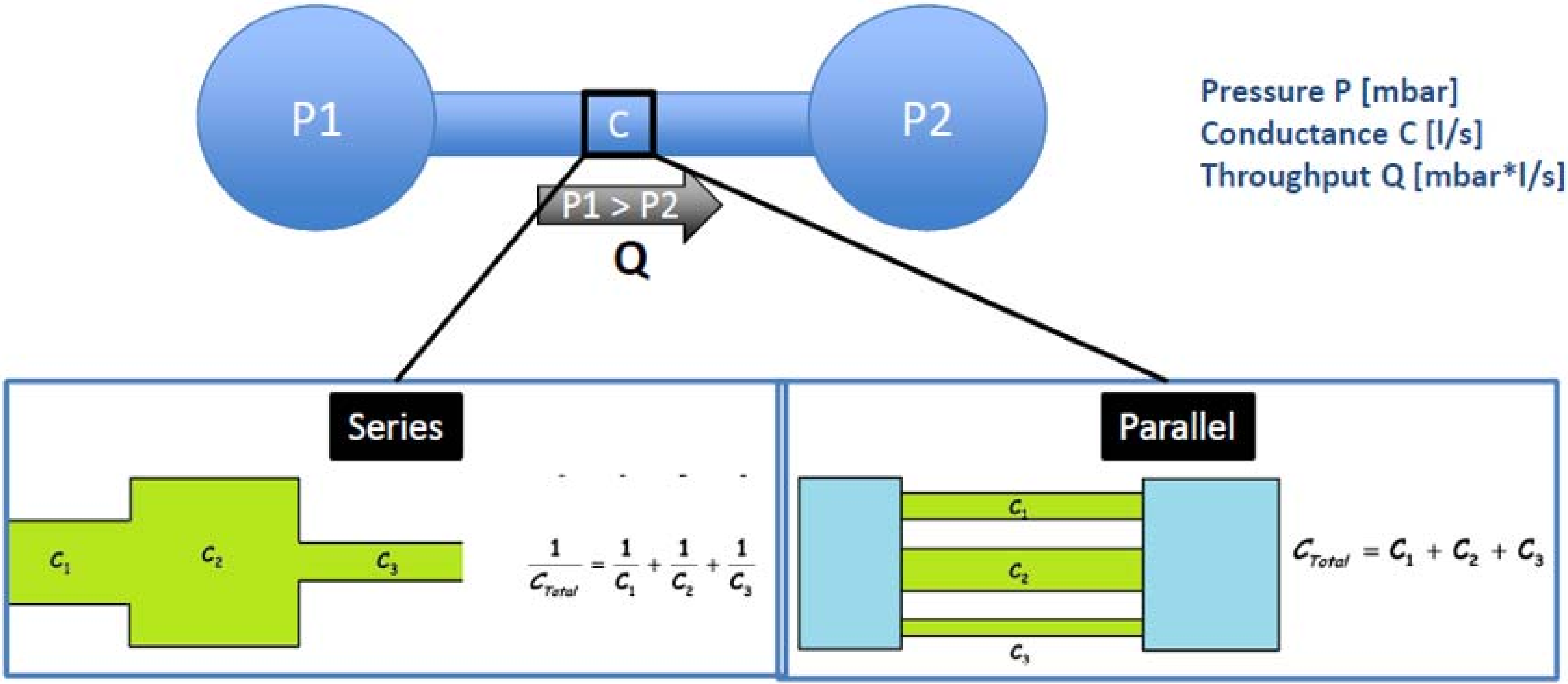




Molflow simulations of lower section of TCV.

Courtesy of Ben Brown and Olivier Février.

Vacuum quantities: C



Gas conductance C is analogous to: conductance G = (1/R) in **Ohm's law** $\Delta V=IR=I/G$

i.e. $I=G\Delta V$ where I=throughput, Q; G=conductance C; ΔV=pressure difference, (p_1-p_2).

For series $R_{tot}=1/G_{tot} = R_1+R_2=1/G_1+1/G_2$ For parallel R, $1/R_{tot}=G_{tot}=1/R_1+1/R_2=G_1+G_2$

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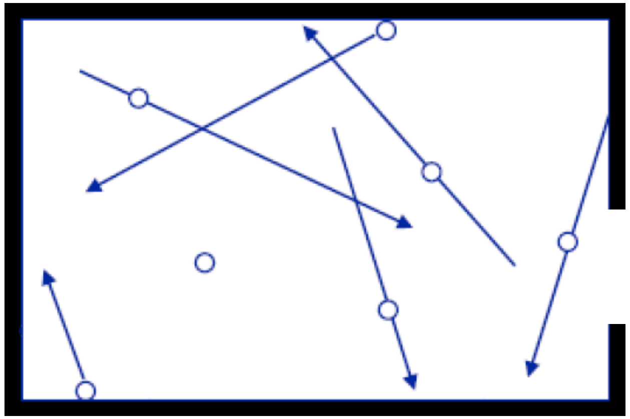
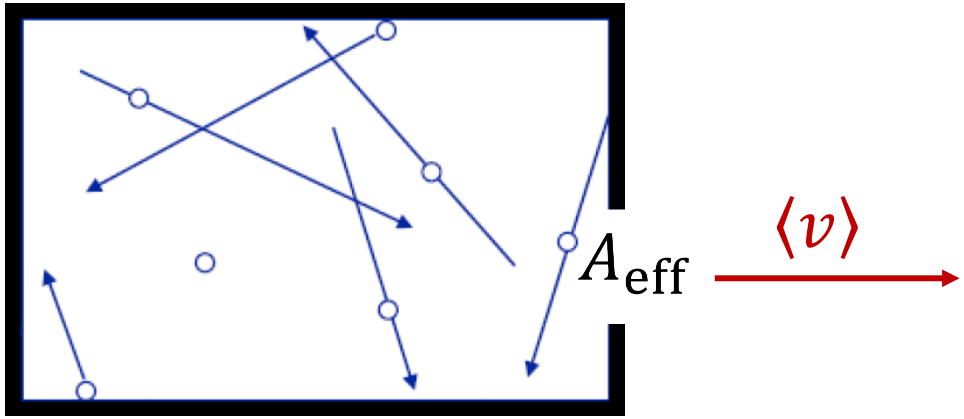
Pumping speed



In molecular flow, a pump can be thought of as a hole that lets particles *move out* of the chamber and **not** come *back in*.

Pumping speed, S_p

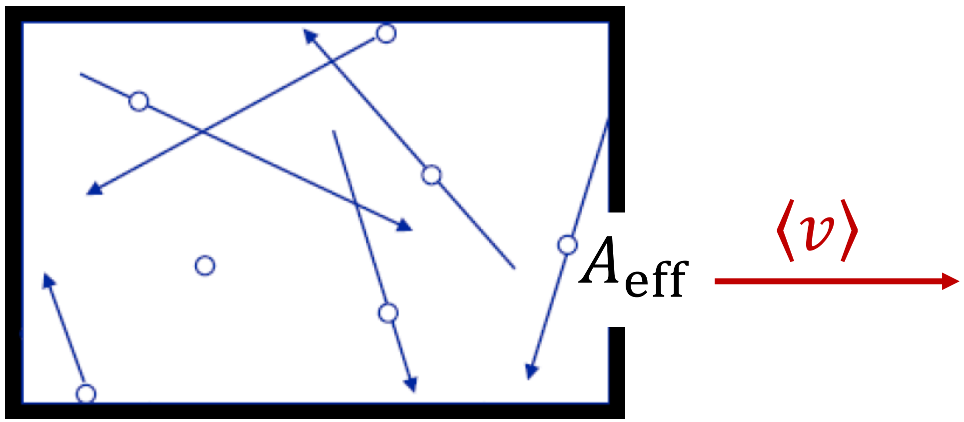


- The pump can be modeled as a value of volumetric rate S that is independent of n or p (at least within specified ranges).

  We call this value the *pumping speed*, S_p.

- Bear in mind, though, that S_p typically varies with the particle mass (and possibly other parameters).

Pump throughput, Q_p and/or Γ_p

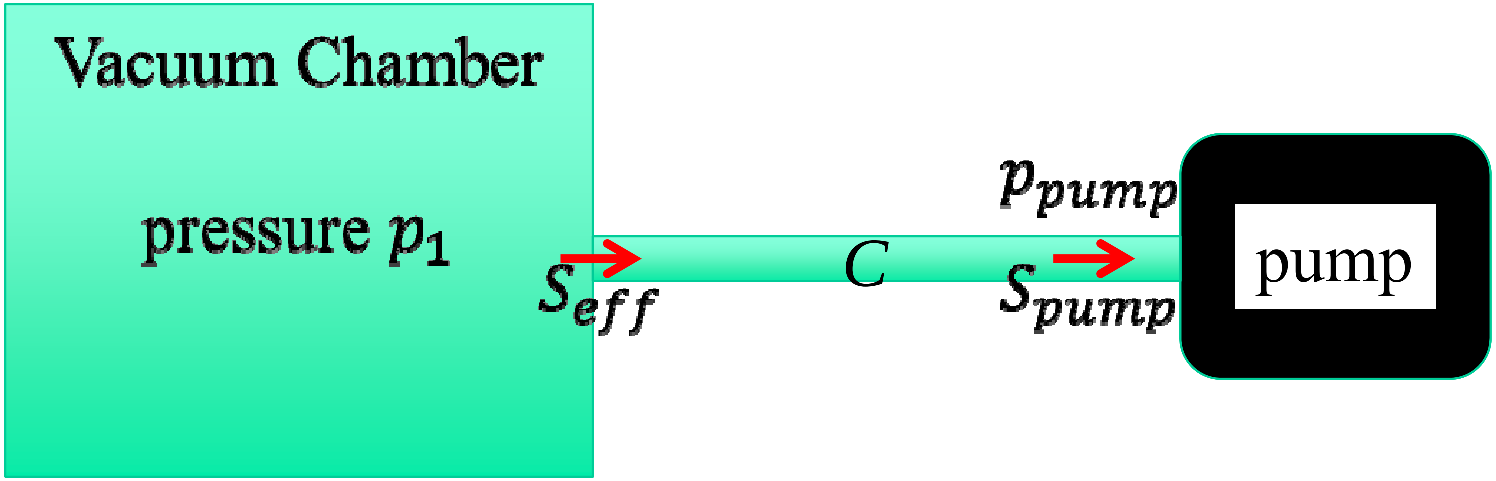


From the preceding definitions, the pump *throughput* is

$Q_\mathrm{p} = p_\mathrm{in} \, S_\mathrm{p}$ where p_in is the pressure at the inlet

Also, $\Gamma_\mathrm{p} = n_\mathrm{in} \, S_\mathrm{p}$ where n_in is the density at the inlet

Effective pumping speed, S_{eff}



A vacuum chamber is connected by a tube, conductance C, to a pump with pumping speed S_{pump}. What is the effective pumping speed, S_{eff}?

Since particle number is conserved, the throughput Q must be constant!

One can then show that :

$$S_{eff} = \left(\frac{S_{pump}}{1+S_{pump}/C}\right) < S_{pump}$$

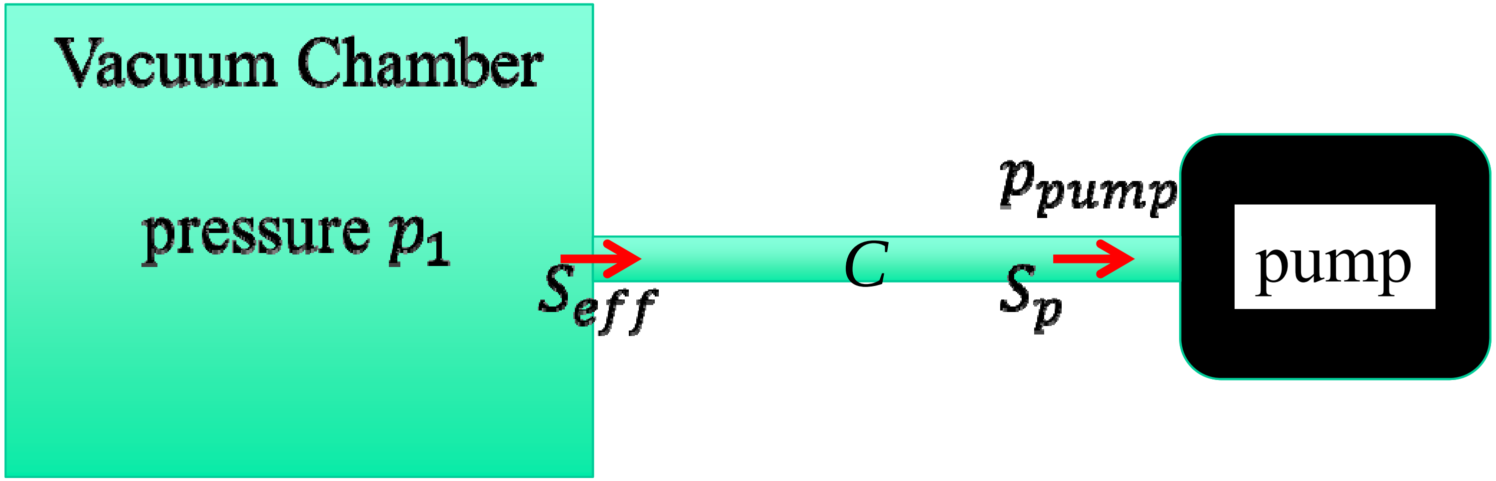
For $C \gg S_{pump},\ S_{eff} \cong S_{pump}$

Good! – full pump speed at chamber

For $C \ll S_{pump},\ S_{eff} \cong C \ll S_{pump}$

Bad! Conductance-limited pump speed at chamber

Effective pumping speed, S_{eff}



Equivalent expression: $$\frac{1}{S_{\text{eff}}} = \frac{1}{S_{\text{p}}} + \frac{1}{C}$$

- **example:**

$L = 100$ cm, $D = 4$ cm $\rightarrow$ $C_{tube}^{mol} = 7.7$ l/s

$S_{\text{p}} = 100$ l/s $\quad S_{eff} = 7.15$ l/s

and $S_{\text{p}} = 1000$ l/s $\quad S_{eff} = 7.64$ l/s

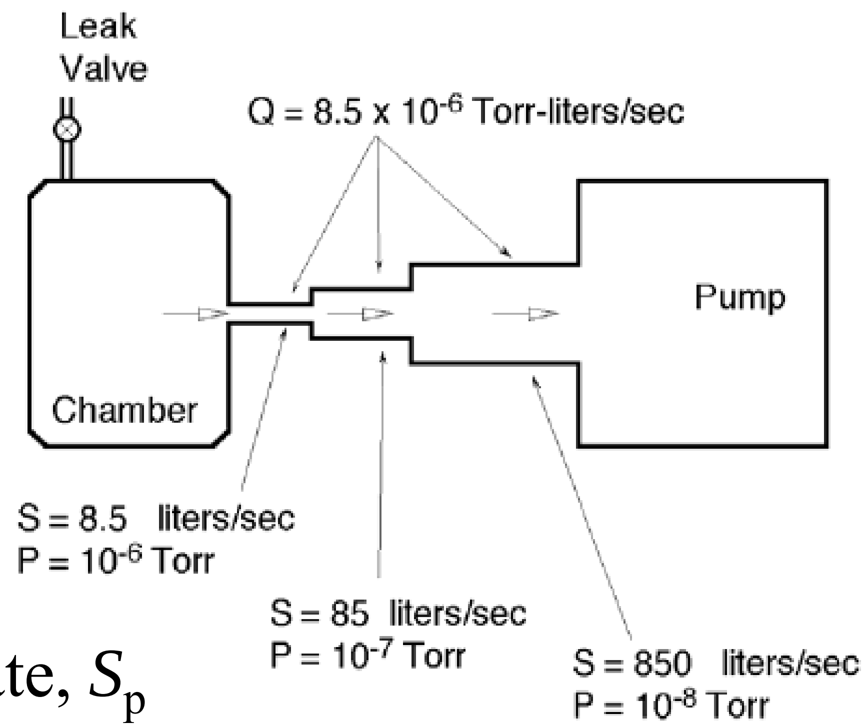
waste of a good pump!

Pumping speed

Gas Flow: Throughput and Pumping Speed

Throughput, Q, is the quantity pV of gas per sec.
Pumping speed, S_p, is the volume pumped per sec.

- gas flow rate, Q
  - called "throughput"
  - essentially the net number of molecules passing a given plane per unit time
  - By the ideal gas law equal to P-V per second
  - same throughout the circuit



- pumping speed = volume flow rate, S_p
  - changes throughout the circuit

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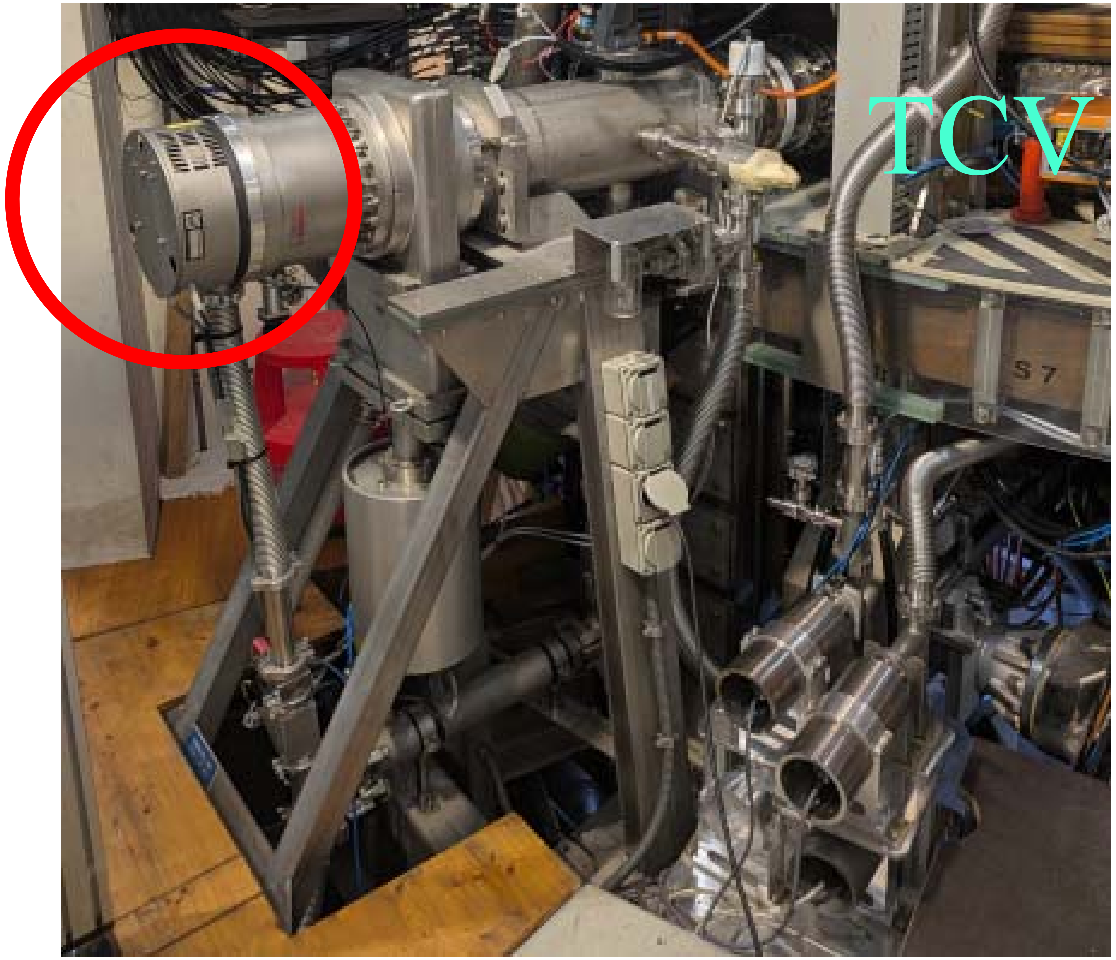
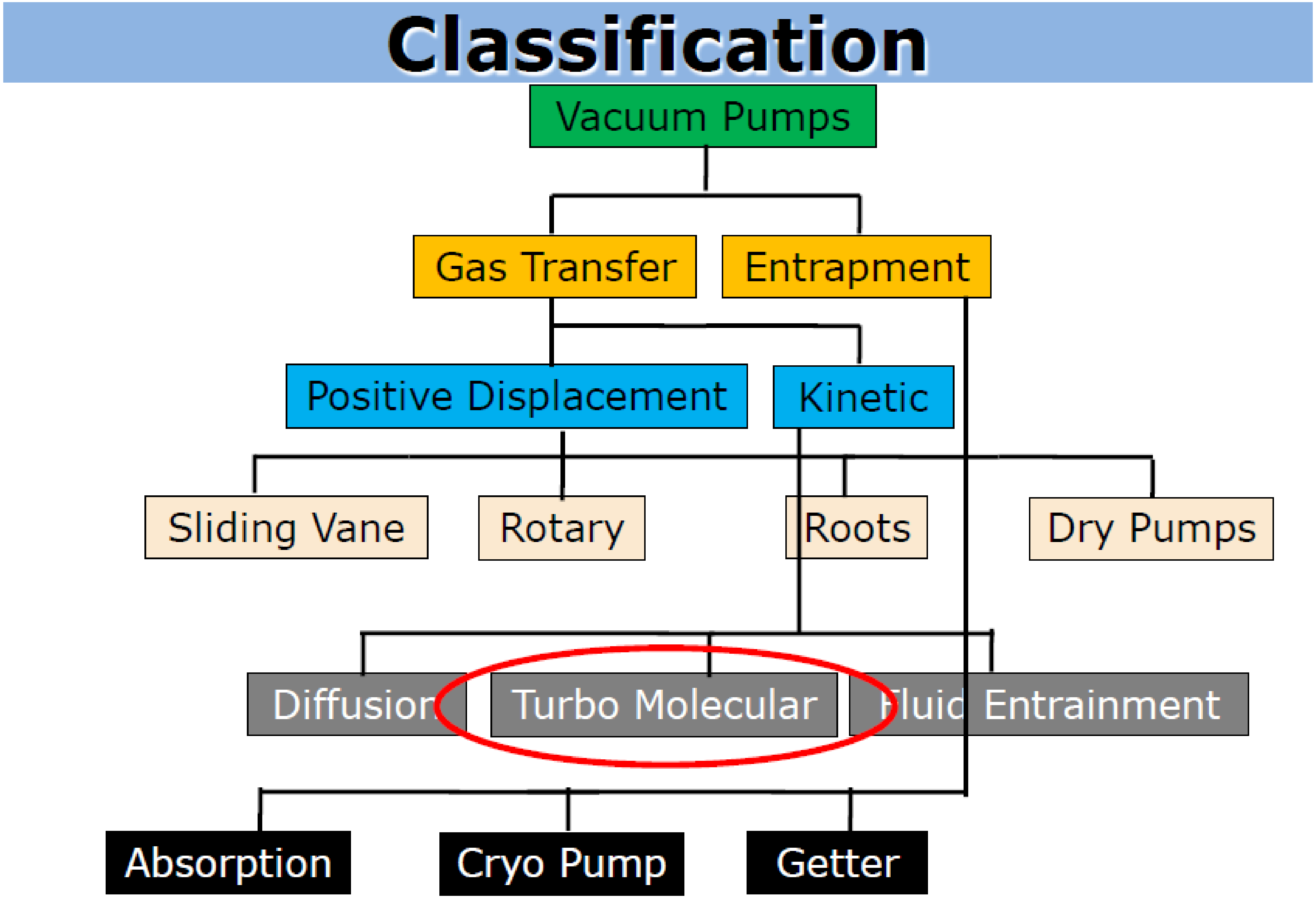
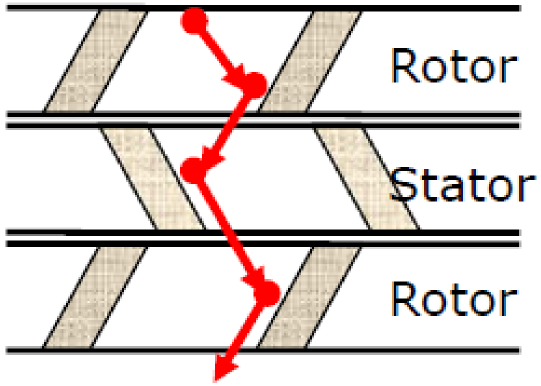
Vacuum pumps

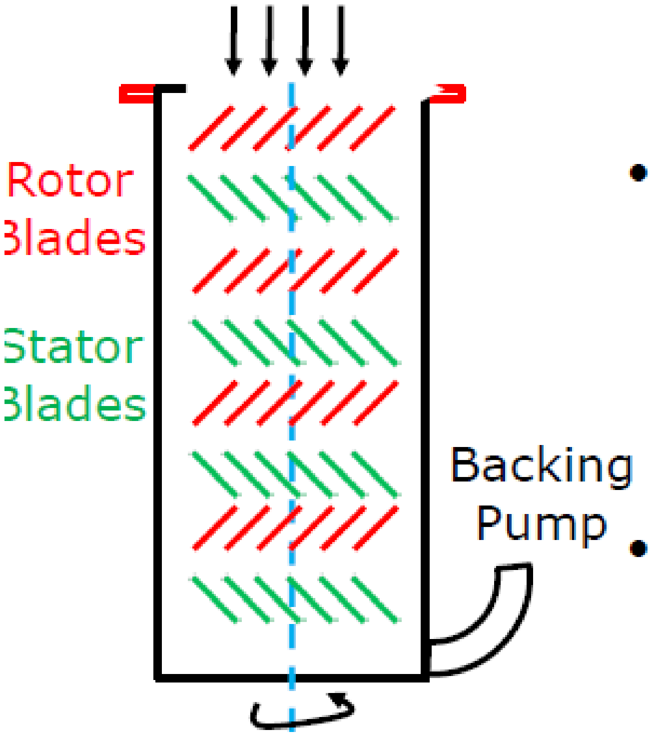


Vacuum pumps



Turbo Molecular Pump





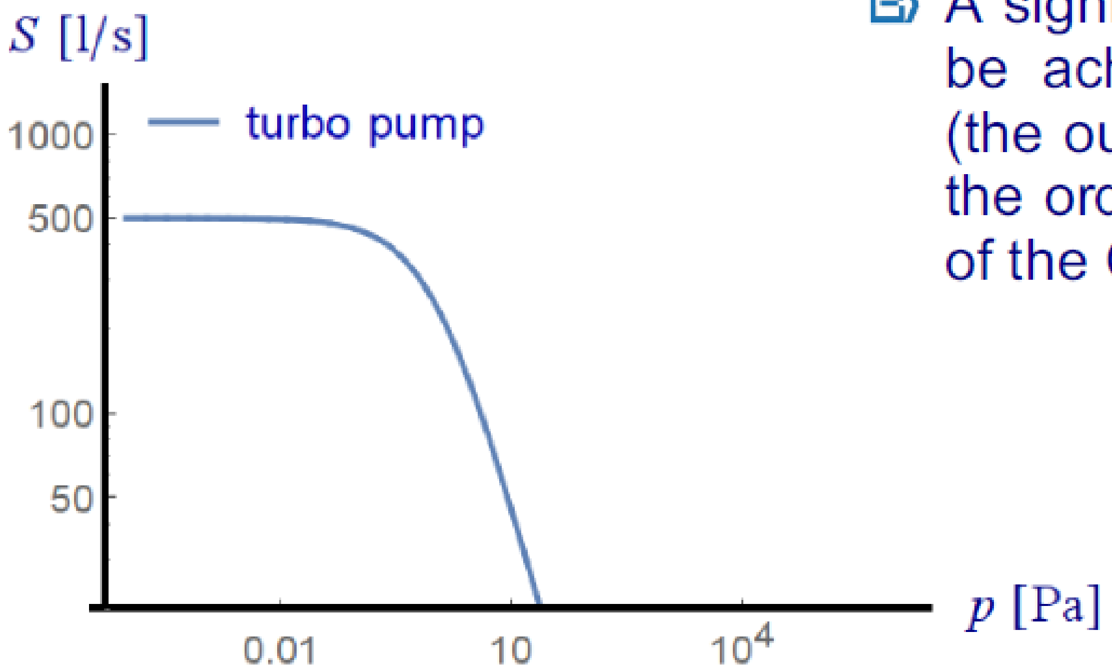
- The schematic of a Turbo Molecular Pump (TMP) is as shown.
- It consists of alternate layers of stator and rotor discs.
- The rotor rotates at a very high RPM, typically, of the orders of 27000 and above.
- The blades are mounted at an optimum angle, on both stator and rotor.

Turbo Molecular Pumps

- High rpm up to 76000 rpm rotor blades impart momentum to molecules
- For molecular flow regime
- Can have vibrations
- Needs mechanical pump.

Turbomolecular Pump – Parameters and Application

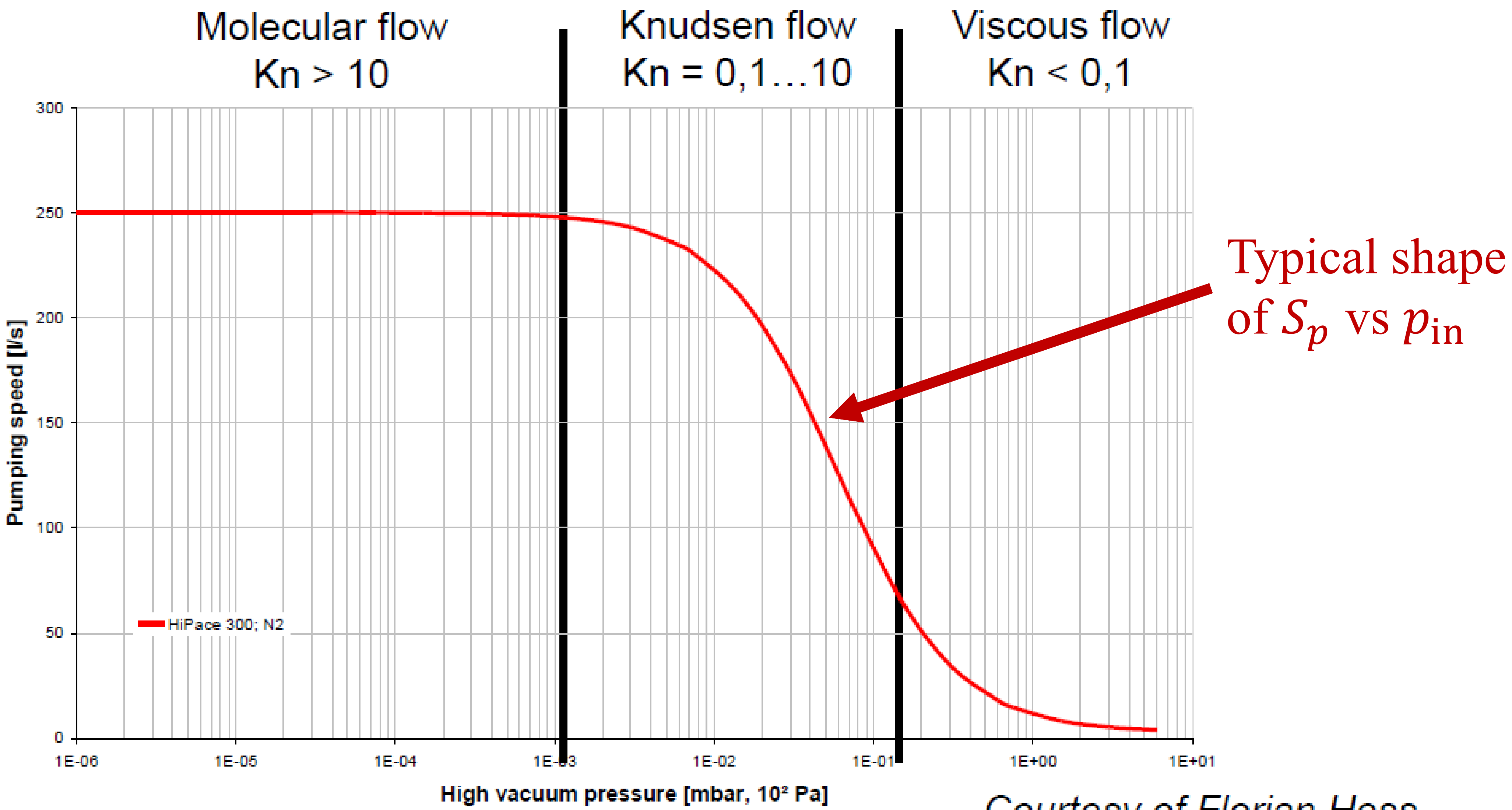
- In the range above 10 Pa the operation of the rotor is disturbed by frequent collisions between the particles. Therefore, a turbo-molecular pump is not capable to pump gases against higher outlet pressure.
- An increasing particle density leads to a higher power consumption and a subsequent heating of the pump. This result also a a upper pressure limit.



- A significant pumping speed only can be achieved if the peripheral speed (the outer edge) of the rotor blades in the order of the mean thermal velocity of the Gas molecules.

Turbo molecular pumps (*turbopumps*)

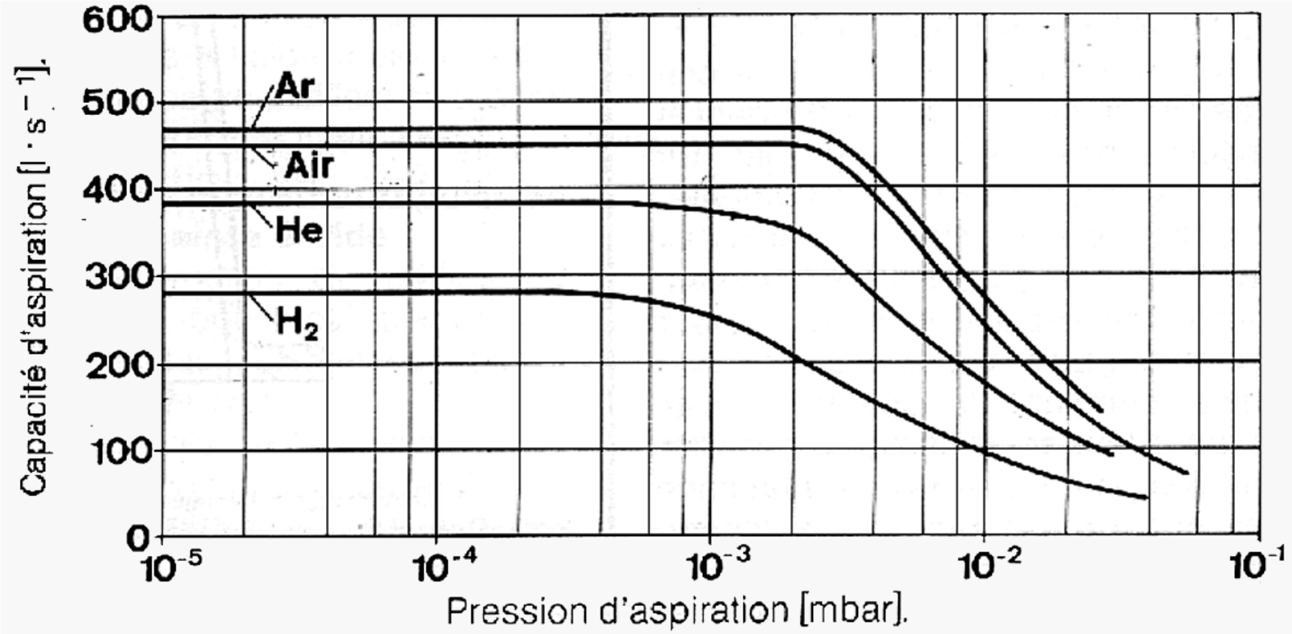
Useful in molecular flow regime



Courtesy of Florian Hess

Turbopumps

S_p depends on gas type

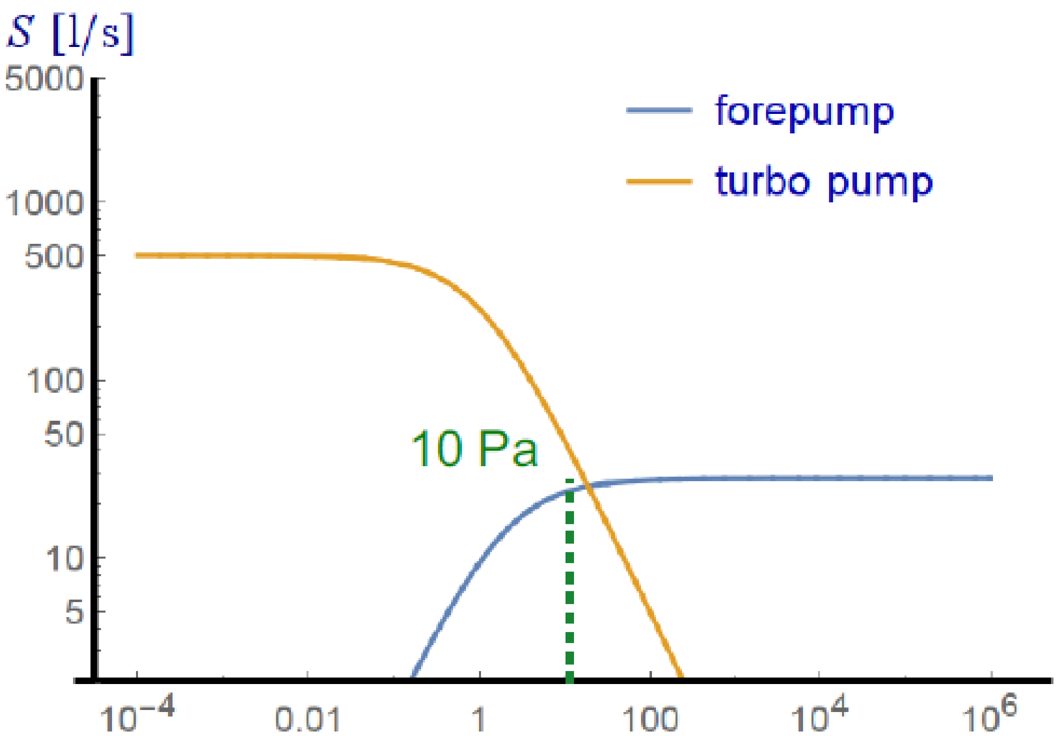


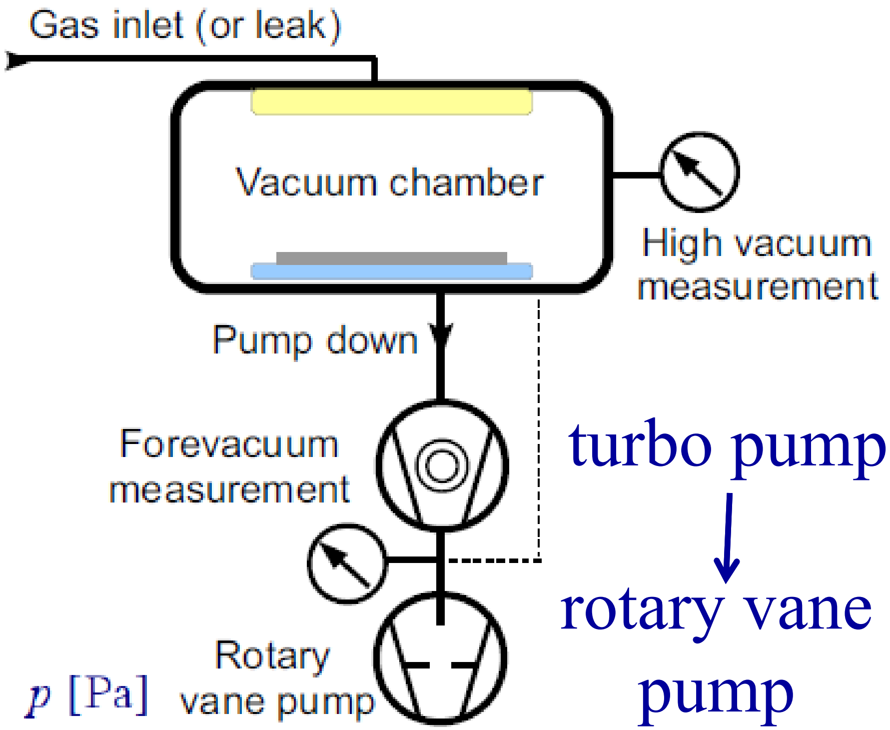
Turbo pumps are not so good for light gases (He, H2) because of their high thermal velocity (this is exploited in the counter-flow technique for leak detectors).

Pressures as low as 10^{-10} mbar are possible.
Pumping speeds from 50 to 5000 *l*/s are available.

Turbomolecular Pumps in Vacuum Systems

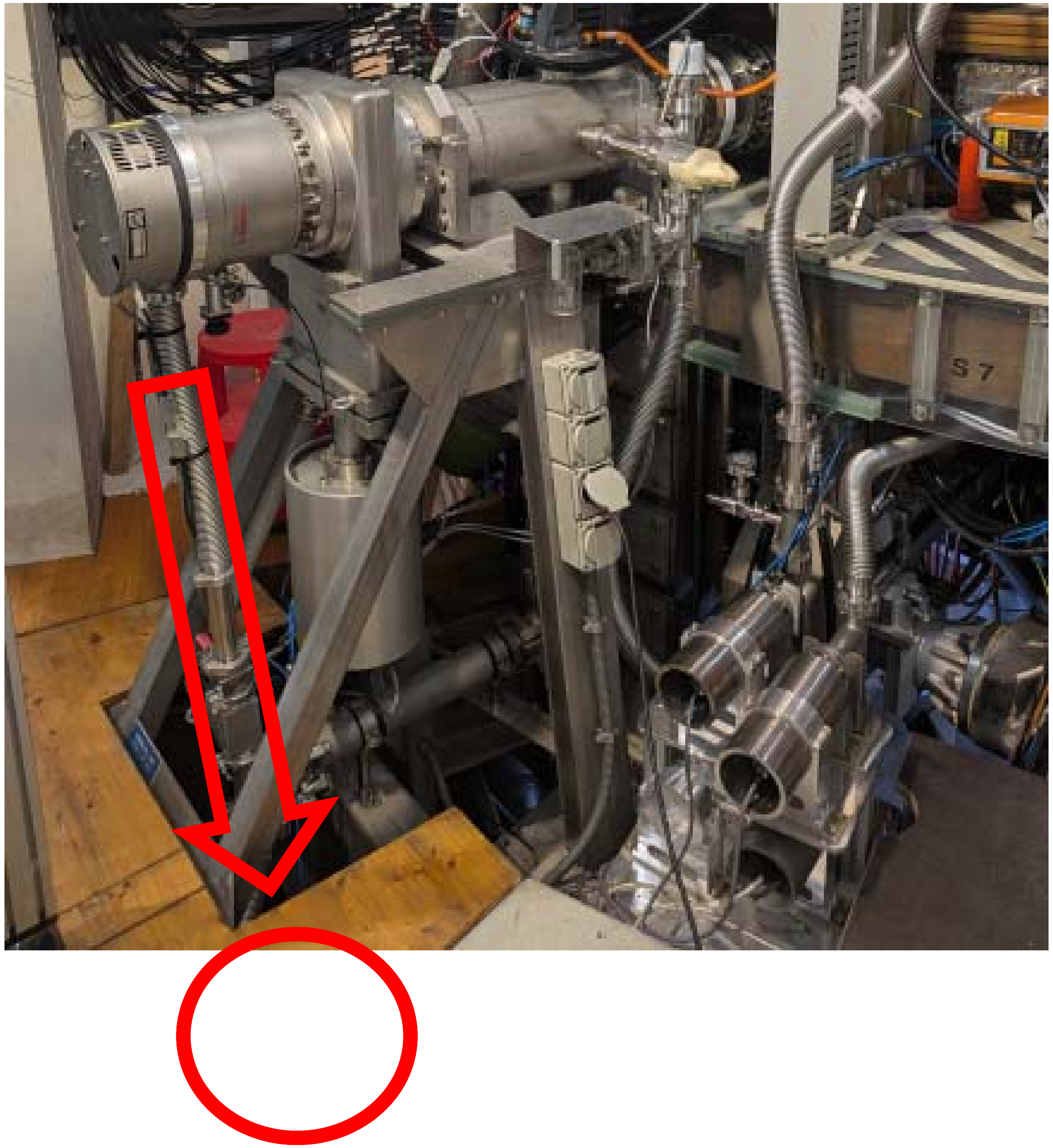
- The classical Turbo-molecular stage must be supported by a properly sized forepump.
- In most of cases the forepump pumps through the turbo pump. Below 10 Pa (75 mTorr), the turbo pump is started.
- Some tools use a special bypass (dashed line) for soft pump down.



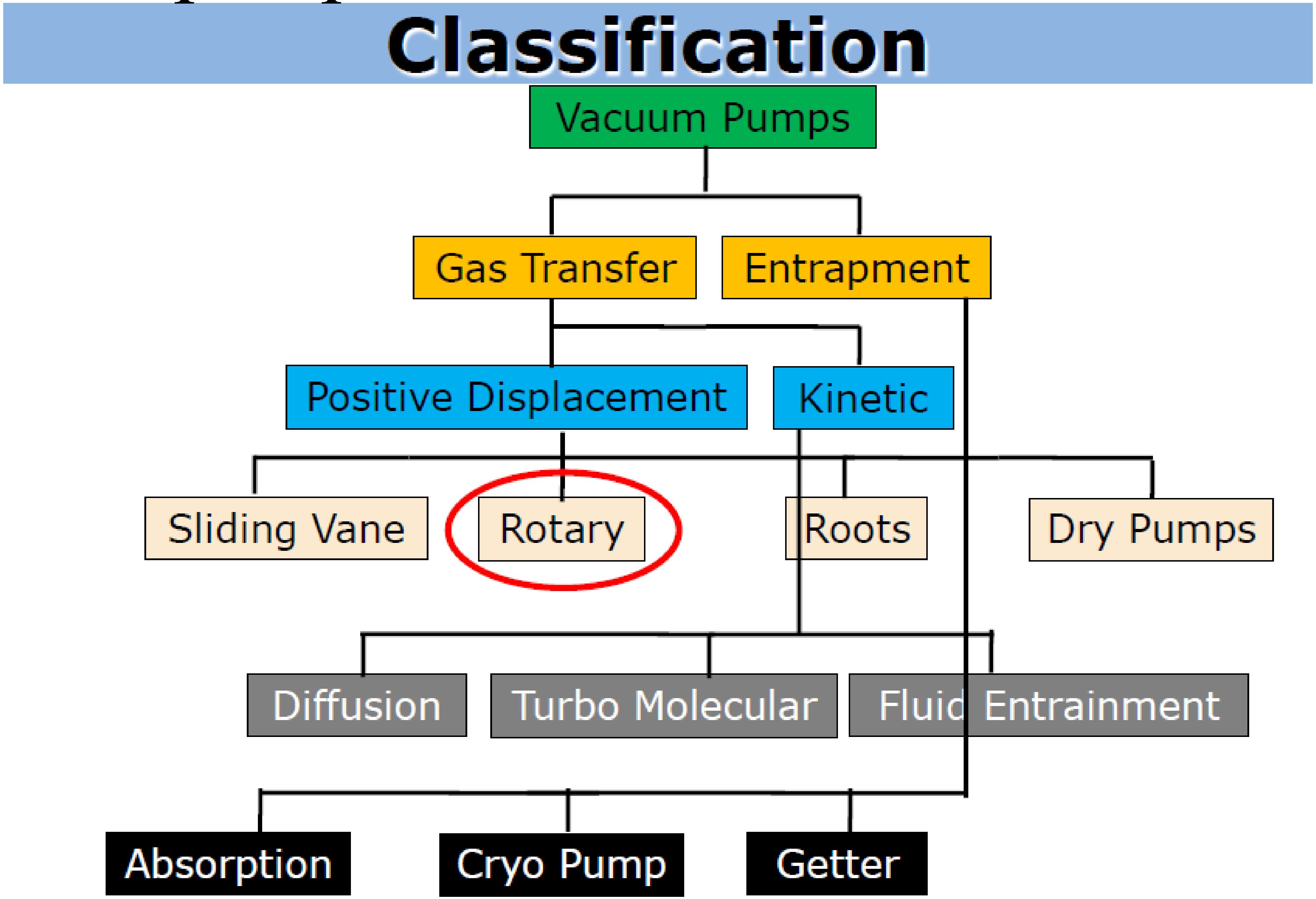


Source: Plasma School Plasmetrex, © Plasmetrex 2014

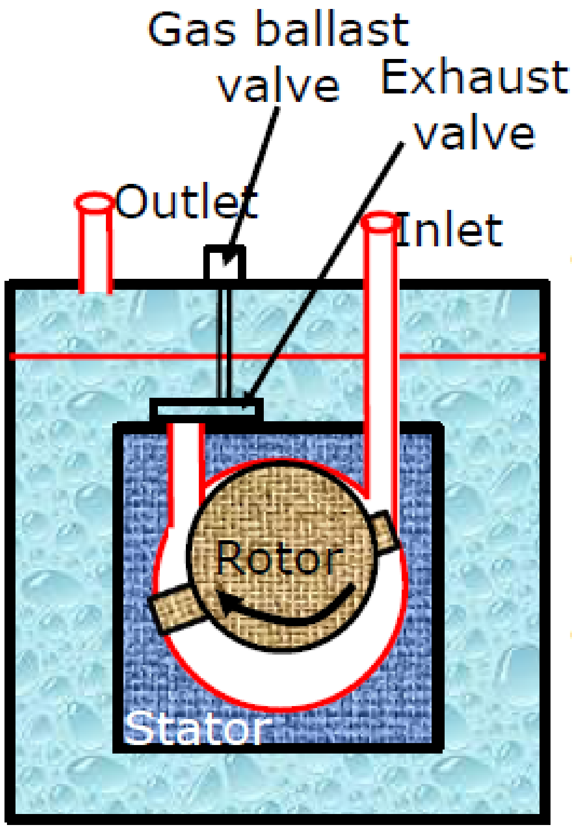
Vacuum pumps



Vacuum pumps

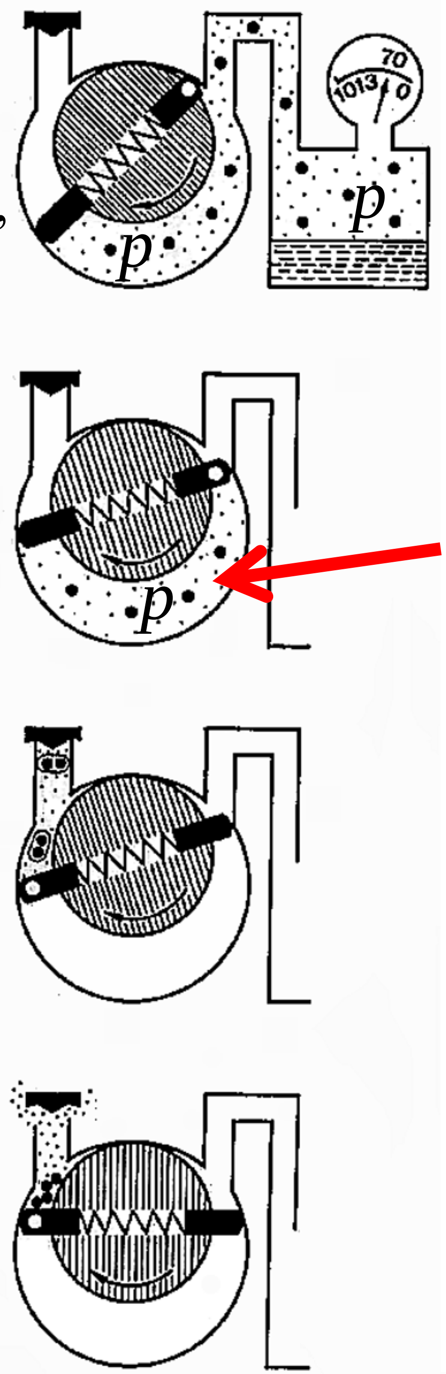


Rotary Vane Pump



- The schematic of a Rotary vane pump is as shown in the figure.
- It consists of a stationary part, Stator and a moving part, Rotor, assembled inside a casing.
- Moving component is an eccentrically placed slotted rotor, which turns inside cylindrical stator.
- Spring loaded sliding vanes are mounted in the slots of the rotor.

Rotary Vane Pump
Pumping Speed S_p



Chamber is open to the pump, gas flows into pump chamber

Volume is isolated from chamber

Volume is compressed, pressure rises

Volume is ejected to atmosphere

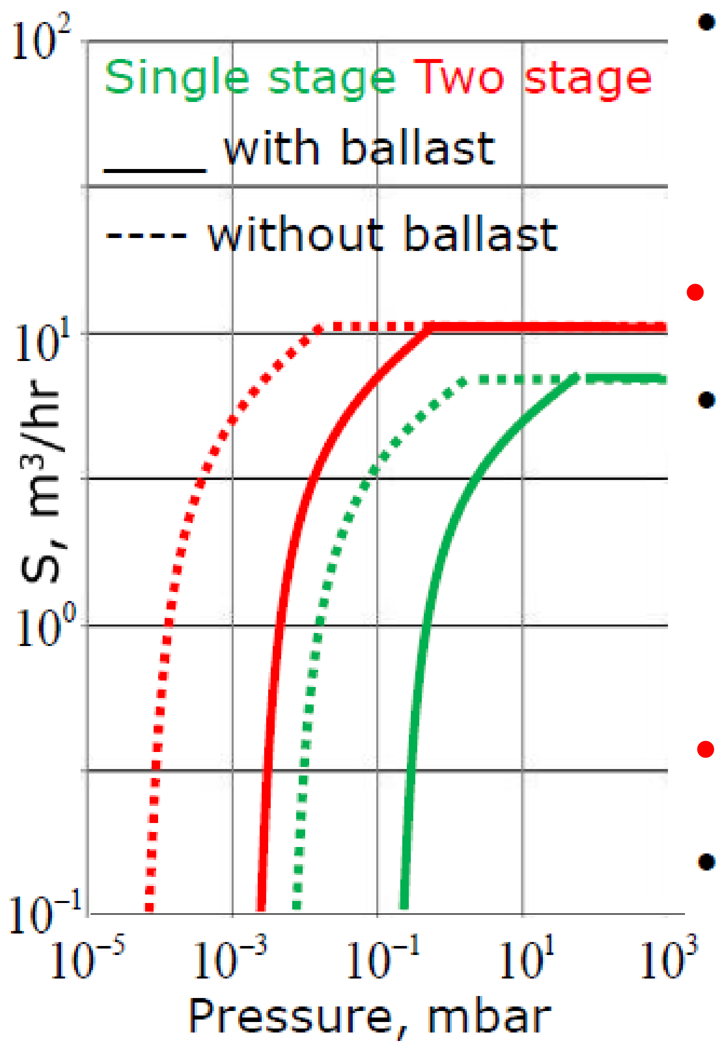
This volume V is removed for each rotation.

Pumping speed S_p $\approx V$ x rotation frequency

OK for the viscous (continuous) flow regime.

Too much backflow for molecular regime (internal leaks).

Rotary Vane Pump



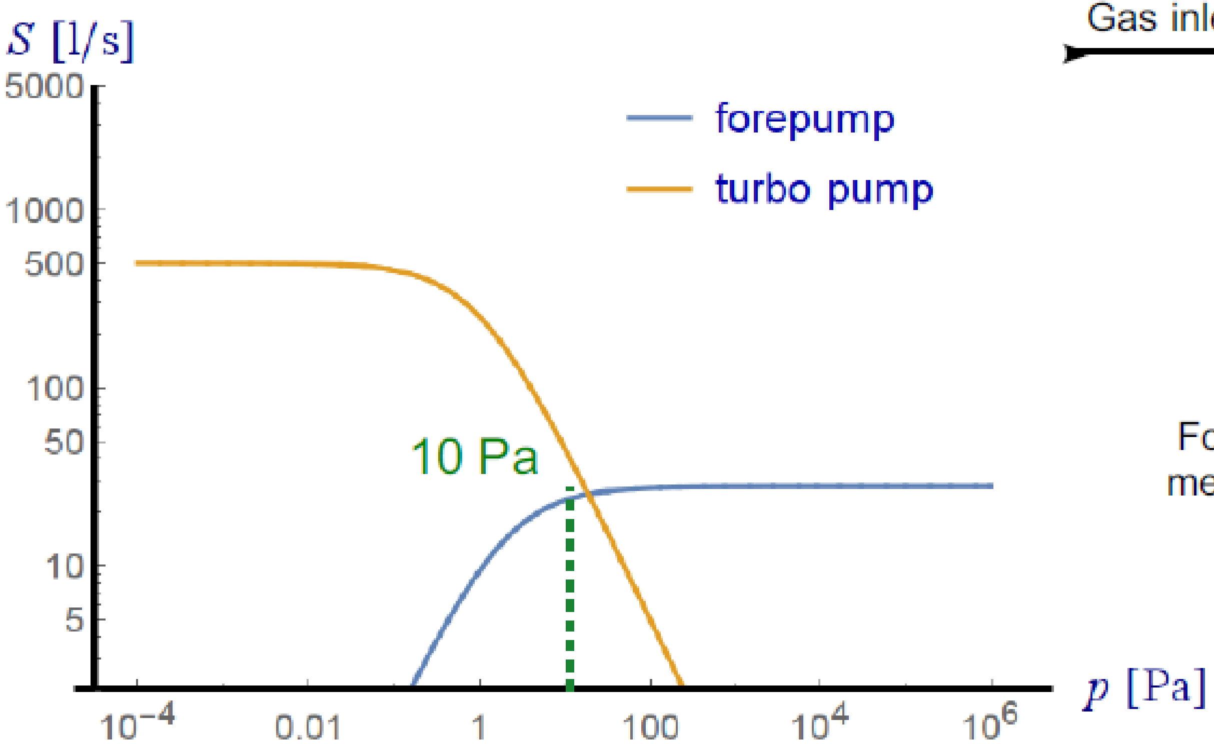
Pumping speed S [m³/h]

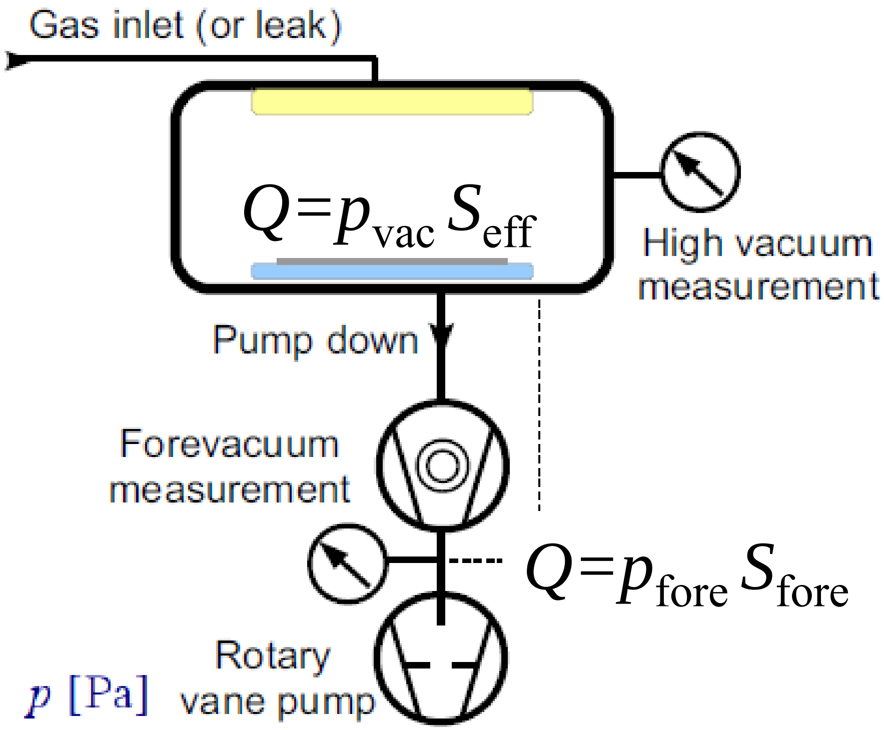
- The adjacent figure shows the pump characteristics for Single and Two stage Rotary pumps.
- **Pumps from atmosphere down to ~0.01 mbar**
- The solid and dotted lines correspond to pumps with and without gas ballast arrangements respectively.
- **S = 15 m³/h – 150 m³/h depending on size**
- Two stage or multi stage pumps are used to improve the performance and the ultimate pressure ($\mathbf{p_u}$) of the system.

Determination of a Suitable Forepump

- The classical Turbo-molecular stage must be supported by a properly sized forepump.

$$Q = p_{vac} S_{eff} = p_{fore} S_{fore} \,, \qquad p_{fore} < 10 \text{ Pa}, \qquad S_{fore} > S_{eff} \frac{p_{vac}^{max}[\text{Pa}]}{10}$$





Source: Plasma School Plasmetrex, © Plasmetrex 2014

Vacuum pumps

Common pumps for industrial plasma processing

	Mechanical	Diffusion	Turbo molecular	Ion	Ti Sublimation	Cryo
Type	Gas Transfer	Gas Transfer	Gas Transfer	Adsorption	Adsorption	Adsorption
Pressure **Range** [mbar]	10^{3} - 10^{-3}	10^{-3} – 10^{-7}	10^{-4} – 10^{-10}	10^{-6} – 10^{-11}	10^{-6} – 10^{-11}	10^{-6} – 10^{-9}
Pump Speed	Up to 300 lt/s	Up to 50K lt/s	50 – 3500 lt/s	Up to 1000 lt/s	Surface area dependent	Vapor dependent (~1000 lt/s)
Pros	Low vacuum workhorse, roughing pump	No vibrations	Clean	Clean, bakeable, no vibrations	Used as an addition to other UHV pumps	Clean
Cons	Vibrations, oil contamination	Hot oil	Vibrations	Lower pump speed	Not for inert gases	Vibrations, not for Helium

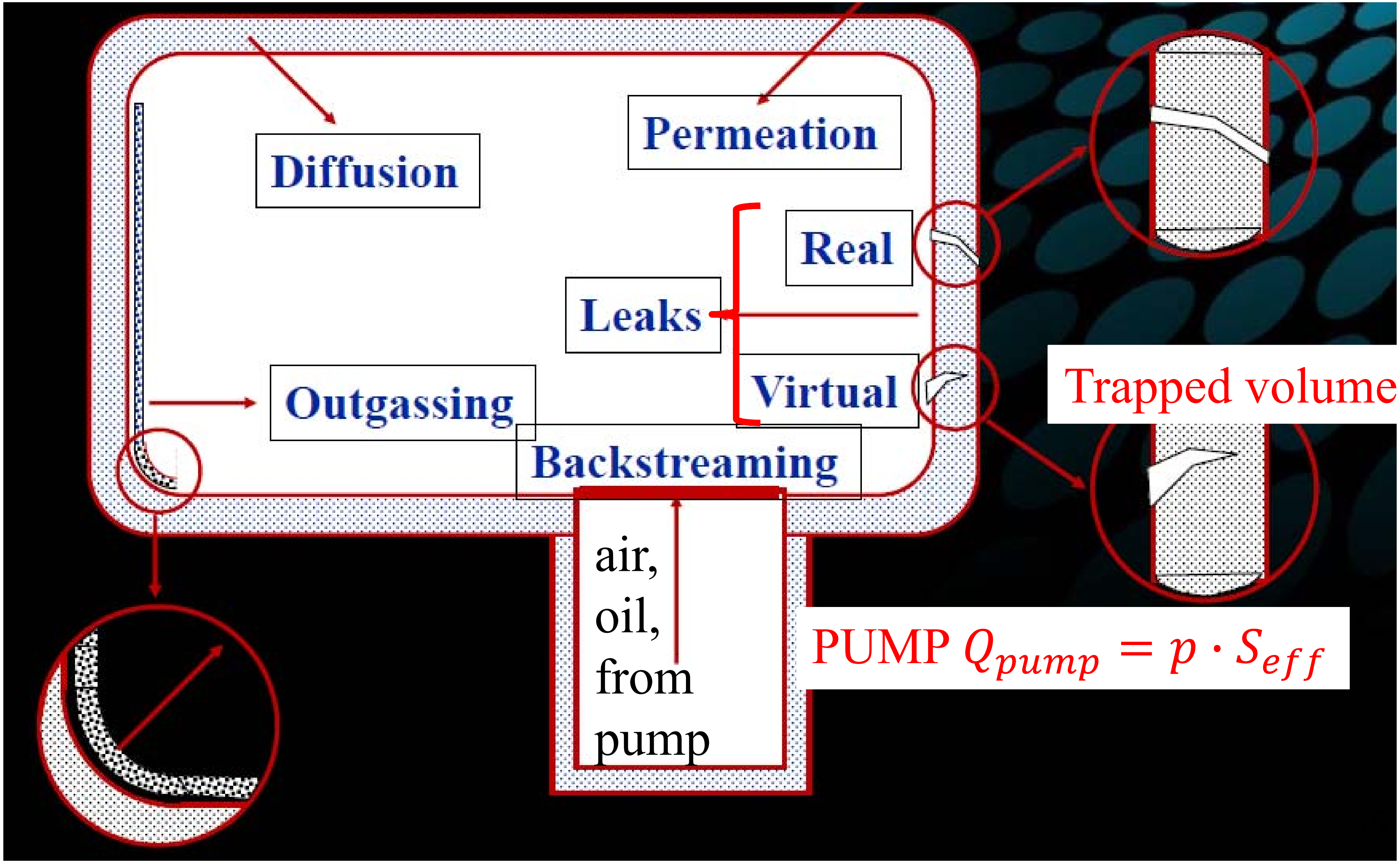
Outline

1. Introduction - vacuum, pressure, mean free path
2. Vacuum quantities - flow rate, conductance, throughput
3. Pumping speed
4. (Some) vacuum pumps - descriptive
5. Sorption, desorbtion, permeation, degassing, outgassing, leaks, virtual leaks, base pressure, ultimate pressure
6. (Some) vacuum gauges and components - descriptive
7. Practical advice, and leak detection (*if time permits*)

Leaks, outgassing, etc.

In steady state, the pumping speed balance is given by:

$$Q_{\text{Leaks}} + Q_{\text{Outgas}} + Q_{\text{Diffn}} + Q_{\text{Perm}} = pS_{\text{eff}} - Q_{\text{Backstreaming}}$$



Leaks, outgassing, etc.

The BASE PRESSURE of the system (vacuum chamber + pump) is:

$$p_{\text{base}} = \frac{Q_{\text{Leaks}} + Q_{\text{Outgas}} + Q_{\text{Diffn}} + Q_{\text{Perm}} + Q_{\text{Backstreaming}}}{S_{\text{eff}}}$$

Base Pressure = pressure in absence of process gas flow (the "off" condition)

- For real vacuum systems, a base pressure must be reached for the sake of process purity and stability. This pressure must be reached in a determined period of time and is always higher than the ultimate pressure.

  Question of contamination and purity of plasma processing

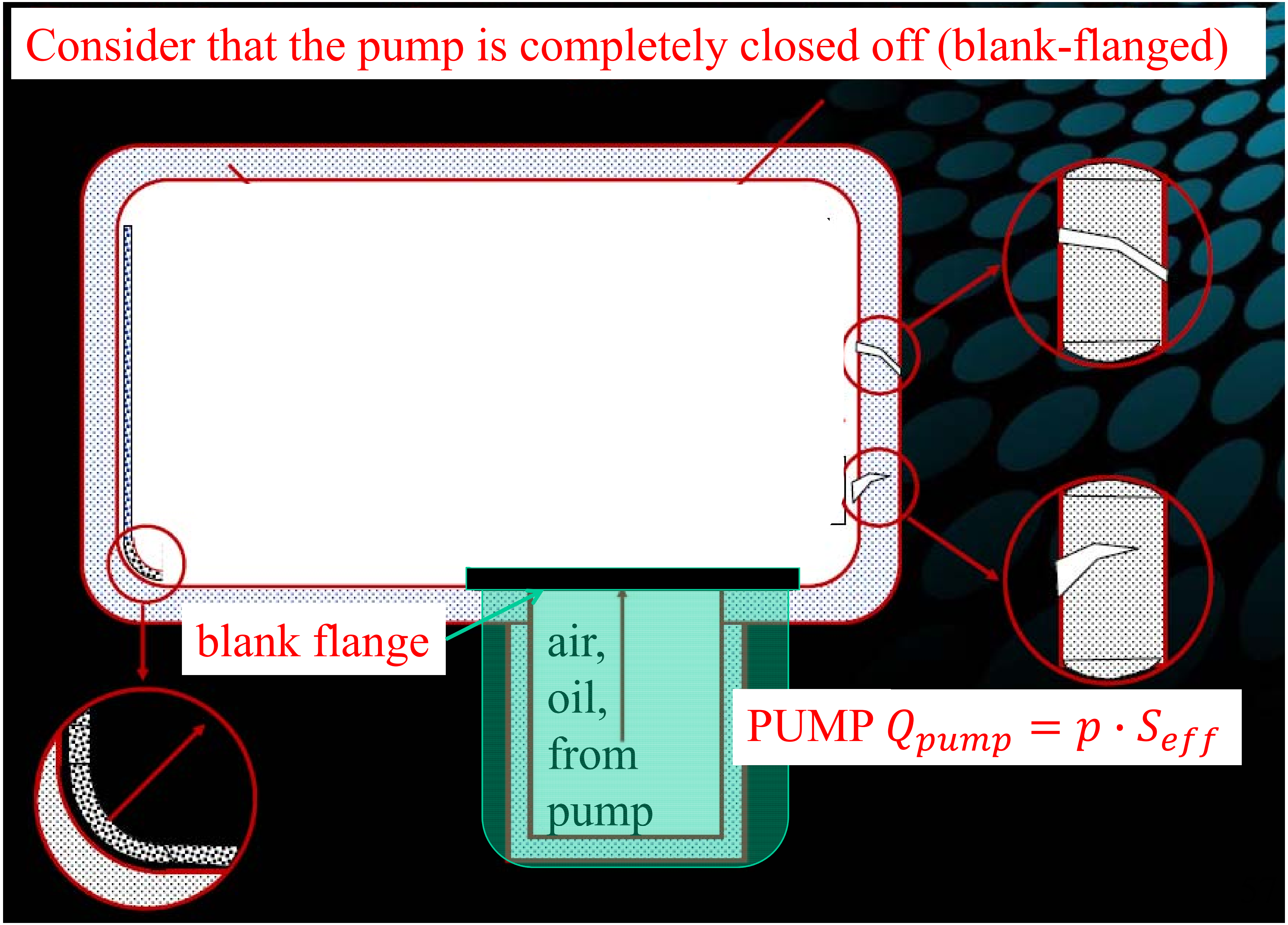
- The base pressure of a process chamber is a technological key parameter indicating that the leakage rate is in regular range.

  Using KF, $p_{\text{base}} \sim 10^{-6}$ mbar is "ok". Using CF, expect $p_{base} < 10^{-8}$ mbar.

- Base pressure checks are often used in semiconductor manufacturing to check process chambers against leaks periodically.

To improve (reduce) the base pressure, $Q \downarrow$ and/or $S_{\text{eff}} \uparrow$

Backstreaming and ultimate pressure



Backstreaming and ultimate pressure

In steady state, the pumping speed balance is given by:

$$0 = pS_{\mathrm{eff}} - Q_{\mathrm{Backstreaming}}$$

The ULTIMATE PRESSURE of a pump is:

$$p_{\mathrm{ultimate}} = \frac{Q_{\mathrm{Backstreaming}}}{S_{\mathrm{eff}}} < p_{\mathrm{base}}$$

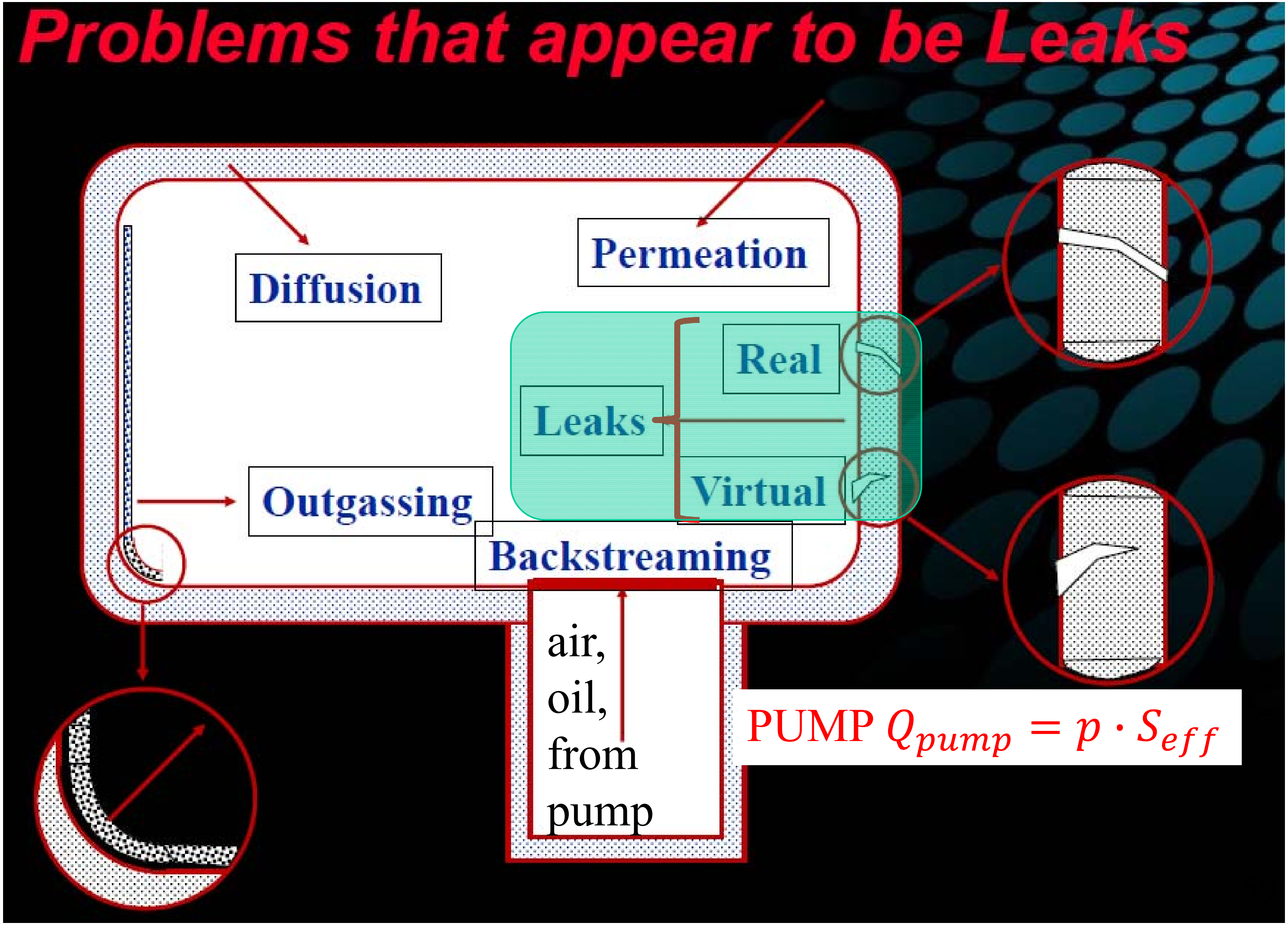
Vacuum Pump Performance – Ultimate Pressure

- Ultimate pressure p_e is the lowest pressure that can be asymptotically reached by blank-flanged vacuum pump. This value can only be observed under special test conditions.

- A pump operating at ultimate pressure has a pumping speed of zero.

$p_{\mathrm{ultimate}} \sim 10^{-3}$ mbar for backing pump; $p_{\mathrm{ultimate}} \sim 10^{-10}$ mbar for turbo.

Leaks

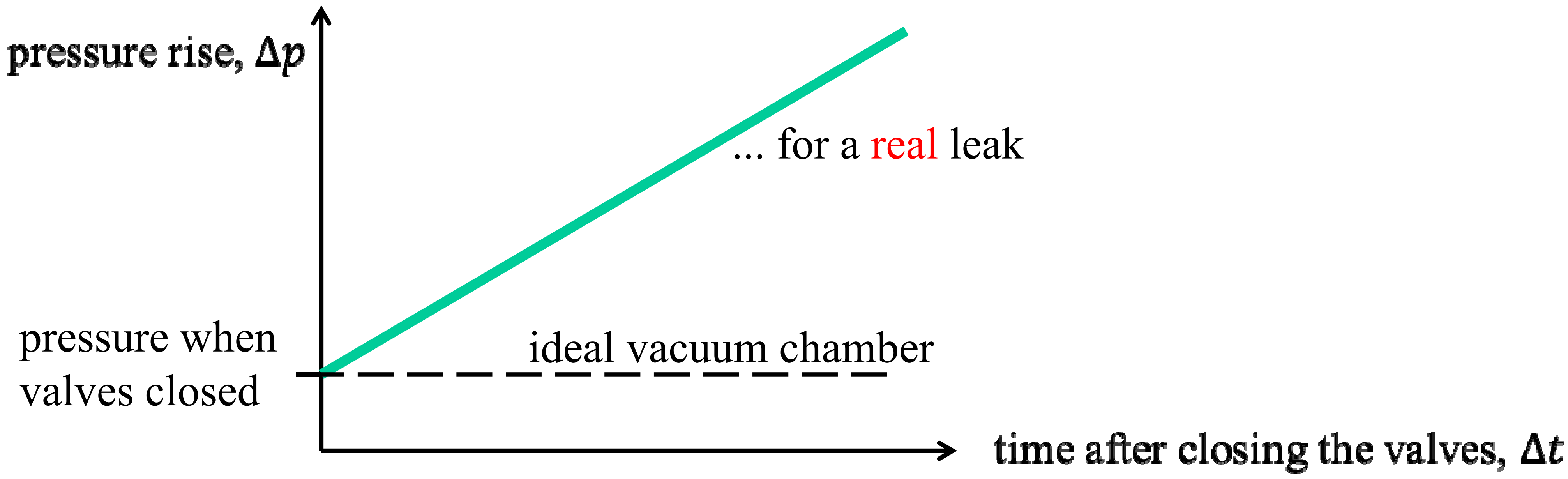


Problems that appear to be Leaks
Permeation
Diffusion
Real
Leaks
Virtual
Outgassing
Backstreaming
air,
oil,
from
pump
PUMP $Q_{pump} = p \cdot S_{eff}$

Leaks (real)

Leak Detection - Pressure rise curves

Careful Pressure follow-up when valving off the pumping provides indications on the leak tightness



Leak rate $Q_{leak} = \frac{\Delta p.V}{\Delta t}$ [mbar litres/s]. Pressure rise rate, for fixed volume.

For a real leak, there must be a hole size >10 molecular diameters, from atmosphere to inside the vacuum chamber. No physical interactions.

Chambers, Fitch and Halliday, "Basic Vacuum Technology" p127.

Leaks (real)

Some orders of magnitude for real leak rates:

Examples

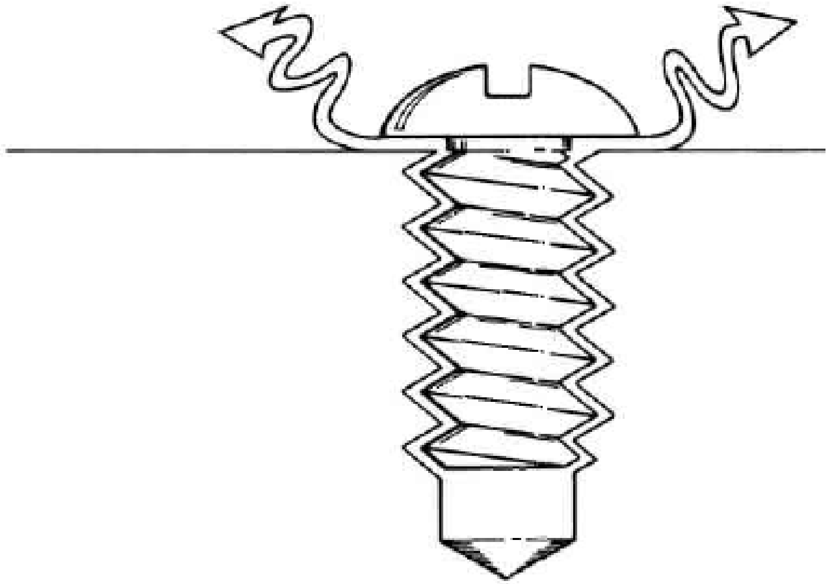
- high vacuum (HV-) system

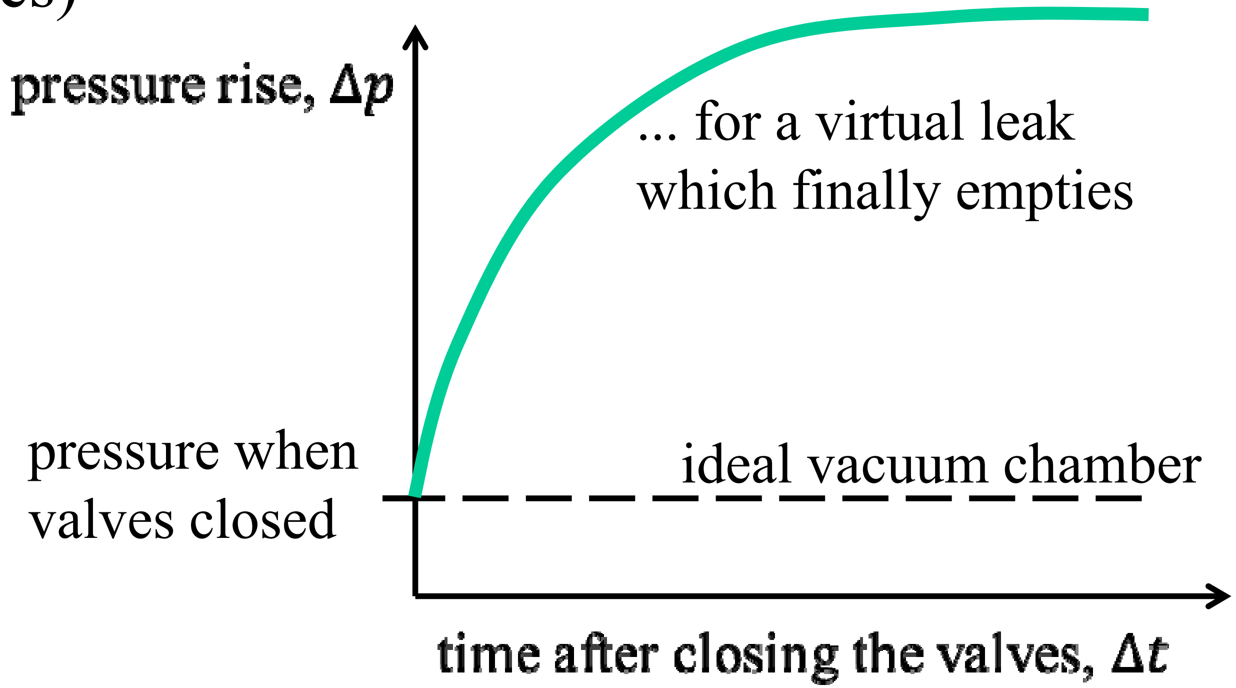
  $Q_l < 10^{-6}$ mbar·l/s ➥ very tight
  $Q_l < 10^{-5}$ mbar·l/s ➥ tight
  $Q_l < 10^{-4}$ mbar·l/s ➥ leaky

Diameter of hole	Leak rate
0.01 mm (hair)	10^{-2} mbar·l/s
10^{-10} m = 1 Å	10^{-12} mbar·l/s

Leaks (virtual)

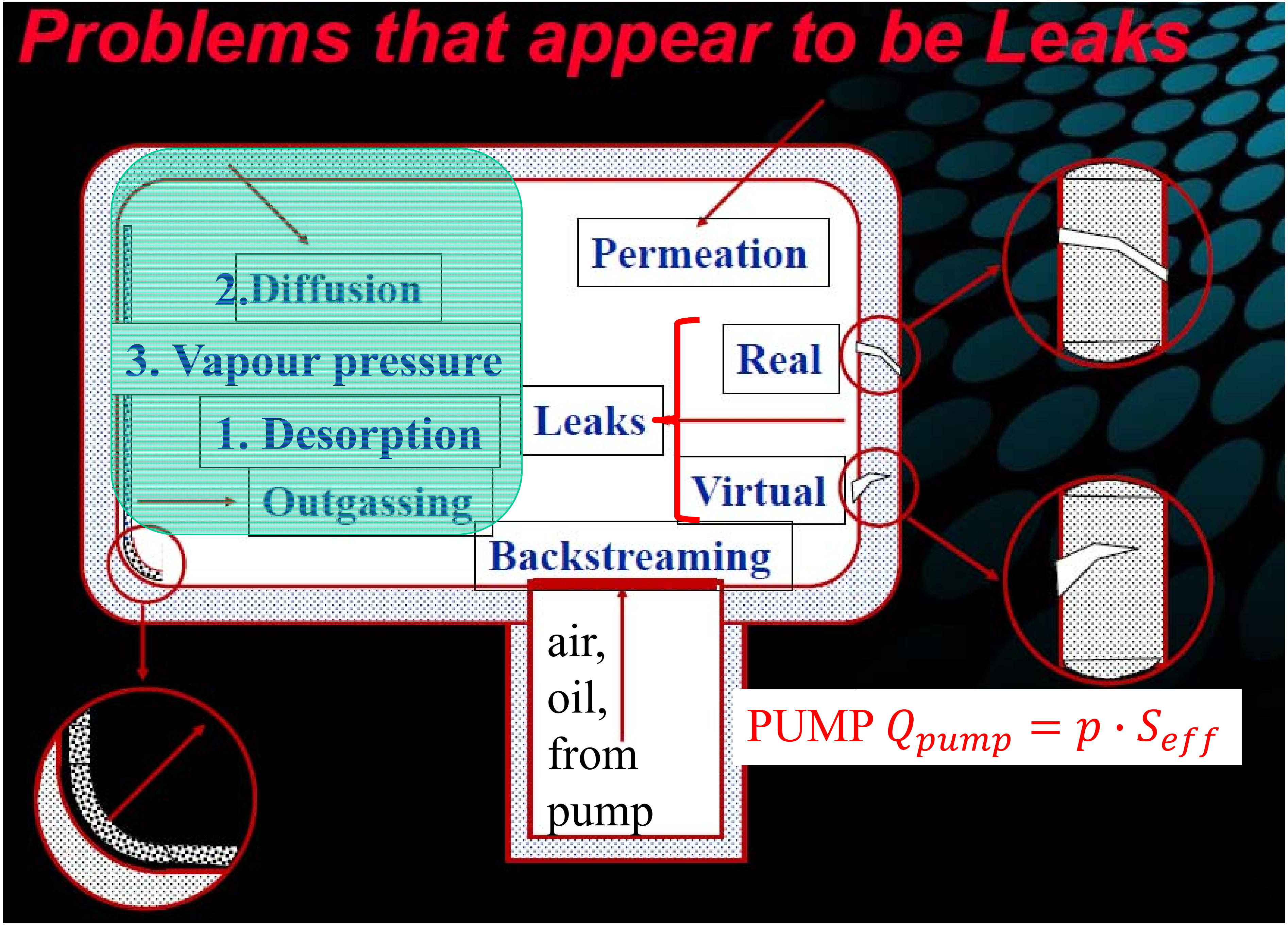
Virtual leaks are due to trapped volumes which release gas (or vapour) slowly (no physical changes)



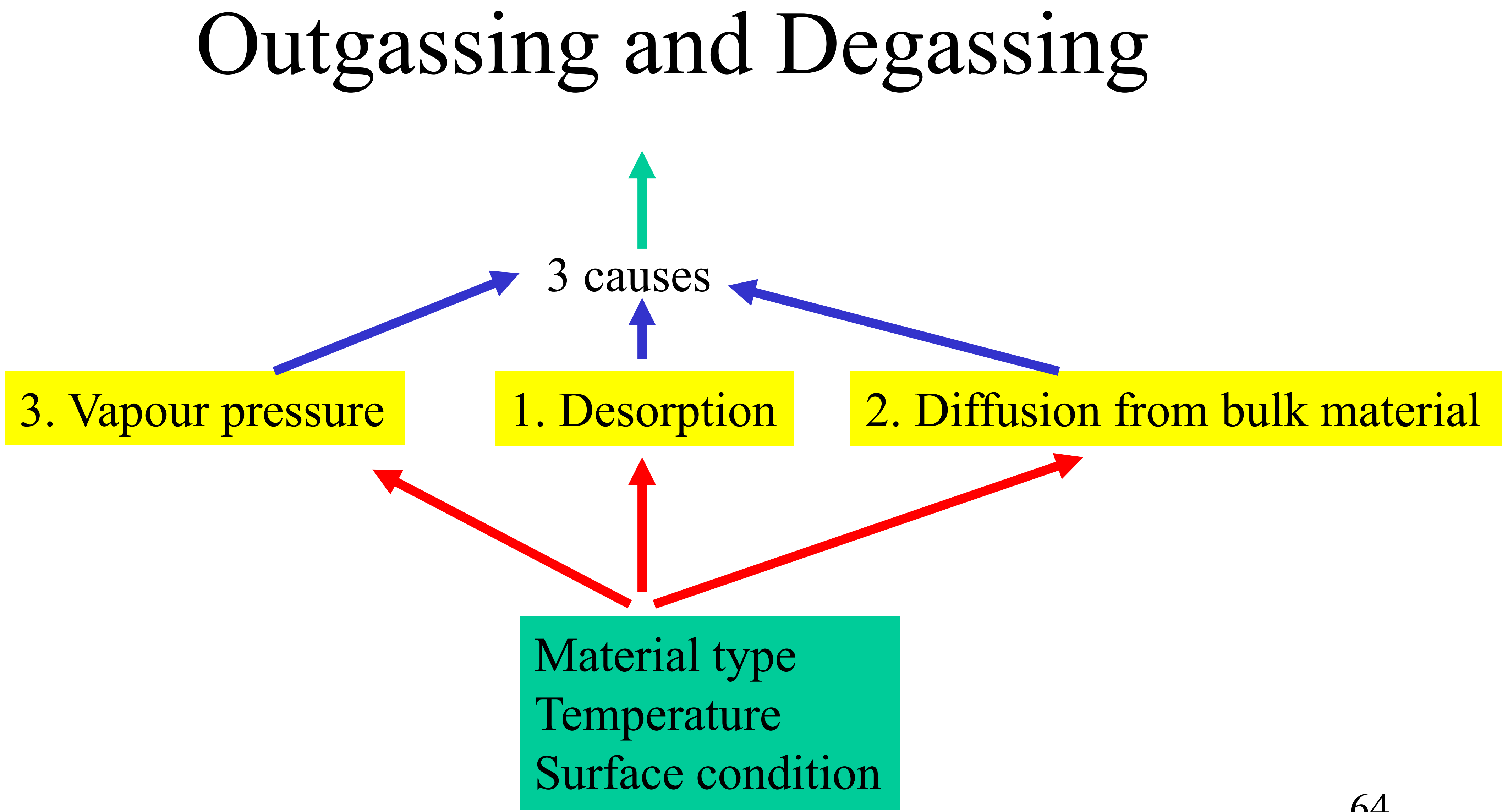


- 3D printed plastics probably very bad.
- Problem of residual pressure in satellites.

Outgassing and degassing

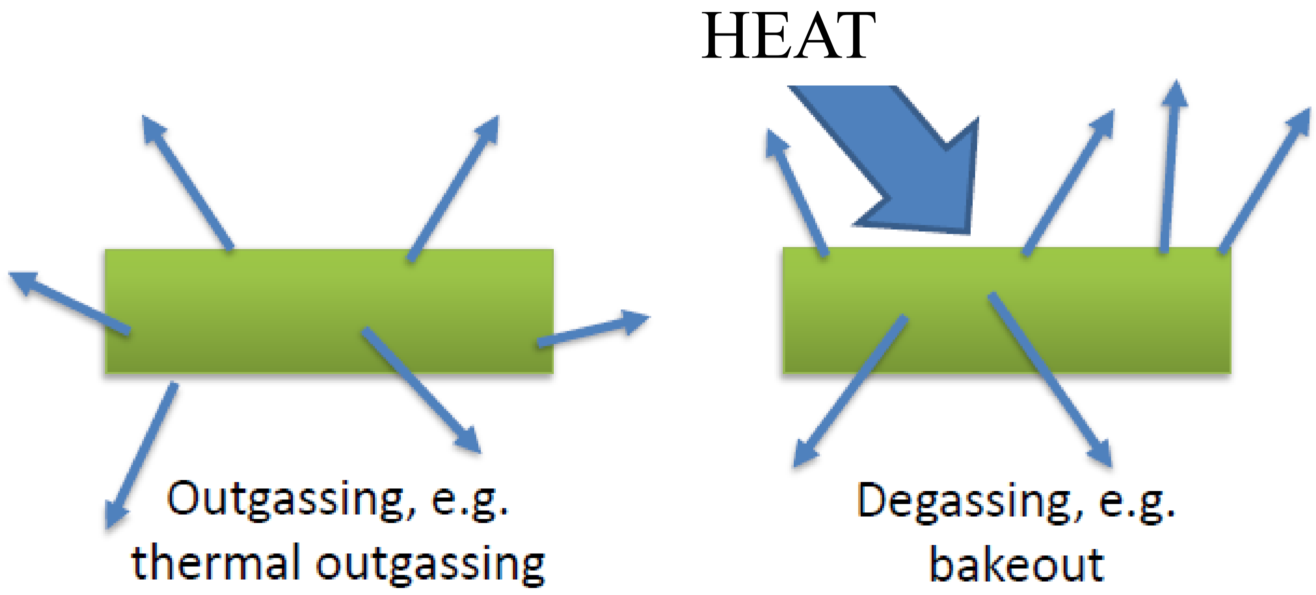


Outgassing and degassing



Outgassing and degassing

- Definitions:
  - Outgassing: spontaneous release of the gas from solid or liquid
  - Degassing: deliberate removal of the gas from solid or liquid



Desorption

Outgassing of Unbaked Metals (for example, after venting to atmosphere)

- Water is the main gas desorbed multiple layers!
- Outgassing rate of water decreases following a 1/t law
- Water outgassing does not depend significantly on the nature of metals, on surface treatments and on temperature (for temperatures lower than 110° C)
- No methods, except heating, exist to quickly remove water from unbaked metals

Outgassing of baked metals

- Hydrogen is the main gas desorbed by baked metals
- Diffusion model predicts values for the hydrogen outgassing

Outgassing and degassing

The *specific* outgassing rate is $Q_{tot}/Area$

For baked clean metals: $<10^{-12}$ mbar l s^{-1} cm^{-2}

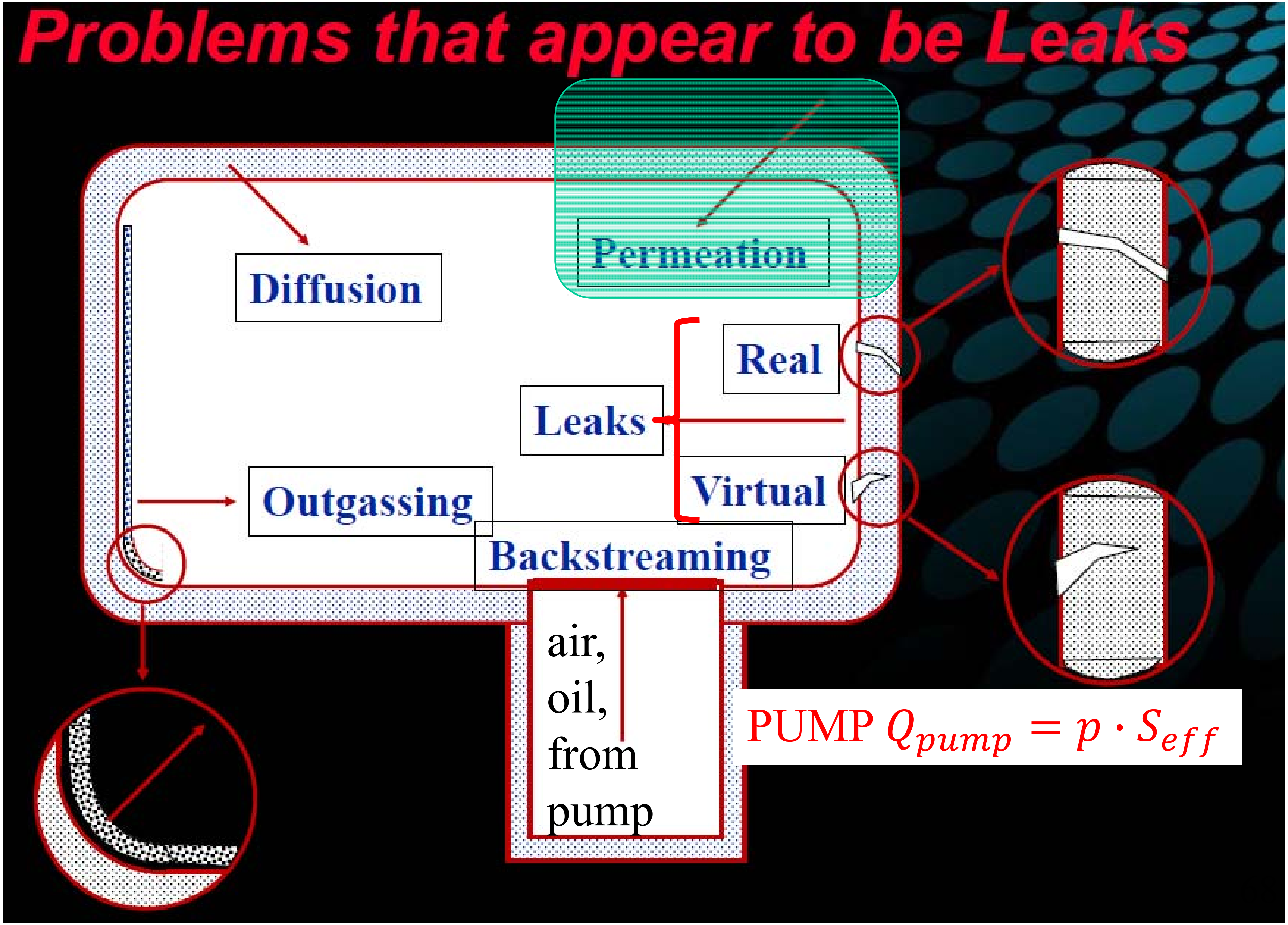
For unbaked clean metals: 10^{-8} - 10^{-9} mbar l s^{-1} cm^{-2}

For elastomers: $>10^{-8}$ mbar l s^{-1} cm^{-2}

Use of polymers only if absolutely necessary!

→ Degassing
→ Cannot handle high temperatures

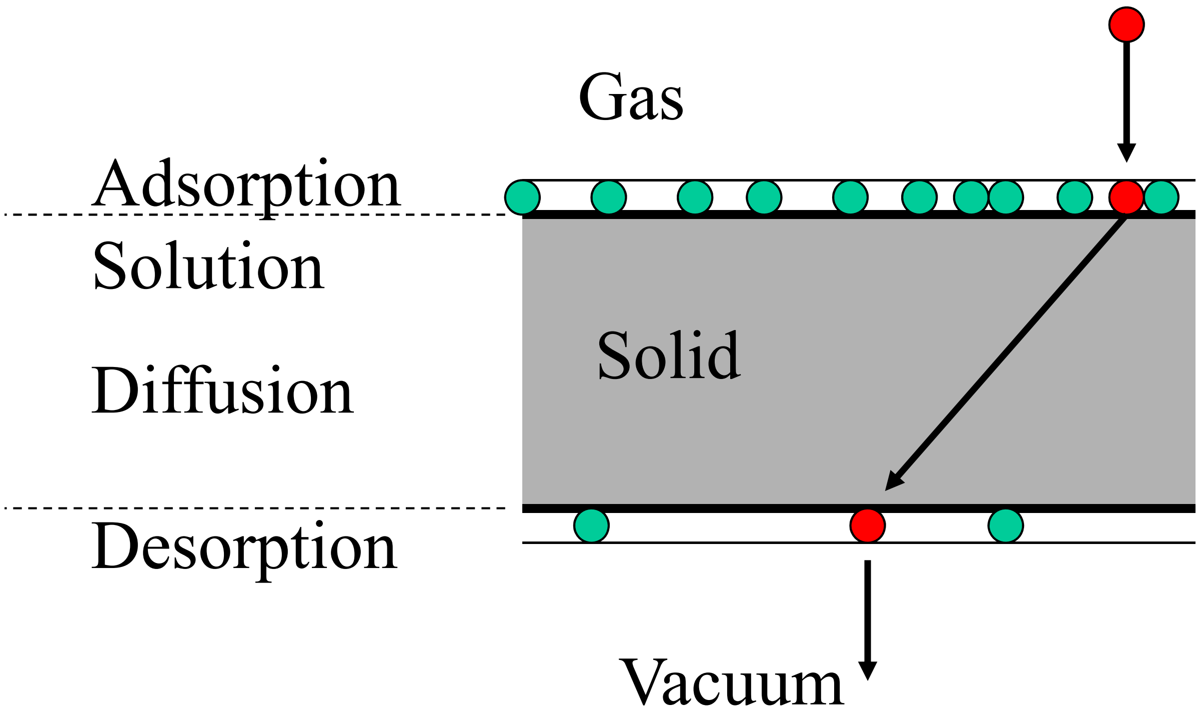
Permeation



Problems that appear to be Leaks
Permeation
Diffusion
Real
Leaks
Virtual
Outgassing
Backstreaming
air,
oil,
from
pump
PUMP $Q_{pump} = p \cdot S_{eff}$

Permeation

Also lasts forever, because the atmosphere is the source



Permeation involves an electronic interaction (not a leak) Chambers p29,127-8.
Examples: He through glass; O_2 through Ag; H_2 and He through Viton.

Roth p161-4: H_2 diffuses through metals as H+H, then desorbs as H_2.
H_2 diffuses through glass and Viton as H_2.

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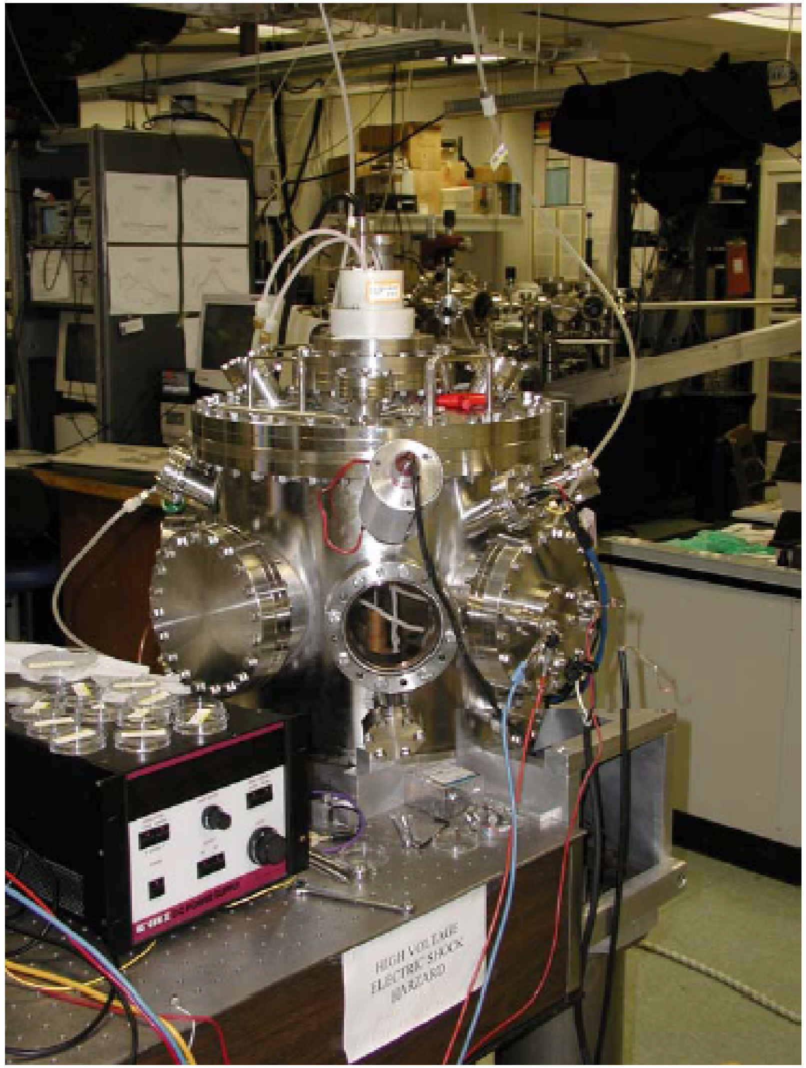
Vacuum chambers

- For standard vacuum, we can use a glass, Pyrex or stainless steel chamber.
  - Use it for CVD, sputtering and vapor deposition.
  - Mostly for lower quality, polycrystalline films
- For UHV, use a stainless steel chamber
  - Use it in MBE, CVD, sputtering
  - High quality, epitaxial films
  - Can be “baked”.

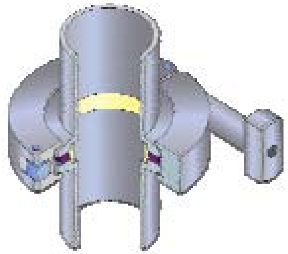


Some materials for vacuum systems

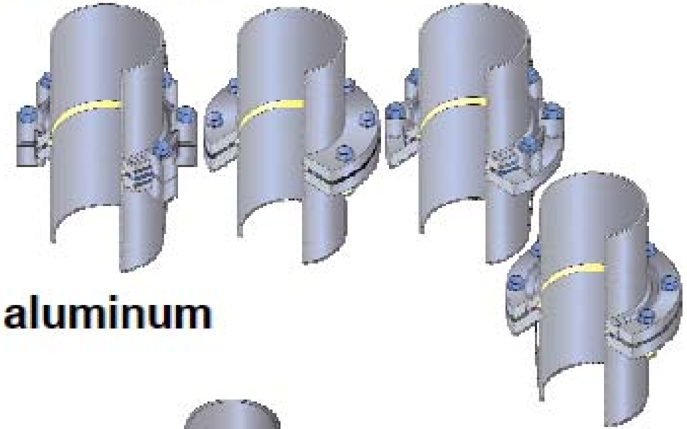
- metals
  - stainless steel (e.g. 304, 316 Ti, 316 L, 316 LN)
  - aluminium (no anodized coating !)
  - copper (OFHC: oxigen free, high conductivity)
  - tungsten, titanium, ...
  - gold and silver for seals and coating
  - indium for seals (melting point 156°C !)
- glass
  - borosilicate glass (Pyrex, Duran, ...)
  - quartz glass
- ceramics
  - Al_2O_3 ceramics (insulaters, el. feedthroughs)
- plastics (mainly for sealing purposes)
  - Viton
  - PTFE (Teflon)

Standard flange connections

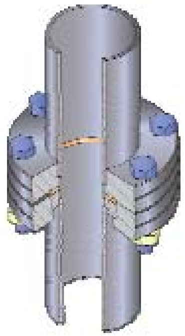
- **KF flange**
  - high vacuum ($p > 10^{-7}$ mbar)
  - temperature range: 0°C ... 120/180°C
  - gaskets: elastomeric o-rings (Viton, ...), aluminum
  - inner diameter: 10mm ... 50 mm



- **ISO flange (ISO-K and ISO-F)**
  - high vacuum ($p > 10^{-7}$ mbar)
  - temperature range: 0°C ... 120/180°C
  - gaskets: elastomeric o-rings (Viton, ...), aluminum
  - inner diameter: 63 mm ... 630 mm



- **CF-(ConFlat™)-Flansch**
  - UHV ($p < 10^{-7}$ mbar)
  - Temperatur: -196°C ... 450°C
  - gaskets: OHFC copper rings
  - inner diameter: 16 mm ... 320 mm



Kurt J. Lesker Company

Standard flanges

- Used to connect vacuum chambers, tubing and vacuum pumps to each other.
- Quick release flanges (QF, KF, LF) **multiple use**
  - up to 10^{-8} Torr, 150 °C
  - Flanges are connected by an elastometer ring and held together by a ring clamp.
- Con-Flat flanges
  - Knife edged rims inside create grooves on the gasket for the seal.
  - up to 10^{-13} Torr, 450 °C ok for baking
  - copper gasket, single use

Do not PINCH the 'o'-ring. Replace old vacuum grease....

Standard flanges

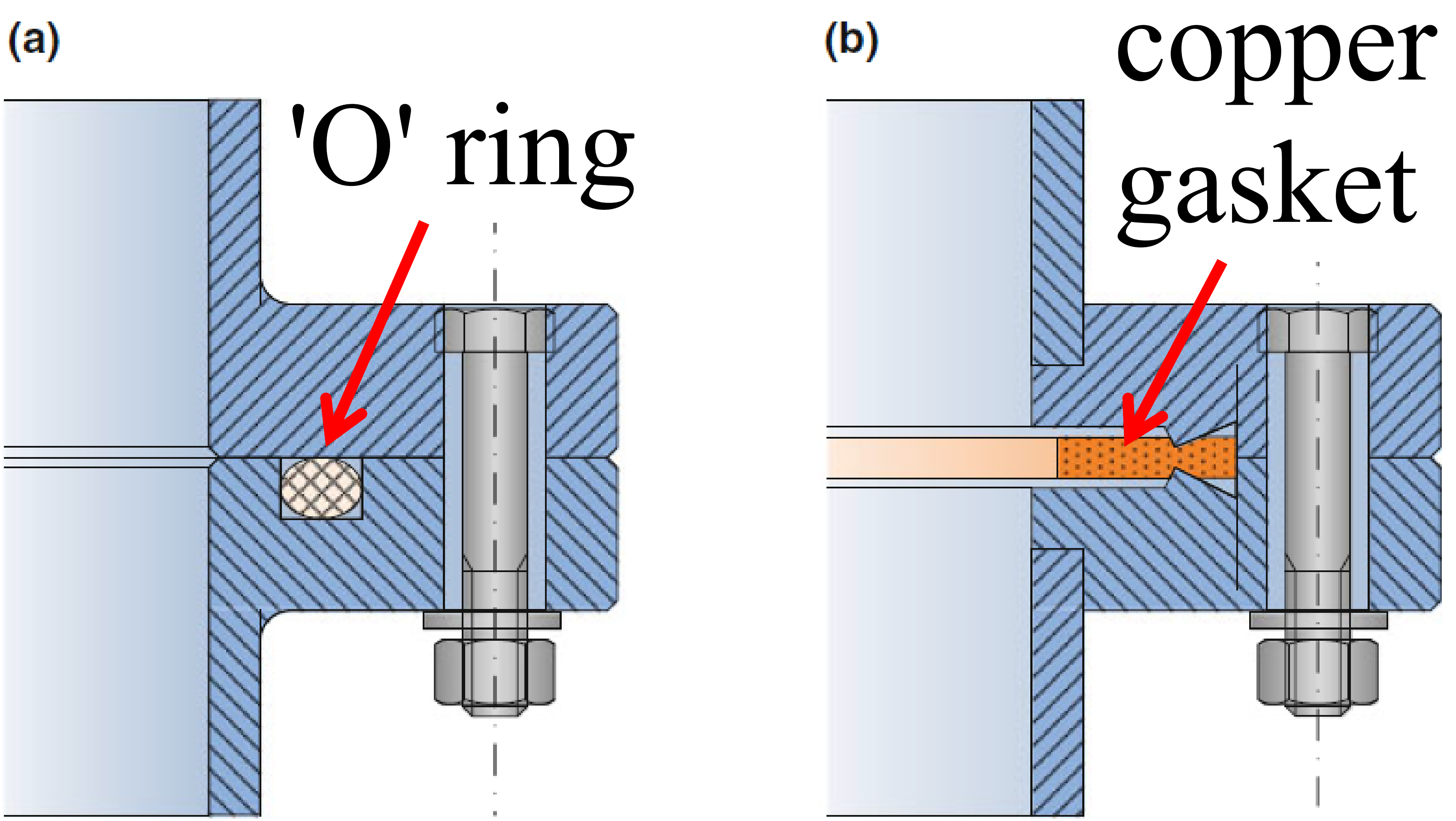


Fig. 2.27 High vacuum seals (adapted from O'Hanlon [1]). **a** O-ring in rectangular groove. **b** ConFlat® type knife edge metal seal

Gas Feed Line Connectors

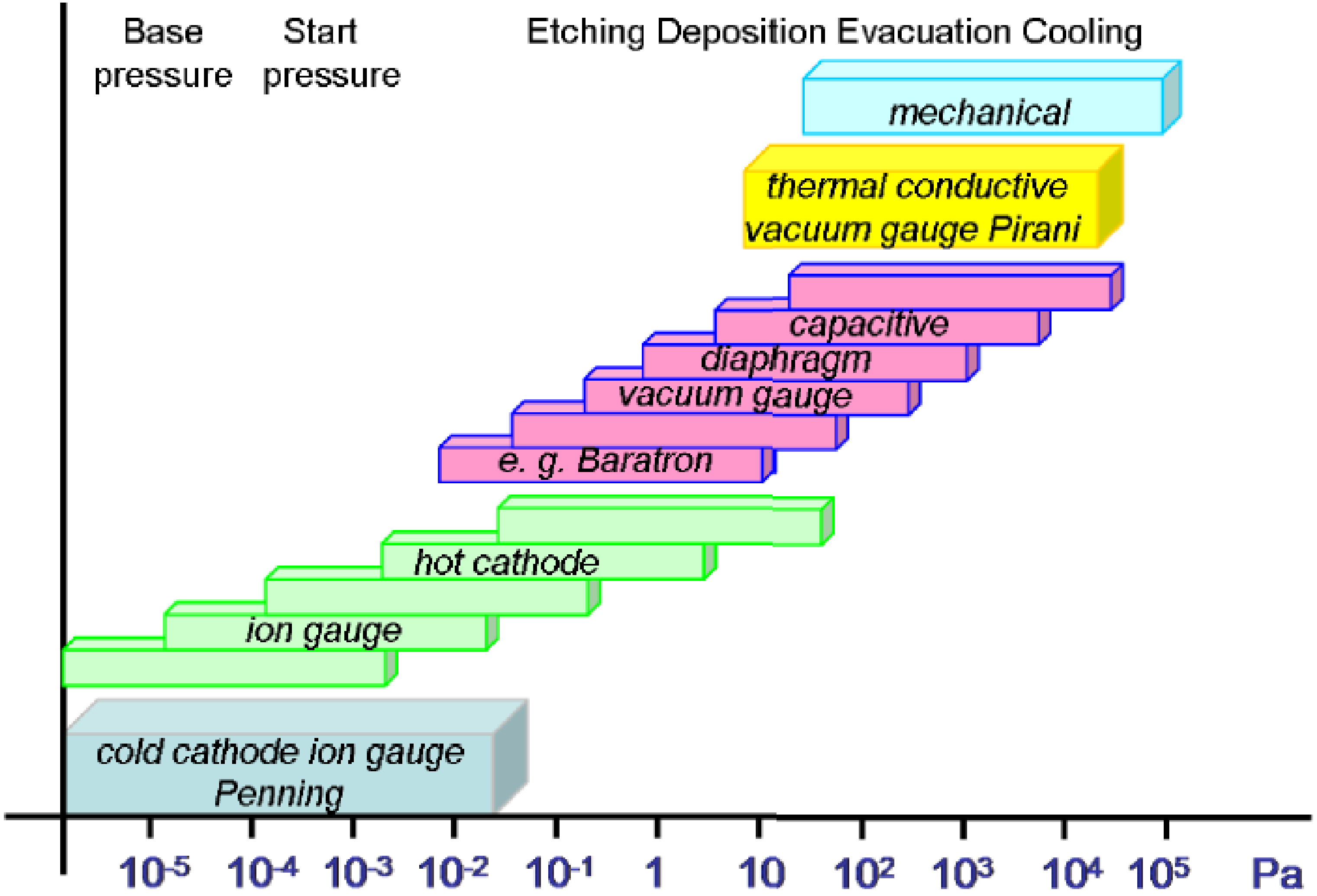
- SwageLok® connectors:

  and

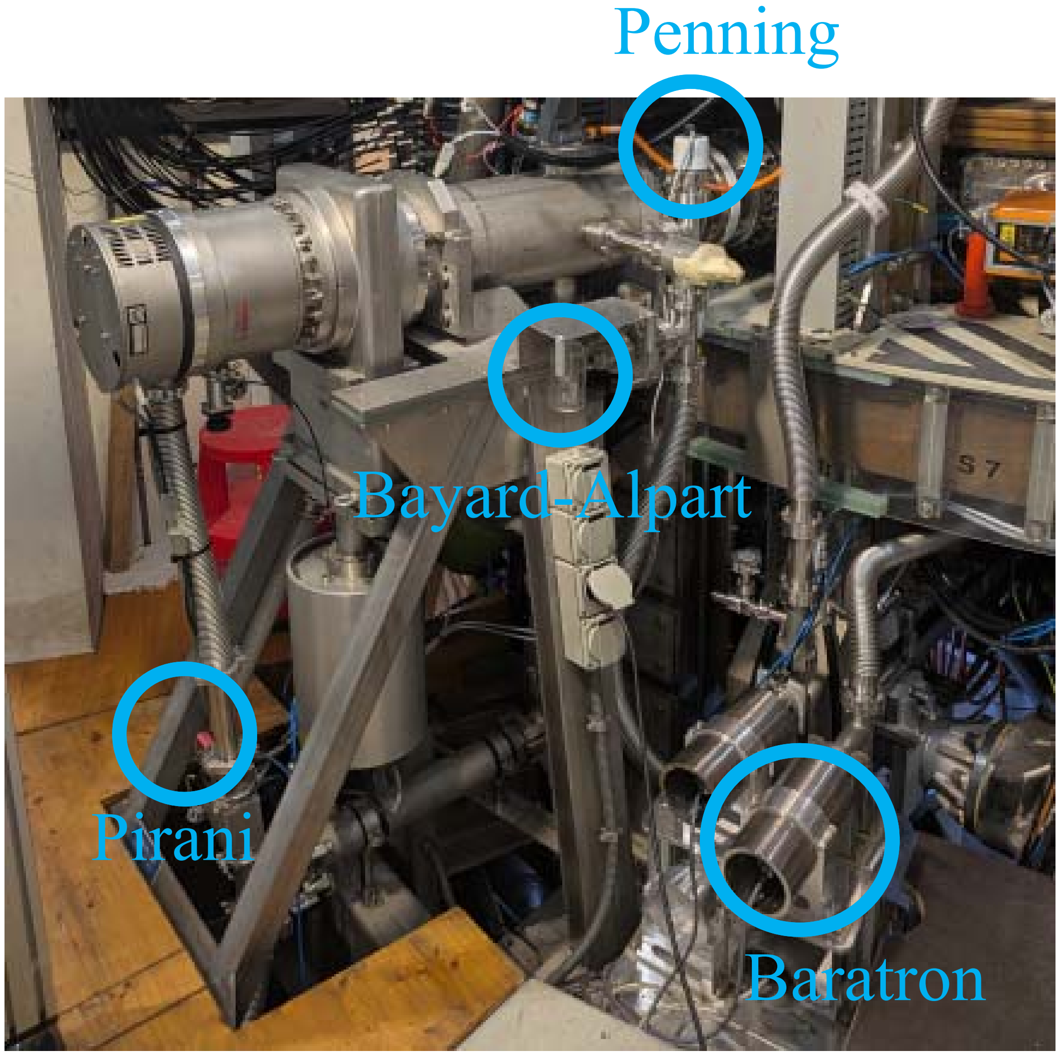
  - VCR® → Metal Gasket Face Seal

Pressure gauges

Rough Classification of Pressure Measurement Gauges

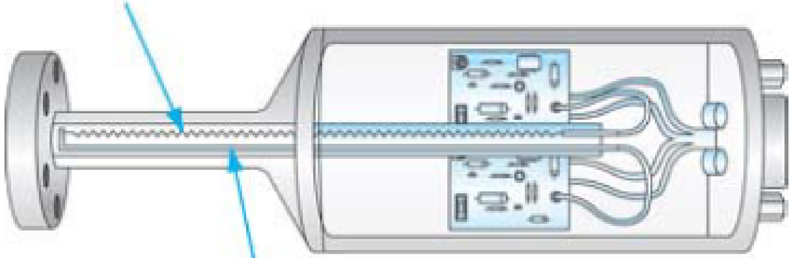


Pressure gauges

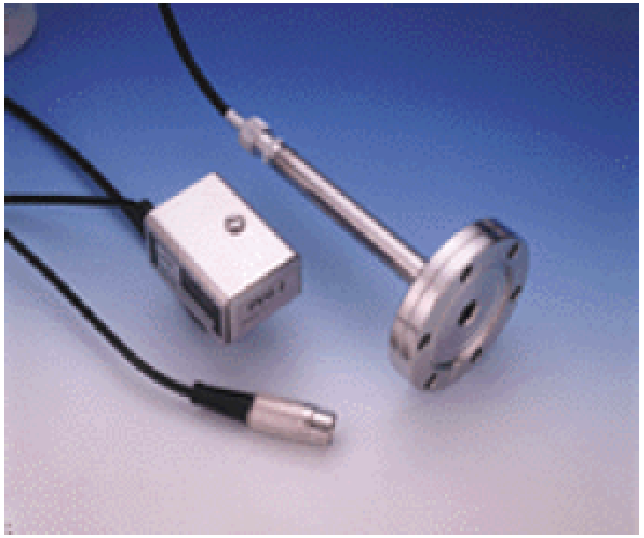


Pirani Gauge

- Gas thermal conductivity $\propto p$ for 0.5 mbar to 5.10^{-4} mbar



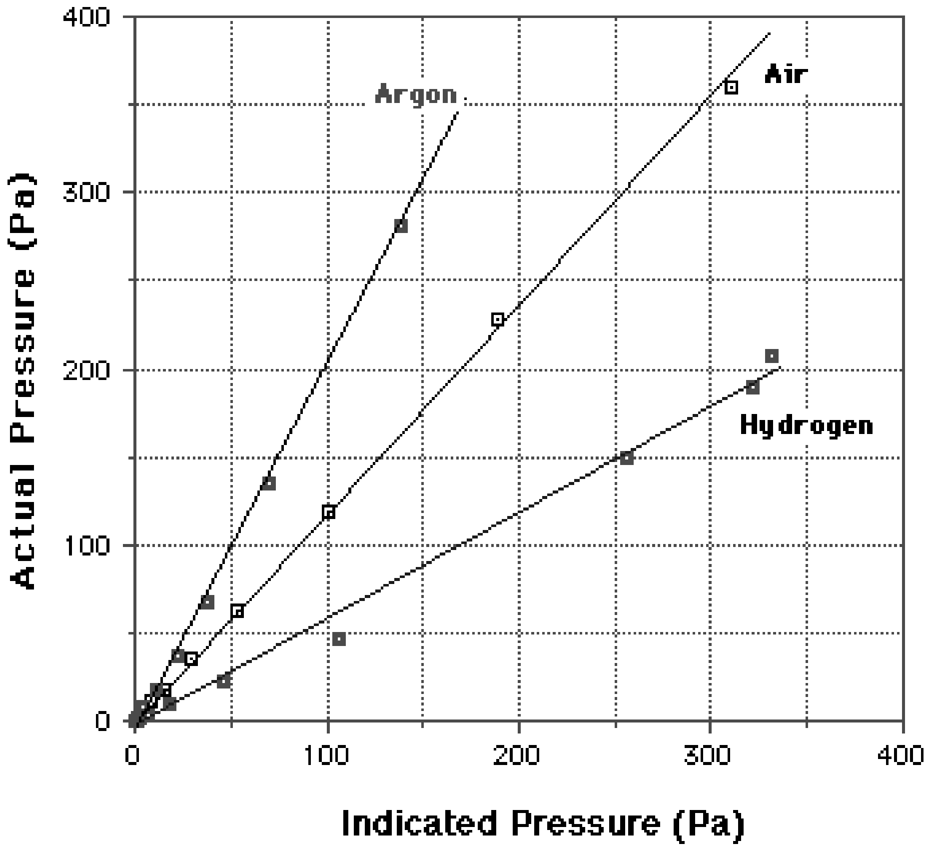
- Operation is based on thermal conductivity.
- A filament is heated and its temperature is measured.
- The temperature depends on the heat loss to the environment which in turn depends on the vacuum level.
- Will work between 10 - 10^{-3} Torr



Pirani gauge

Pirani calibration

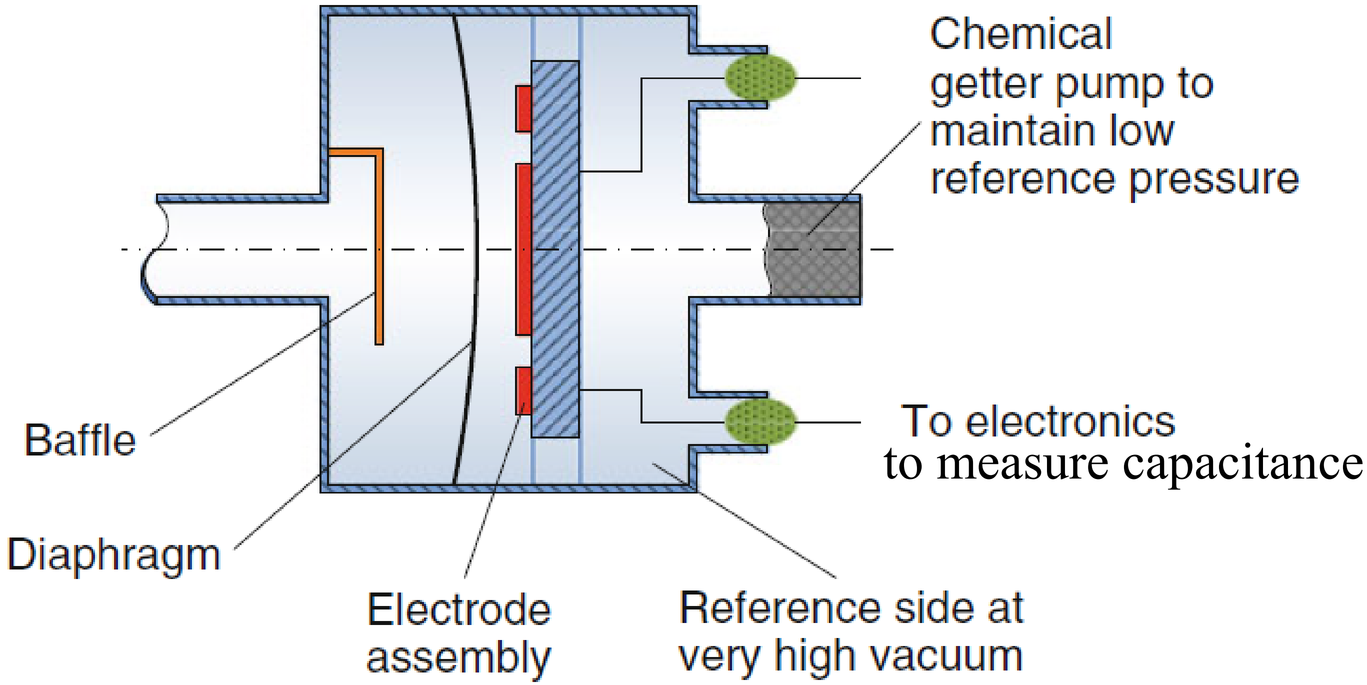
The calibration of a Pirani depends on thermal conductivity and so on the actual gas in the system



Gas Correction Curves for Pirani Gauges

Capacitive gauge

- A diaphragm deforms with pressure.
- Measures true (mechanical) pressure, independent of gas type.
- OK for reactive gases.
- Use multiple gauges for a wide pressure range.
- Not reliable below 5% full range value.



Capacitance manometer ("Baratron®"; adapted from MKS Instruments [35])

- The photo shows a well known type of a diaphragm vacuum gauge made by MKS. Baratron is MKS Trademark.

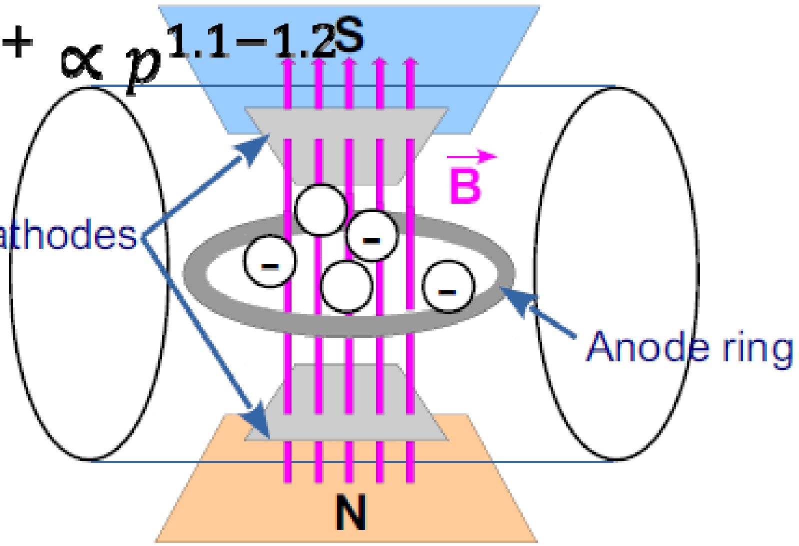
Cold cathode (or Penning) gauge

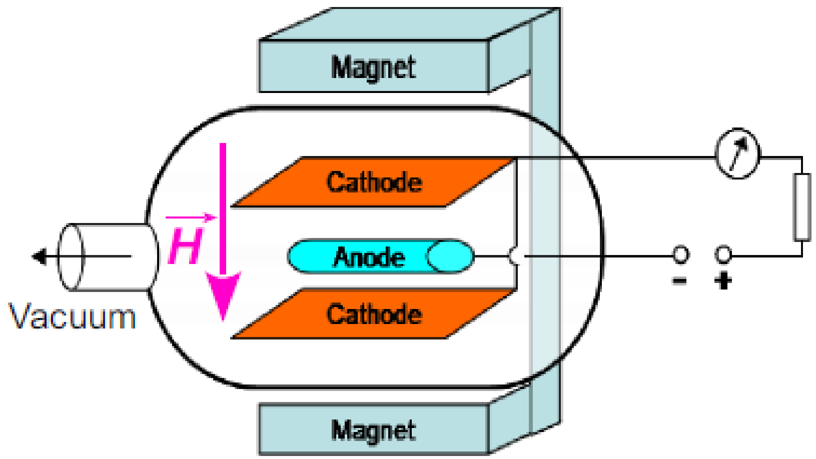
Invented by Penning in 1937

- In a cold cathode ion gauge the gas discharge is created by a high voltage (more than 1000 V) and a strong magnetic field. The electrons are accelerated in the external electric field and create ions.

  - Cold cathode gauges are accurate from 1 Pa (10^{-2} Torr) to 10^{-7} Pa (10^{-9} Torr).

$$i^{+} \propto p^{1.1-1.2}$$





Cold cathode ionization gauge

Beware - a Penning gauge reads zero current when the pressure is both very low and very high. The gauge must 'strike' to be operational. Check with a Pirani gauge if in doubt

Cold cathode (or Penning) gauge

- Ionization gauge calibration is very sensitive to construction geometry, chemical composition of gases being measured, corrosion and surface deposits.
- Typical sensitivity is 1 mA ion current per 10^{-2} Pa. Such currents are easily measured directly without any amplification. The response of the gauge is gas dependent and the discharge not quite stable. However, they are robust and reliable and provide an adequate measure of the status of a vacuum.

Operating Parameters:

Voltage:	600 ... 1000 V
Magnetic flux density B:	1000 … 2000 G (100 ... 200 mT)
Pressure range:	10^{-5} … 1 Pa 10^{-7} …10^{-3} Torr

Hot cathode (Bayard-Alpart) gauge

- In high vacuum gauges the ion current of a gas discharge is measured. This ion current is dependent on pressure.

- The required gas discharge is generated in a hot cathode system by using a filament emitting electrons due to the very high temperature above 1000°C.

- The resulting ions are collected at the negative electrode. The current depends on the number of ions, which depends on the pressure in the gauge.

Problems: heat, light, filament failure, depends on gas type, not for reactive gases!

Source: Plasma School Plasmetrex, © Plasmetrex

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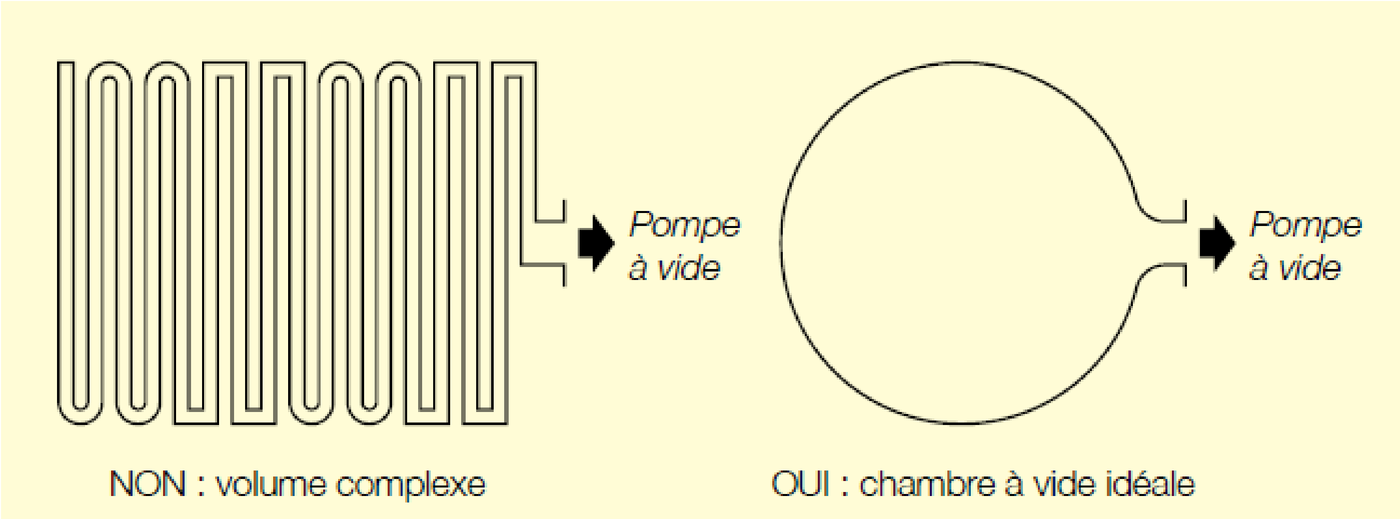
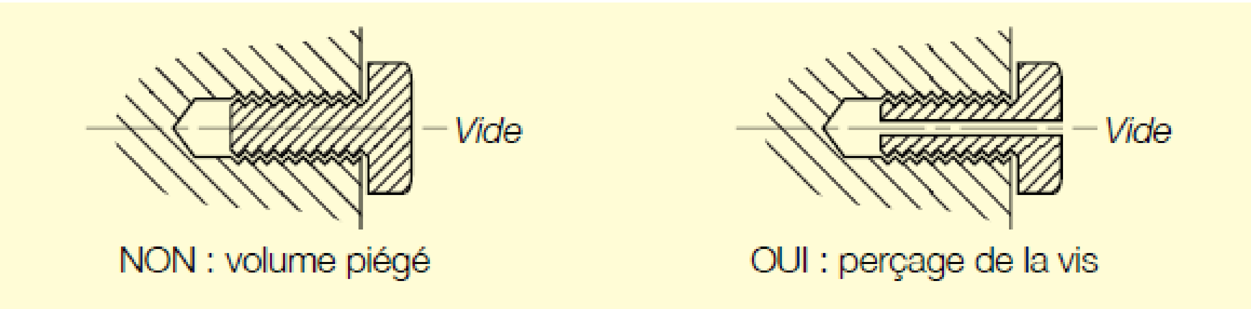
Practical advice

Gas lines
anecdote
(purge, not pump)





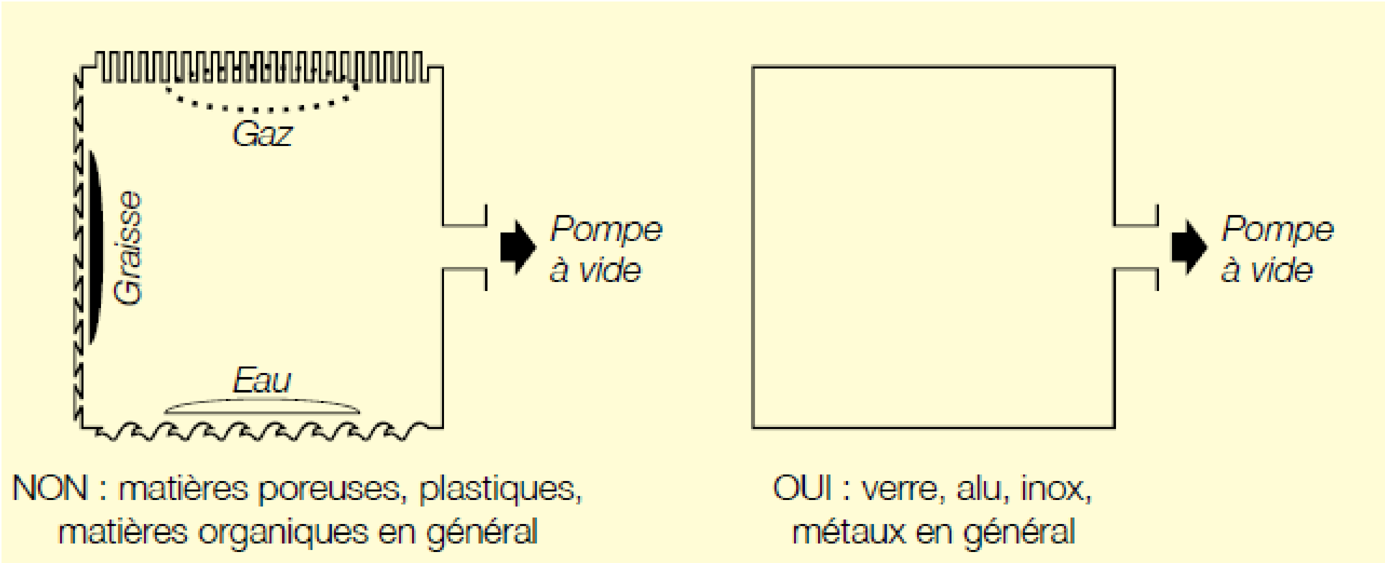
better: a channel cut down on the side of the screw

Practical advice

Gas lines electro-polished (internally!)

Keep vacuum chamber hot (40 °C)

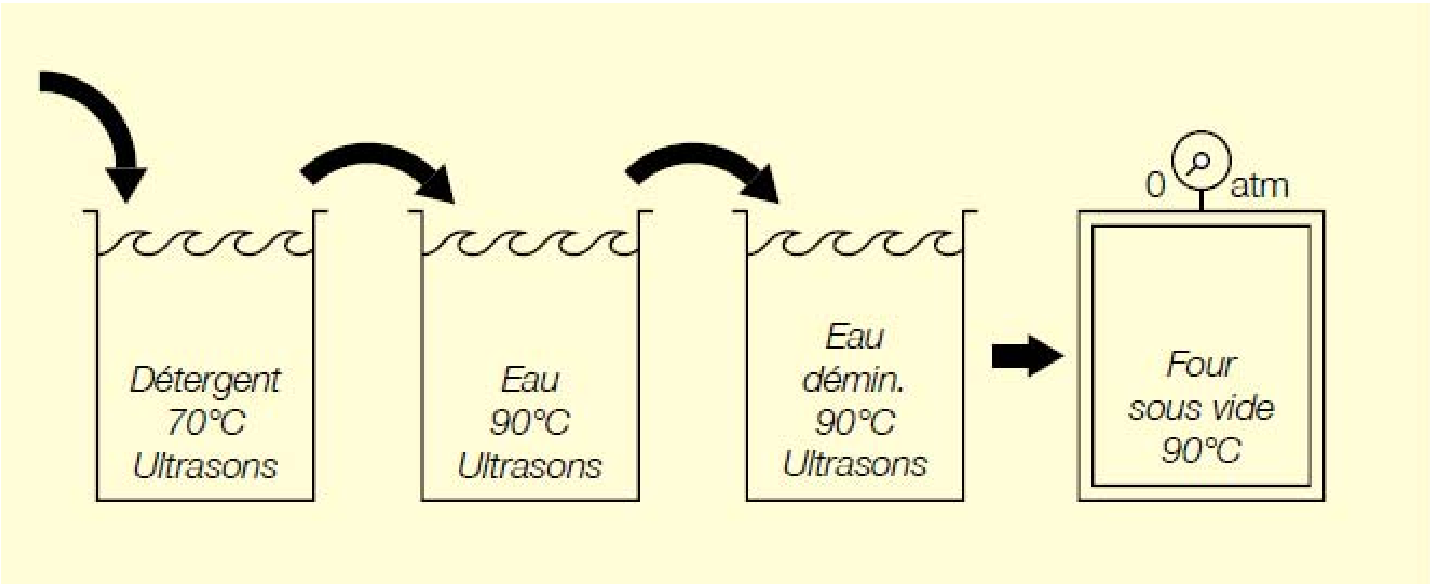
Vent to dry nitrogen (not humid air)



Practical advice

Remove oil, grease, corrosion, finger prints, water, particles, oxides, welding flux.

Baking to accelerate desorption, for $p < 10^{-7}$ mbar



Practical advice

DO NOT LEAVE VALVES OPEN TO A CHAMBER UNDER VACUUM IF THE PUMPS ARE OFF – OIL BACKSTREAMING!!!!!

ALWAYS VENT to atmosphere A PUMP WHICH IS OFF!

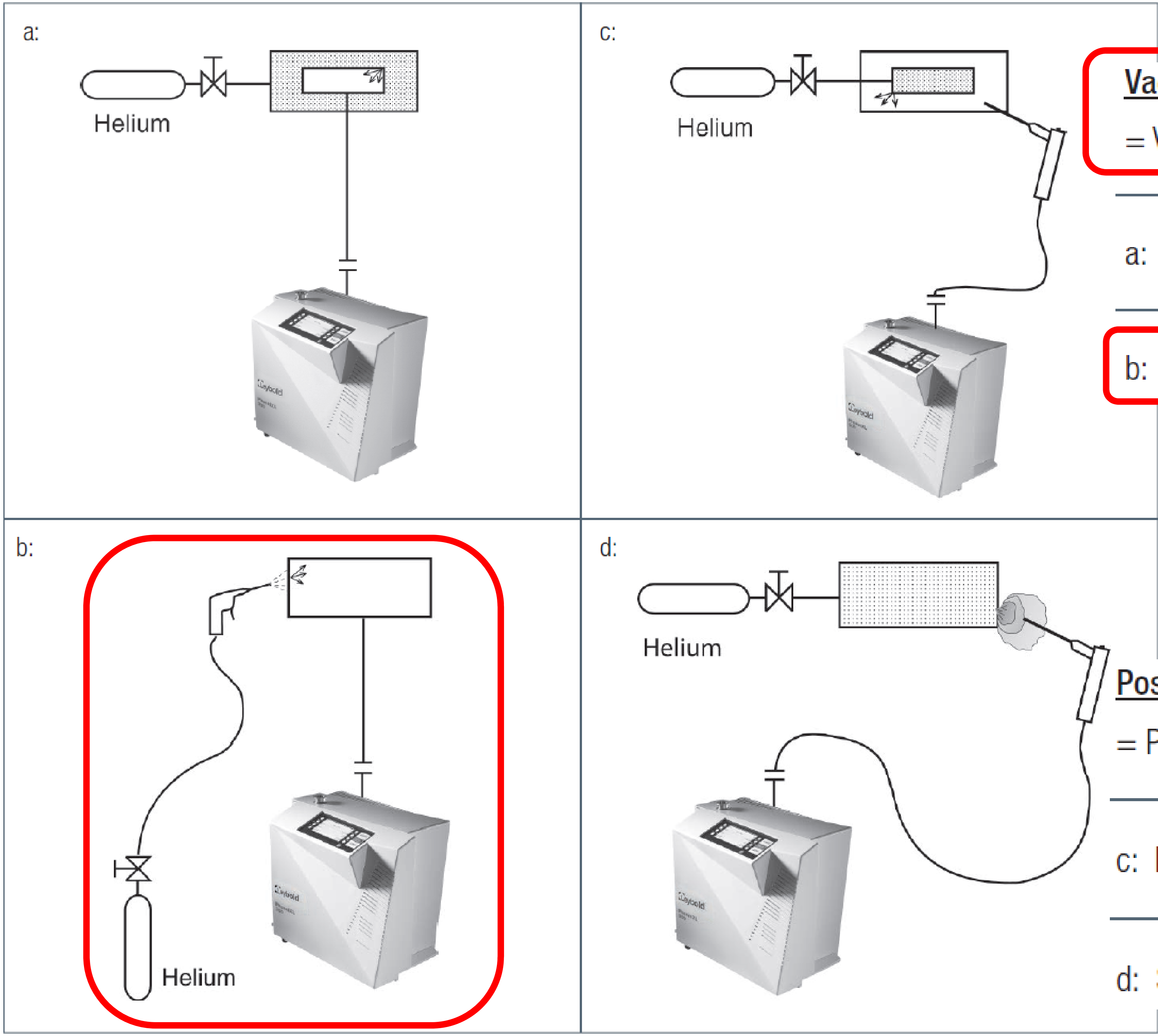
- should be automatic (in case of power disruption)

Generally, leave pumps on to avoid re-sorption of water vapour! (Ar+ becomes ArH+ after opening).

Dry pumps for clean processes

Universal pressure gauges (automatic switch-over between combinations of gauges).

Leak detection



Vacuum method

= Vacuum inside specimen

a: Enclosure test (integral leak detection)

b: Spray technique (local leak detection)

Positive pressure method

= Pressurized test gas inside specimen

c: Enclosure test (integral leak detection)

d: Sniffer technique (local leak detection)

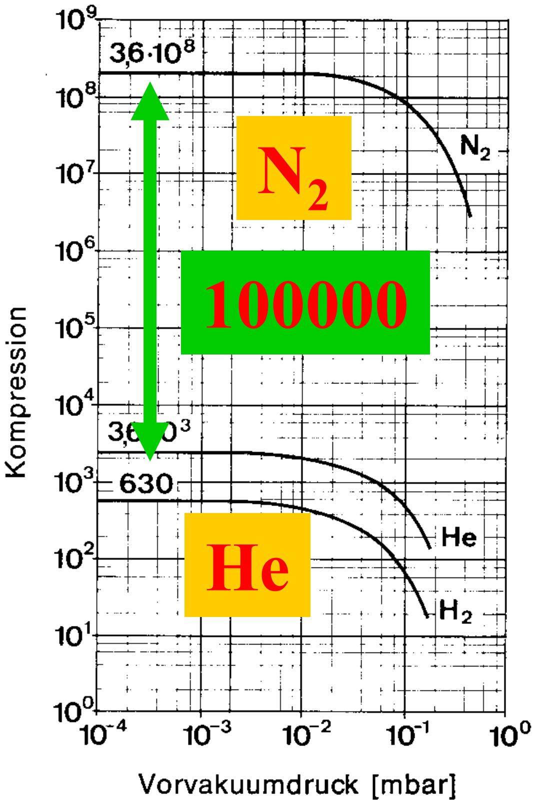
Leak detection

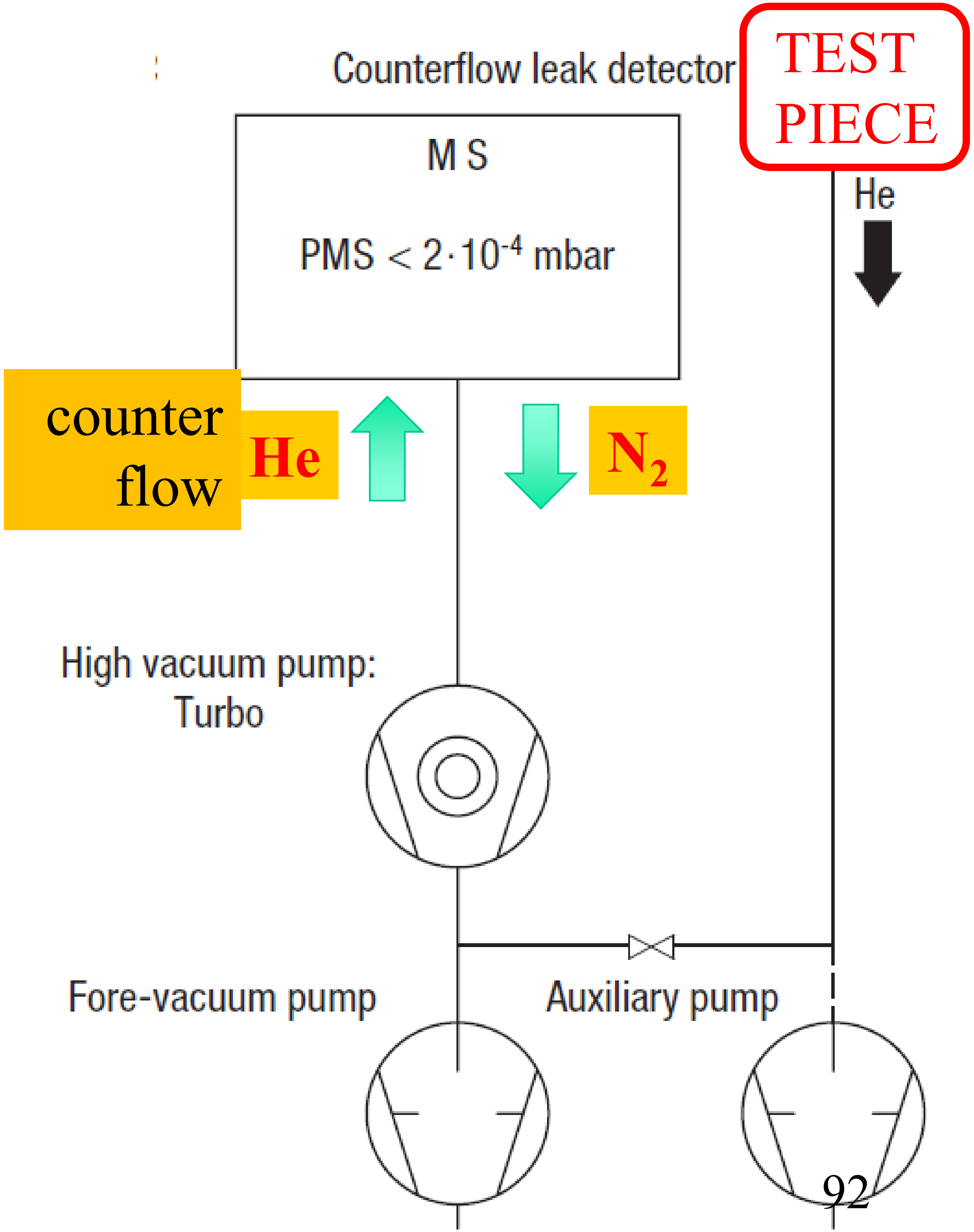
Why Leak Detection with Helium ?

- Helium atoms move faster through the air due to the low atomic mass and small cross section. Therefore the measurement is very fast.
- Only a tiny percentage of Helium is contained in the atmosphere. Adding Helium to the atmosphere close to a potential leak, enables even small leaks to be detected.
- Advantages
  - Highest sensitivity in detection of smallest leaks
  - Quantitative measurement of leaks rate
  - Excellent reproducibility of the measurement results
  - Helium is non-toxic and not flammable
  - Can not be used with cryopumps.

Leak detection

Courbe de compression





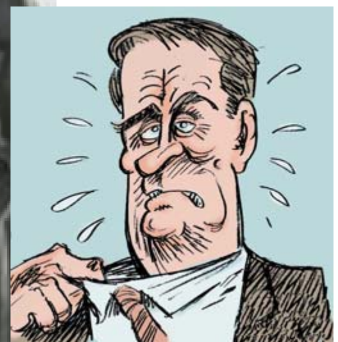
Turbo pumps are not so good for light gases (He, H2) because of their high thermal velocity (this is exploited in the counter-flow technique for leak detectors).

Practical advice

What sequence to pump down the chamber?

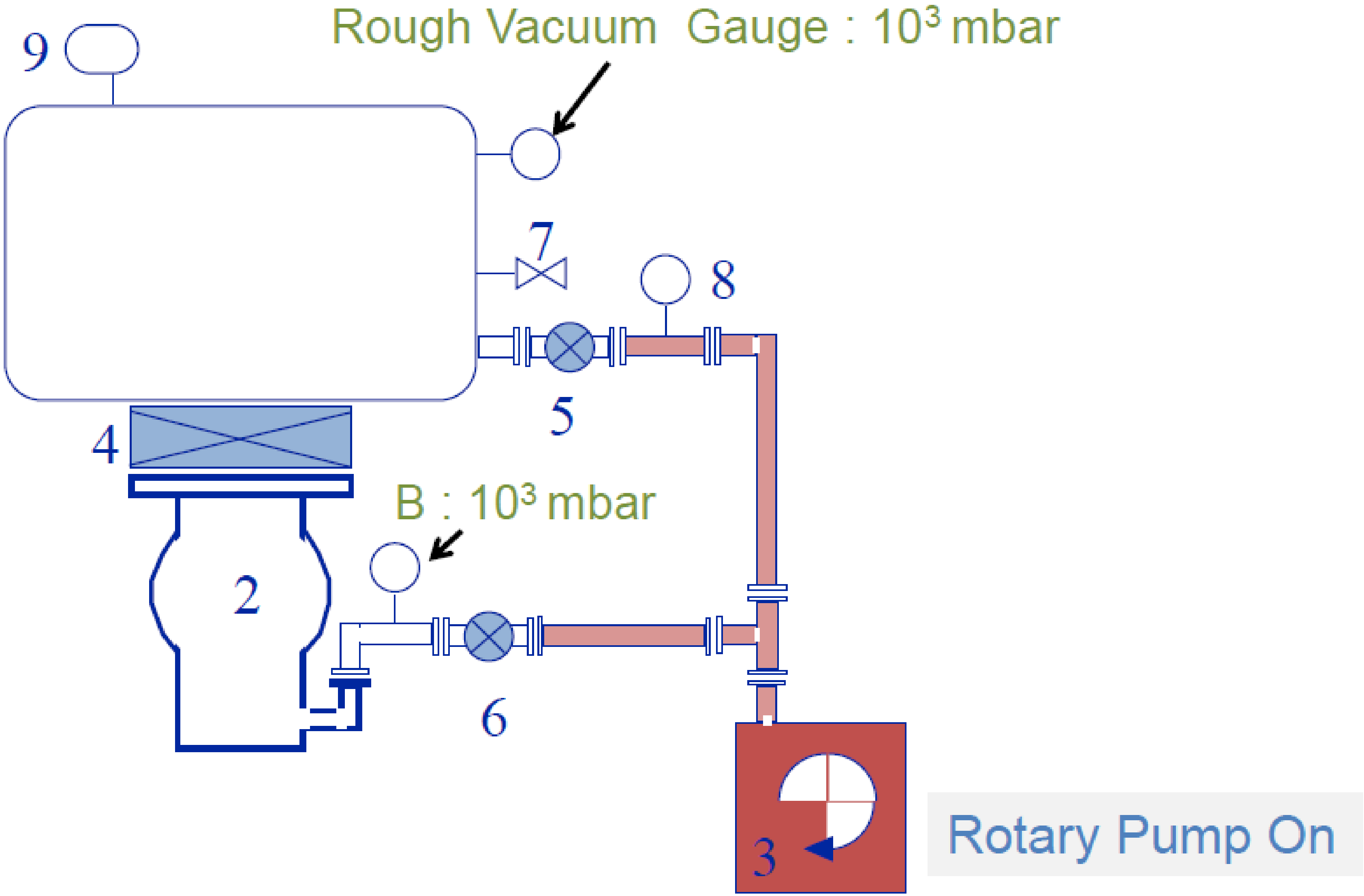
Do not switch on the turbopump, and then open to atmosphere!

The main drawback of TMP is related to possible **mechanical failures** leading to definitive damage of the high-speed rotor.

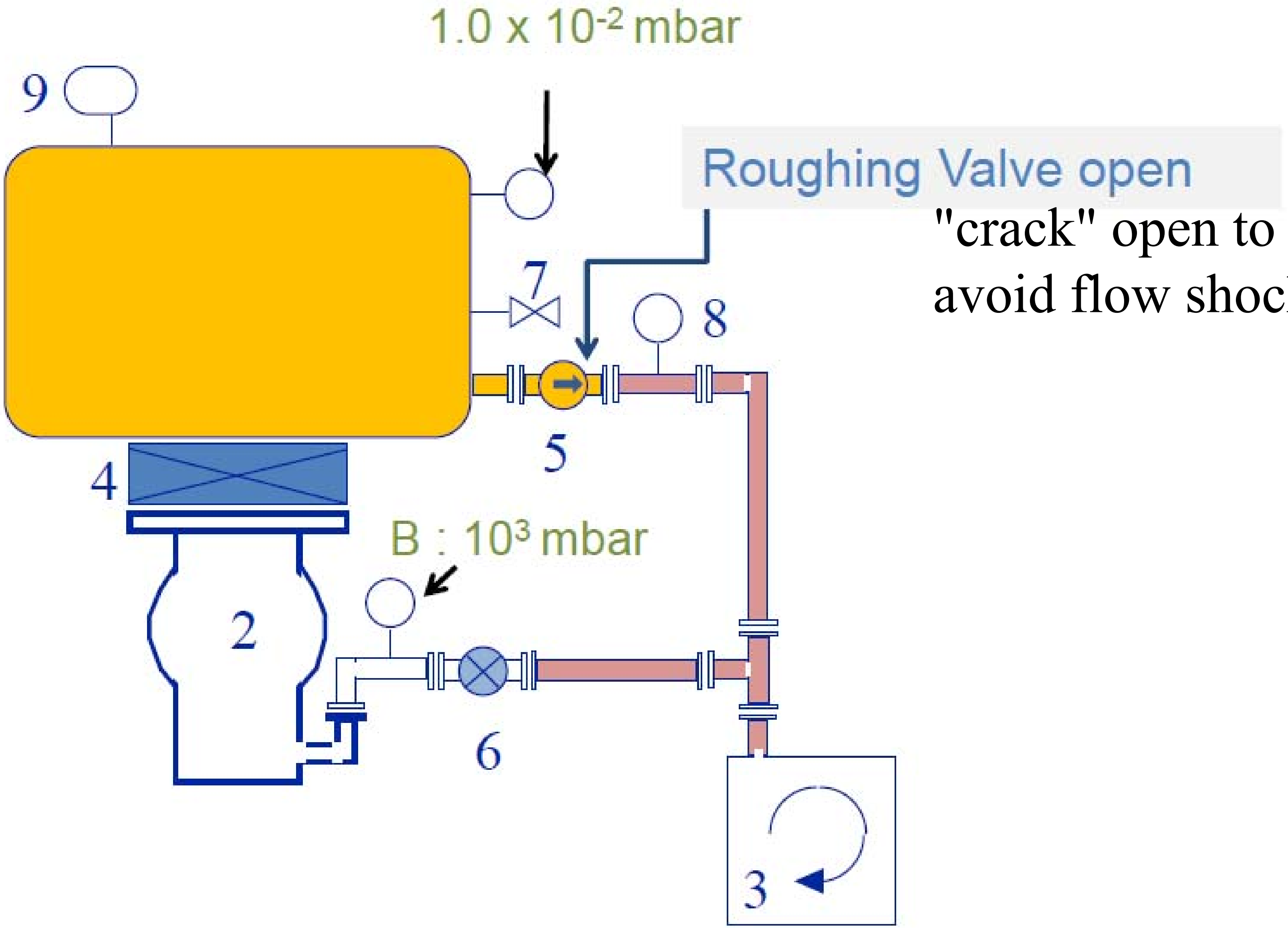


Pumpdown

Start up

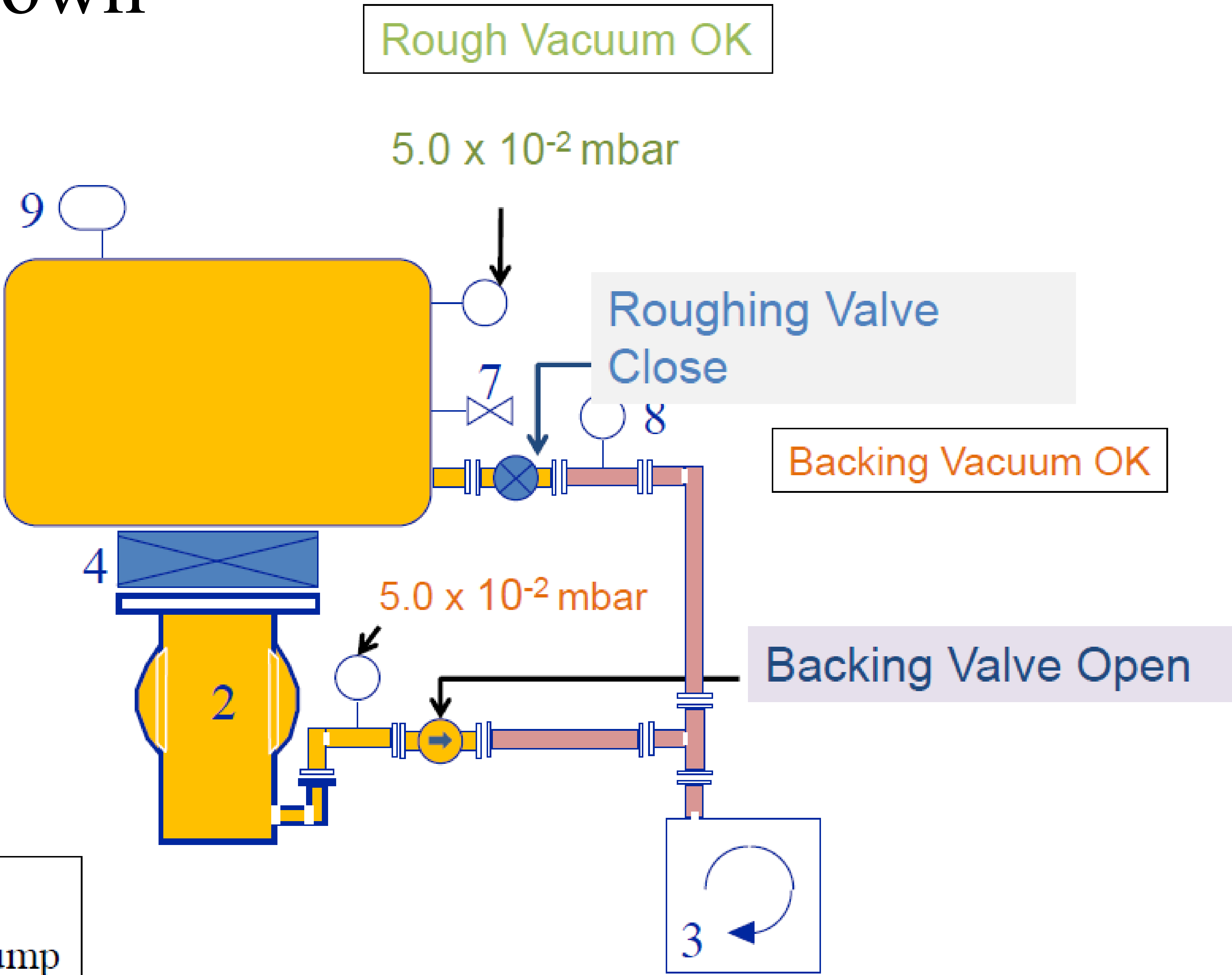


Pumpdown



"crack" open to avoid flow shock

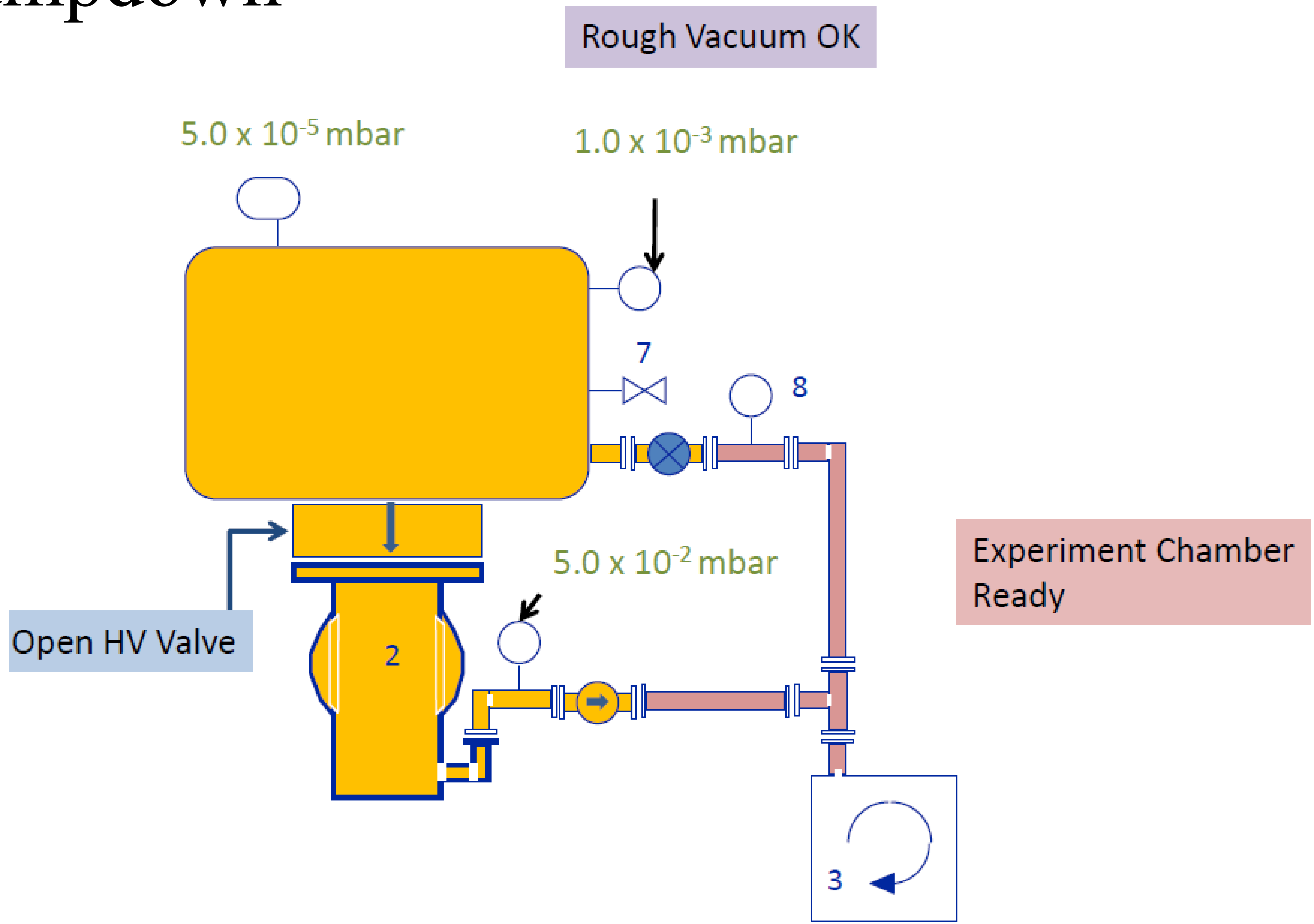
Pumpdown



For TP

- Start Pump

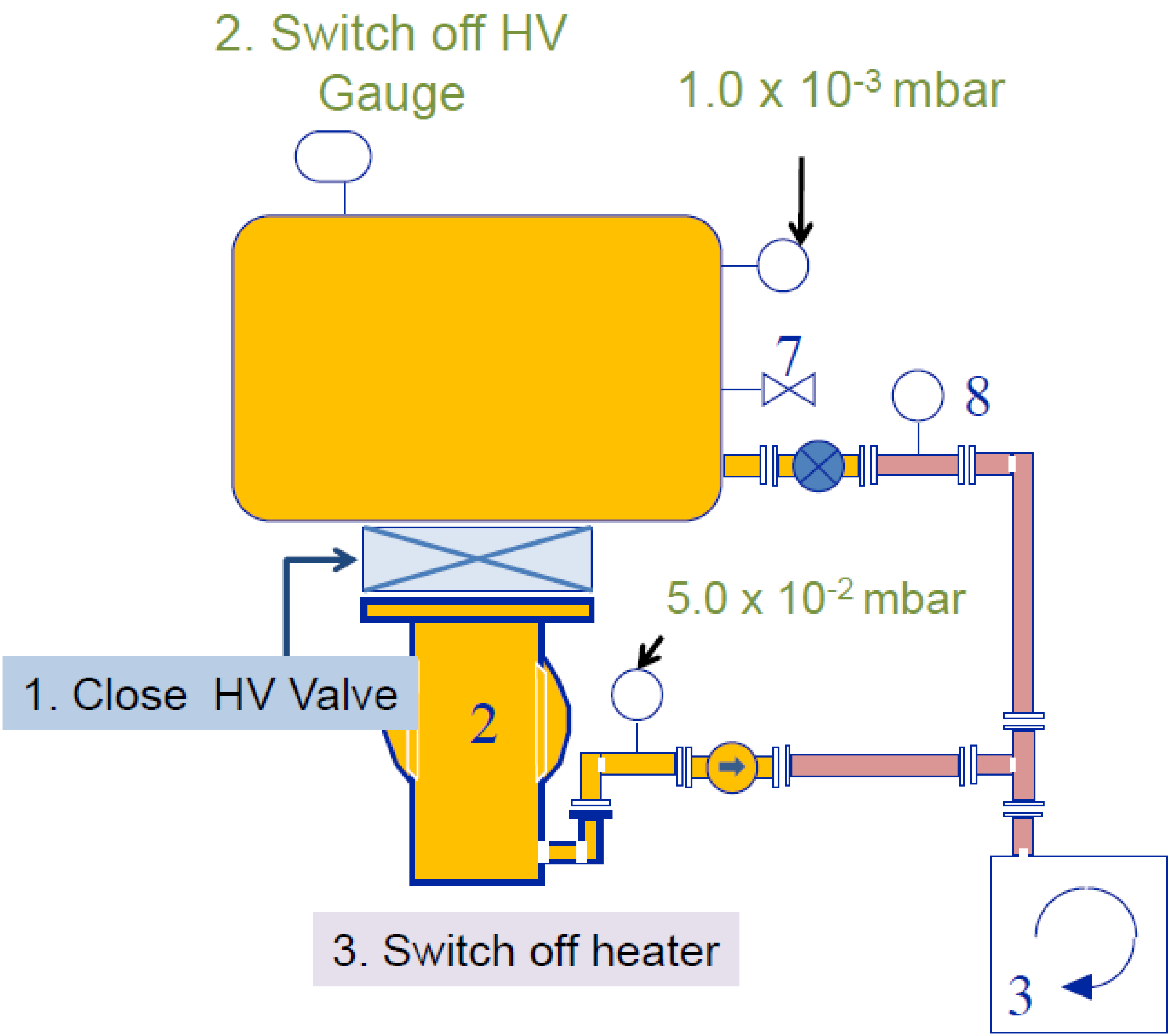
Pumpdown



Rough Vacuum OK
5.0 x 10-5 mbar
1.0 x 10-3 mbar
7
8
Experiment Chamber Ready
5.0 x 10-2 mbar
Open HV Valve
2
3

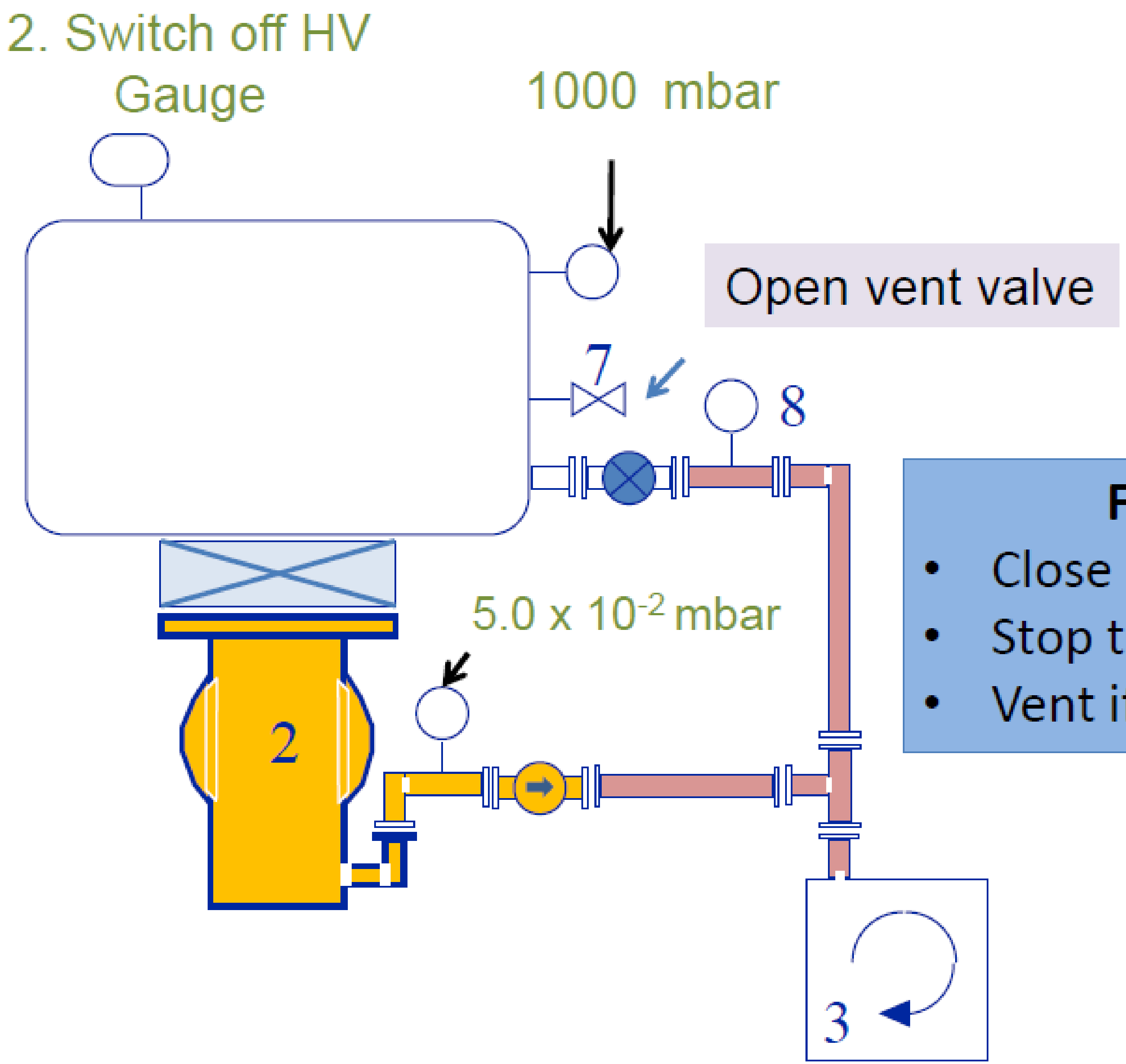
Venting

Shut down



Shut down

Venting

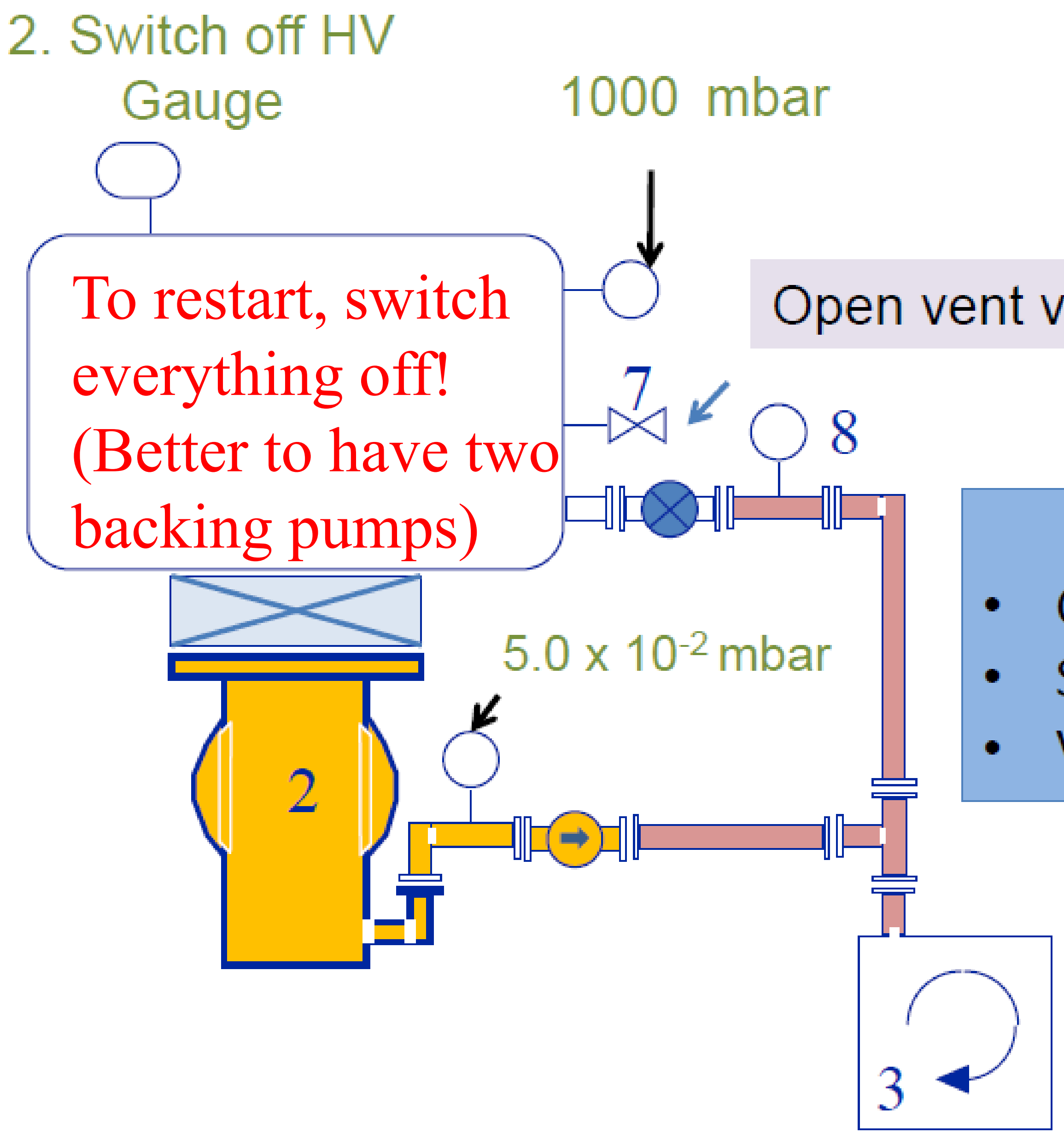


For TP

- Close backing valve
- Stop the Pump
- Vent if required

Shut down

Venting



Open vent valve

For TP

- Close backing valve
- Stop the Pump
- Vent if required