Ultra-high vacuum

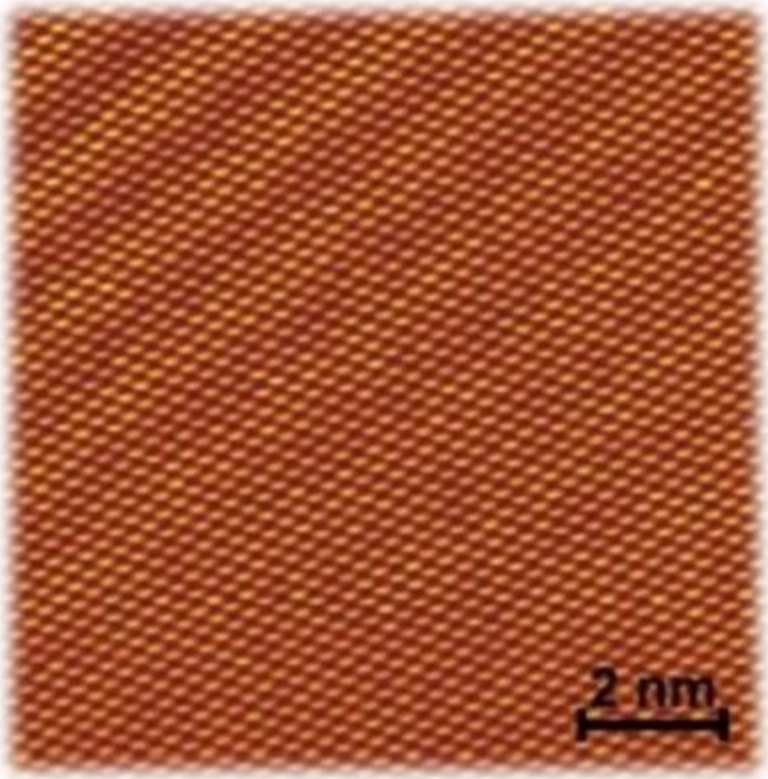
Why do we need vacuum?

I – Preparation of atomically clean surfaces

Molecules of residual atmospheric gases in the environment can contaminate the sample surface.

Example: if we have a clean Cu surface in air at atmospheric pressure (10^5 Pa – 1 bar), in 1 ns it will be completely covered by a layer of molecules (H_2O, O_2, …). Cu atoms bond chemically to the adsorbates, forming an oxide layer.

To maintain a clean surface for a time scale long enough for carrying out an experiment, it is necessary to remove the gas from the measurement chamber, lowering the pressure to 10^{-13} bar and below.



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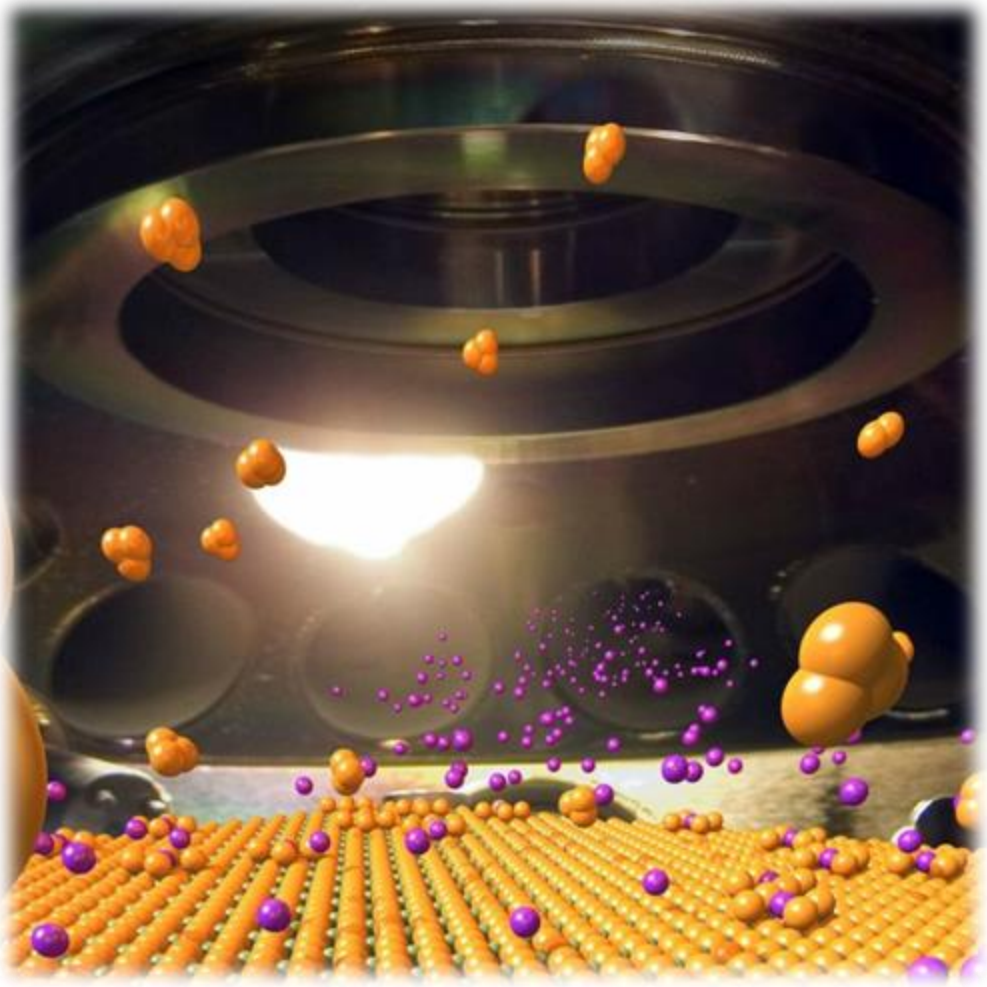
II – Synthesis of materials with controlled composition

Suppose that we want to synthesize a sample with a well-defined composition and with a low density of contaminants.

Depending on the quality we want to achieve, the contamination density should be in the order of one ppb or lower.

Again, it becomes fundamental to remove the residual gas from the preparation chamber, achieving 10^{-13} bar and below.



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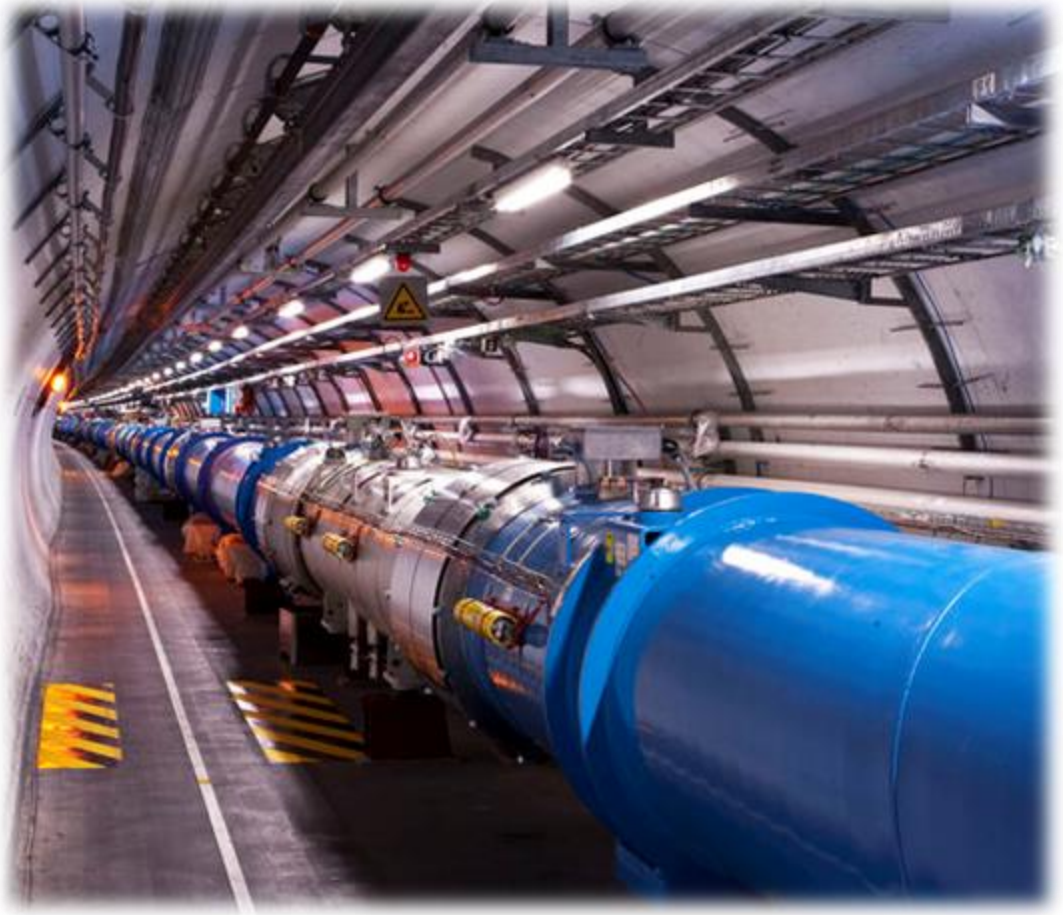
III – Use of particle beams (atoms, molecules, electrons, ions, …)

To generate, sustain and reveal particle beams, their mean free path (the average distance travelled between collisions) should be at least comparable to the relevant size of the experimental system.

Example: electrons with energies between 1 eV and 1 MeV in air at atmospheric pressure travel less than few mm.

Pressures between 10^{-8} - 10^{-13} bar are required.



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IV – Sample cooling

If we cool the sample to cryogenic temperatures, like 77 K (liquid nitrogen) or 4 K (liquid helium), molecules in the air mixture (H_2O, O_2, N_2, CO_2, …) condense on the cold surfaces.

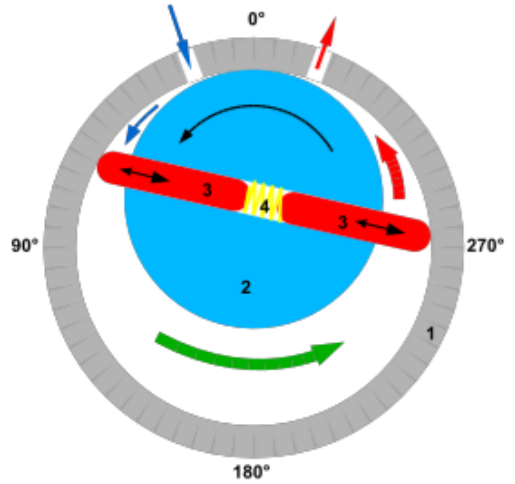
Moreover, gases conduct heat and make cooling more inefficient: the system must be operated in vacuum for a better insulation and to keep the sample surface clean.

Depending on the cases, pressures from 10^{-6} bar to 10^{-13} bar can be required.

Vacuum regimes

		Rough vacuum	Medium vacuum	High vacuum	Ultrahigh vacuum
Pressure	p (mbar)	1013 - 1	$1 - 10^{-3}$	$10^{-3} - 10^{-7}$	$< 10^{-7}$
Particle number density	n (cm^{-3})	$10^{19} - 10^{16}$	$10^{16} - 10^{13}$	$10^{13} - 10^{9}$	$< 10^{9}$
Mean free path	λ (cm)	$< 10^{-2}$	$10^{-2} - 10$	$10 - 10^{5}$	$> 10^{5}$
Impingement rate	Z_a ($cm^{-2} \cdot s^{-1}$)	$10^{23} - 10^{20}$	$10^{20} - 10^{17}$	$10^{17} - 10^{13}$	$< 10^{13}$
Vol.-related collision rate	Z_v ($cm^{-3} \cdot s^{-1}$)	$10^{29} - 10^{23}$	$10^{23} - 10^{17}$	$10^{17} - 10^{9}$	$< 10^{9}$
Monolayer time	τ (s)	$< 10^{-5}$	$10^{-5} - 10^{-2}$	$10^{-2} - 100$	> 100
Type of gas flow		Viscous flow	Knudsen flow	Molecular flow	Molecular flow
Other special features		Convection dependent on pressure	Significant change in thermal conductivity of a gas	Significant reduction in volume related collision rate	Particles on the surfaces dominate to a great extend in relation to particles in gaseous space

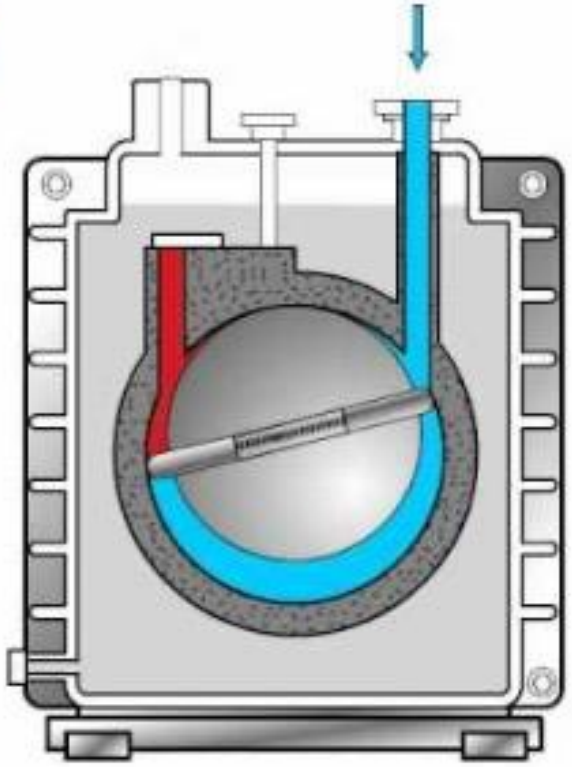
Rotary vane pumps



A rotary vane pump is composed by a cylindrical cavity containing a rotor with blades of variable length that are constantly in contact with the cavity walls. The seal between the blades and the walls is ensured by circulation of a lubricating oil.
The axes of the rotor body and of the cavity are offset, thus creating variable volumes.

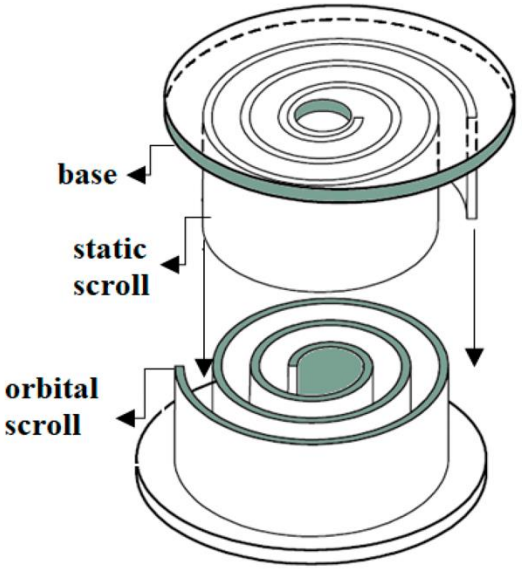
In the inlet side, the volume increases, aspirating the gas from the vacuum chamber. The volume is then compressed on the outlet side, expelling the gases from the system.

Some multistage pumps can achieve pressures down to 10^{-3} mbar.



Next

Scroll pumps

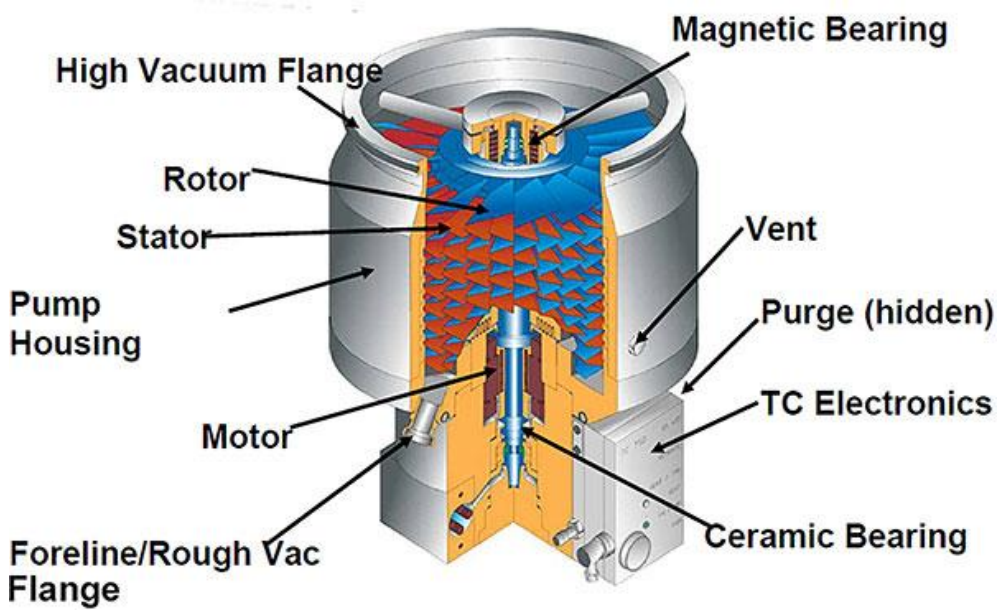


In contrast to rotary vane pumps these are dry pumps. A common design uses two intertwined spirals, a static one and an eccentrically orbiting one. The seal in this case is ensured by polymer gaskets mounted on both spirals.

The eccentric rotation of the spiral creates pockets with variable volumes in which the gas is trapped and expelled from the system.

Scroll pumps typically pump down to 10^{-2} mbar.

Turbomolecular pumps



They rely on the fact that momentum can be transferred to the gas molecule via the collision with a solid body. The turbine blades rotate at high frequency (~1500 Hz), and their geometry is designed to push gas molecules towards the pump outlet. This mechanism works if the mean free path of the molecules is longer than the distance between rotor and stator blades (molecular flow, $p < 10^{-3}$ mbar).

The compression ratio can be increased, at the cost of a lower pumping flux, by tilting the blades as much as possible (above 45°). The compression ratio scales linearly with the rotation speed, and scales exponentially with the square root of the molecular mass of the gas: light gases like H and He are pumped less efficiently.

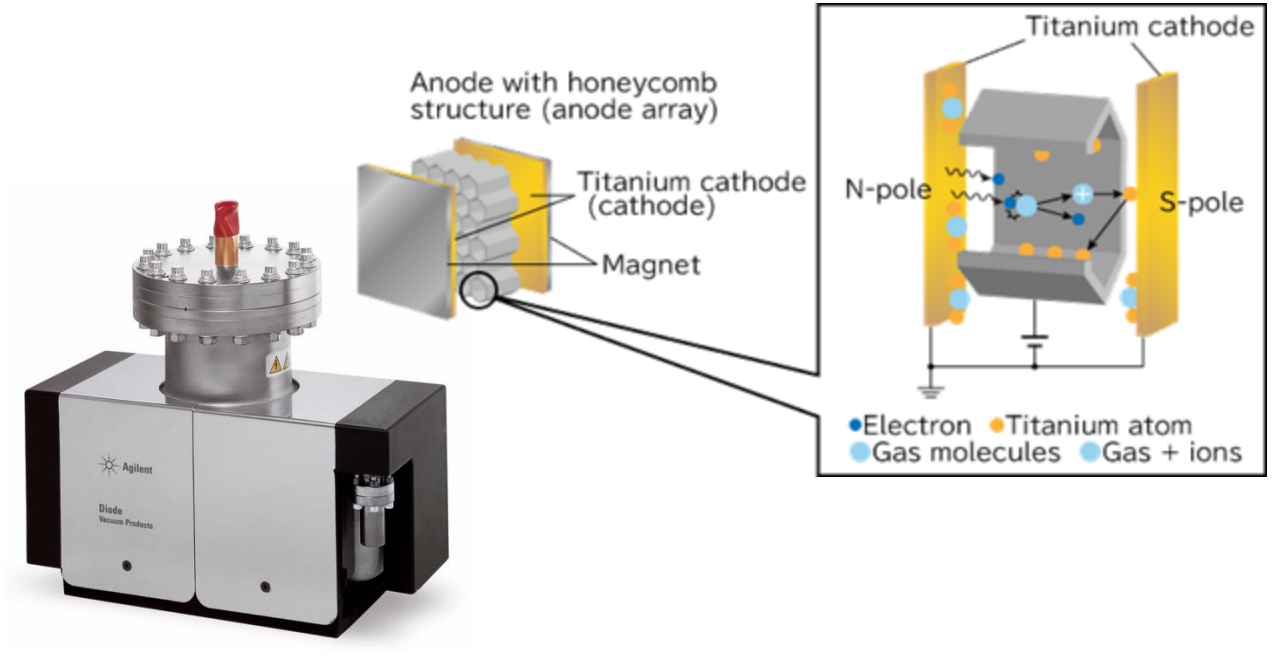
These pumps allow achieving and maintaining pressures of the order of 10^{-10} mbar.

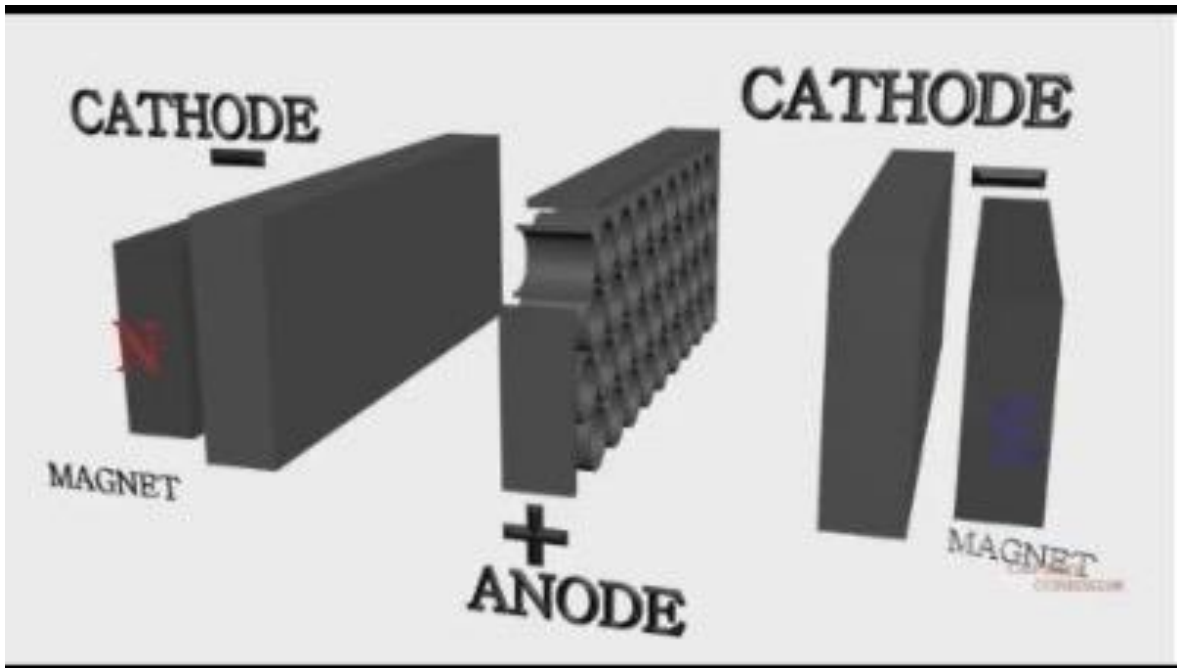
Ion pumps

Ion pumps allow to achieve pressures even lower than 10^{-11} mbar. In an ion pump, the gas is ionized and accelerated > 1 kV towards some electrodes. The gas is ionized by electrons that are trapped inside honeycomb cells by a magnetic field.

Ions that hit the cathodes get adsorbed or implanted in the metal and are effectively removed from the chamber volume. In addition, the collision of the ions with the cathodes can cause the emission of Ti atoms, which can then coat the anode surface, further increasing the pumping efficiency.

With no moving parts and no sealing oil, ion pumps are clean, require low maintenance, and produce no vibrations.





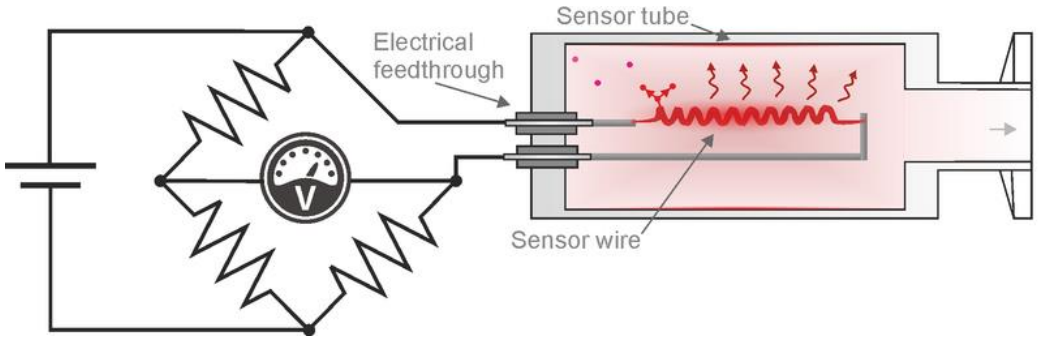
Other pump types

- Low vacuum
  - Membrane pumps
  - Roots pumps
- Ultra-high vacuum
  - Titanium sublimation pumps
  - Getter pumps (with porous materials)
  - Cryogenic pumps
  - Diffusion pumps

Vacuum gauges

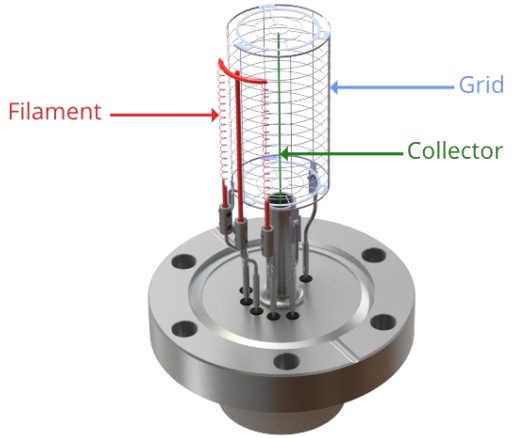
Pirani gauge
Measures the heat transfer with the gas by monitoring the resistance of a filament.

Working range:
10^{3} – 10^{-4} mbar.



Bayard-Alpert gauge
Electrons produced by a filament ionize the gas, and the ions generate a measurable current on the collector.

Working range:
10^{-4} – 10^{-12} mbar.



Penning gauge
They have no filament (cold cathode); a discharge creates secondary electrons which ionize the gas molecules, and the current on the cathode is read as in ion pumps.

Working range:
10^{-2} – 10^{-9} mbar.

Vacuum connectors

The more diffused standards are:

KF flanges (Klein Flansch)

Sealing via elastomer o-ring (Viton)

Down to 10^{-8} mbar

CF flanges (ConFlat)

Sealing via copper gasket

Down to 10^{-12} mbar

Exercise

What is the force acting on a CF63 flange (the 63 indicates the inner diameter of the flange in mm), when the pressure inside the UHV chamber is 10^{-10} mbar?

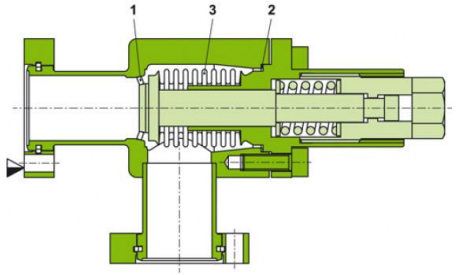
Area of the flange: $\sim 3115\ mm^2 \sim 0.003\ m^2$

p_{atm}= 1 bar, $p_{internal} \sim 0$ bar, $\Delta p = 1\ bar = 10^5\ Pa$

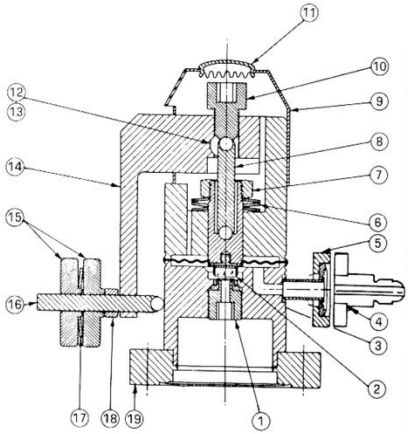
$p = F/A$, $F = p \times A = 10^5\ Pa \times 0.003\ m^2 = 300\ N$ (weight of ~ 30 kg)

Valves

Gate valve



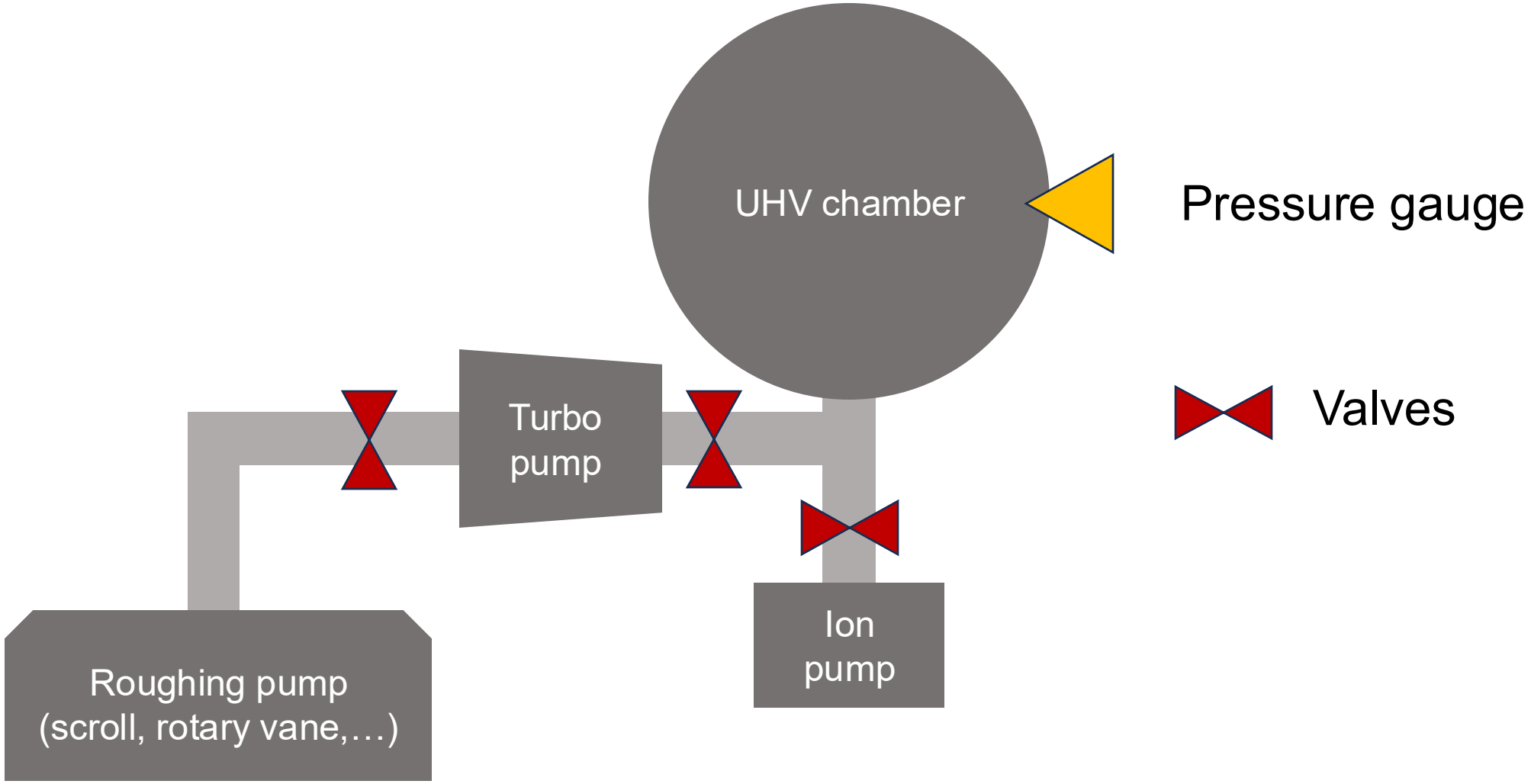
Right-angle valve



Leak valve

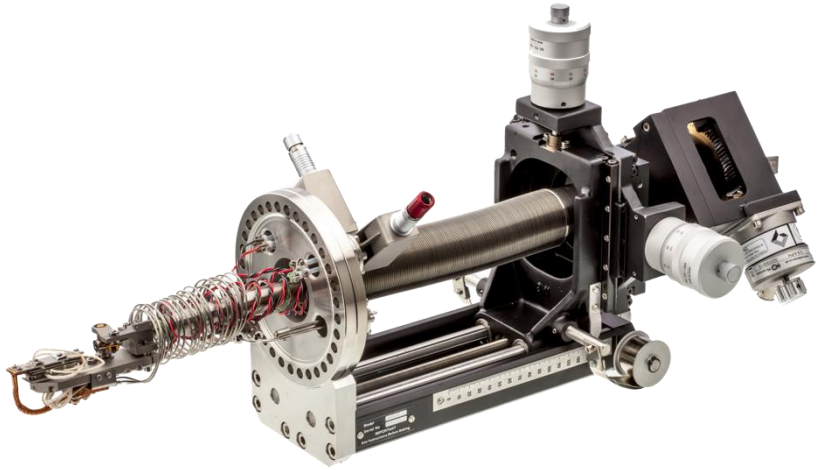
And other types…

A basic UHV system



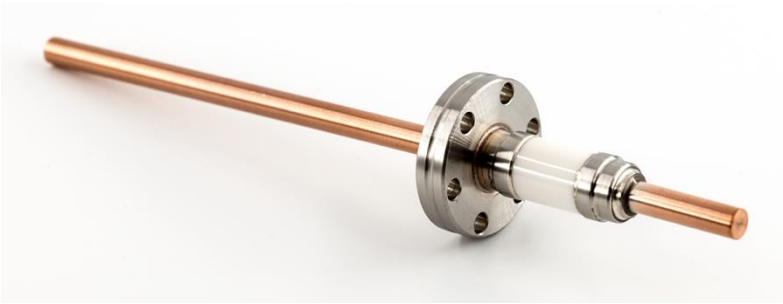
Other useful additions

Manipulator and sample holder



Viewports

Electrical feedthroughs



Wobblestick

Fast-entry load locks

Some fundamental concepts

Bake-out

To achieve UHV in reasonable times, the system is “baked” to temperatures > 100 °C to desorb the gases (mostly H_20) from the inner walls of the chamber.

Leak test

To detect leaks in the system, a common practice is to flux He in critical spots of the setup, while monitoring the mass spectrum with a residual gas analyzer.

Venting

It may be required to bring the chamber back to atmospheric pressure (“in air”) for maintenance or upgrades of the instruments mounted in the system. To do so, we need to ensure to switch off any instrument that could get damaged (ion and turbo pumps, filaments, …) and preferably flux pure nitrogen to minimize contamination and speed up the following pump-down time.