Vacuum I

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Index

Introduction to Vacuum

Vacuum and the Beam

Flow Regimes

Creating Vacuum

Vacuum in accelerators

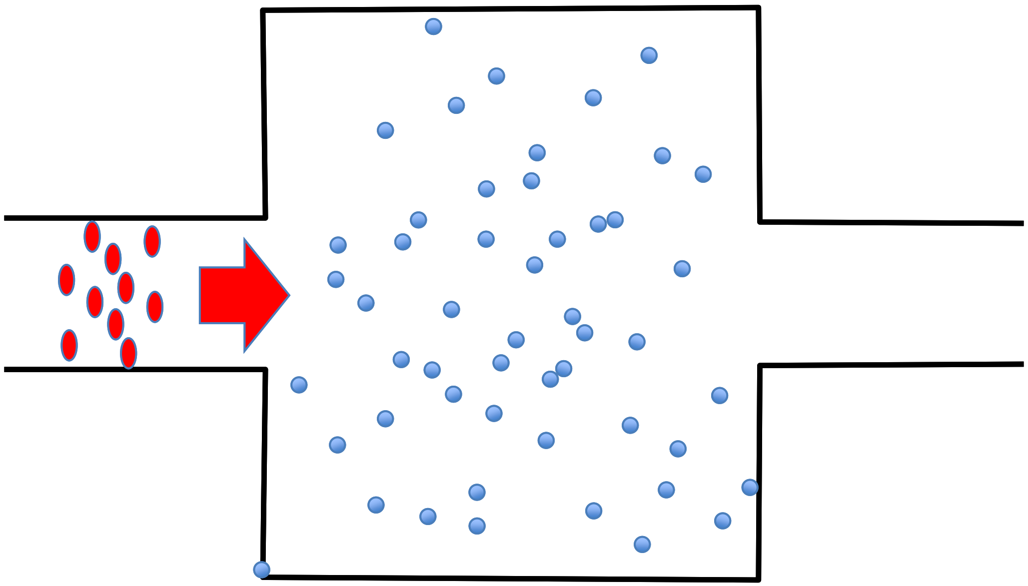
All beam dynamics has the purpose of controlling a charged beam particle

$$\frac{d}{dt}m\gamma\vec{v} = e\vec{E} + e\vec{v}\times\vec{B}$$

Structure of magnets and RF structure have the purpose of creating a proper guiding (E,B) structure

However in an accelerator are present a jungle of unwanted particles which creates a damaging background for beam operation

Characteristic of Vacuum



Vacuum is considered as a Gas which is characterized by

Macroscopic Quantities

Pressure

Temperature

Density

Composition

Aim:

Minimize the interaction of beam with vacuum gas

Microscopic Quantities

Kinetic Theory

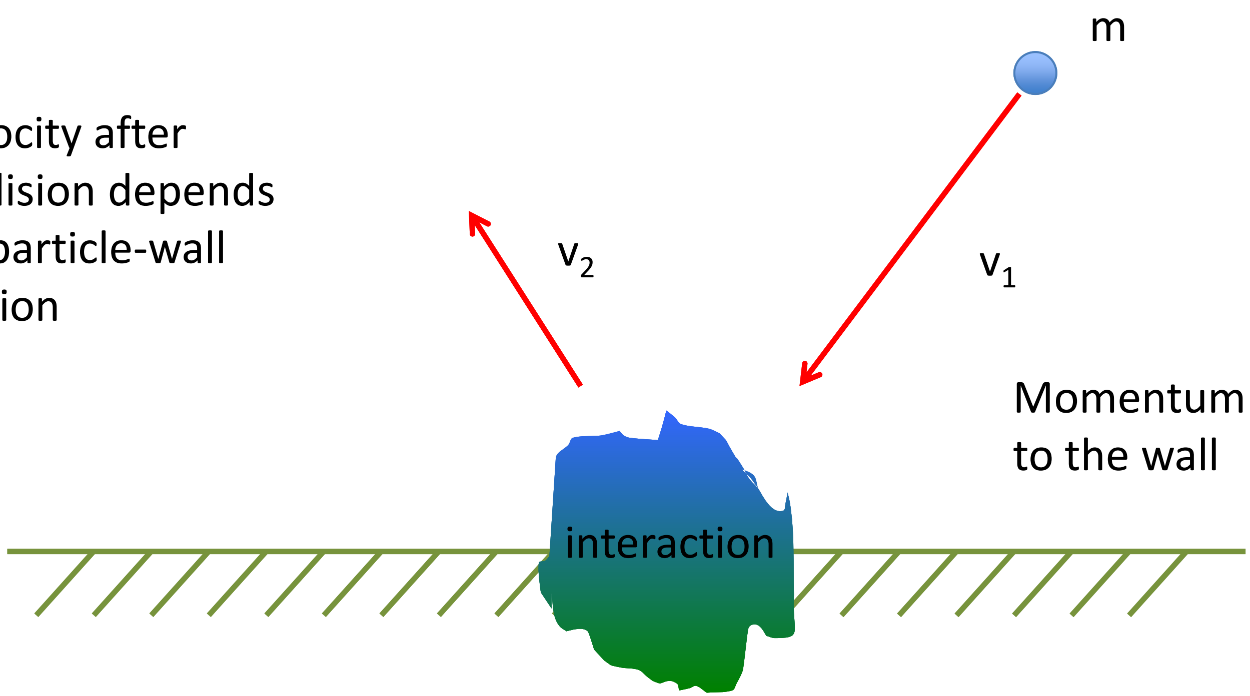
Typical numbers

	Particles m^{-3}
Atmosphere	2.5×10^{25}
Vacuum Cleaner	2×10^{25}
Freeze dryer	10^{22}
Light bulb	10^{20}
Thermos flask	10^{19}
TV Tube	10^{14}
Low earth orbit (300km)	10^{14}
H_2 in LHC	$\sim 10^{14}$
SRS/Diamond	10^{13}
Surface of Moon	10^{11}
Interstellar space	10^{5}

R.J. Reid

Particle – Wall collision

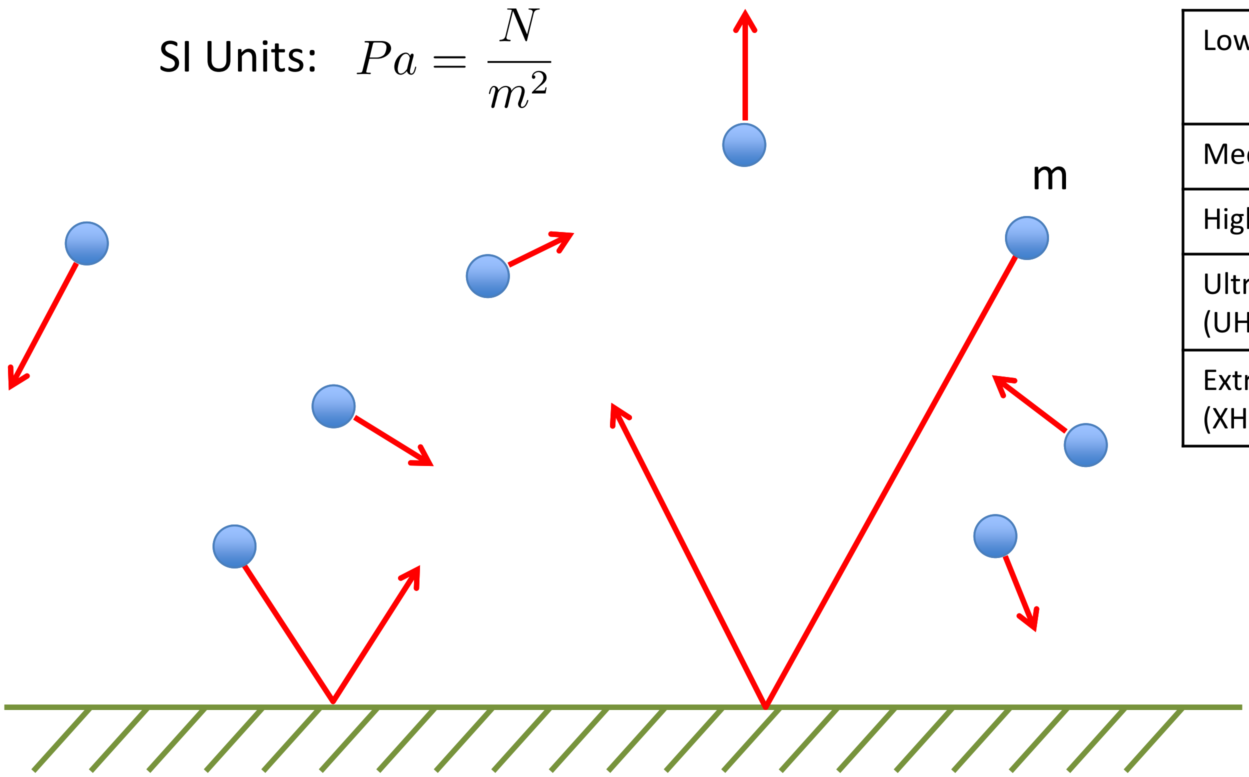
The velocity after wall collision depends on the particle-wall interaction



Momentum is propagated to the wall

Pressure

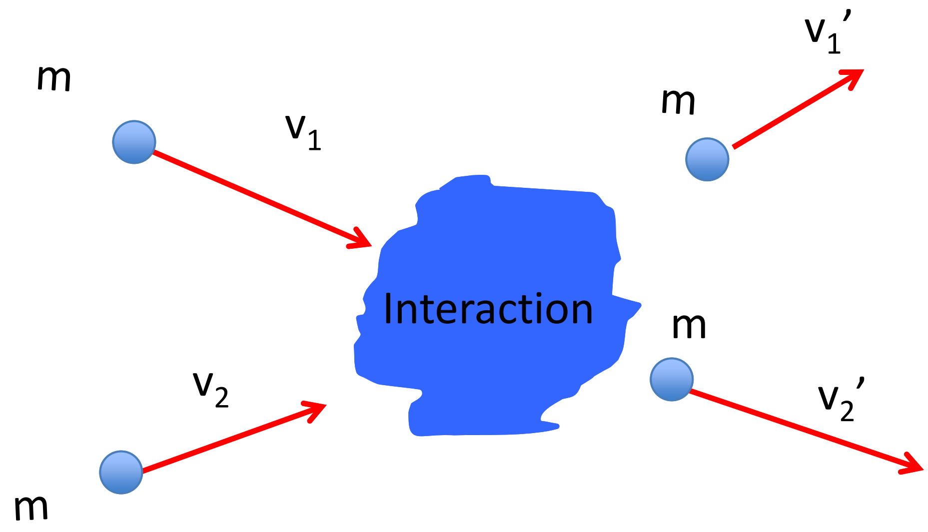
SI Units: $Pa = \frac{N}{m^2}$



Low vacuum	Atm. pressure to 1 mbar
Medium vacuum	1 to 10^{-3} mbar
High Vacuum (HV)	10^{-3} to 10^{-8} mbar
Ultrahigh vacuum (UHV)	10^{-8} to 10^{-12} mbar
Extreme high vacuum (XHV)	less than 10^{-12} mbar

other units: $1\,\mathrm{Pa} = 10^{-2}\,\mathrm{mbar} = 7.5 \times 10^{-3}\,\mathrm{Torr} = 9.87 \times 10^{-6}\,\mathrm{atm}$

Particle – Particle interaction



In a gas large number of collisions

Most likely process P-P collision

For elastic collisions:
1) Energy conservation
2) Momentum conservation

Temperature $$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}k_B T$$

$$k_B = 1.38 \times 10^{-23} \quad [JK^{-1}]$$

Typical numbers

Air at T= 20° C

20% O_2 → M_O = 8x2 g-mole = 8x2/N_A = 2.65 x 10^{-23} g
80% N_2 → M_N = 7x2 g-mole = 7x2/N_A = 2.32 x 10^{-23} g

Therefore

$$< v_{N_2}^2 >= \frac{3K_B T}{M_{N_2}} = \frac{3 \times 1.38 \times 10^{-23} \times 293}{2 \times 2.32 \times 10^{-26}}$$

$$\sqrt{< v_{N_2}^2 >} = 511\,\mathrm{m/s}$$

Molecules run fast !

But the average velocity is $v_a =< v >= 0.92\sqrt{< v^2 >} = 470\,\mathrm{m/s}$

Velocity Distribution

When a gas is at equilibrium the distribution of the velocity follows the Maxwell-Boltzmann distribution

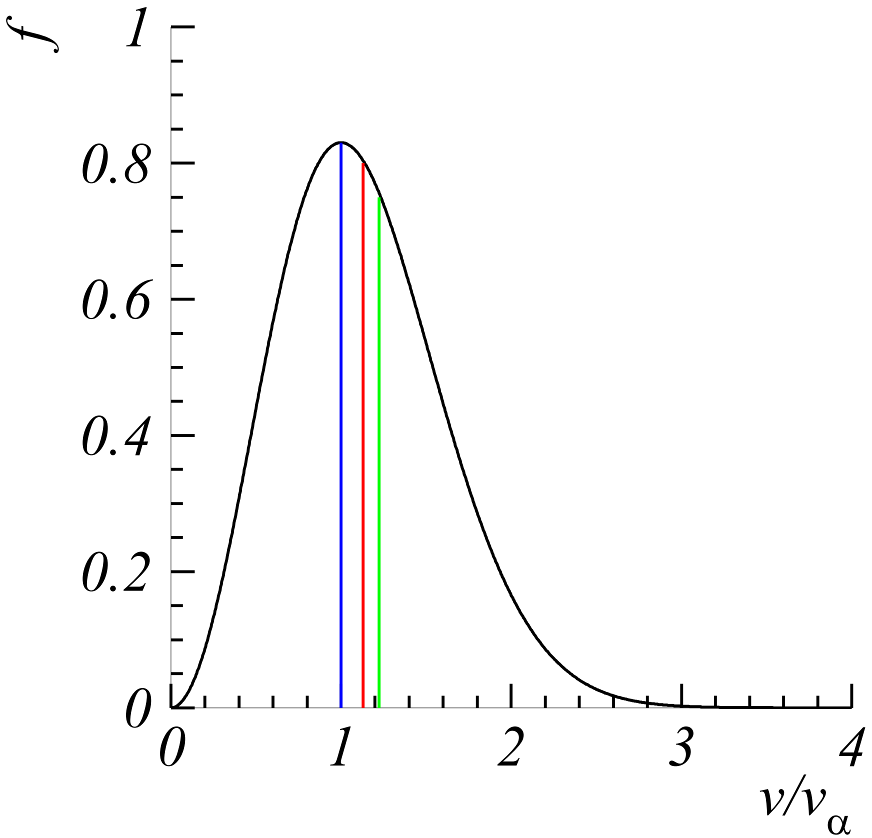
$$v = \sqrt{v_x^2 + v_y^2 + v_z^2}$$

$$\frac{1}{N}\frac{dN}{dv} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2k_BT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2k_BT}}$$

$$v_\alpha = \sqrt{\frac{2k_BT}{m}}$$ max velocity

$$v_a = \sqrt{\frac{8}{\pi}\frac{k_BT}{m}}$$ ave. velocity

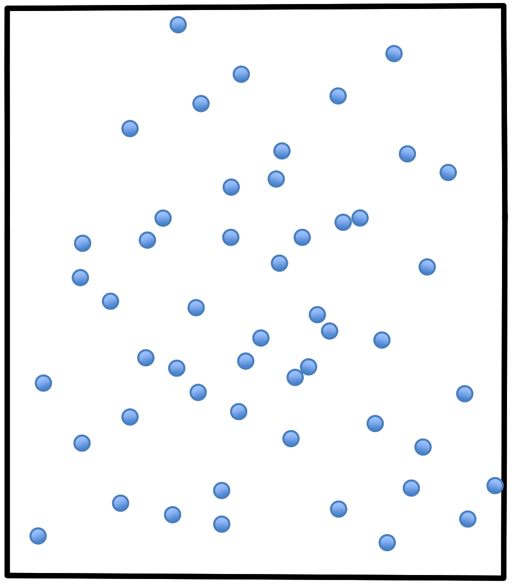
$$< v^2 >= \frac{3k_BT}{m}$$



Equation of state

An ideal gas in a container of volume V satisfies the equation of state

For a gas in equilibrium



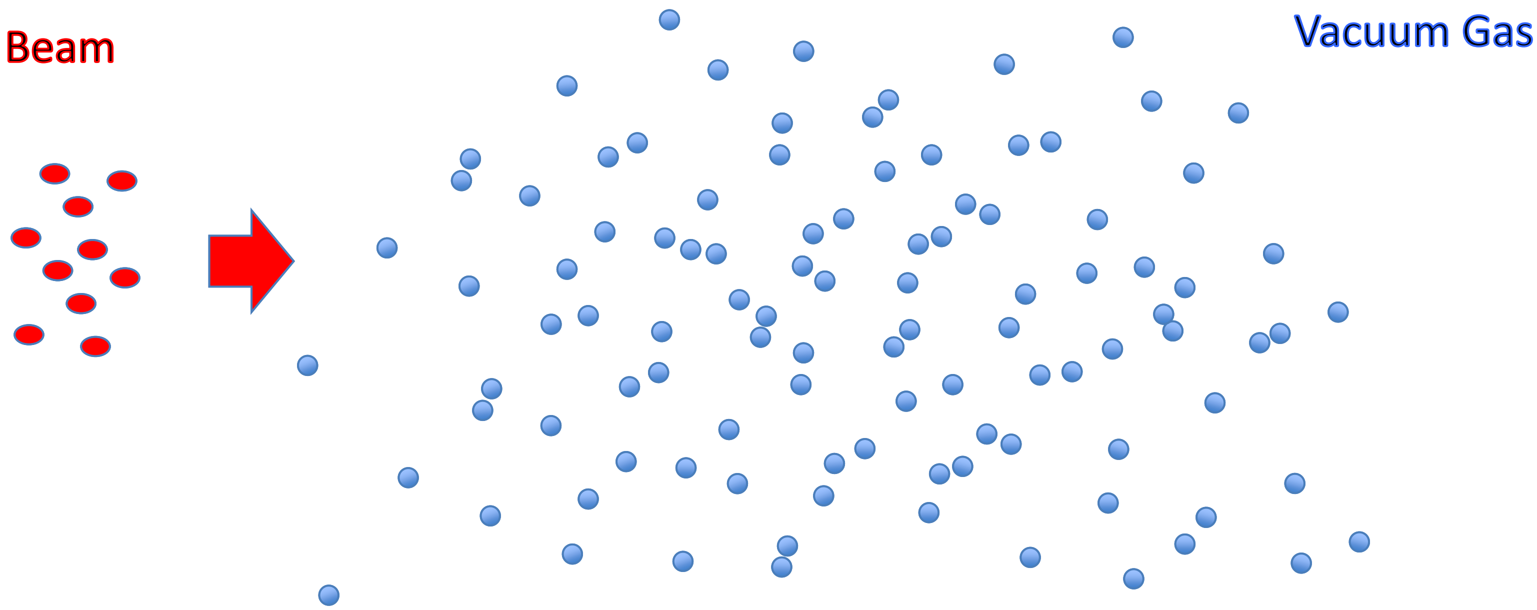
$$PV = nR_0T$$

SI units

P → Pressure [Pa]
V → Volume in [m^3]
n → moles [1]
T → absolute temperature [K]
R_0 = 8.314 [Nm/(mole K)] universal constant of gas
k_B = 1.38×10^{-23} [JK^{-1}] Boltzmann constant
N_A = 6.022×10^{23} [1] Avogadro's Number

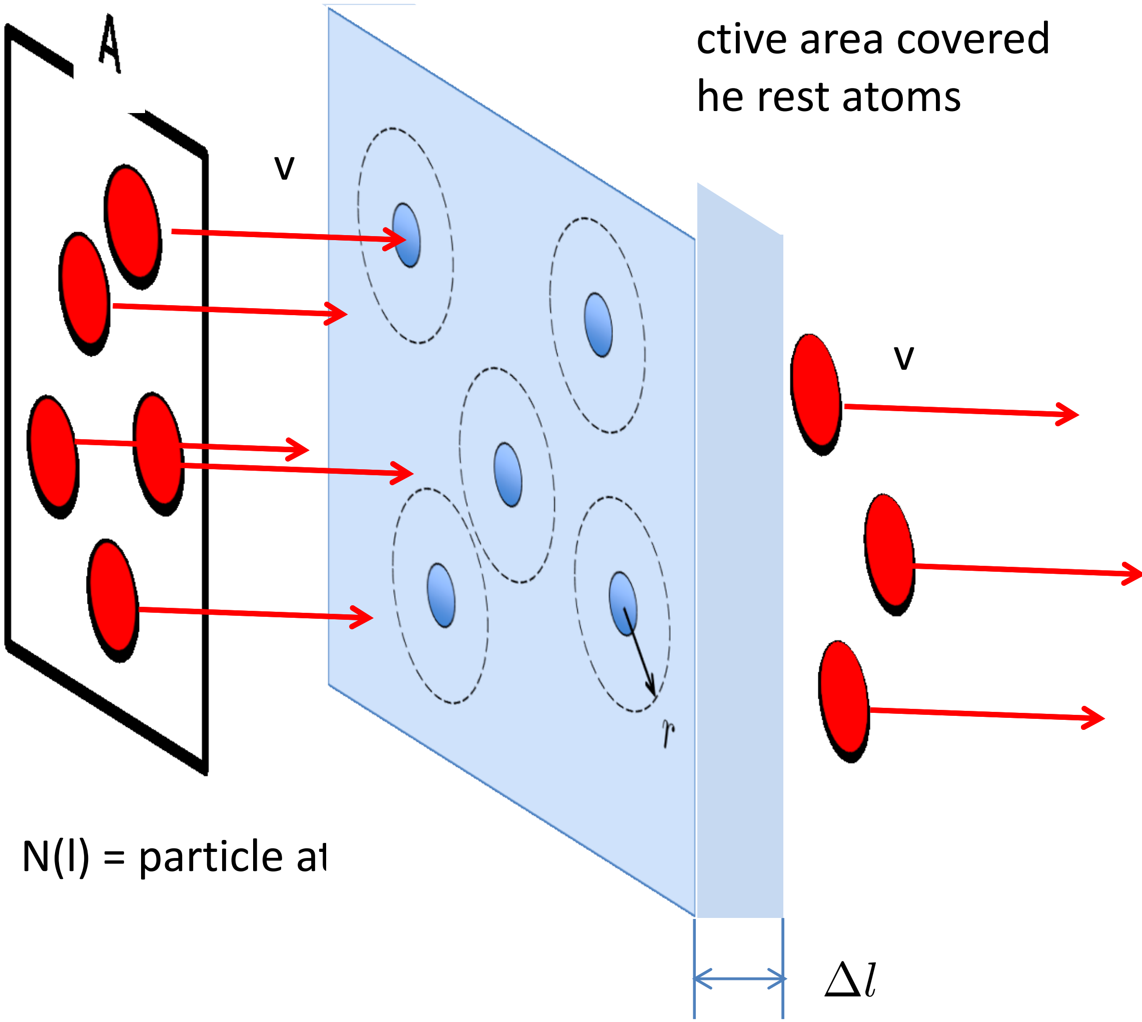
$$R_0 = k_B N_A$$

Mean free path



free path = path of a particle between two collisions

Mean free path



ctive area covered
he rest atoms

N(l) = particle at

$\sigma = \pi r^2$	Cross-section
$\tilde{n}$	Density of atoms
A	Transverse area

$$N(l+\Delta l) = N(l) - \frac{\sigma \Delta l A \tilde{n}}{A} N(l)$$

particles at l + Δl that did not collide

$$\frac{dN}{N} = -\sigma \tilde{n} dl$$

Particles that did not collide

Mean free path

How many particles collide between l and $l + \Delta l$?

$$dN = N(l)\sigma\tilde{n}dl$$

Therefore dN particles travelled a distance l and then collided

Probability that a particle travel l and then collide is

$$dP = \frac{N(l)}{N_0}\sigma\tilde{n}\,dl$$

In a gas

Mean free path $\lambda = \int_0^\infty l dP(l) = \frac{1}{\sigma\tilde{n}}$

$$\lambda = \frac{1}{\sqrt{2}\sigma\tilde{n}}$$

Example

Air at T = 20^0 C and P = 1 atm

From equation of state

$$\tilde{n} = \frac{P}{k_B T} = \frac{10^5}{1.38 \times 10^{-23} 293} = 2.47 \times 10^{25}$$ atom/m^3

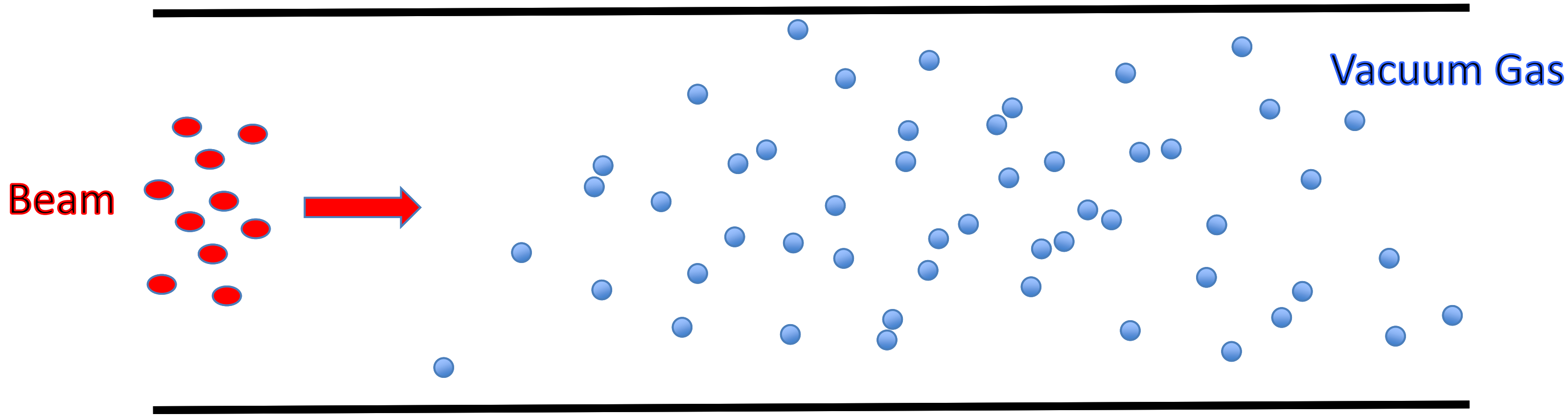
Diameter of molecule of air $d = 3.74 \times 10^{-10}\,\mathrm{m}$ → $\sigma = \pi d^2 = 4.39 \times 10^{-19}\,\mathrm{m}^2$

Mean free path ➡ $\lambda = 6.51 \times 10^{-8}\,\mathrm{m}$

N_2 at T = 20^0 C, d = 3.15 10^{-10} m

Pressure	P Pa	n m^{-3}	ρ kg m^{-3}	ν $m^{-2}s^{-1}$	*l* m
atm	10^5	2.5 10^{25}	1.16	2.9 10^{27}	9 10^{-8}
primary vacuum	1 10^{-1}	2.5 10^{20} 2.5 10^{19}	1.16 10^{-5} 1.16 10^{-6}	2.9 10^{22} 2.9 10^{21}	9 10^{-3} 9 10^{-2}
high vacuum	10^{-4} 10^{-7}	2.5 10^{16} 2.5 10^{13}	1.16 10^{-9} 1.16 10^{-12}	2.9 10^{18} 2.9 10^{15}	9 10^{1} 9 10^{4}
uhv	10^{-10}	2.5 10^{10}	1.16 10^{-15}	2.9 10^{12}	9 10^{7}
xhv	$<10^{-11}$				

Vacuum and Beam



Beam lifetime

After a beam particle collides with a gas atom, it gets ionized and lost because of the wrong charge state with respect to the machine's optics

Beam of particles going through a vacuum gas survives according to

$$N(l+\Delta l) = N(l) - \frac{\sigma \Delta l A \tilde{n}}{A} N(l) \quad \Rightarrow \quad \frac{dN}{dl} = -\sigma \tilde{n} N(l)$$

As beam particle have a velocity v_0, then

$$\frac{dN}{dt} = -\sigma \tilde{n} v_0 N(t)$$

From the equation of state

$$\tilde{n} = \frac{P}{k_B T} \quad \Rightarrow \quad \frac{dN}{dt} = -\frac{\sigma P v_0}{k_B T} N(t)$$

Beam lifetime

$$\tau = \frac{k_B T}{\sigma P v_0}$$

Beam lifetime sets the vacuum constrain

Example

It is important to know the cross-section of the interaction beam-vacuum

Of what is formed the vacuum ?
Does it depends on the energy ?

Example LHC

H_2 at 7 TeV at T = 5^0 K

$$\sigma = 9.5 \times 10^{-30}\,\mathrm{m}^2$$

for $\tau = 100\,\mathrm{hours}$

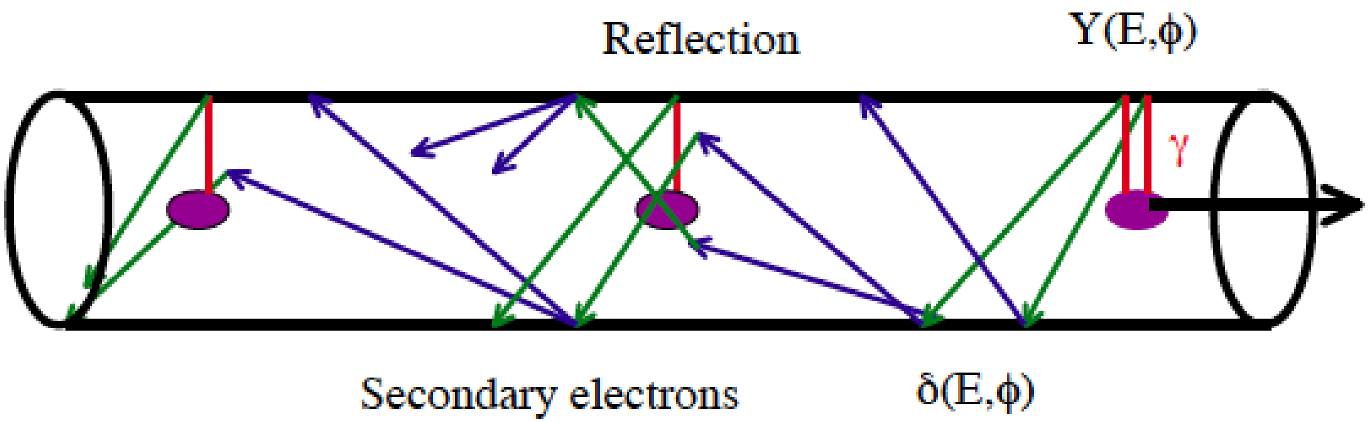
$$P = 6.7 \times 10^{-8}\,\mathrm{Pa}$$

Nuclear scattering cross section at 7 TeV for different gases and the corresponding densities and equivalent pressures for a 100 hours beam lifetime

GAS	Nuclear scattering cross section(cm^2)	Gas density (m^{-3}) for a 100 hour lifetime	Pressure (Pa) at 5 K, for a 100 hour lifetime
H_2	$9.5\ 10^{-26}$	$9.8\ 10^{14}$	$6.7\ 10^{-8}$
He	$1.26\ 10^{-25}$	$7.4\ 10^{14}$	$5.1\ 10^{-8}$
CH_4	$5.66\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
H_2O	$5.65\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
CO	$8.54\ 10^{-25}$	$1.1\ 10^{14}$	$7.5\ 10^{-9}$
CO_2	$1.32\ 10^{-24}$	$7\ 10^{13}$	$4.9\ 10^{-9}$

LHC Design Report

Electron cloud



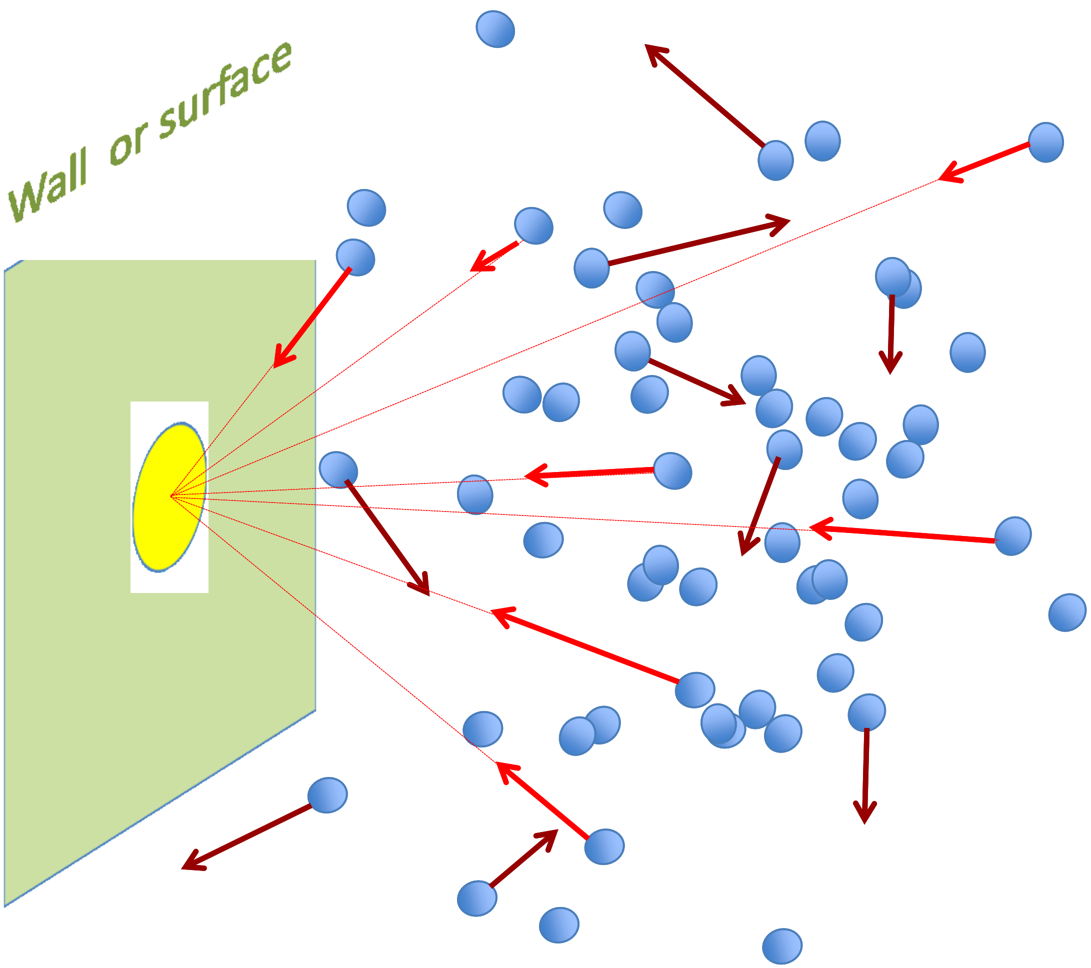
Key parameters

O. Gröbner, CAS 2007

Synchrotron radiation
Y(E,ϕ) photoelectric yield
δ(E,ϕ) second. electron Y
Second. electron energy
residual gas ionization

Photon reflectivity
Beam pipe shape
Bunch intensity and spacing
External fields (magnetic, electric, space charge)

Impingement rate



For a Maxwell-Boltzmann distribution

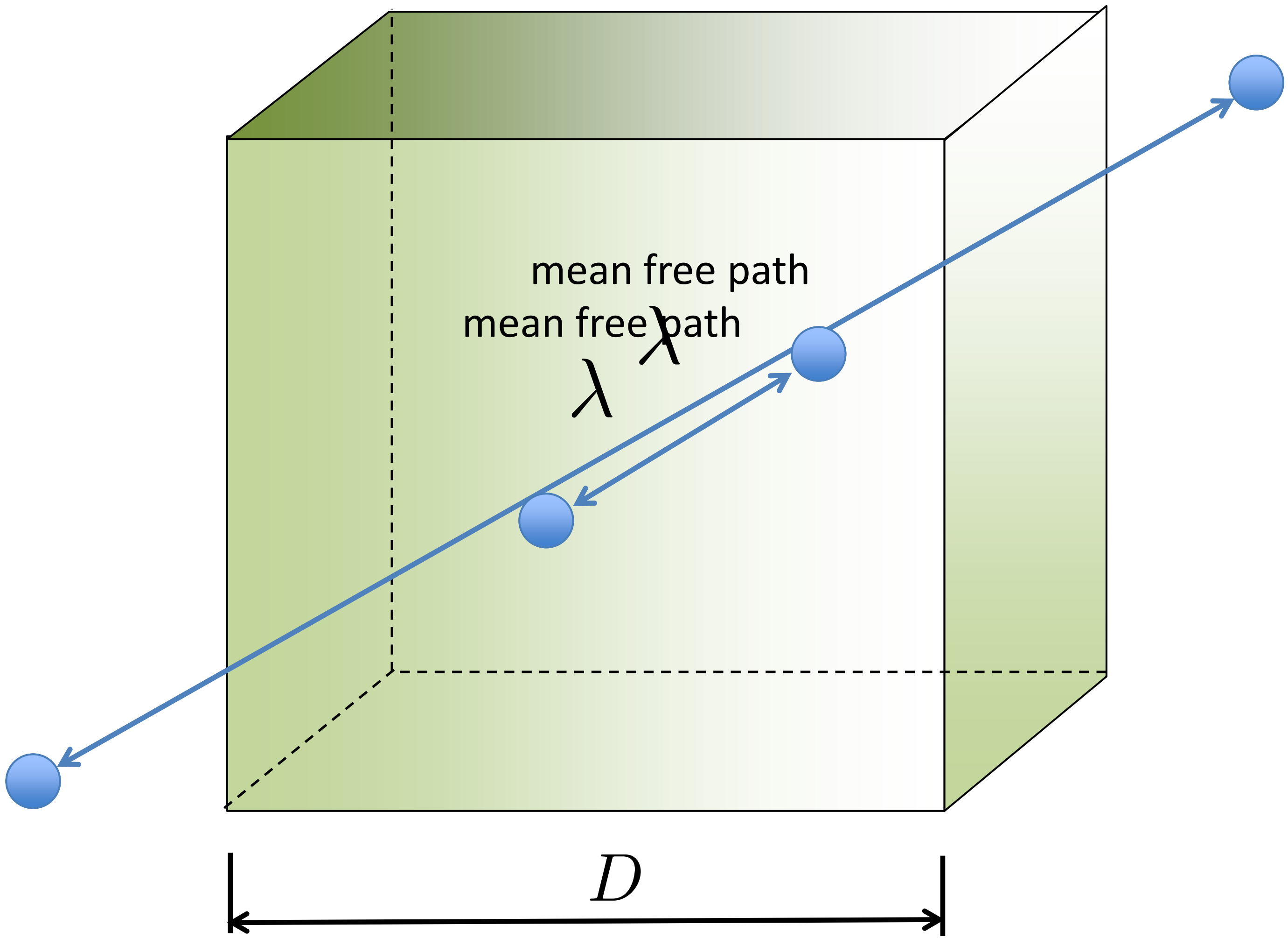
$$J = \frac{1}{4}\tilde{n}v_a$$

J → units: [#/(s m^2)]

and

$$v_a = \sqrt{\frac{8}{\pi}\frac{k_B T}{m}}$$

More on collision



Knudsen Number

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

SI units: [1]

Flow Regimes

$K_n < 0.01$ **Continuous Regime**

Particles collide mainly among them the fluid is continuous

$0.01 < K_n < 0.5$ **Transitional Regime**

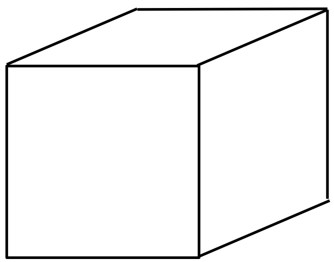
This is a regime in between continuous and molecular

$K_n > 0.5$ **Molecular Regime**

particles collide mainly with walls

The Throughput

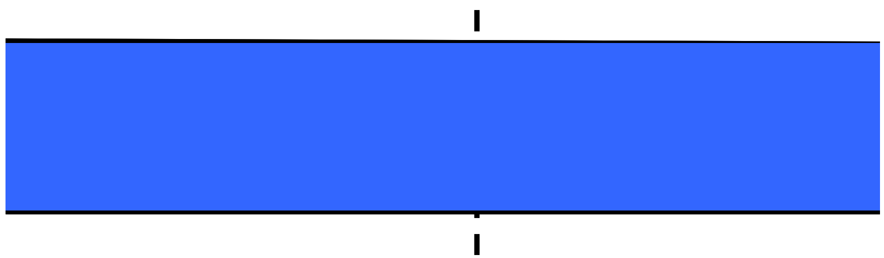
Vessel with a gas at
P, V, N, T



Number of particles

$$N = \frac{PV}{k_B T}$$

The quantity $Q = PV$ is proportional to the number of particles

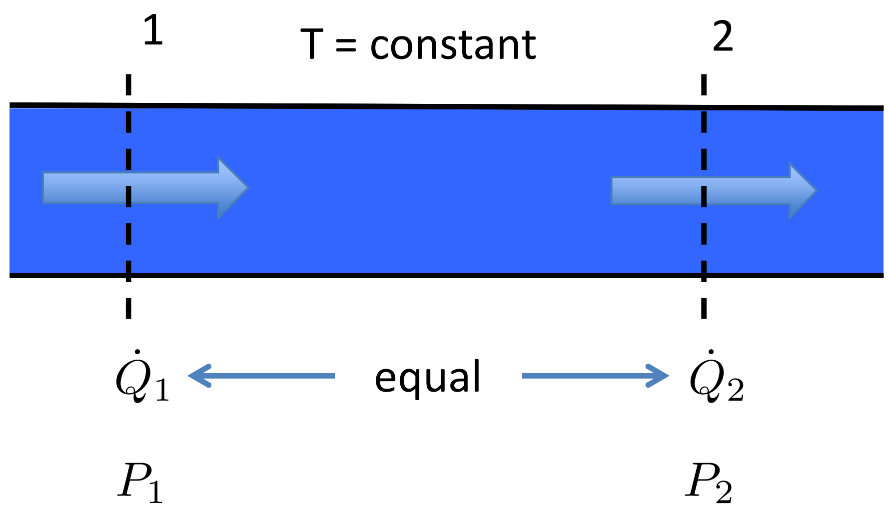


$$\frac{dN}{dt} = \tilde{n} v A = \frac{P}{k_B T} v A = \frac{P}{k_B T} \frac{dV}{dt} = \frac{1}{k_B T} \frac{d}{dt} PV \qquad \frac{dN}{dt} = \frac{1}{k_B T} \dot{Q}$$

$\dot{Q}$ **is called throughput** SI units: [Pa m^3/s]

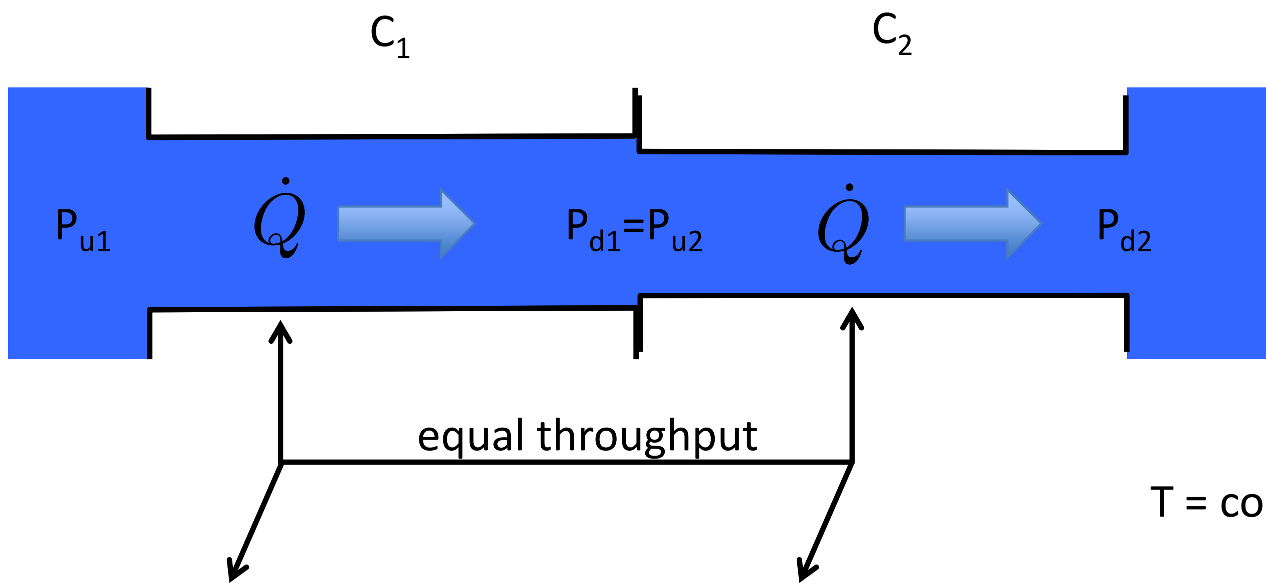
Conductance

In absence of adsorption and desorption processes the throughput does not change



Conductance $$C = \frac{\dot{Q}}{P_1 - P_2}$$ SI units: [m^3/s]

Composition (Series)

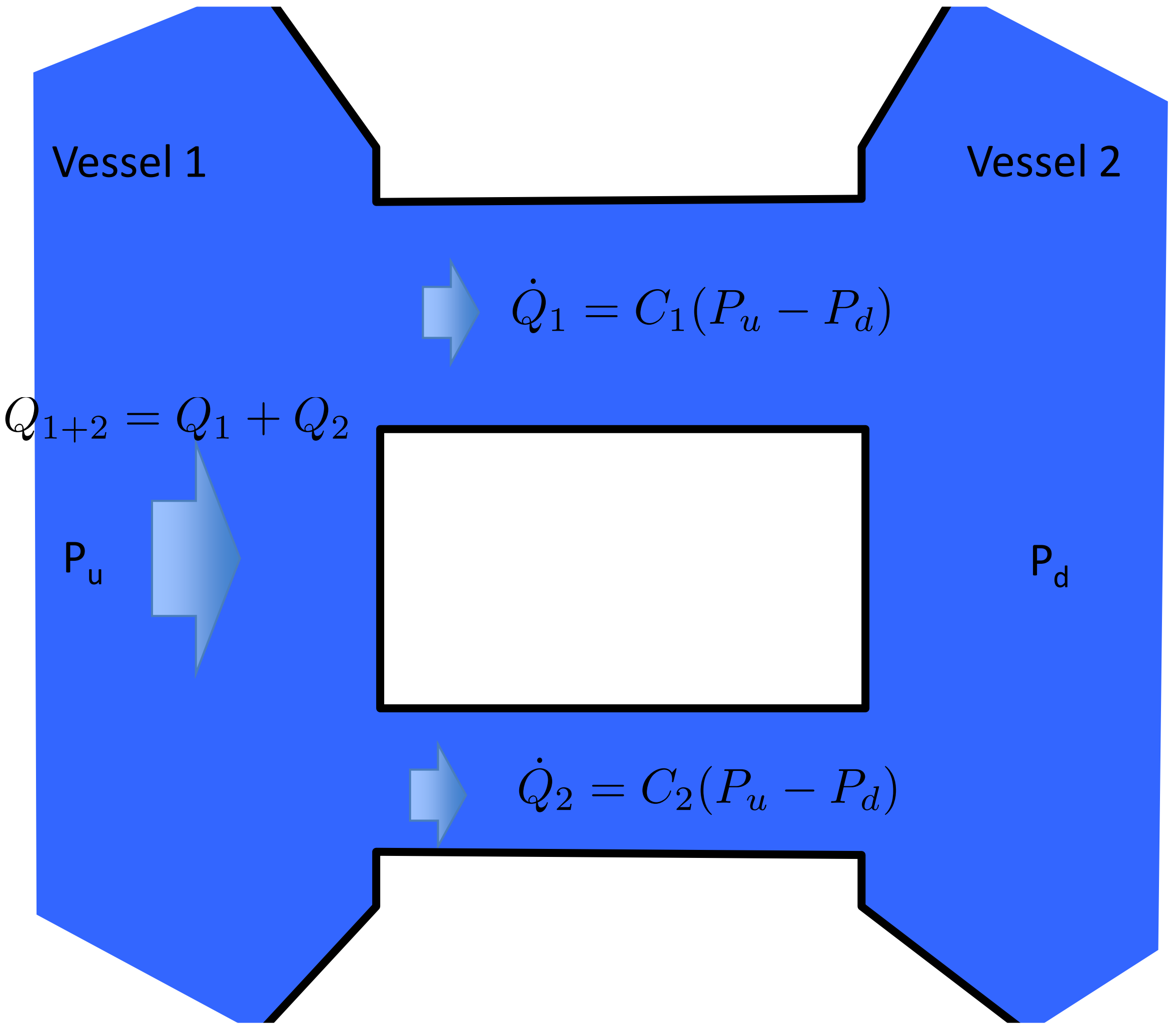


T = constant

$$\dot{Q} = C_1(P_{u1} - P_{d1}) \qquad \dot{Q} = C_2(P_{u2} - P_{d2})$$

Conductance of 1+2 $$\frac{1}{C_{1+2}} = \frac{1}{C_1} + \frac{1}{C_2}$$

Composition (Parallel)



Conductance of 1+2

$$C_{1+2} = C_1 + C_2$$

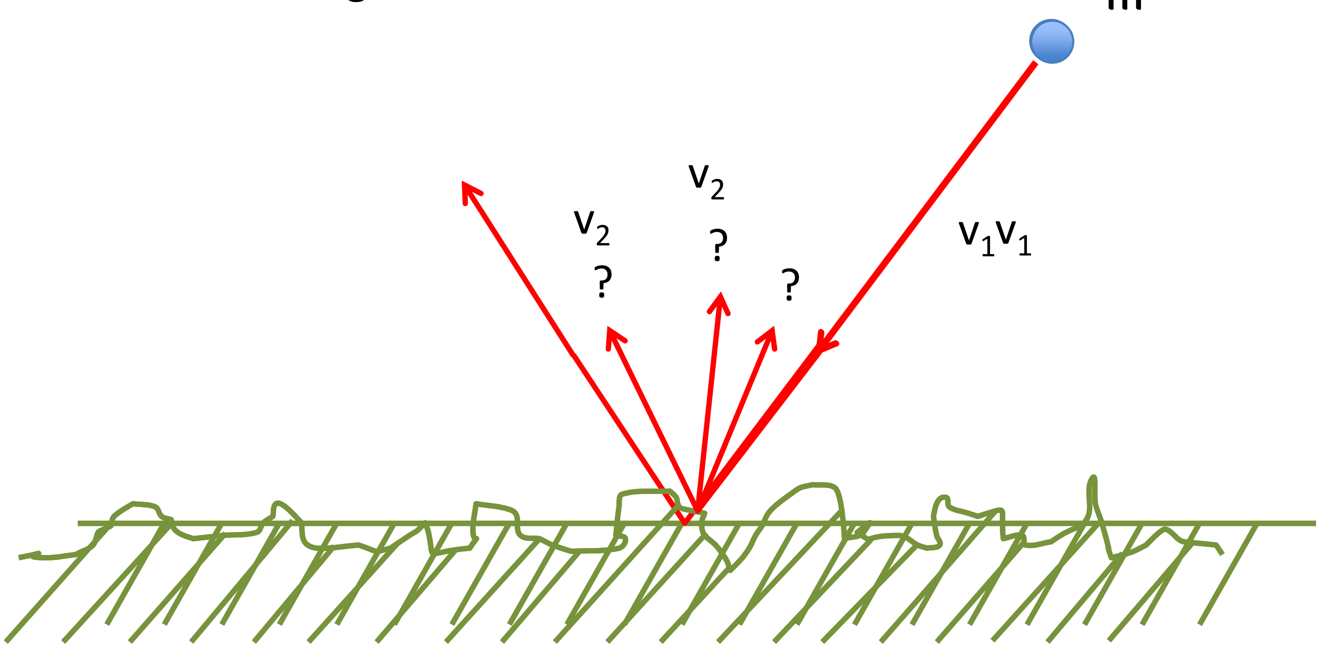
T = constant

Molecular Flow

$K_n > 0.5$
$P < 1.3 \times 10^{-3}$ mbar
$D = 0.1$ m

Regime dominated by Particle – Wall interaction

Molecular regime
Classical Mechanics



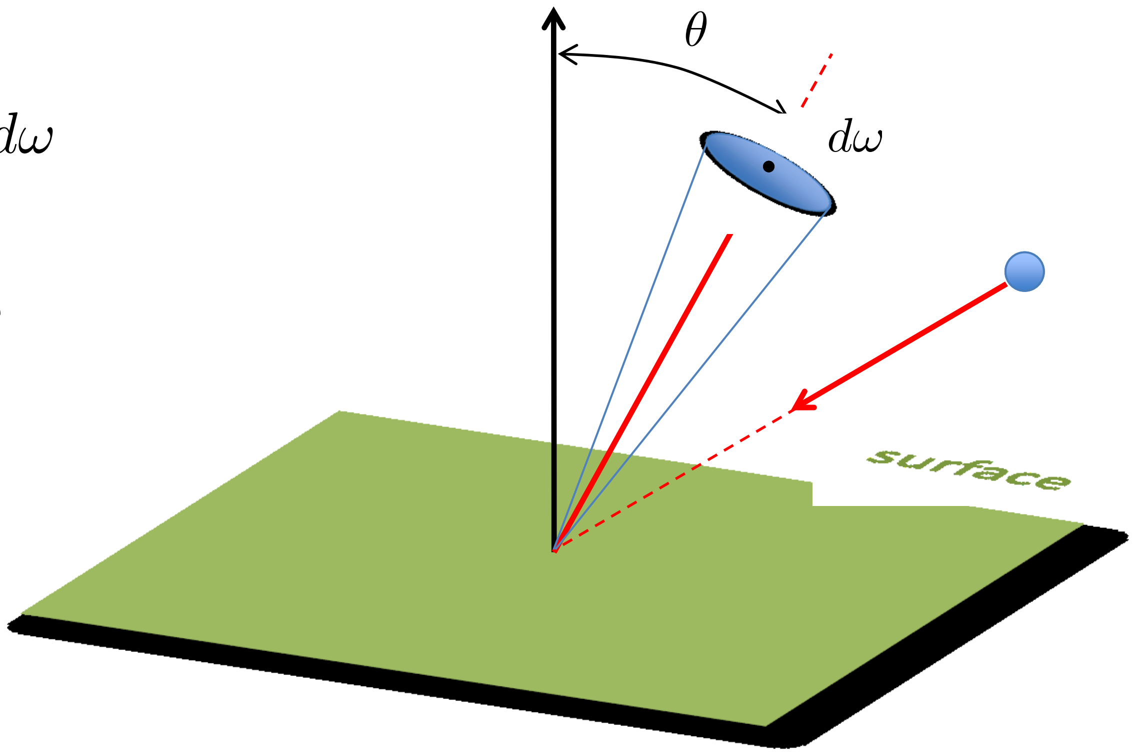
Cosine-Law

1. A particle after a collision with wall will loose the memory of the initial direction
2. After a collision a particle has the same velocity |v|
3. The probability that particles emerge in a certain direction follow the cosine law

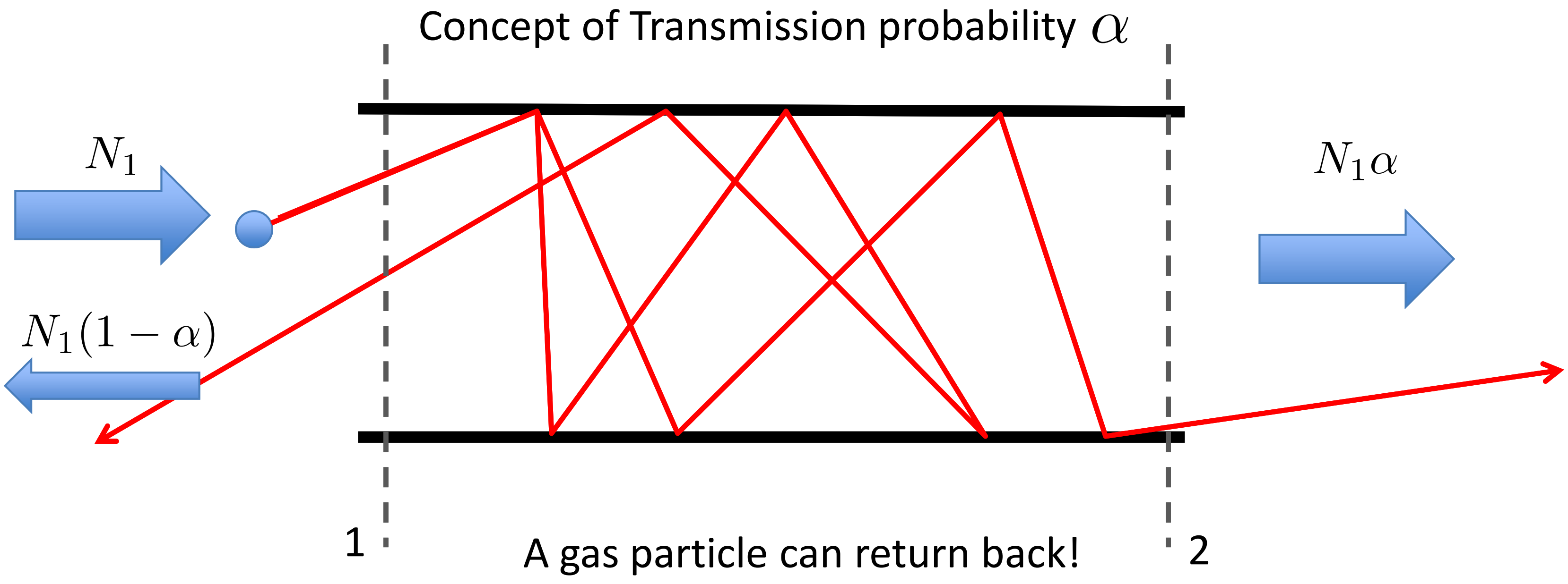
$$dP = \frac{1}{\pi} \cos\theta d\omega$$

$d\omega$ = solid angle

$$\int dP = 1$$



Consequences

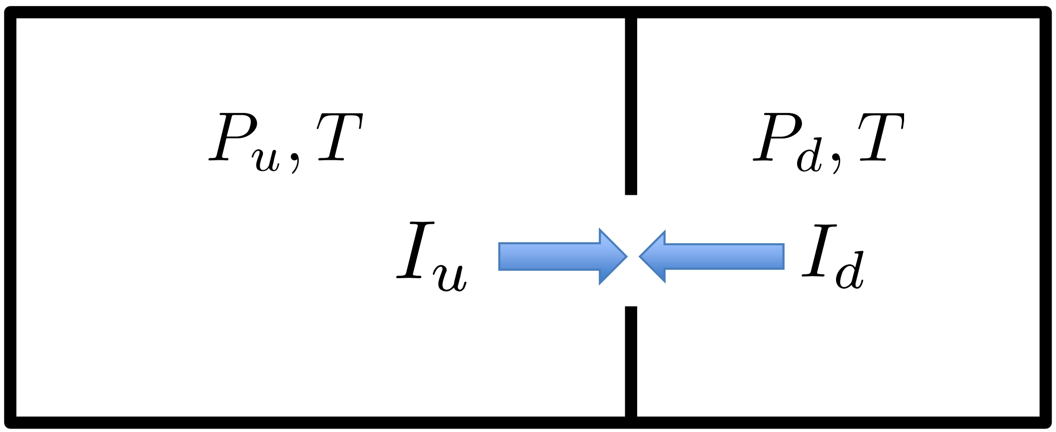


In the molecular regime two fluxes in opposite direction coexist

particle flux = $\alpha(N_1 - N_2)$

N_1 = particle per second through 1
N_2 = particle per second through 2

Conductance of an Aperture



	Gas current	Volumetric flow
Downstream	$I_d = J_d A = \frac{1}{4}\tilde{n}_d v_a A$	$\frac{I_d}{\tilde{n}_d} = \frac{1}{4} v_a A$
Upstream	$I_u = J_u A = \frac{1}{4}\tilde{n}_u v_a A$	$\frac{I_u}{\tilde{n}_u} = \frac{1}{4} v_a A$

Throughput

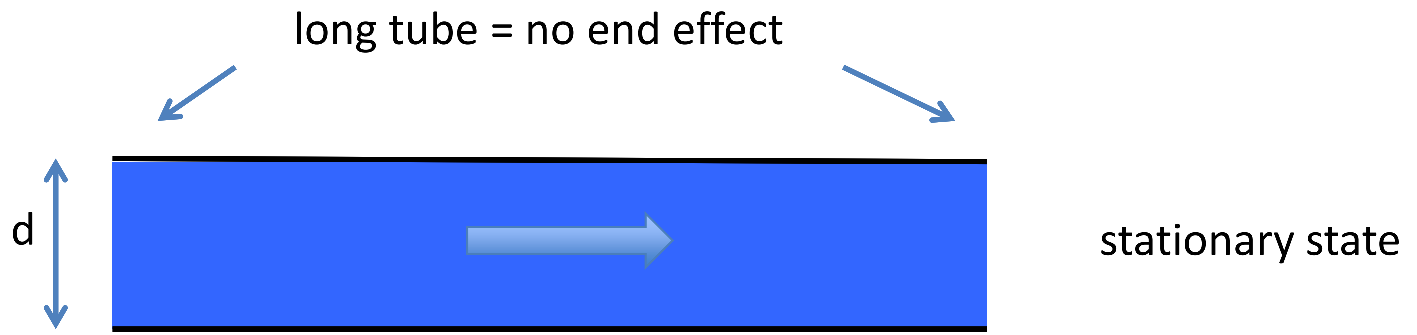
$$\dot{Q} = \dot{Q}_u - \dot{Q}_d = P_u \dot{V}_u - P_d \dot{V}_d = \frac{1}{4} v_a A (P_u - P_d)$$

⇒

Conductance

$$C_a = A\sqrt{\frac{1}{2\pi}\frac{R_0 T}{M}}$$

Conductance of a long tube



$$C_L = \alpha C_a \qquad \alpha = \frac{4}{3}\frac{d}{L}$$

L → 0 make α → ∞ which is wrong:
<u>This result is valid for L long</u>

The dependence of 1/L is consistent with the rule of composition of conductance

Continuum flow regime

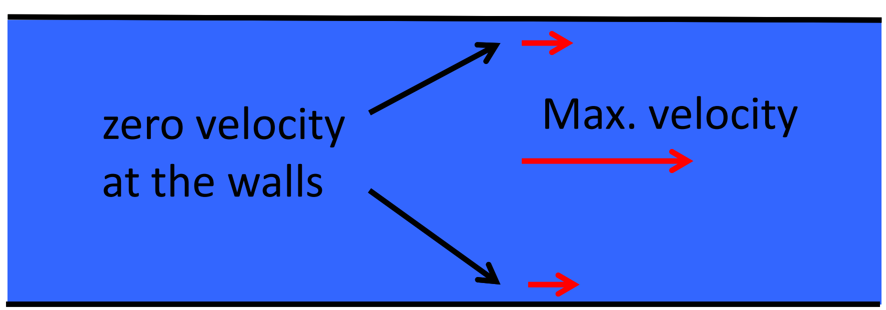
$K_n < 0.01$
P > 6.5 x 10^{-2} mbar
V = 0.1 m

$K_n < 0.01$ Roughly more than 100 collision among particles before wall collision

Local perturbation of $\tilde{n}, P, T$ propagate through a continuum medium

Collision among particles create the **Viscosity**

Collision with walls cancel the velocity



Viscous/Laminar regime

Reynold Number

$$Re = \frac{\rho v D_h}{\eta}$$

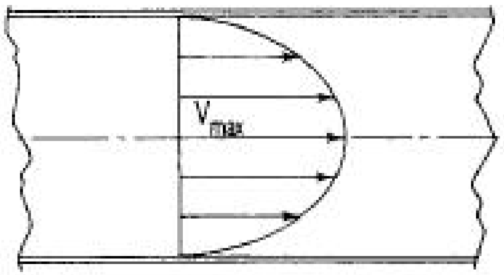
ρ = density of gas [Kg/m³]
v = average velocity [m/s]
D_h= hydraulic diameter [m]

$$D_h = \frac{4A}{B}$$

A = cross sectional area
B = perimeter

η = fluid viscosity [Pa-s]

Laminar Regime $Re < 2000$



Turbulent Regime $Re > 3000$

M. Lesiuer, Turbulence in Fluids, 4th Edition, Ed. Springer

Reynold Number as function of Throughput

$$Re = 4\frac{\dot{Q}}{B}\frac{M}{R_0 T}\frac{1}{\eta}$$

For air (N_2) at T=20C η = 1.75 x 10^{-5} Pa-s $Re = \frac{\dot{Q}}{B} k_b$ with $k_b = 2.615 \quad s/(m^2 Pa)$

Therefore the transition to a turbulent flow takes place at the throughput of

$$\dot{Q}_T = 24d$$

[mbar l /s] [mm]

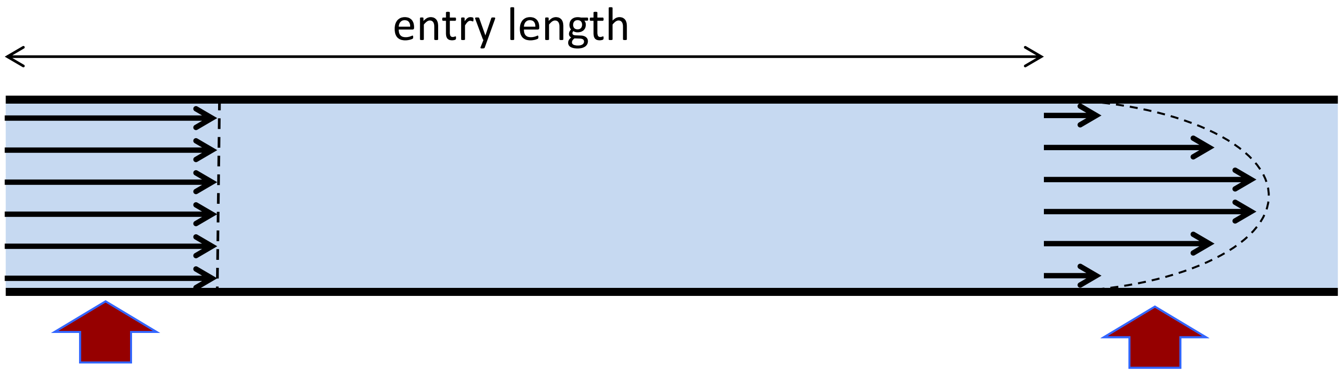
For a pipe of d = 25 mm $\dot{Q}_T = 600 \quad \mathrm{mbar\ l/s}$

At P = 1 atm this threshold corresponds to v = 0.389 m/s

Laminar Regime

1. Fluid is incompressible: true also for gas when Ma < 0.2
2. Fluid is fully developed
3. Motion is laminar ←→ Re < 2000
4. Velocity at Walls is zero

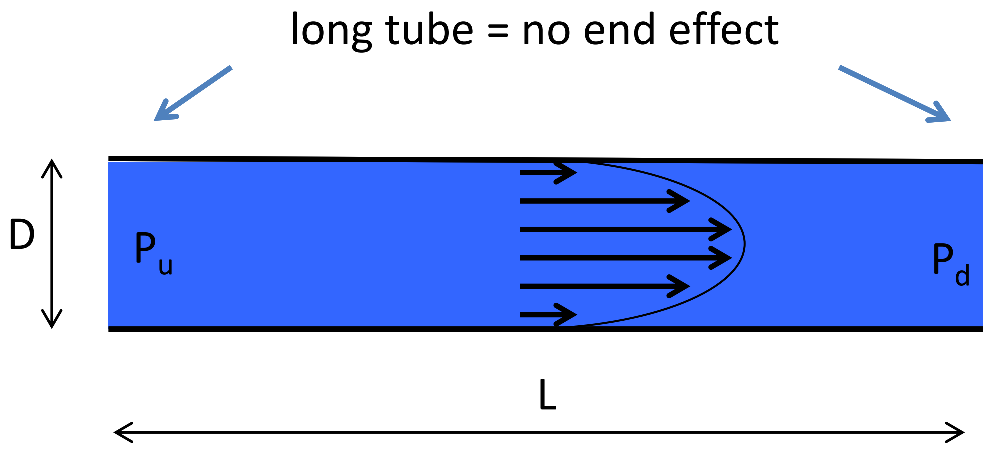
Fully developed flow



velocity distribution at injection in the pipe

velocity distribution of a fully developed flow

Conductance in Laminar Regime

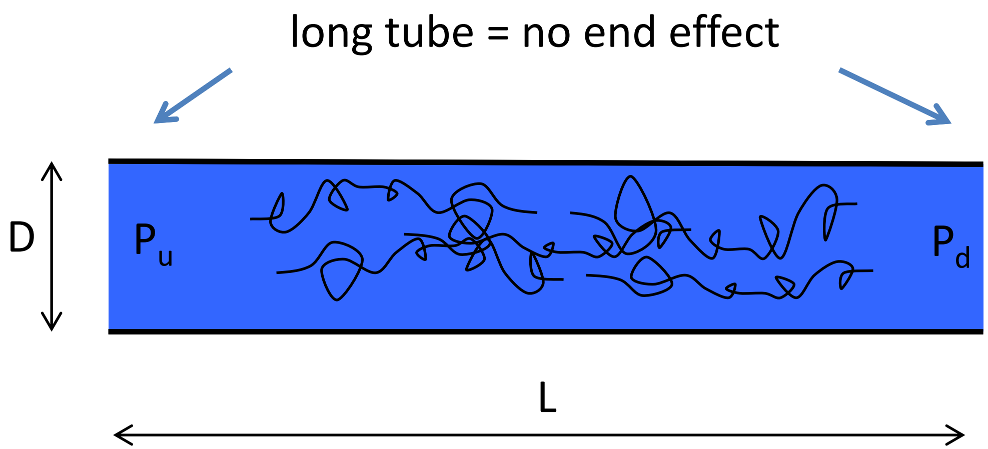


$$\dot{Q} = C(P_u - P_d)$$

Conductance: $$C = \frac{\pi D^4}{128 \eta L}\overline{P}$$ where $$\overline{P} = \frac{P_u + P_d}{2}$$

The conductance now depends on the pressure!

Conductance in Turbulent Regime



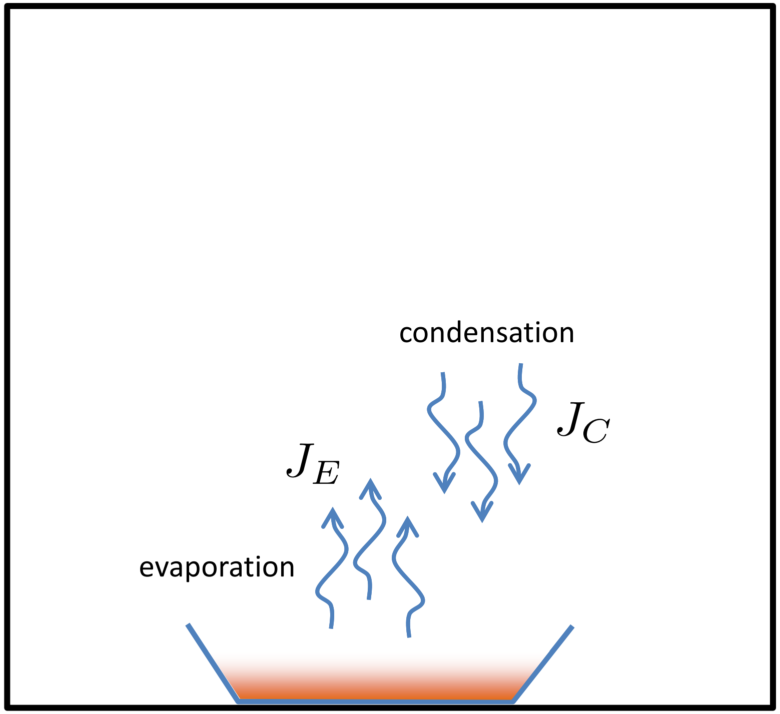
The throughput becomes a complicated relation (derived from the Darcy-Weisbach formula)

$$\dot{Q} = A\sqrt{\frac{R_0 T}{M}}\sqrt{\frac{D_h}{f_D L}}\sqrt{P_u^2 - P_d^2}$$

$f_D =$ Darcy friction factor, dependent from the Reynold number

Sources of vacuum degradation

Evaporation/Condensation

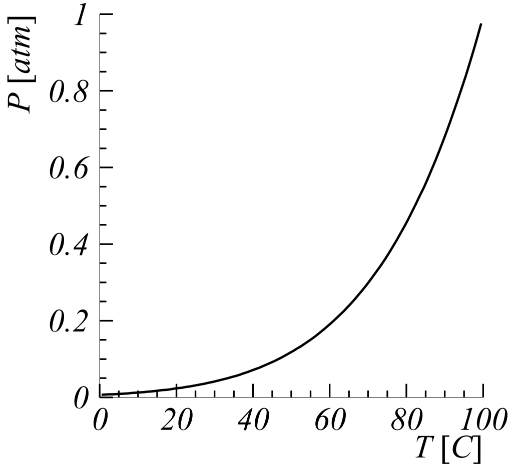


At equilibrium $J_C = J_E$

$$J_E = P_E N_A \frac{1}{\sqrt{2\pi R_0 T M}}$$

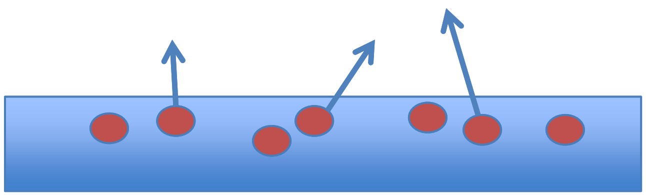
P_E = saturate vapor pressure

Example: water vapor pressure



Outgassing

The outgassing is the passage of gas from the wall of the Vessel or Pipe to the vacuum



Θ = fraction of sites occupied

$$\frac{d\Theta}{dt} = -\frac{\Theta}{\tau_d}$$

"Throughput" due to outgassing

$$\dot{Q}_G = k_B T \frac{N_s \Theta}{\tau_d}$$

$N_s = A \times 3 \times 10^{15}$ A = surface in cm^2

Mean stay time

$$\tau_d = \tau_0 e^{\frac{E_d}{RT}} \qquad \tau_0 = 10^{-13}\ \mathrm{s}$$

E_d [Kcal/mole]	Cases	τ_d [s]
0.1	Helium	1.18×10^{-13}
1.5	H_2 physisorption	1.3×10^{-12}
3-4	Ar,CO,N_2,CO_2 physisorption	1.6×10^{-11}
10-15	Weak chemisorption	2.6×10^{-6}
20	H_2 chemisorption	66
25		3.3×10^{5} (~half week)
30	CO/Ni chemisorption	1.6×10^{9} (~50 years)
40		4.3×10^{16} (~half age of earth)
150	O.W chemisorption	1.35×10^{98} (larger than the age of universe)

P. Chiggiato, CAS 2007

Leaks

High vacuum 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	leaks

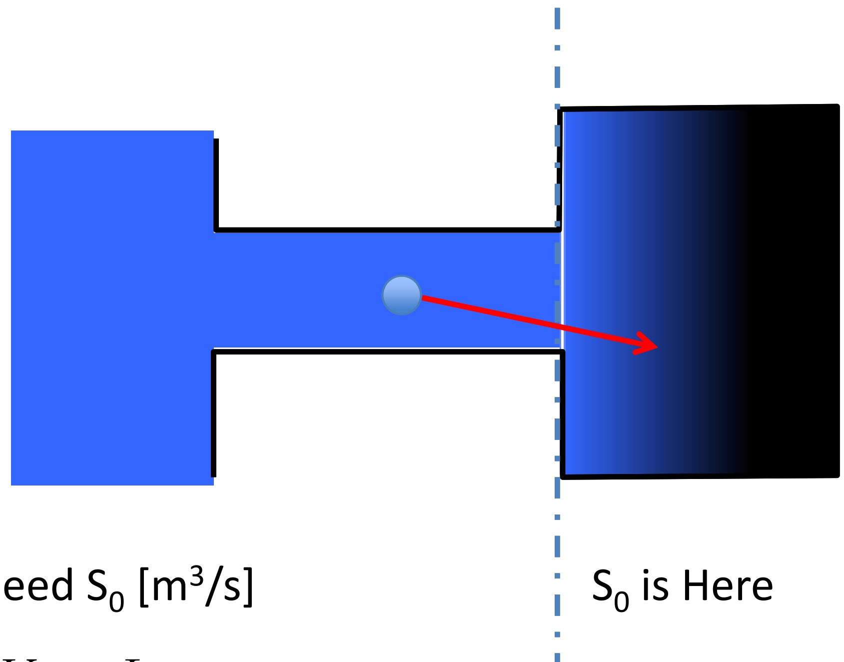
Small Channels

Diameter hole	Leaks rate
0.01 mm	10^{-2} mbar-l/s
10^{-10} m	10^{-12} mbar-l/s

K. Zapfe, CAS 2007

317 years for leakage of 1 cm^3

Pumps and Gas flow



Ideal Pump

particles that enter
in this chamber never
returns back !!

Pumping speed S_0 [m^3/s]

S_0 is Here

$$S = \frac{dV}{dt} = \frac{I}{\tilde{n}}$$

but

$$I = J\frac{D^2\pi}{4}$$

$$S = v_a\frac{D^2\pi}{16}$$

Example

N_2 at T=20C

Take D=0.1m

S_0 = 0.92 m^3/s

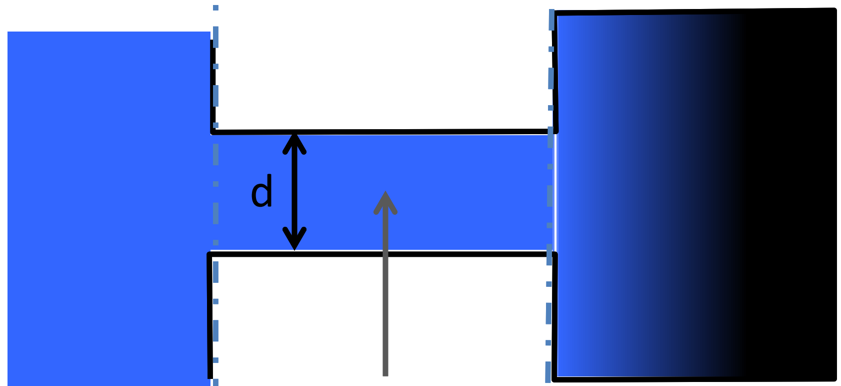
Pumps and Conductance

Pumping speed S [m^3/s]

$$\dot{Q} = PS$$

Pumping speed of ideal pump S_0

$$\dot{Q}_0 = P_0 S_0$$



conductance C

$$\dot{Q} = C(P - P_0)$$

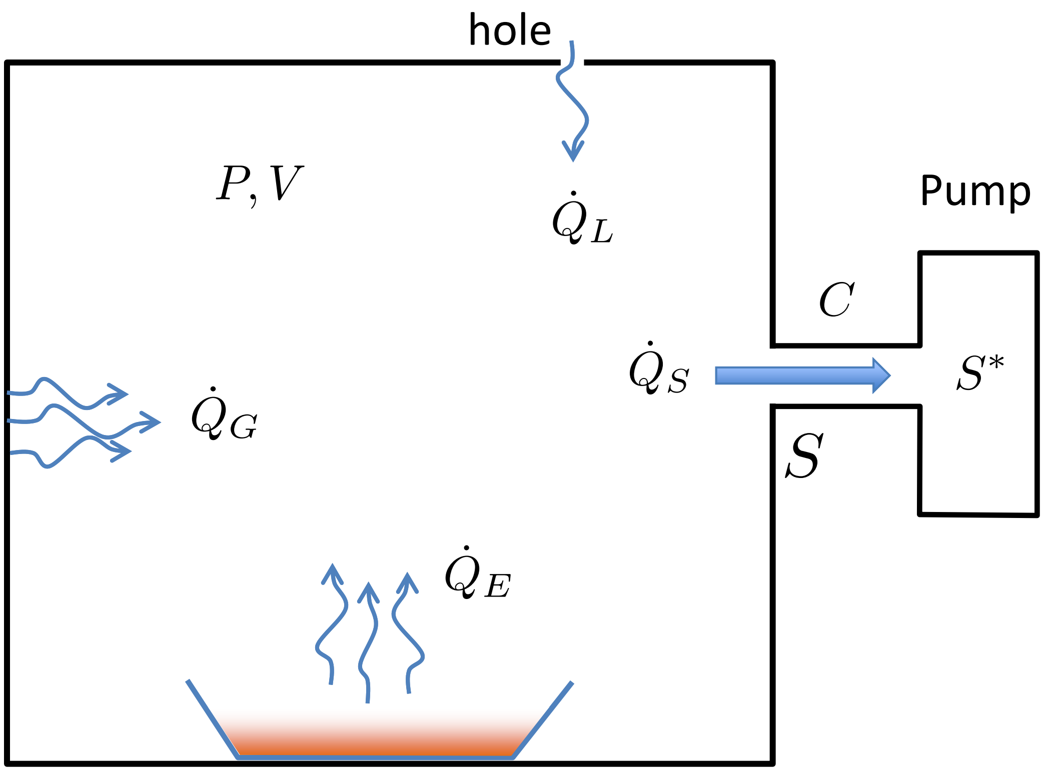
As the throughput is preserved

$$\frac{1}{S} = \frac{1}{C} + \frac{1}{S_0}$$

Example: if the pipe is long l=100d

$$S_{eff} = \frac{0.922}{1 + 3l/(4d)} = 0.012 \ \text{m}^3/\text{s}$$

Pumping Process -- Pump-down Time -- Ultimate Pressure



$\dot{Q}_E$ throughput due to evaporation

$\dot{Q}_G$ throughput due to outgassing

$\dot{Q}_L$ throughput due to leaks

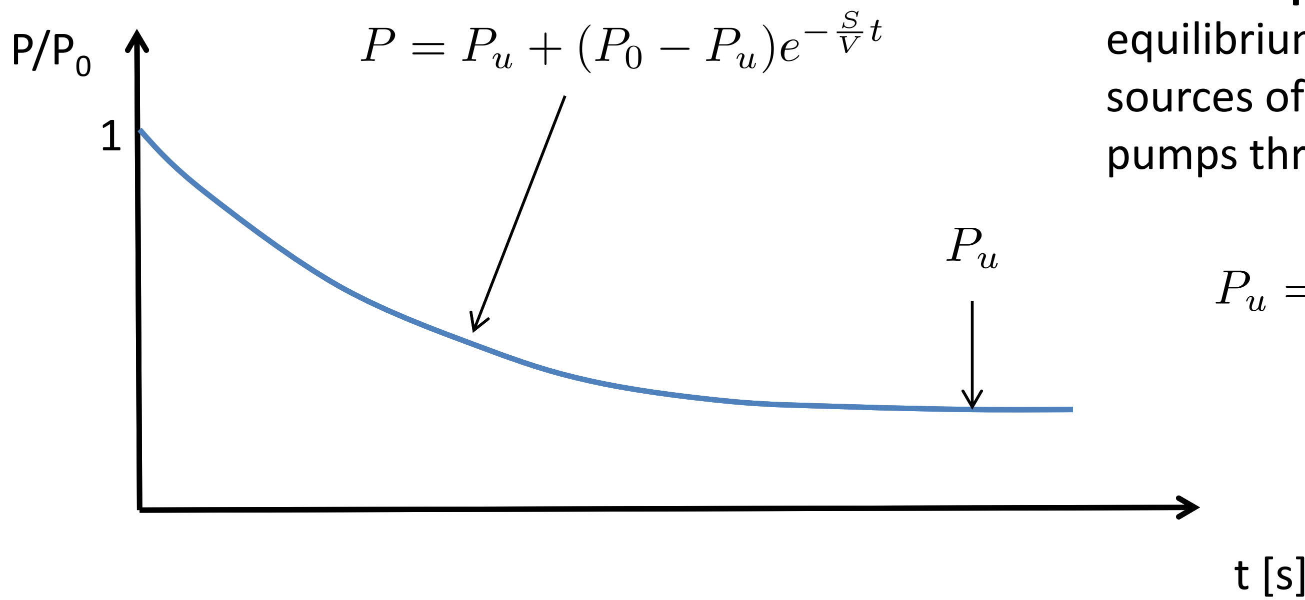
$\dot{Q}_S$ effective throughput

$$\dot{Q} = \underbrace{\dot{Q}_E + \dot{Q}_G + \dot{Q}_L}_{} - \dot{Q}_S$$

$$\frac{dP}{dt}V = \dot{Q}_T - PS$$

Pumping Process -- Pump-down Time -- Ultimate Pressure

Therefore

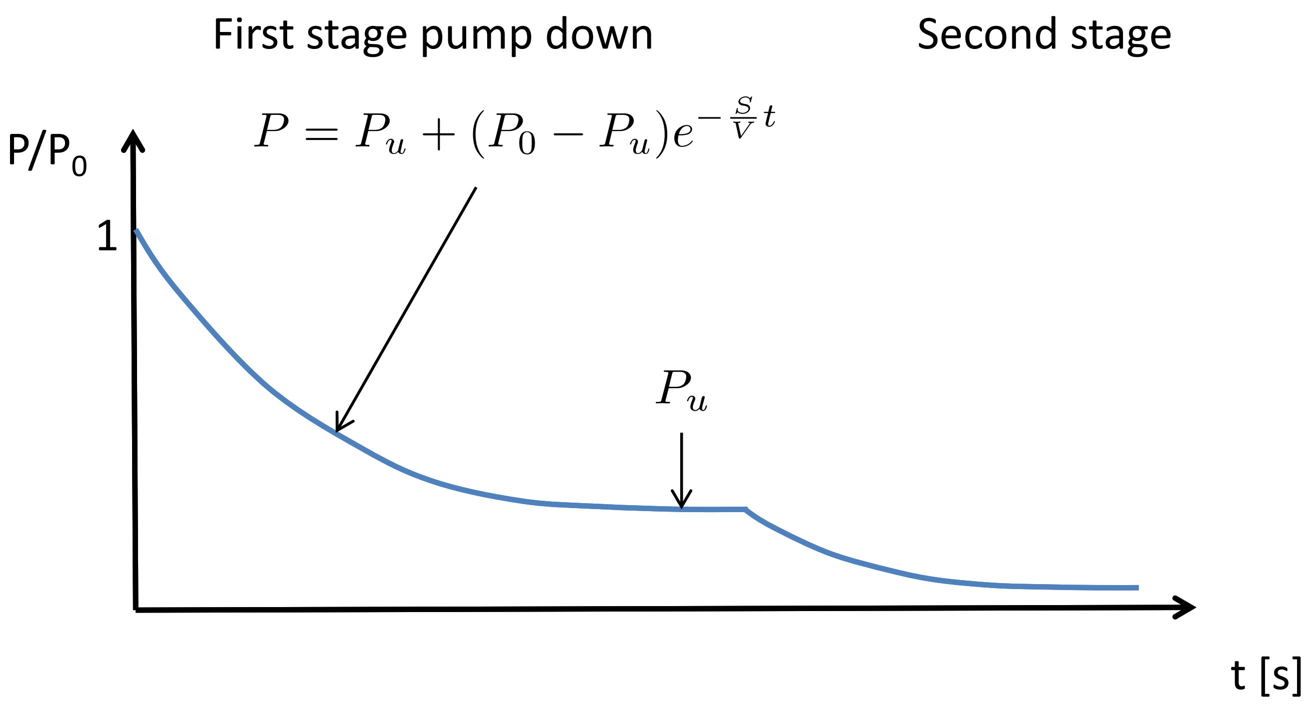


Ultimate pressure → equilibrium between sources of throughput and pumps throughput

$$P_u = \frac{\dot{Q}_T}{S}$$

Pump down time → $\tau_{pd} = \frac{V}{S}$

Multistage pumps



Creating the Vacuum: Pumps

Examples of vacuum in some accelerators

Table 1: SNS Vacuum Level Requirements

Front End	1×10^{-4} to $4\text{x}10^{-7}$ Torr
DTL	$2\text{x}10^{-7}$ Torr
CTL	$5\text{x}10^{-8}$ Torr
SCL	$<1\text{x}10^{-9}$ Torr
HEBT	$5\text{x}10^{-8}$ Torr
Ring	$1\text{x}10^{-8}$ Torr
RTBT	$1\text{x}10^{-7}$ Torr

J.Y. Tang ICA01, TUAP062

LHC → 10^{-10} – 10^{-11} mbar

(LHC Design Report)

FAIR

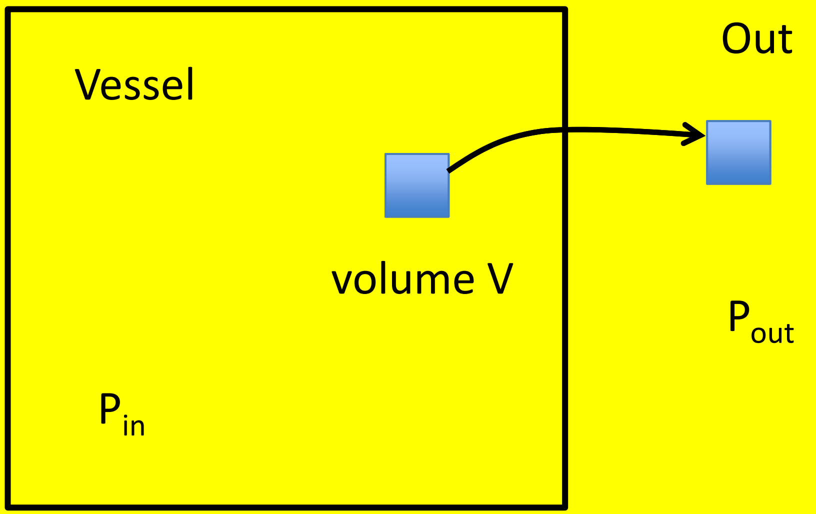
HEBT → 10^{-9} mbar

SIS100 → 10^{-12} mbar

A. Kraemer EPAC2006, TUPCH175

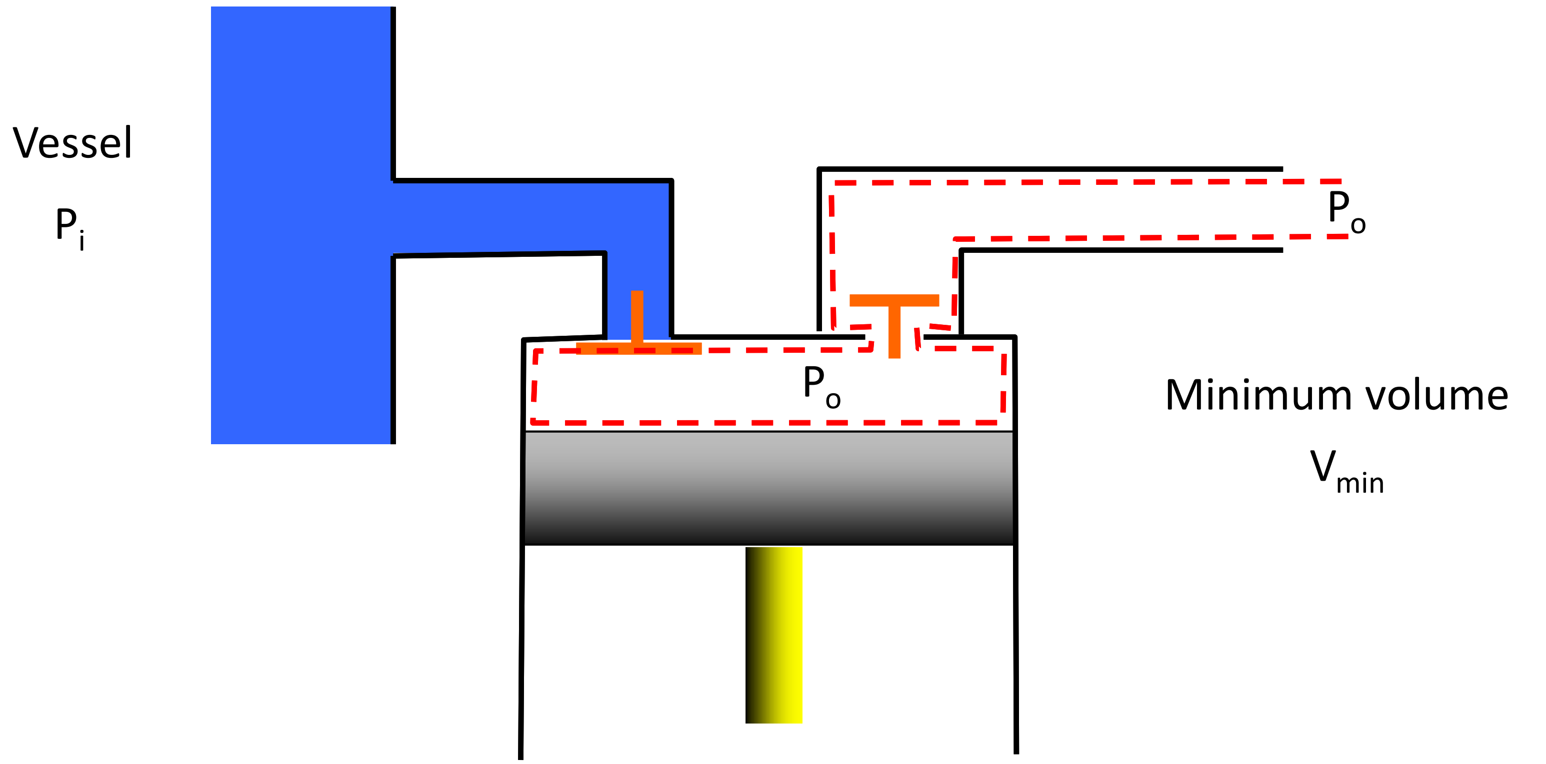
Positive Displacement Pumps

Principle:
A volume of gas is displaced out of the Vessel

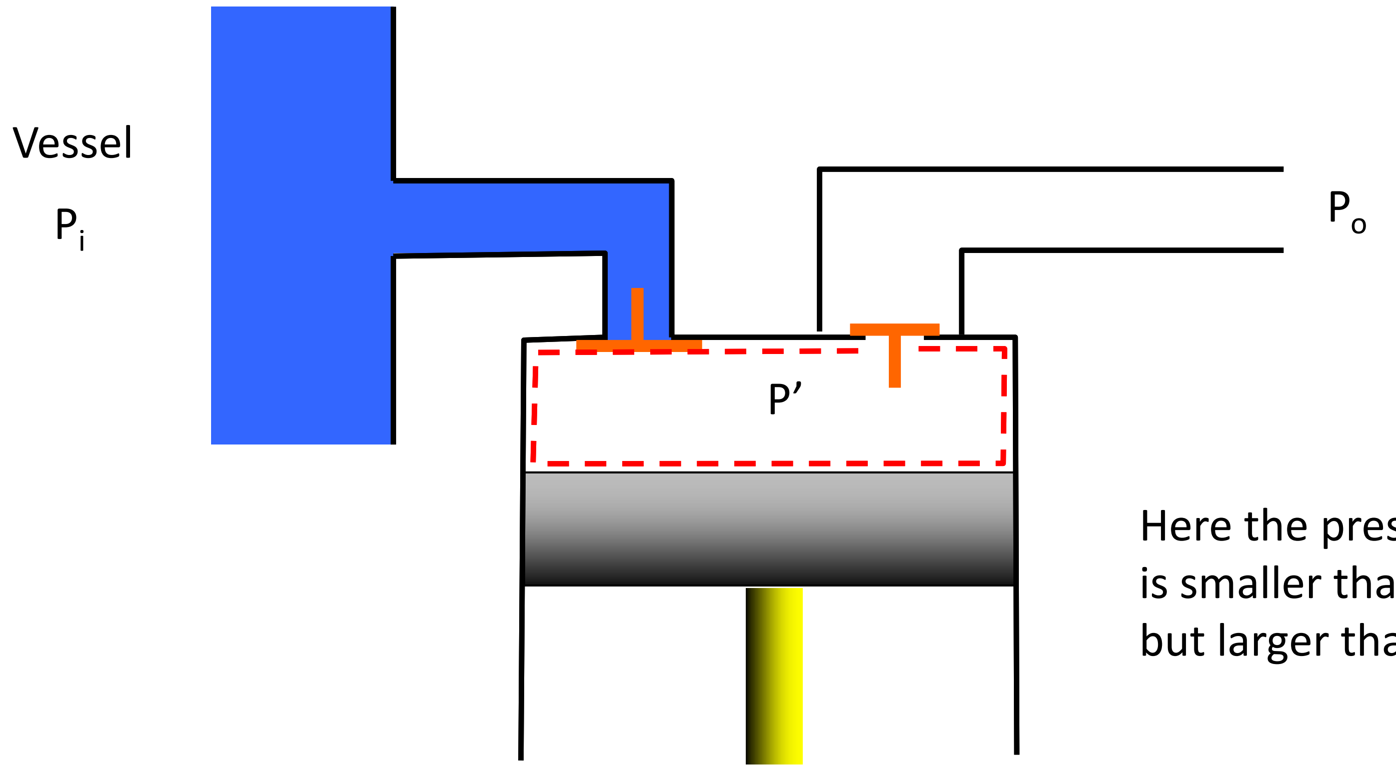


A compression of the volume V is always necessary to bring the pressure from P_{in} to a value larger then P_{out}

Piston Pumps

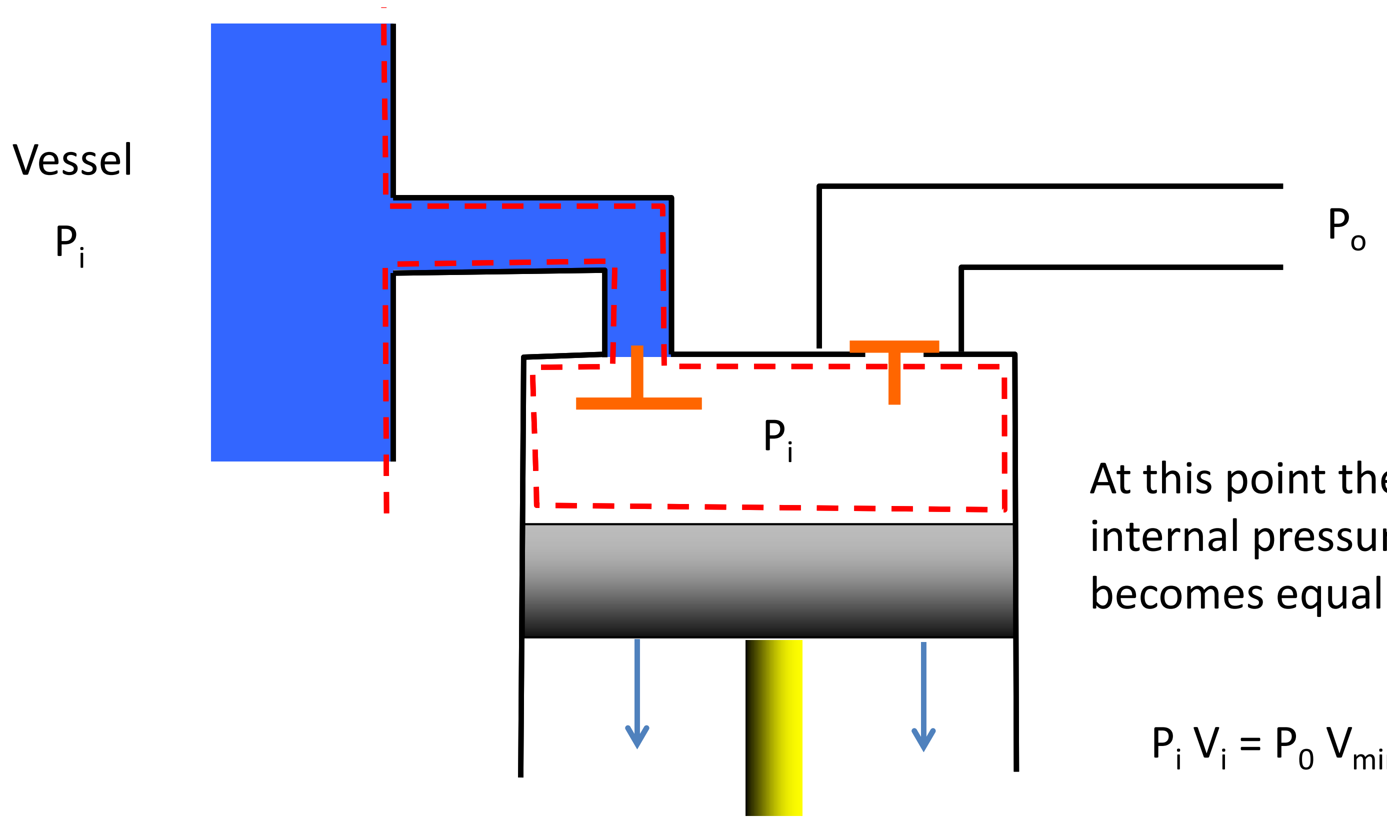


Piston Pumps



Here the pressure P’ is smaller than P_o but larger than P_i

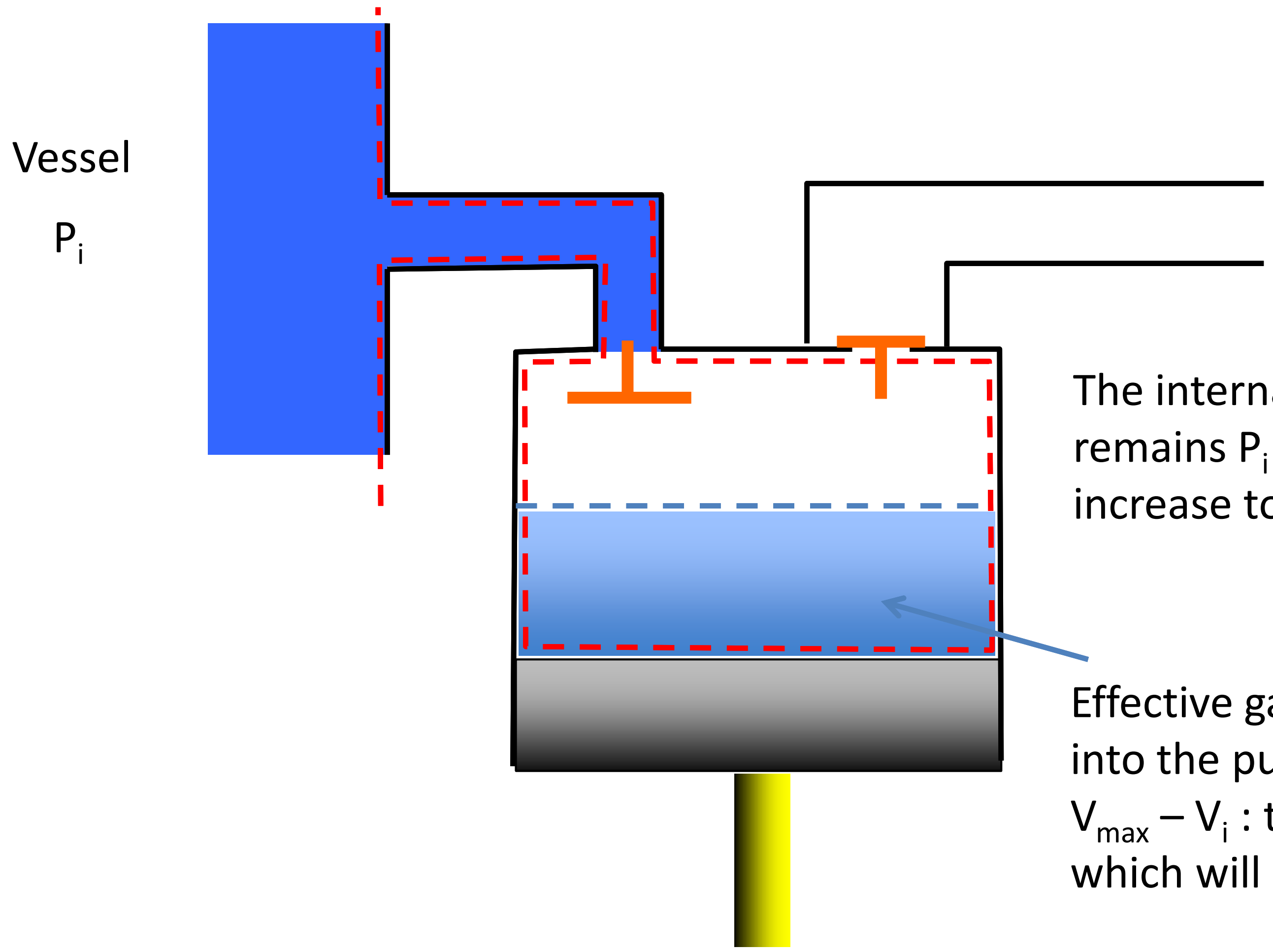
Piston Pumps



At this point the internal pressure becomes equal to P_i

$$P_i V_i = P_0 V_{min}$$

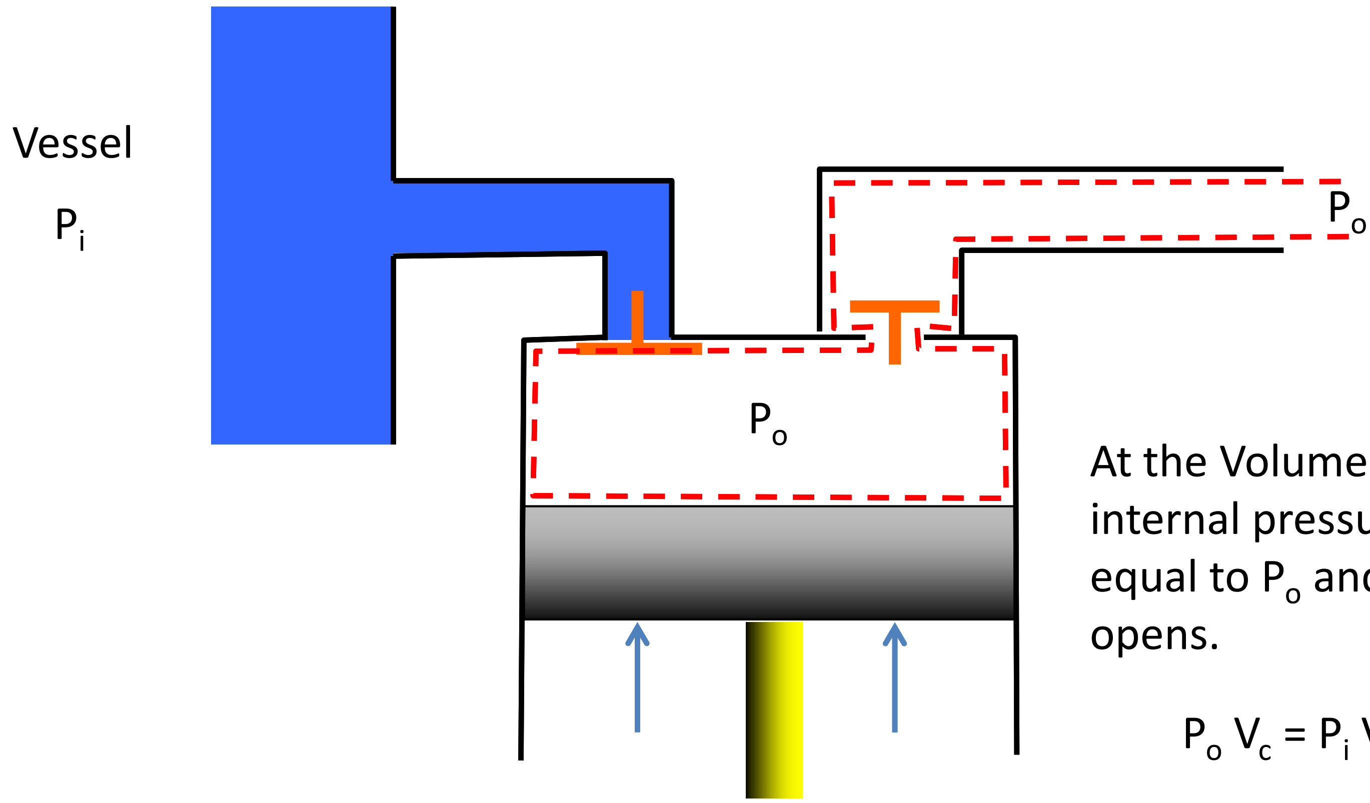
Piston Pumps



The internal pressure remains P_i but the volume increase to V_{max}

Effective gas volume entered into the pump equal to $V_{max} - V_i$: this is the gas which will be expelled

Piston Pumps



At the Volume V_c the internal pressure becomes equal to P_o and the valve opens.

$$P_o V_c = P_i V_{max}$$

and from now on the gas entered into the pump goes out

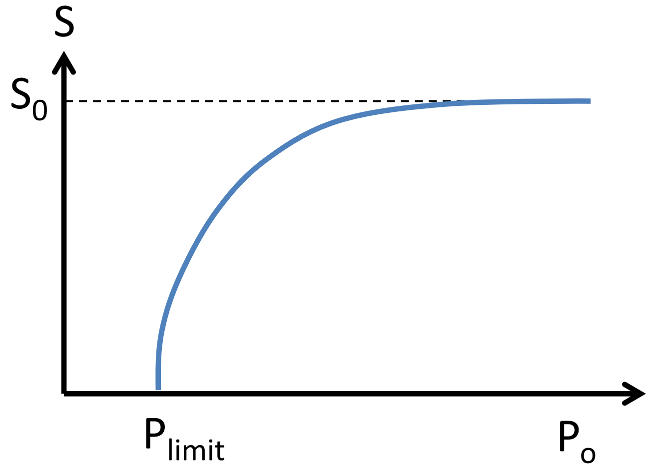
Piston Pumps

Therefore if the pumps make N_c cycles per second

$$S = N_c(V_{max} - V_i) = S_0 \left(1 - \frac{P_0}{P_i}\frac{V_{min}}{V_{max}}\right)$$

Conclusion: the pumping speed depends on the ratio of outlet/inlet pressure

When the inlet pressure is too low the pump stops pumping



If the gas compression/expansion is isentropic then all transformation follow the law

$$PV^\gamma = const.$$

hence

$$S = S_0 \left[1 - \left(\frac{P_0}{P_i} \right)^{1/\gamma} \frac{V_{min}}{V_{max}} \right]$$

Clearly the dependence affects the ultimate pressure even in absence of sources of throughput

$$\frac{dP}{dt} V = -PS(P)$$

Ultimate pressure

$$\frac{d}{dt} P = 0$$

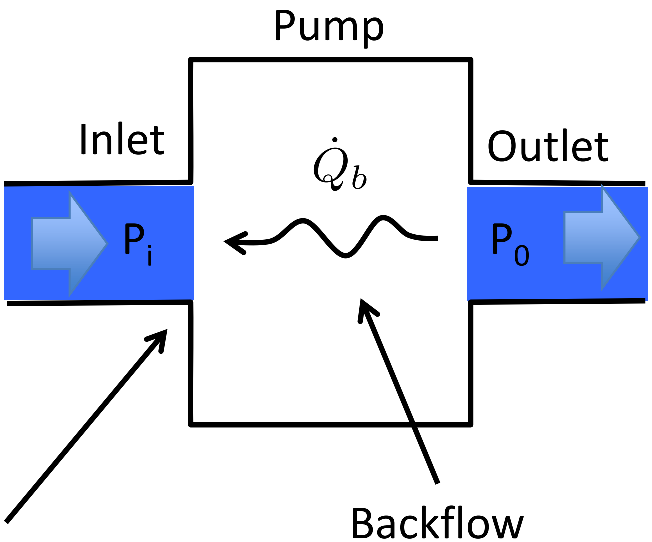
$$P_u = P_0 \left(\frac{V_{min}}{V_{max}} \right)^\gamma$$

General Pump

Pumping speed of ideal pump S_0

$$\dot{Q}_0 = P_0 S_0$$

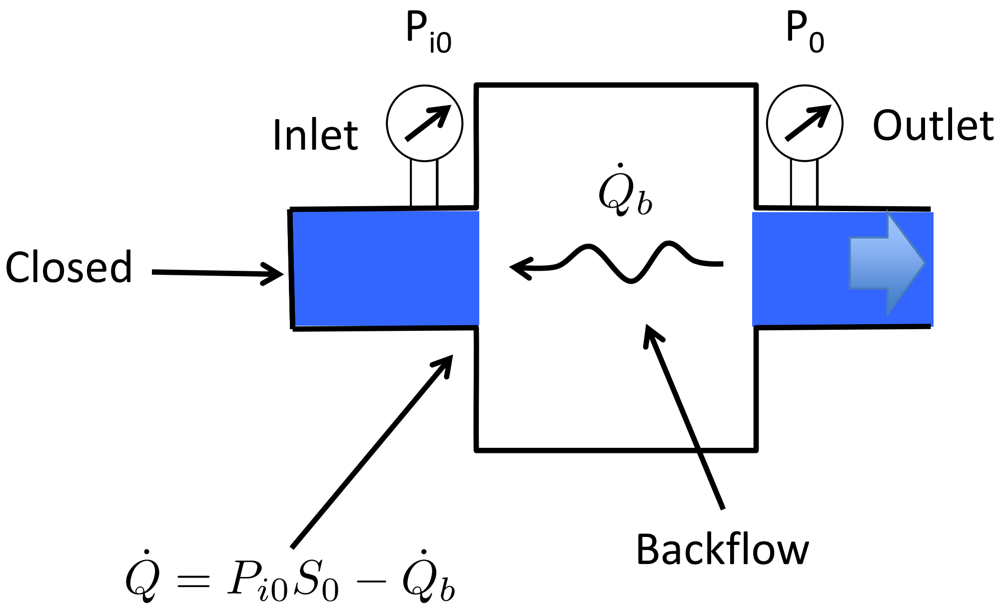
But in real pumps there is a backflow



Pump throughput

$$\dot{Q} = P_i S_0 - \dot{Q}_b$$

Zero Load Compression Rate



Zero Load compression rate

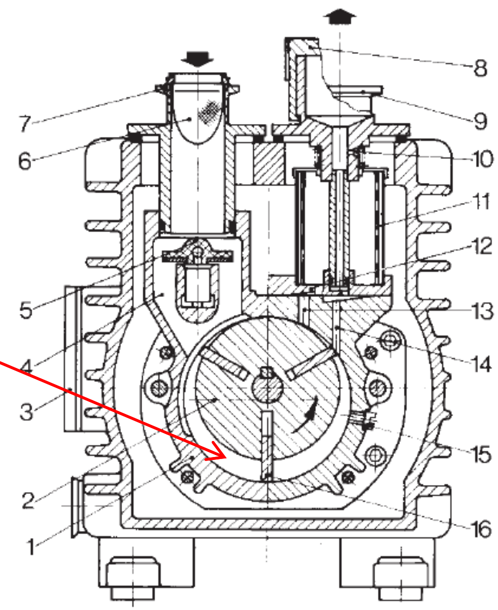
$$K_0 = \frac{P_0}{P_{i0}}$$

The backflow is found

$$\dot{Q}_b = \frac{S_0 P_0}{K_0}$$

Rotary Pumps

Gas displaced in the moving vane



1 Pump housing
2 Rotor
3 Oil-level sight glass
4 Suction duct
5 Anti-suckback valve
6 Dirt trap
7 Intake port
8 Lid of gas ballast valve
9 Exhaust port
10 Air inlet silencer
11 Oil filter
12 Exhaust valve
13 Exhaust duct
14 Gas ballast duct
15 Oil injection
16 Vane

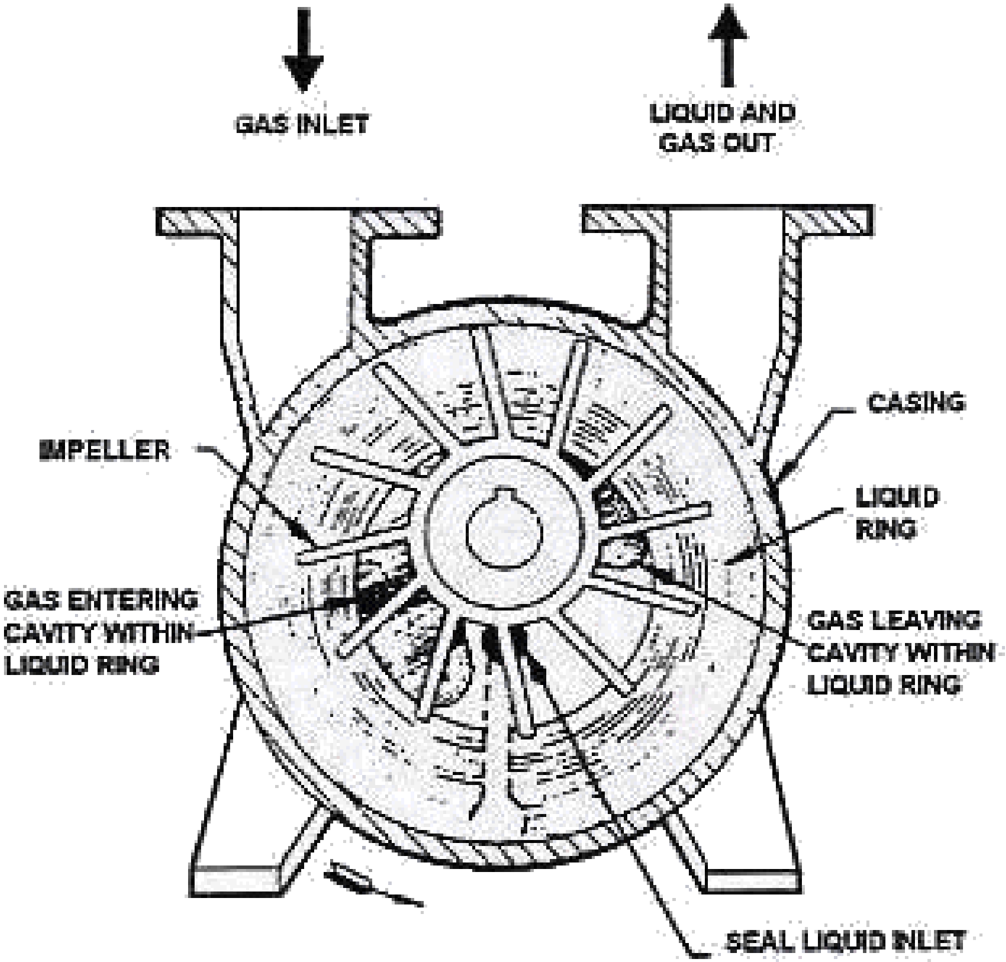
S = 1-1500 m^3/h
Pl = 5 x 10^{-2} mbar (1stage)
Pl = 10^{-3} mbar (2stage)

Gas Ballast

During the compression there can be gas component (G), which partial pressure P_G can be too high → condensation

But the maximum pressure during compression do not exceed P_0 therefore by injectionng non condensable gas during the compression rate P_G is lowered blow the condensation point

Liquid Ring Pumps



$S = 1 – 27000\ m^3/h$
$P = 1000$ mbar → 33 mbar

The gas enter in the cavity which expand. When the pressure in the cavity reaches the sature vapor pressure P_s the water boils.

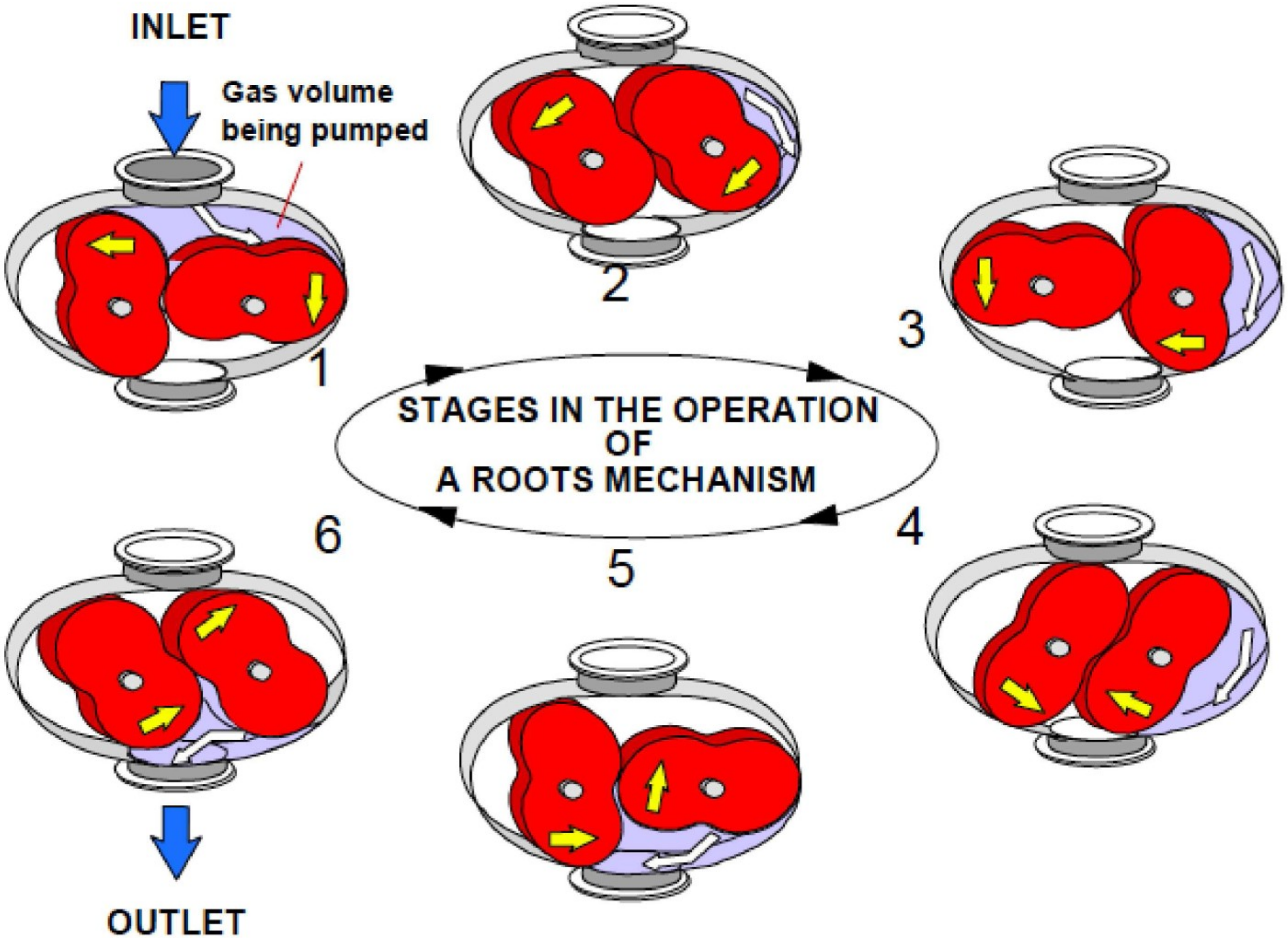
During the compression the vapor bubbles implode creating the **CAVITATION**

At $T = 15^0$ C → $P_s = 33$ mbar which sets the P_{limit}=Ps

Dry Vacuum Pumps: Roots

pumping speed:
75 – 30000 m^3/h

operating pressure:
10 – 10^{-3}mbar



Kinetic Vacuum Pumps

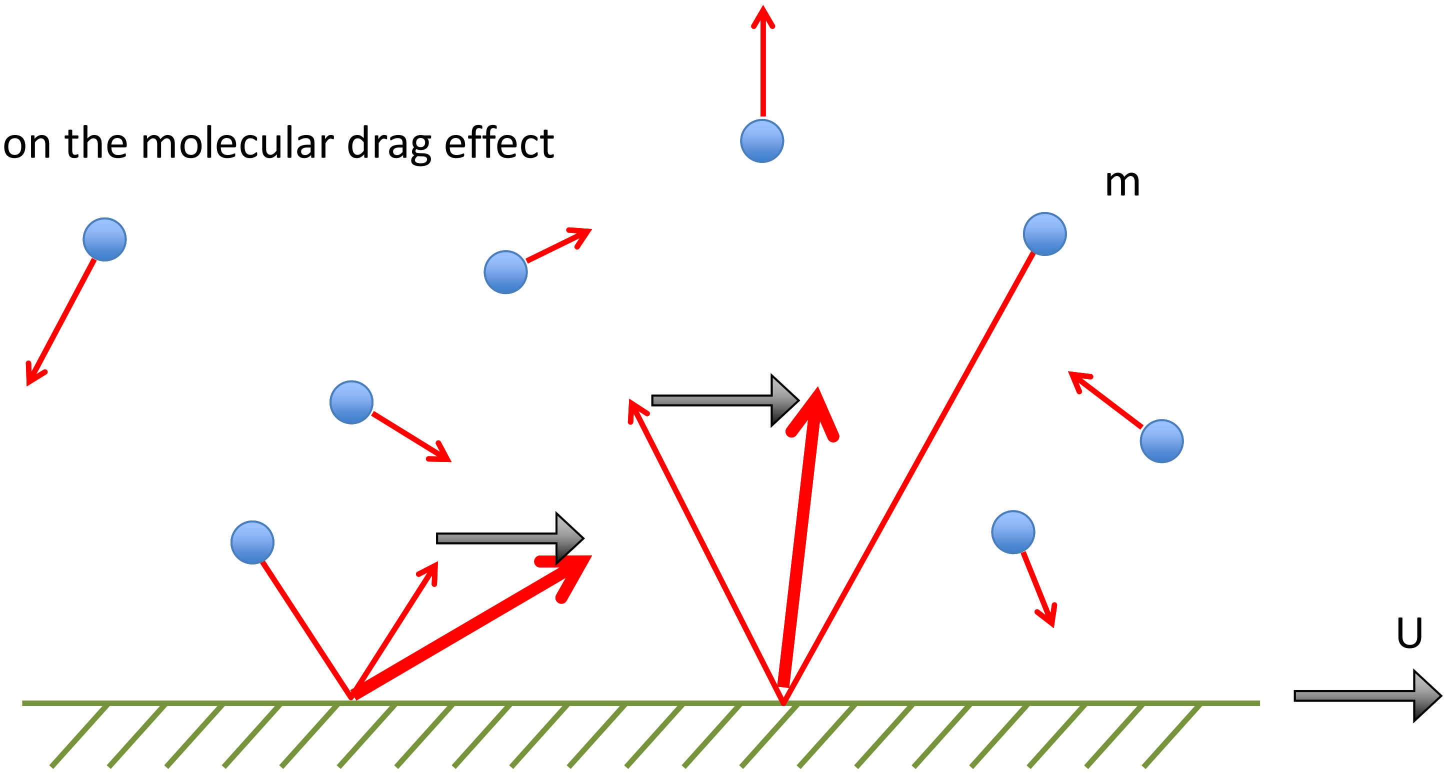
Molecular drag pump

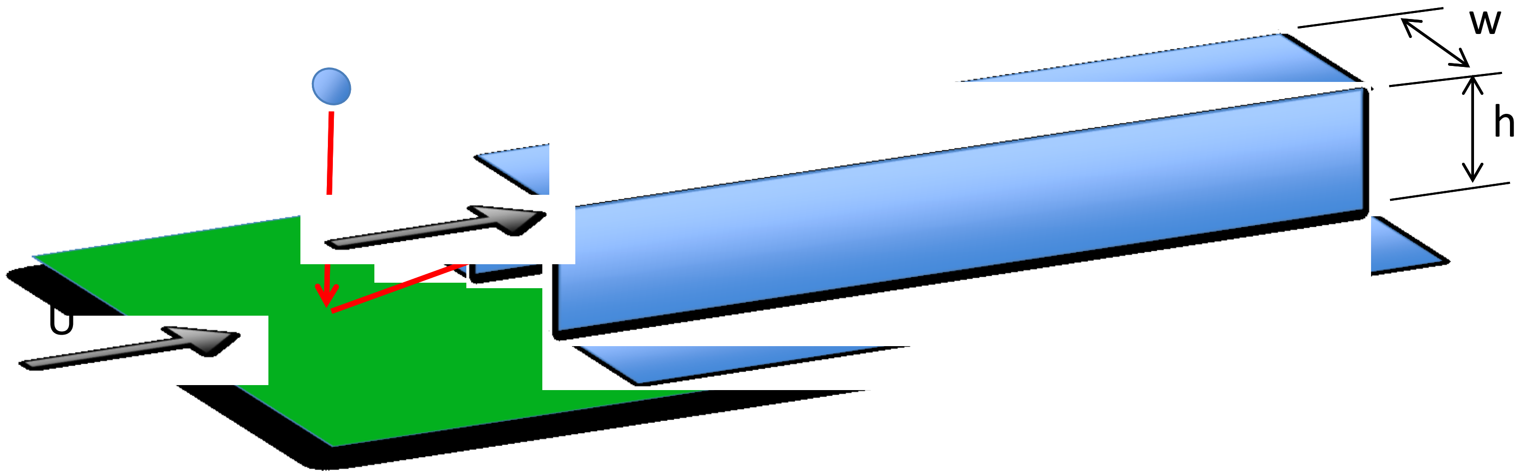
Turbo molecular Pump

Diffusion Ejector pump

Molecular Drag Pumps

Based on the molecular drag effect

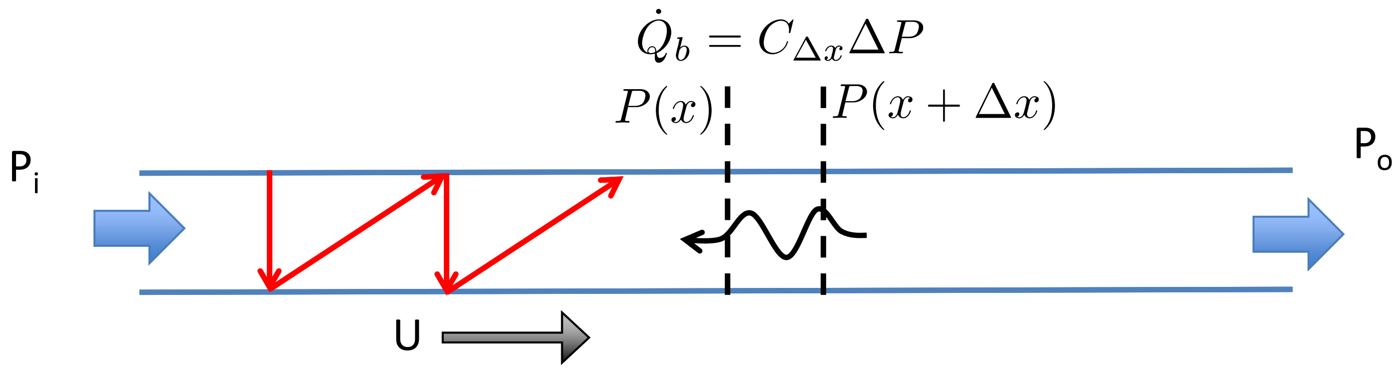




Volumetric flow: $S_0 = wh\frac{U}{2}$

Taking into account of the backflow $S_i = S_0 \frac{K - K_0}{1 - K_0}$

K_0 = zero load compression rate, $K = \frac{P_{outlet}}{P_{inlet}}$



The zero load compression rate is $K_0 = e^{S_0/C}$

But for a long tube $\frac{S_0}{C} = \frac{3}{4}\frac{U}{h}\frac{L}{v_a}$ if $U \sim v_a$ → $\frac{S_0}{C} = \frac{3}{4}\frac{L}{h}$

Example $L = 250$ mm, $h = 3$ mm → $S_0/C > 10$ and $K_0 \gg 1$

$$S = S_0\left(1 - \frac{K}{K_0}\right)$$

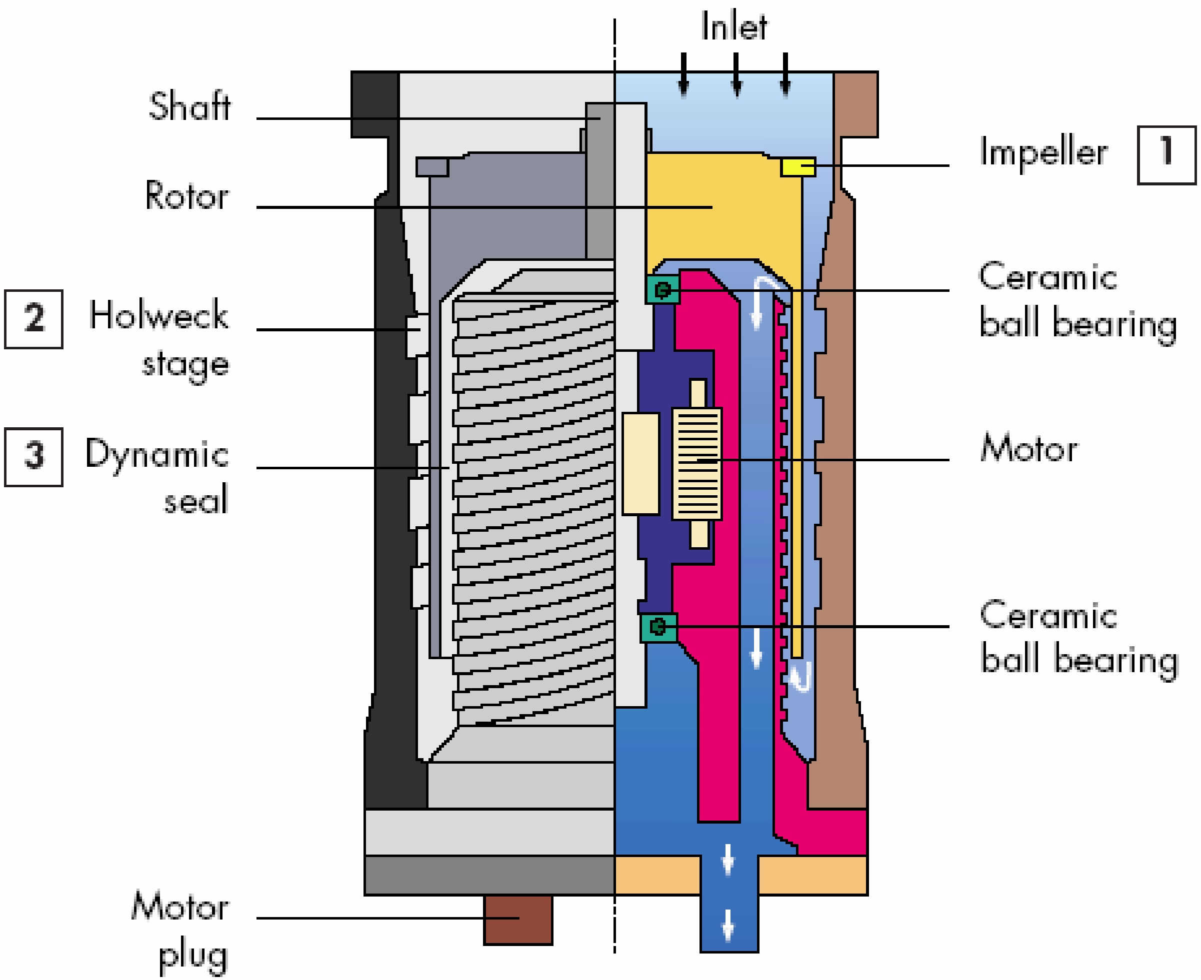
A. Chambers, Modern Vacuum Physics, CRC, 2005

Example of Molecular drag pump

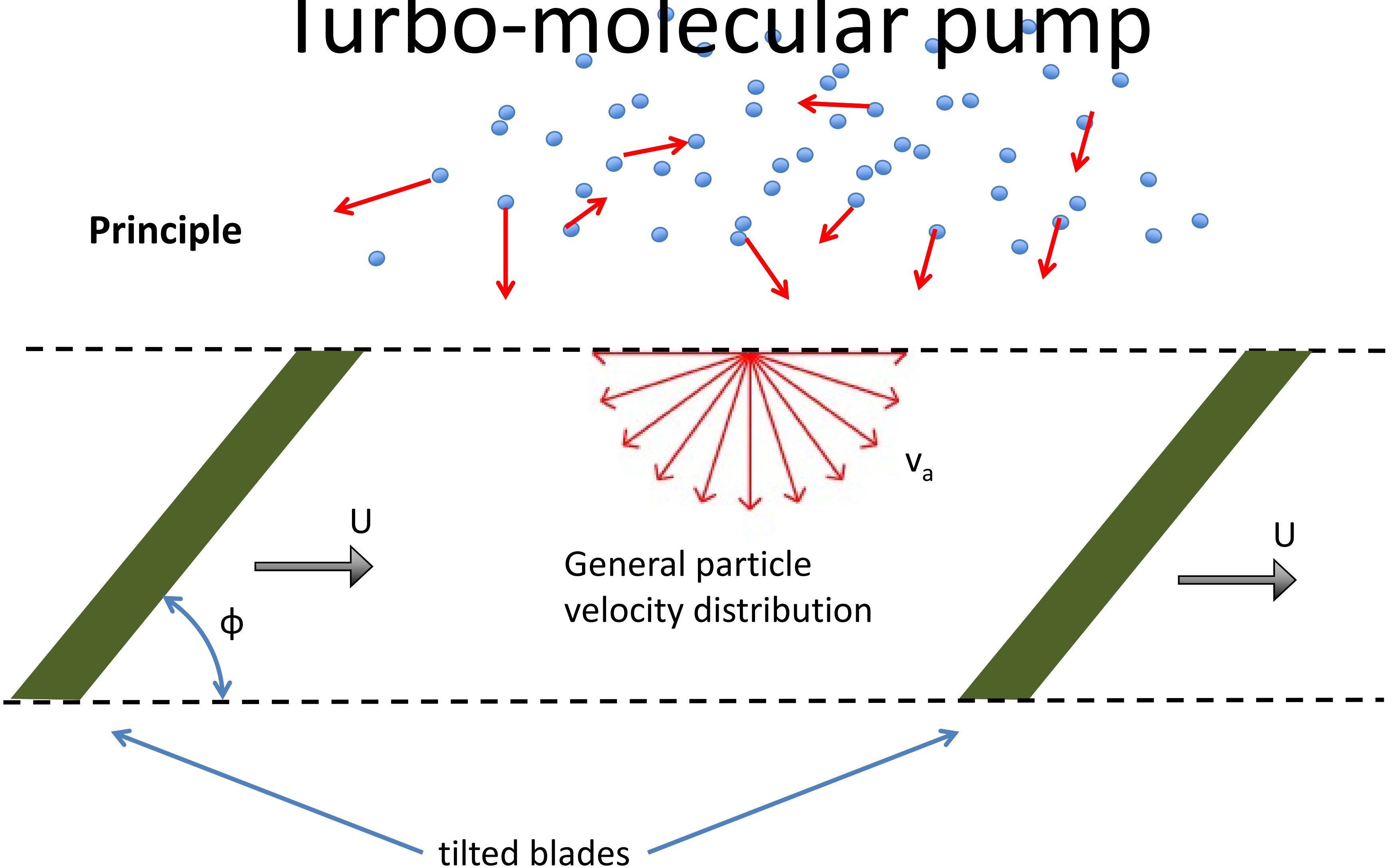
pumping speed:
7- 300 l/s

operating pressure:
$10^{-3} – 10^{3}$ Pa

ultimate pressure
10^{-5} to 10^{-3} Pa

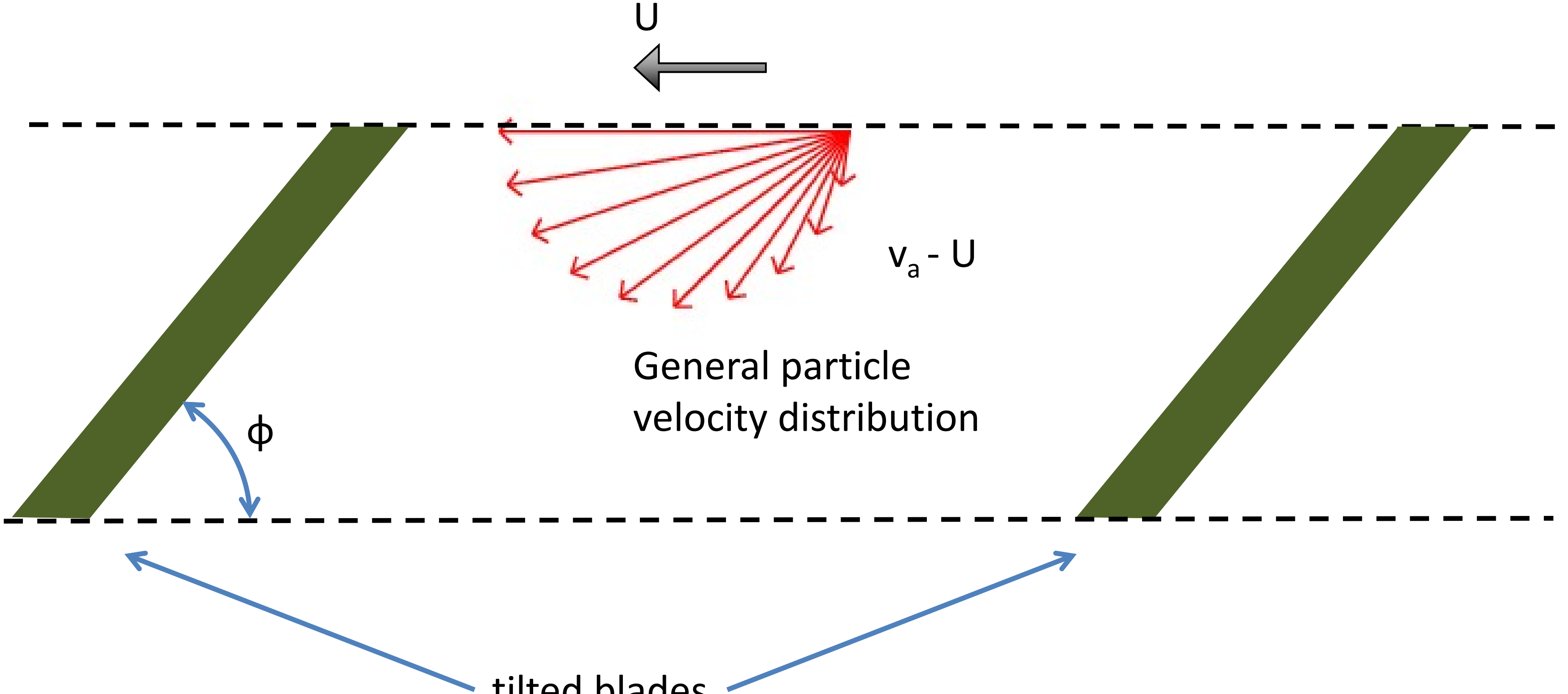


Turbo-molecular pump



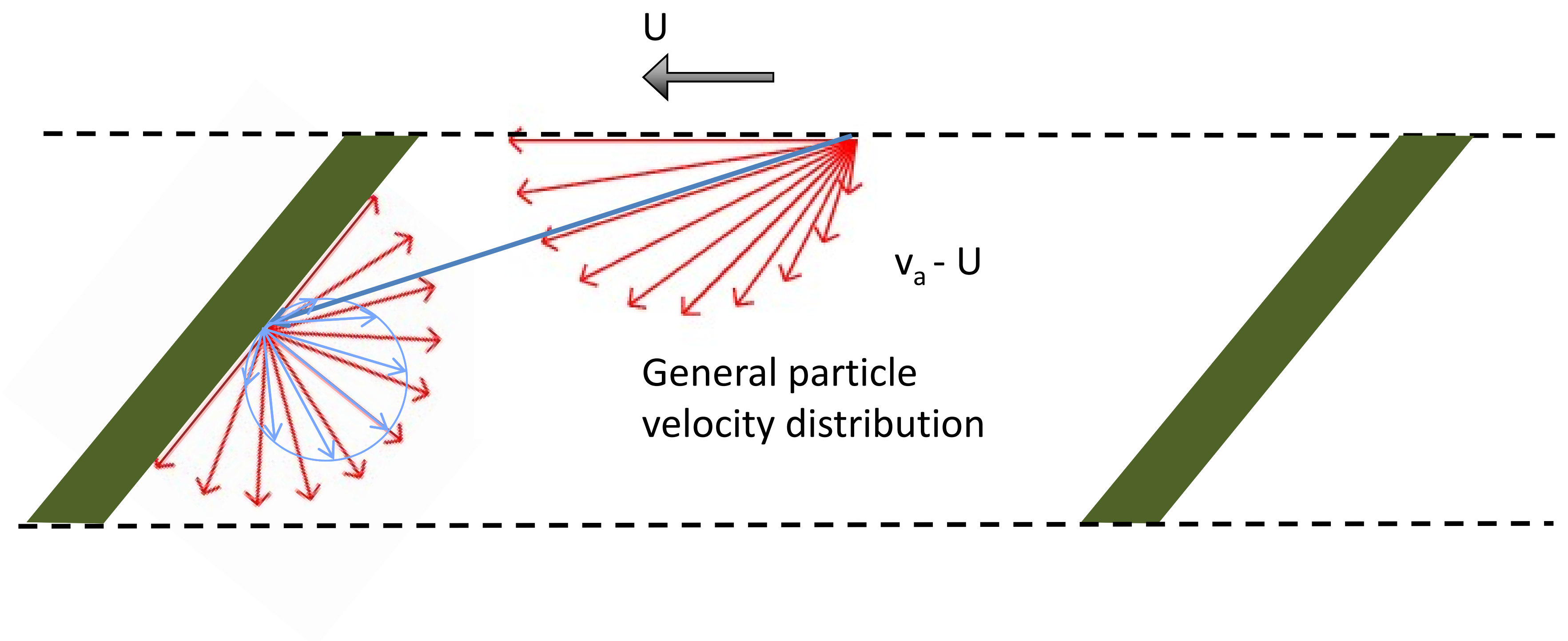
Turbo-molecular pump

In the reference frame of the rotating blades



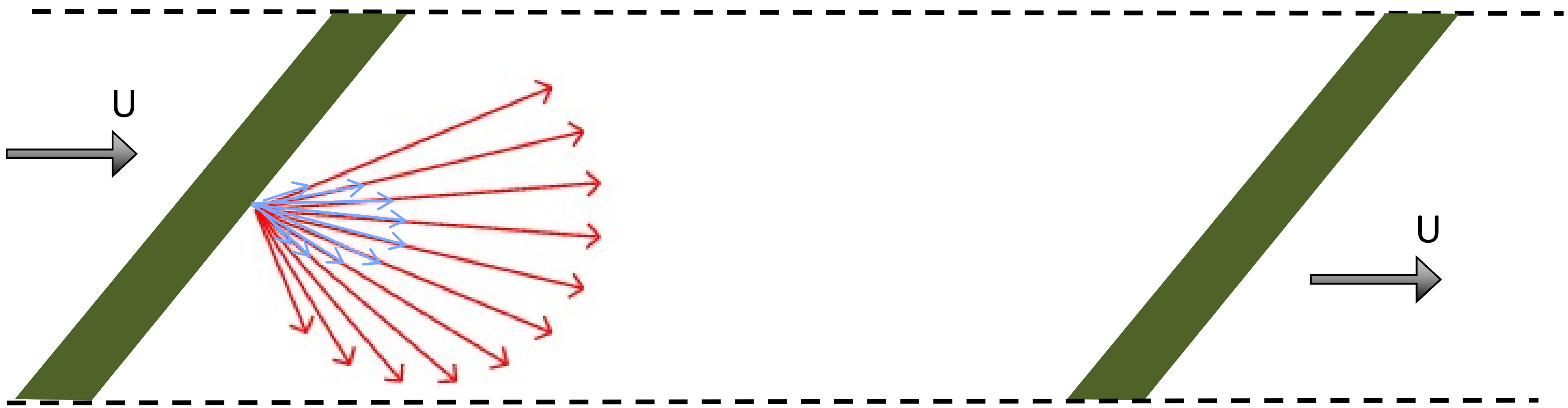
Turbo-molecular pump

In the reference frame of the rotating blades



Turbo-molecular pump

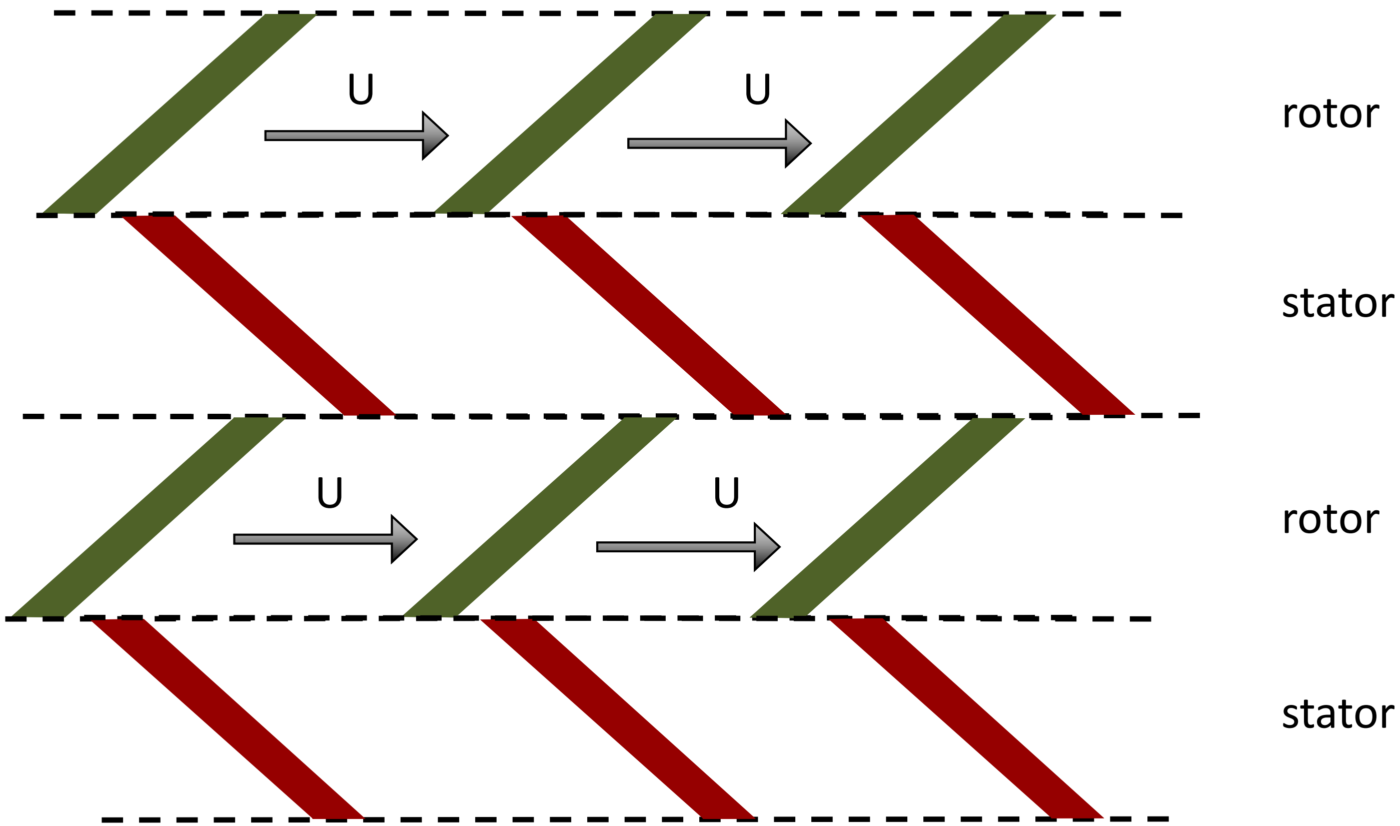
Returning in the laboratory frame



The vacuum particle
has received a momentum
that pushes it down

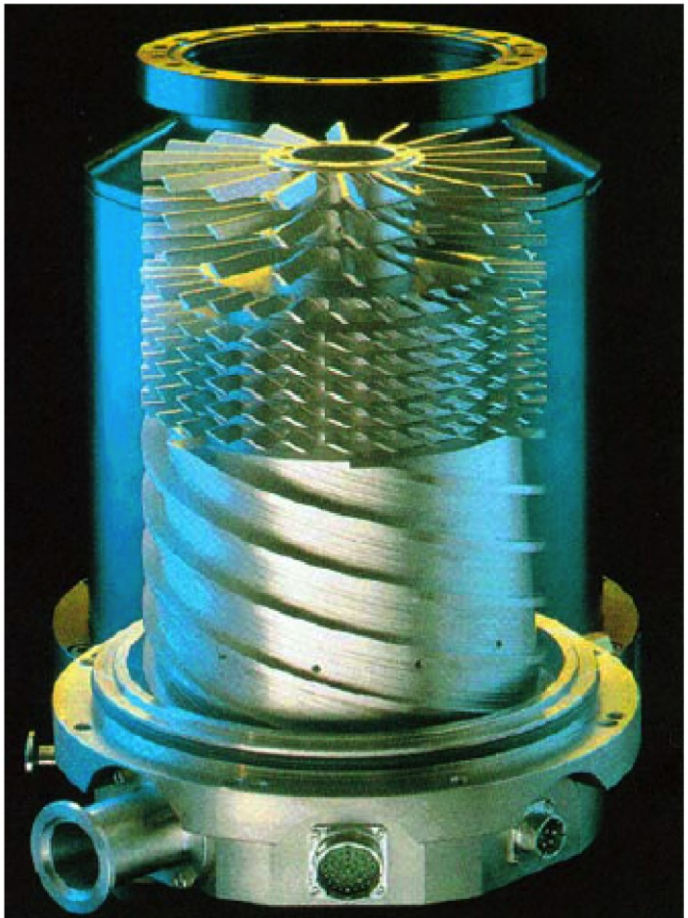
but the component of velocity
tangential becomes too large

Multistage



The rotational component is lost and another stage can be placed

Turbo-molecular pump



Probability of pumping

$$W = \frac{\dot{N}}{J_i A}$$

The maximum probability W_{max} is found when $P_i = P_o$

And we also find that

$$W = W_{max} \frac{K_0 - K}{K_0 - 1}$$

K_0 = compression rate at zero load

The compression rate at zero load $K_0 \propto g(\phi) \exp(U/v_\alpha)$

Therefore $K_0 \propto \exp(\sqrt{M})$ → therefore different species have different pumping probability

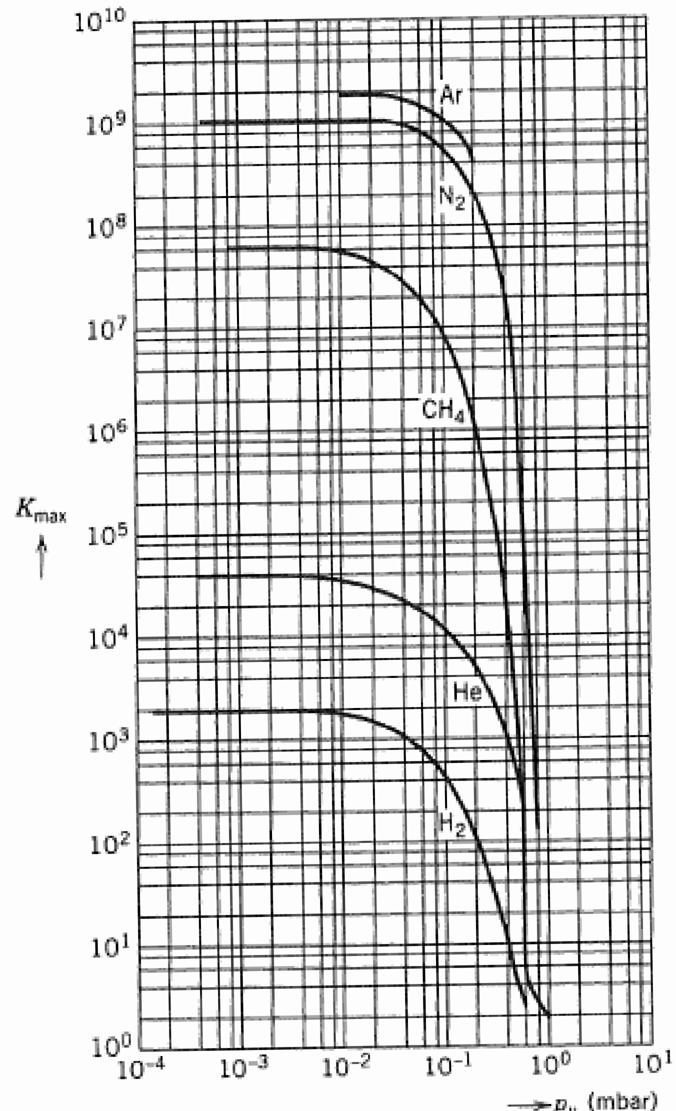
In addition the maximum pumping probability W_{max} is

$$W_{max} \propto U/v_\alpha \propto \sqrt{M}$$

Therefore we find that the maximum pumping speed $S_{max} = W_{max} J$ is independent on the gas mass

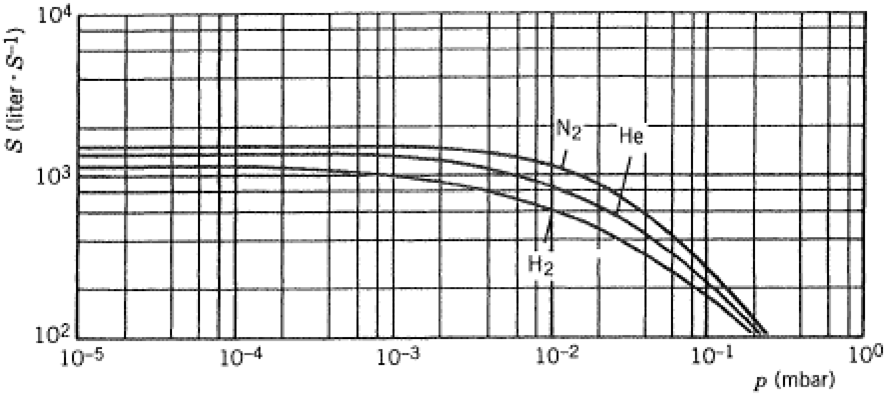
$$\frac{S}{S_{max}} = \frac{K_0 - K}{K_0 - 1}$$

Maximum compression as function of foreline pressure



(Blazers Pfeiffer)

Pumping speed as function of the inlet pressure



(Blazers Pfeiffer)

pumping speed:
35- 25000 l/s

ultimate pressure
10^{-8} to 10^{-7} Pa

End of Vacuum I