Vacuum Technique

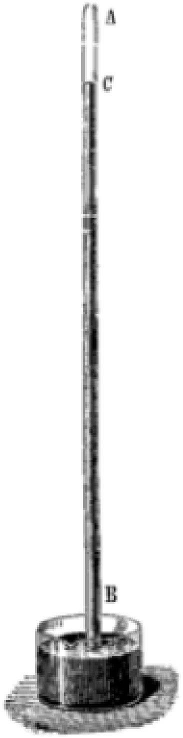
Vacuum – volume of space empty
of matter

History

Aristotle – vacuum impossible – "nothing
could be something"

Christians – held idea of a vacuum
heretical, "absence of anything
implied absence of God"

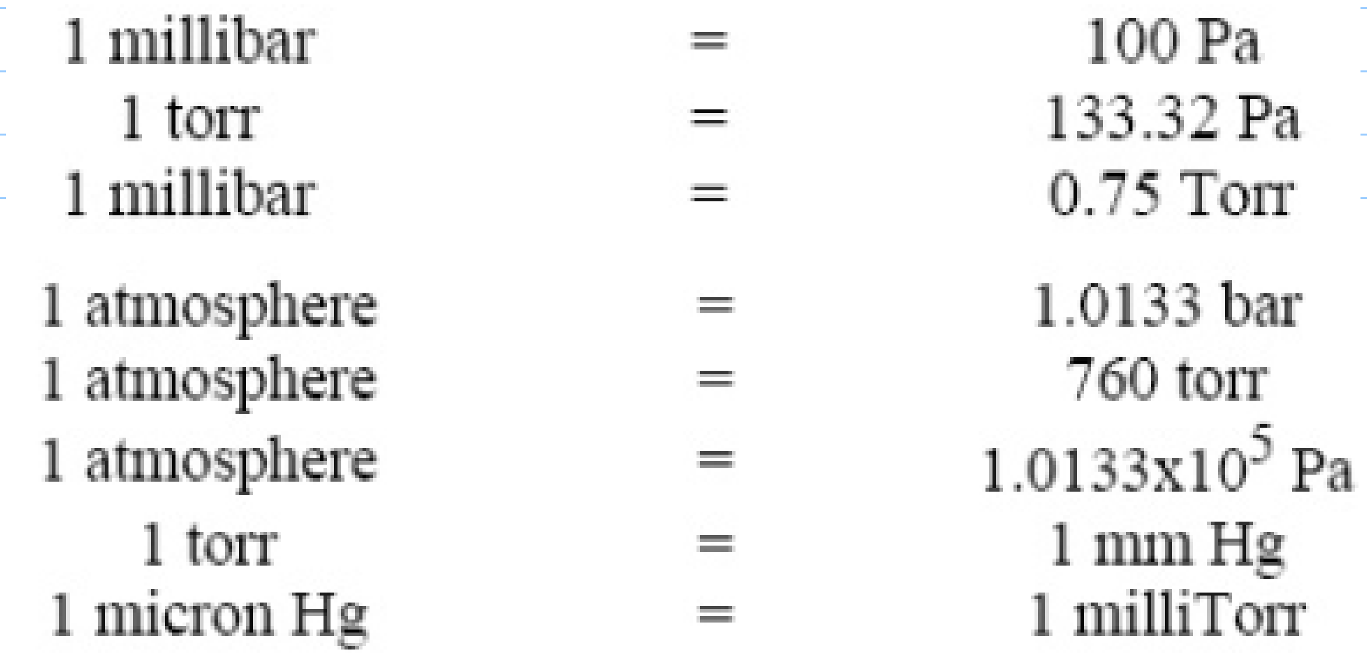
Evangelista Torricelli 1645




Portrait of Evangelista Torricelli.

Torricelli's mercury barometer produced

Vacuum Units



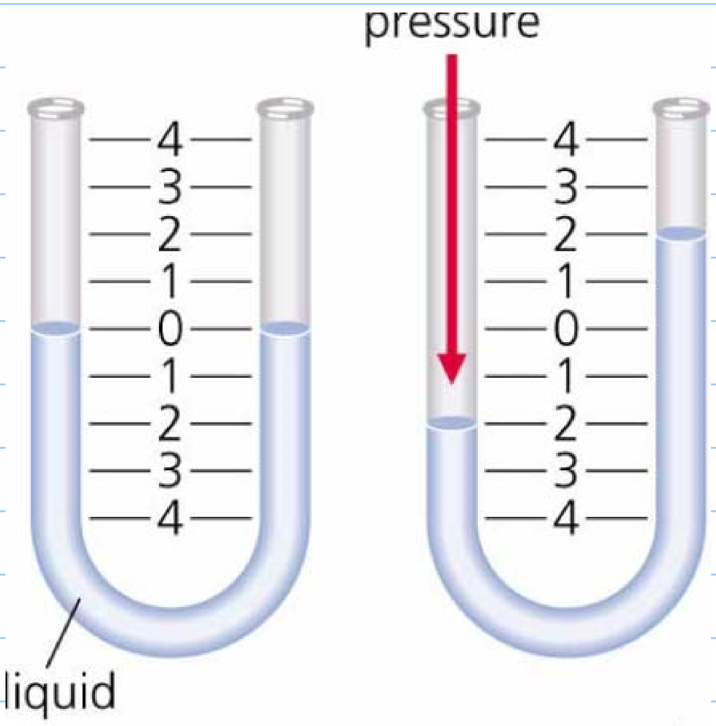
1 millibar	=	100 Pa
1 torr	=	133.32 Pa
1 millibar	=	0.75 Torr
1 atmosphere	=	1.0133 bar
1 atmosphere	=	760 torr
1 atmosphere	=	1.0133×10^5 Pa
1 torr	=	1 mm Hg
1 micron Hg	=	1 milliTorr

Pascal 1 newton per sq. meter

1 torr = 133.322 Pa

Measurements of Pressure

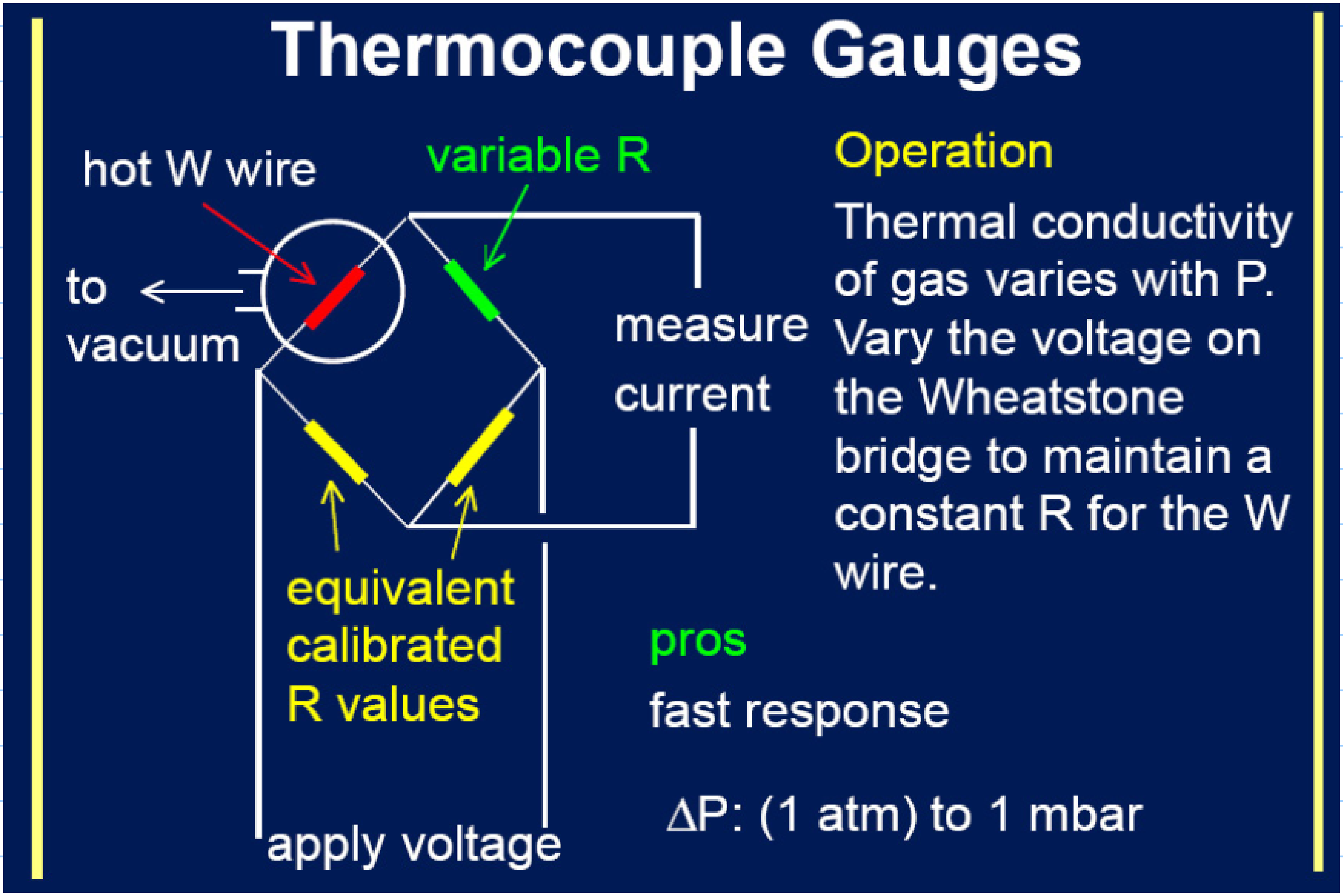
Manometer



Precision Graphics

Pressures above 1 Torr

For pressures < 1 torr



Thermocouple Gauges

Operation

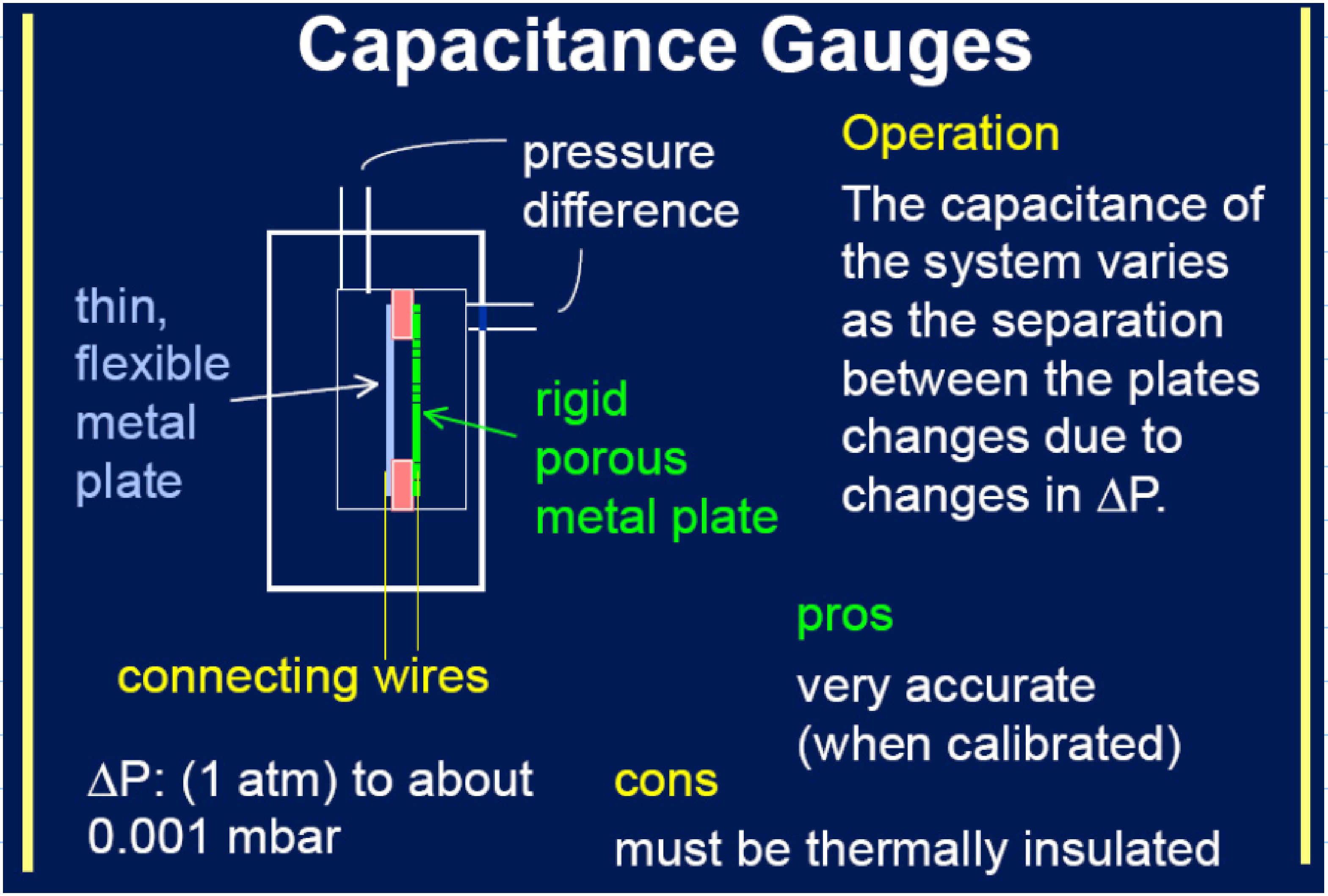
Thermal conductivity of gas varies with P. Vary the voltage on the Wheatstone bridge to maintain a constant R for the W wire.

pros

fast response

ΔP: (1 atm) to 1 mbar

Pressures < 1 Torr cont.



Capacitance Gauges

pressure difference

thin, flexible metal plate

rigid porous metal plate

connecting wires

Operation

The capacitance of the system varies as the separation between the plates changes due to changes in ΔP.

pros

very accurate (when calibrated)

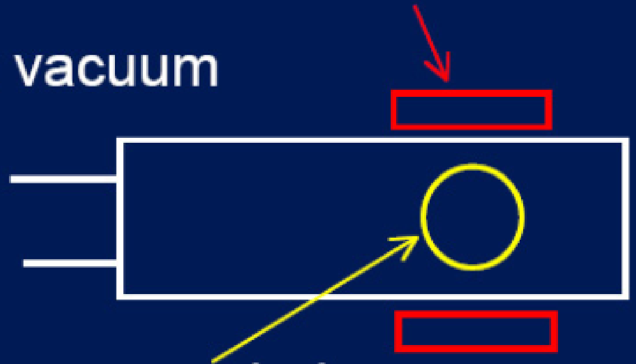
cons

must be thermally insulated

ΔP: (1 atm) to about 0.001 mbar

Pressure < 1 Torr

Spinning Ball Rotors



oscillating
magnetic field

to vacuum

suspended
spinning ball

P: 10^{-1} to 10^{-7} mbar

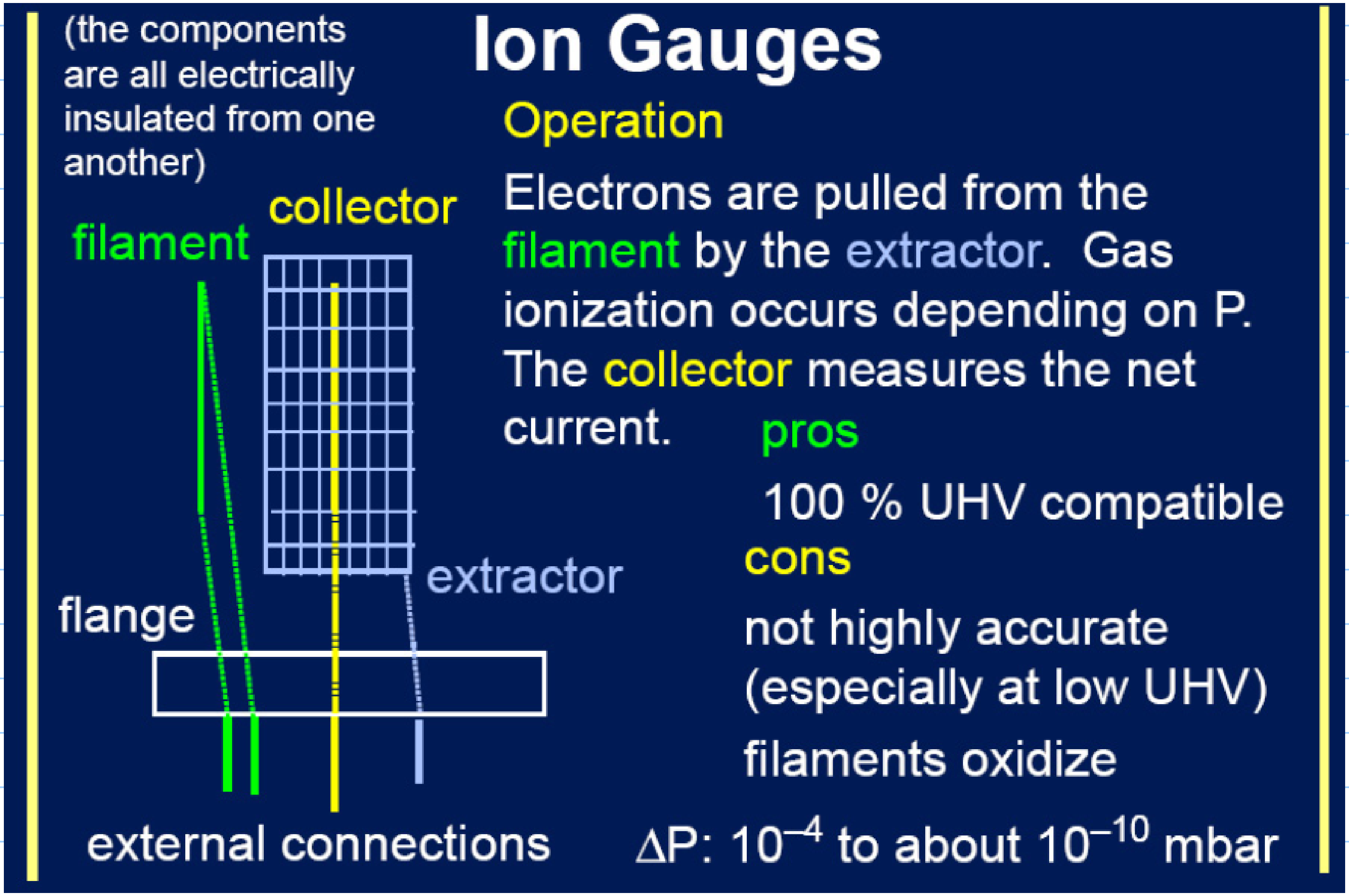
Operation

Gas viscosity depends on P. Measure the energy needed to keep the ball spinning under various P.

pros

highly accurate
(when calibrated)

Pressure < 1 Torr. Cont.



Ion Gauges

Operation

Electrons are pulled from the filament by the extractor. Gas ionization occurs depending on P. The collector measures the net current.

pros

100 % UHV compatible

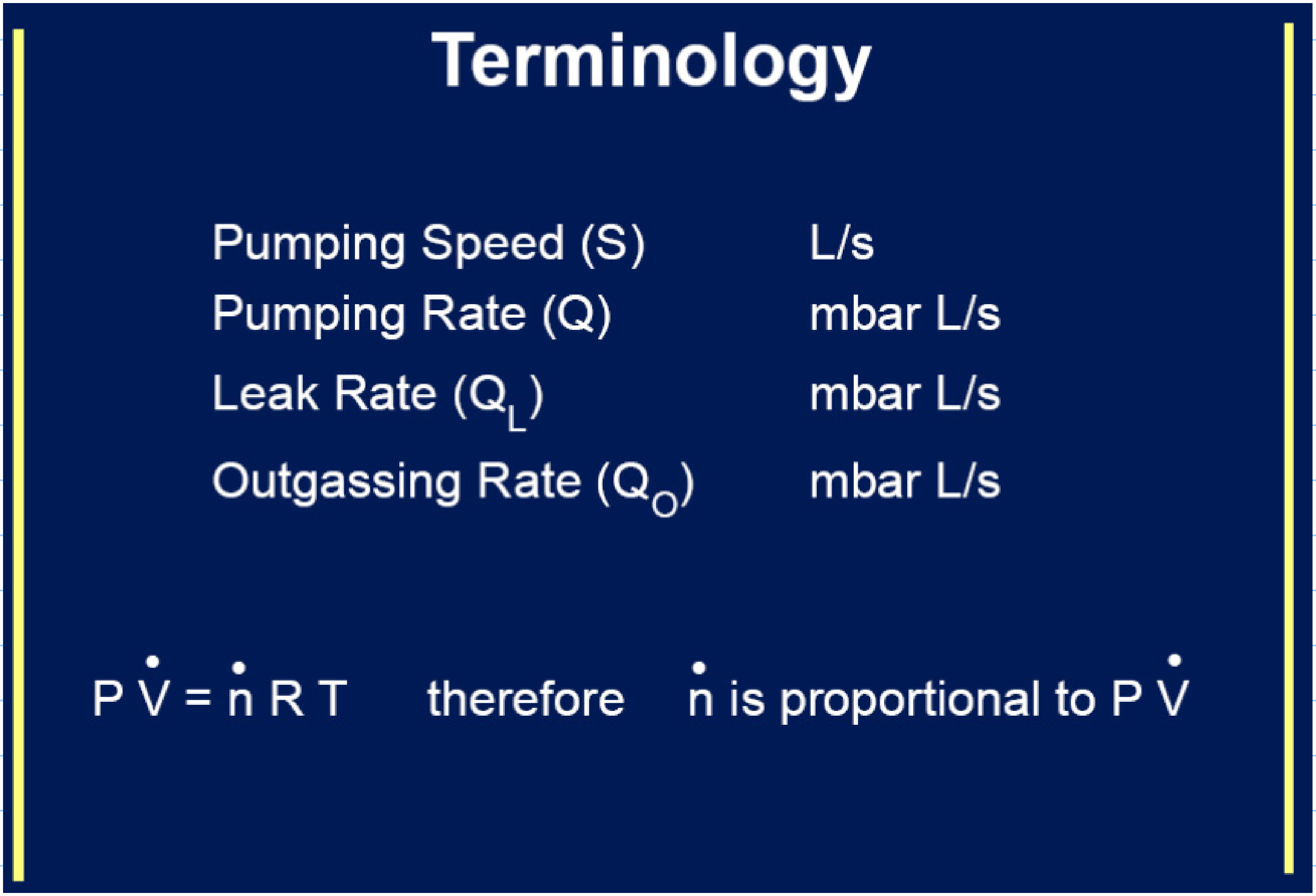
cons

not highly accurate (especially at low UHV)

filaments oxidize

ΔP: 10^{-4} to about 10^{-10} mbar

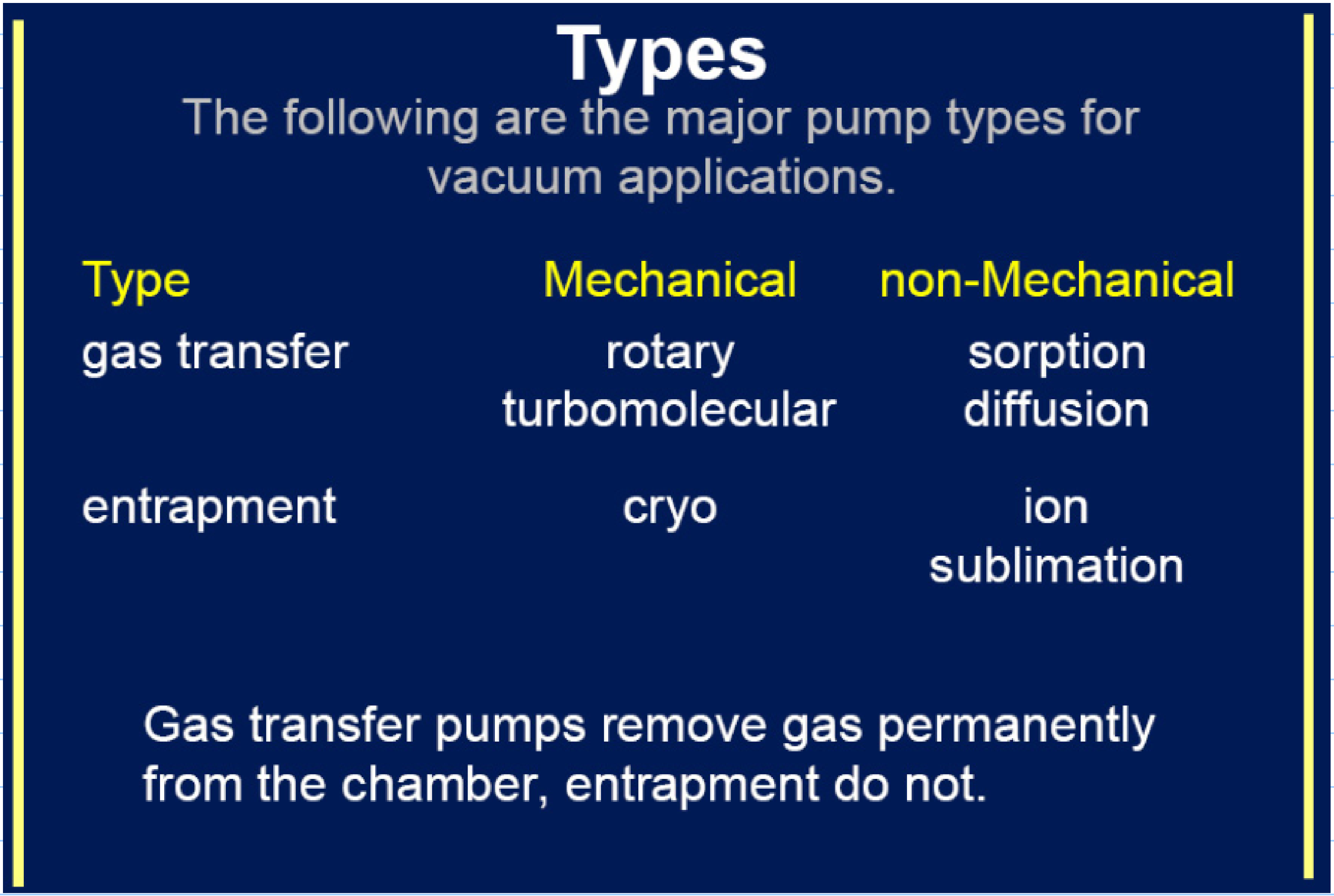
Vacuum Pumps



Terminology

Pumping Speed (S)	L/s
Pumping Rate (Q)	mbar L/s
Leak Rate (Q_L)	mbar L/s
Outgassing Rate (Q_O)	mbar L/s

$P\dot{V} = \dot{n}RT$ therefore $\dot{n}$ is proportional to $P\dot{V}$



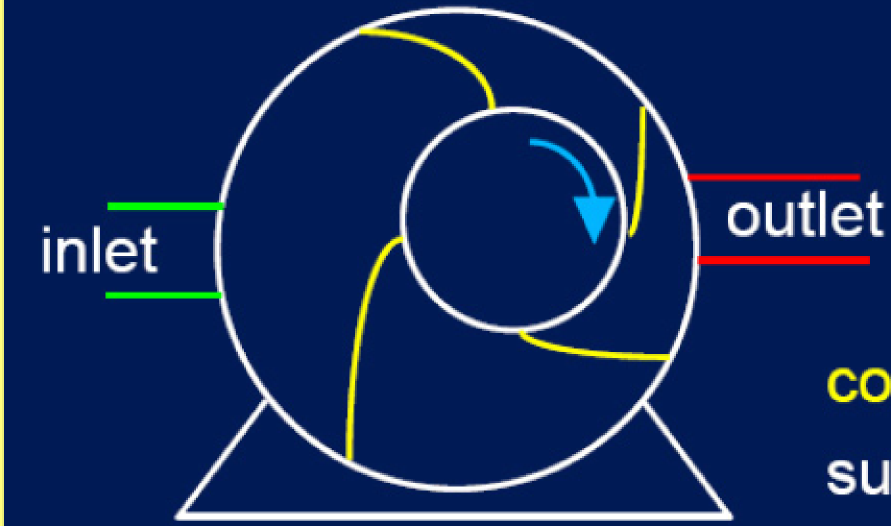
Types

The following are the major pump types for vacuum applications.

Type	Mechanical	non-Mechanical
gas transfer	rotary turbomolecular	sorption diffusion
entrapment	cryo	ion sublimation

Gas transfer pumps remove gas permanently from the chamber, entrapment do not.

Rotary



pros

- low maintanence
- high Q

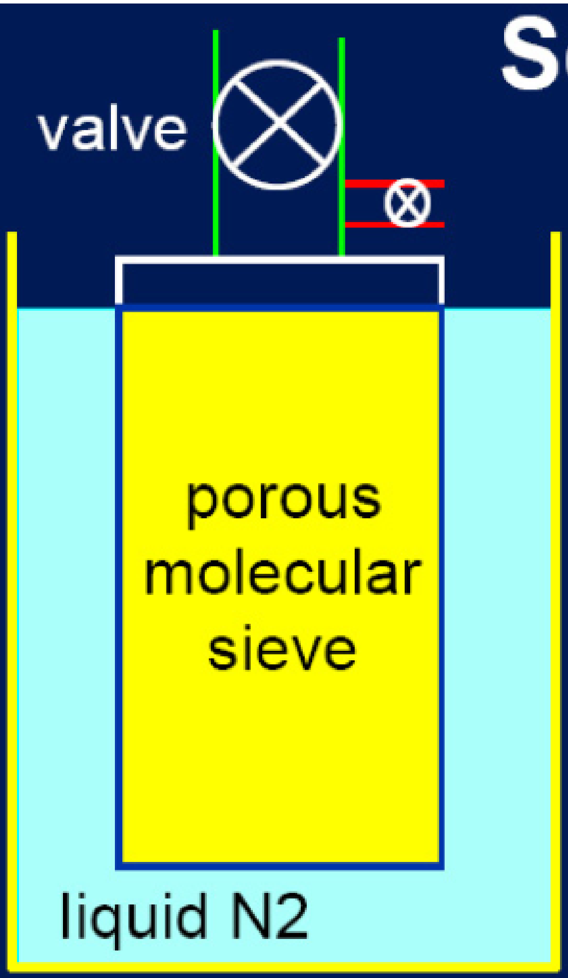
cons

- subject to wear
- not UHV compatible
- do not pump condensable gases well
- cause vibrations

operation

Pi Vi = Pf Vf

Sorption



pros

very low maintenance

no vibrations

clean

cons

Q depends strongly on P

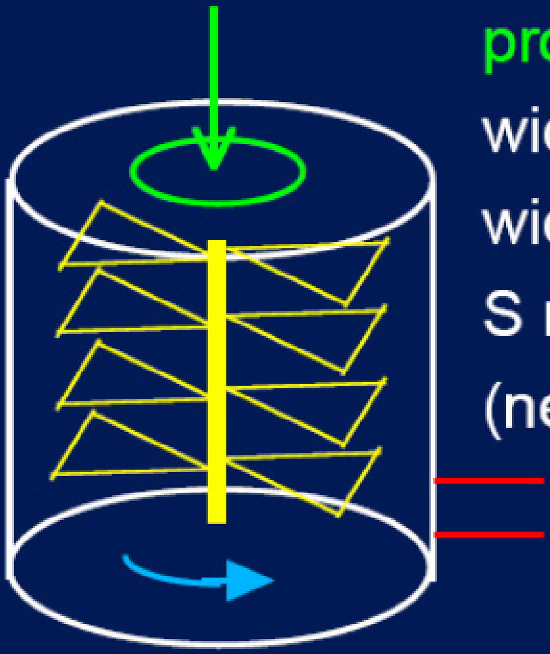
must be recharged each time

not capable of reaching UHV

operation

molecular adsorption on large surface area (100s of m^2)

Turbomolecular



tilted vanes

very high rotation rate

pros

- wide range of P
- wide range of Q
- S nearly constant with P
- (nearly) 100% UHV compatible

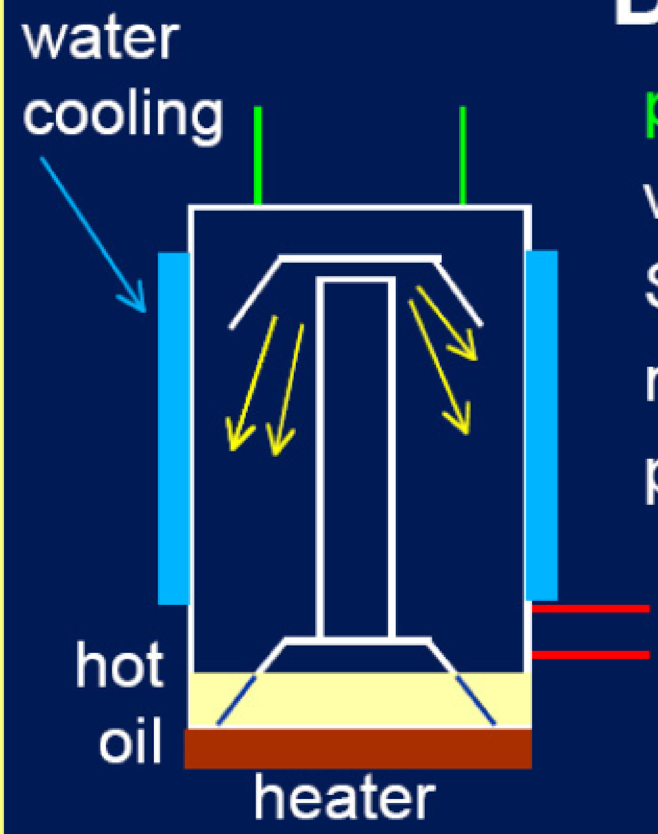
cons

- pump light gases poorly
- requires additional stage
- causes vibrations

operation

vanes change the direction of travel of gas molecules

Diffusion



pros

- wide range of Q
- S nearly constant with P
- no vibrations
- pump light gases well

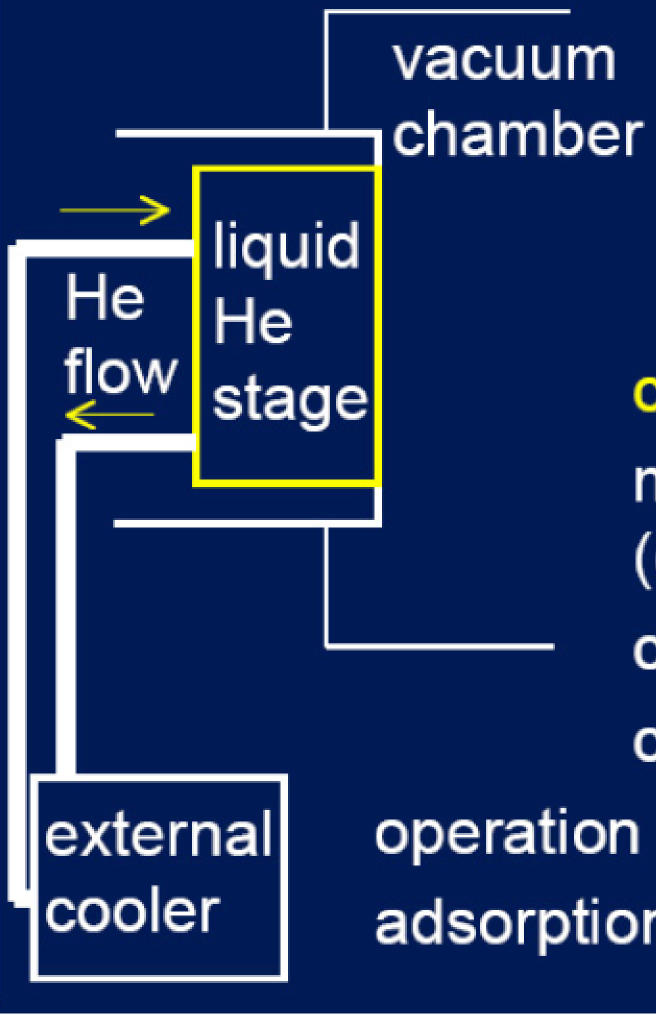
cons

- must use liquid N2 trap to reach UHV
- requires additional stage
- high operational costs

operation

oil spray changes the momentum of gas molecules

Cryopump



pros

high Q

(nearly) 100 % UHV compatible

cons

must recharge occasionally (other pumps needed)

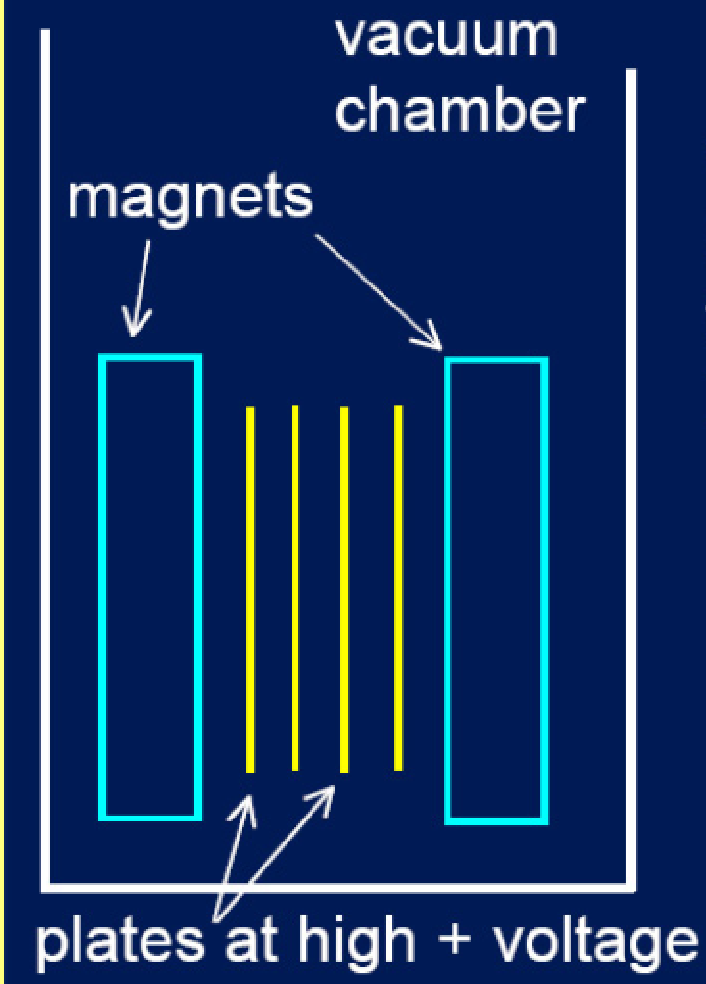
causes vibrations

can be high maintenance

operation

adsorption of gases on the cold pump wall

Ion



operation

B field causes gas ions to spiral into walls and imbed themselves

pros

wide range of Q

wide range of P

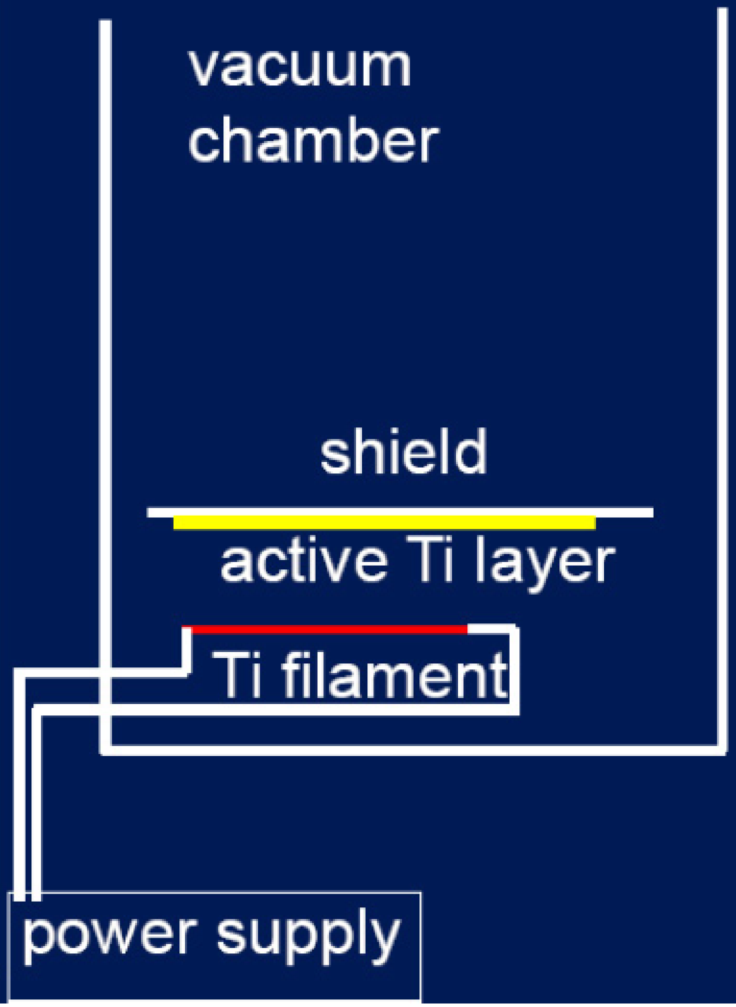
no vibrations

cons

magnetic field

high voltage

Sublimation



operation

freshly evaporated Ti layeractively retains adsorbing gas molecules

pros

no vibrations

100 % UHV compatible

cons

not continuous

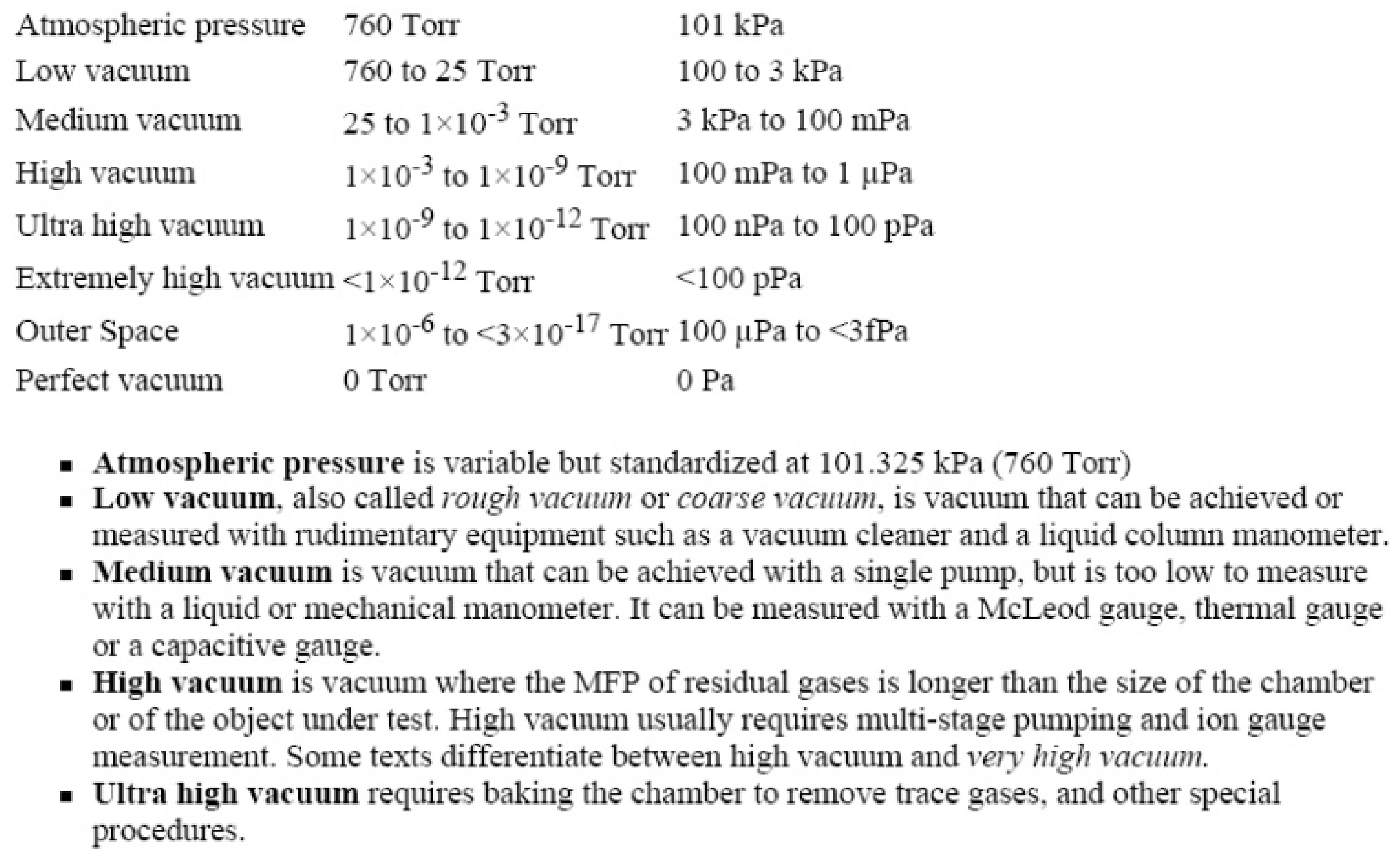
low Q

narrow range of P

Summary

Type	P range (mbar)	S (L/s)
rotary	1000 - 0.001	
sorption	1000 - 10^{-5}	
turbo	(1000) - UHV	
diffusion	10^{-5} - UHV	
ion	(1000) - UHV	
cryro	10^{-5} - UHV	
sublimation	10^{-7} - UHV	

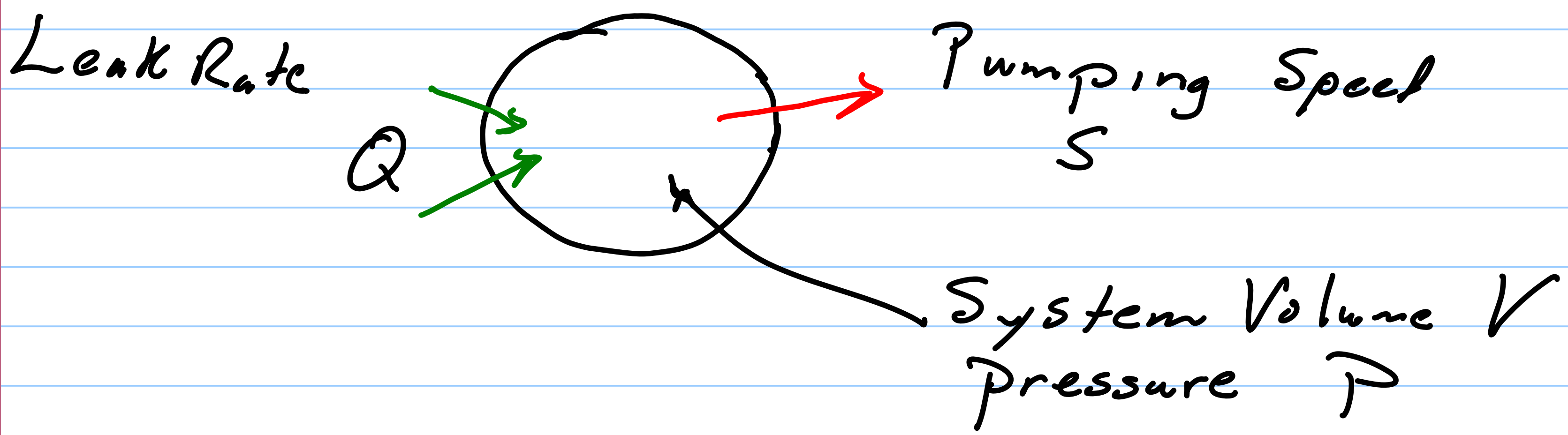
Kinds of Vacuum



Atmospheric pressure	760 Torr	101 kPa
Low vacuum	760 to 25 Torr	100 to 3 kPa
Medium vacuum	25 to 1×10^{-3} Torr	3 kPa to 100 mPa
High vacuum	1×10^{-3} to 1×10^{-9} Torr	100 mPa to 1 µPa
Ultra high vacuum	1×10^{-9} to 1×10^{-12} Torr	100 nPa to 100 pPa
Extremely high vacuum	$<1\times10^{-12}$ Torr	<100 pPa
Outer Space	1×10^{-6} to $<3\times10^{-17}$ Torr	100 µPa to <3fPa
Perfect vacuum	0 Torr	0 Pa

- **Atmospheric pressure** is variable but standardized at 101.325 kPa (760 Torr)
- **Low vacuum**, also called *rough vacuum* or *coarse vacuum*, is vacuum that can be achieved or measured with rudimentary equipment such as a vacuum cleaner and a liquid column manometer.
- **Medium vacuum** is vacuum that can be achieved with a single pump, but is too low to measure with a liquid or mechanical manometer. It can be measured with a McLeod gauge, thermal gauge or a capacitive gauge.
- **High vacuum** is vacuum where the MFP of residual gases is longer than the size of the chamber or of the object under test. High vacuum usually requires multi-stage pumping and ion gauge measurement. Some texts differentiate between high vacuum and *very high vacuum*.
- **Ultra high vacuum** requires baking the chamber to remove trace gases, and other special procedures.

Vacuum Concepts



Pump-down Equation

$$pS = -V\frac{dp}{dt} + Q$$

Leak Rate

$$Q = Q_1 + Q_0$$

Q_1 true leak rate

Q_0 virtual leak rate (outgassing)

Soln:

i) Short time limit

$$P = P_0 e^{-t/\tau} \quad \text{where } \tau = V/S$$

- leak rate negligible

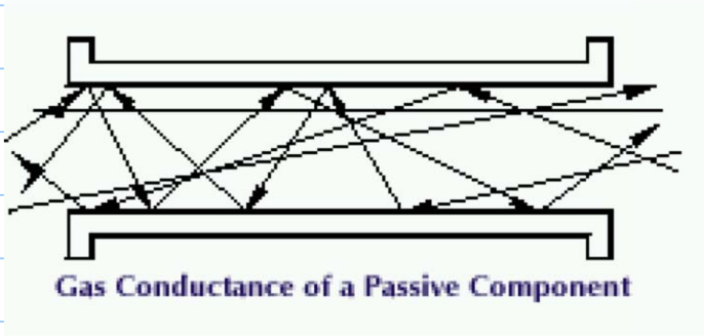
ii) long time limit

$$P_u = Q/S$$

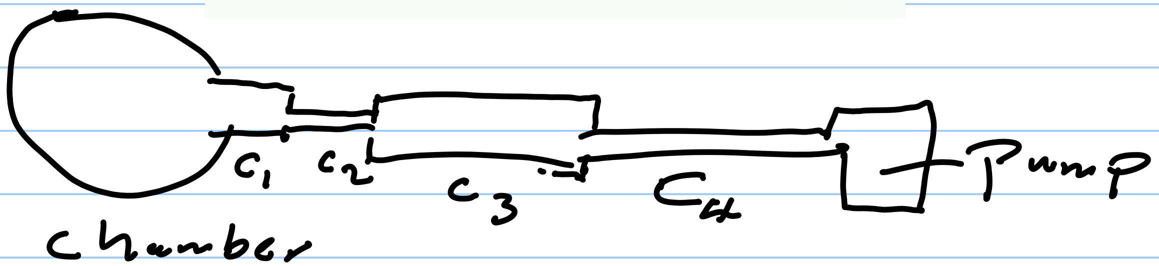
ultimate pressure

If no leaks $Q = Q_0$ depends on surface prep

Idea of Conductance


Gas Conductance of a Passive Component

Pipe work



Effective Pump speed

$$S^{-1} = \sum C_i^{-1} + S_0^{-1}$$

Measurement of System Pressure

- different at different points in system

By continuity

$$P_0 S_0 = P S = Q$$

Since $$Q = (P - P_0)$$

Thus $$P - P_0 = P_0 S_0 / C \Rightarrow P = P_0 (1 + S_0/C)$$

Problems when C small, S_0 large

UHV?

Monolayer time

$$t = 3.2 \times 10^{-6} / P$$ unity sticking coefficient

P in millibar

$\Rightarrow$ For 1 hour with less than a monolayer

$$P < \underline{\underline{10^{-9}\text{ millibar}}}$$

Vacuum Theory (Ideal Gas)

(non-interacting gas)

mean velocity

$$V = \left(\frac{8KT}{\pi M}\right)^{1/2}$$

mean free path

$$\lambda = \frac{1}{\sqrt{2}\,\pi d_0^2 n_a}$$

gas density

For air at room temp

$$\lambda_{mm} = 6.6/P \quad , P \text{ in } Pa$$

Flux

$$\Gamma = n\left(\frac{kT}{2\pi M}\right)^{1/2}$$

For a fixed volume containing different non-interacting gases

$$P_T = n_1 kT + n_2 kT \ldots + n_i kT = \sum_i P_i$$

Three Regions of Gas Flow

1) Mean free path < characteristic dimension d

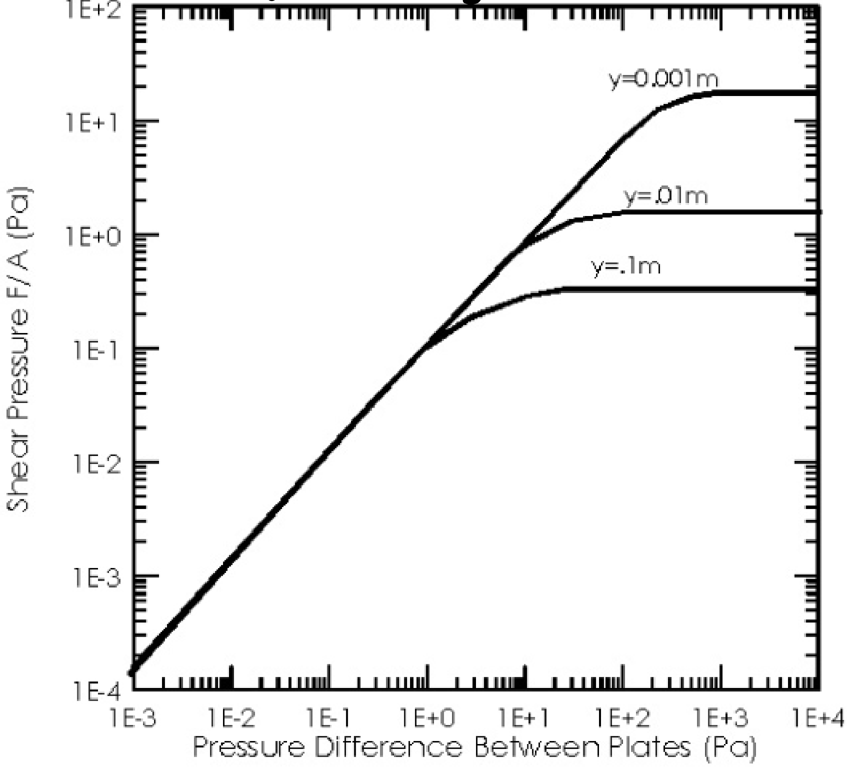
$$\frac{\lambda}{d} << 1$$

viscous force intedendent of pressure

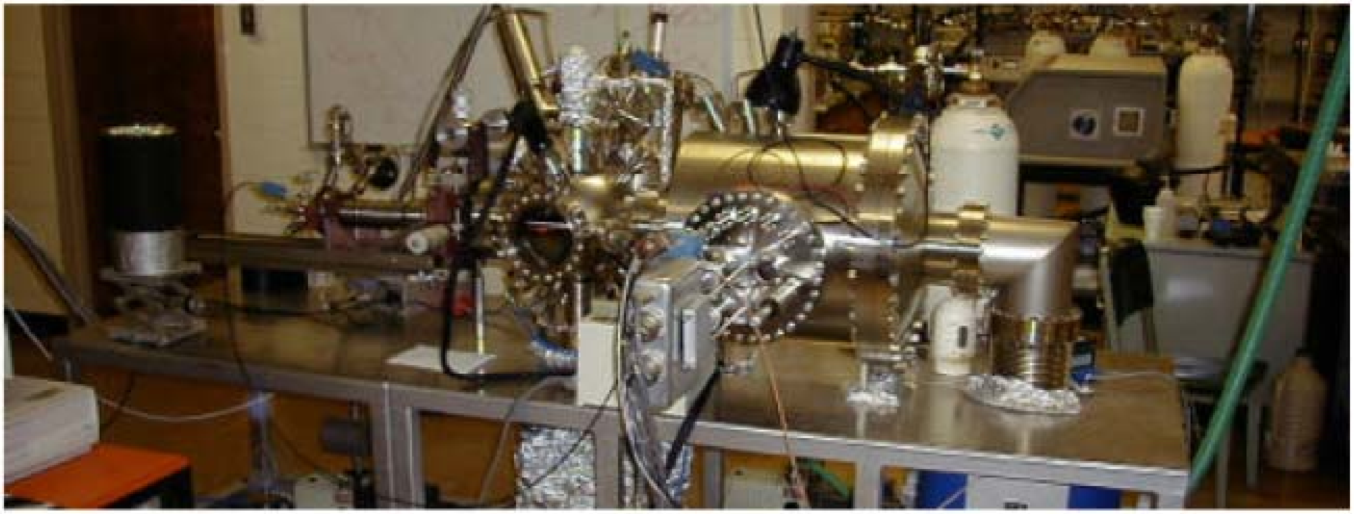
2) $\lambda/d >> 1$ free-molecular flow regime viscous drag $\propto$ pressure

3) Knudson or transition flow in between limits

Viscous Shear



1.3. General Vacuum Chamber Features



Several different types of pumps (different operating pressures)

Pressure measurement (multiple gauges)

Sample movement, heating, cooling, cleaning, viewing

Gas/vapor admission system (controlled "leak")

Multiple analytical techniques (neutral or charged particles or radiation)