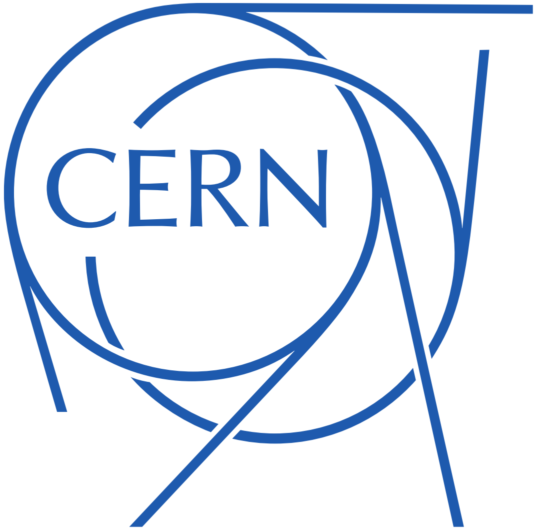
CERN

Vacuum Systems
Slot 1

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CERN TE-VSC, Geneva

Joint Universities Accelerator School

What will this course (lectures, exercises, tutorials, and practical days) do for you?

- The course will introduce you to the basics of:
  - gas kinetics and dynamics
  - analysis and design of vacuum components
  - description and use of vacuum hardware, procedures, computational tools, and materials
  - … with a particular focus on particle accelerators.

- There will be quizzes and exercises proposed during short breaks within the lectures

- Please don’t be shy to ask questions, even trivial ones!

What is vacuum?

"A portion of space, or a volume, where sub-atmospheric pressures exist"

Why Do We Need Vacuum in Accelerators?

"To reduce the collisions of the beams' particles with the residual gas"

- This basic requirement helps to achieve among other things:
  - Beam emittance preservation (of the accelerated beams and secondary beams as well)
  - Longer beam lifetimes (e.g. higher luminosity in colliders)
  - Lower probability of generation of secondary particles (e.g. electrons, ions, radioactive species, etc…)
  - Reduce activation of tunnel and accelerator components and improve maintainability, lower radiation dose to personnel
  - Preserve "good" properties of vacuum surfaces (self serving, e.g. photocathodes)

Outline

1. Introduction
2. Gas kinetic theory
3. Gas flows

1. Introduction

Vacuum

- “Perfect vacuum” is a philosophical concept: it <u>does not</u> exist neither on earth nor in space!
- Example: interstellar medium in a galaxy such as the Milky Way:
  - Composed of molecules, ionized atoms, cosmic rays & dust (size ~ 0.1 μm)
  - In molecular clouds, which are cold (>10 K) and dense regions n ~ 10^4 molecules/cm^3
  - Atomic density:
    - 50 H/cm^3 at 100 K (~10^{-13} Pa)
    - 1 H/cm^3 at 10 000 K (~10^{-13} Pa)

The Pillars of the Creation
NASA – J. Webb

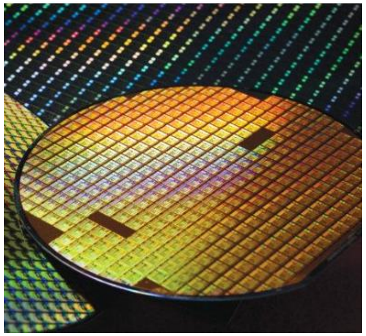
Vacuum Systems on Earth

- **Vacuum technology** is embedded in many devices/systems (here a few examples)

Vacuum pump for wine: Vacuum preserves flavour by reducing oxidation

Light bulb
0.7 atm of Ar

Electron beam welding machine
$10^{-5} – 10^{-2}$ mbar



Semiconductor industry
$10^{-10} – 10^{-2}$ mbar depending on process

Vacuum brazing
10^{-7}-10^{-6} mbar at 200-1300°C

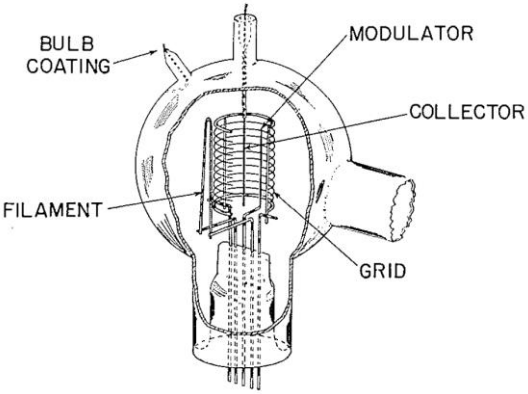
Accelerator: the LHC

Designed for:
H_2-equivalent density $<10^{15}/m^3$
i.e. $2.1 \cdot 10^{-9}$ mbar at 15 K
or $4.1 \cdot 10^{-8}$ mbar at 300 K

The objective of vacuum is to reduce the collision rate of molecules with the surrounding environment to preserve the quality of the process

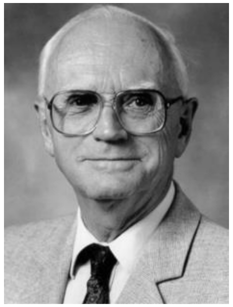
Vacuum gauges & (capture) pumps

1964: $7 \cdot 10^{-15}$ Torr
obtained with a multi-baked
Aluminosilicate glass finger immersed
in liquid helium

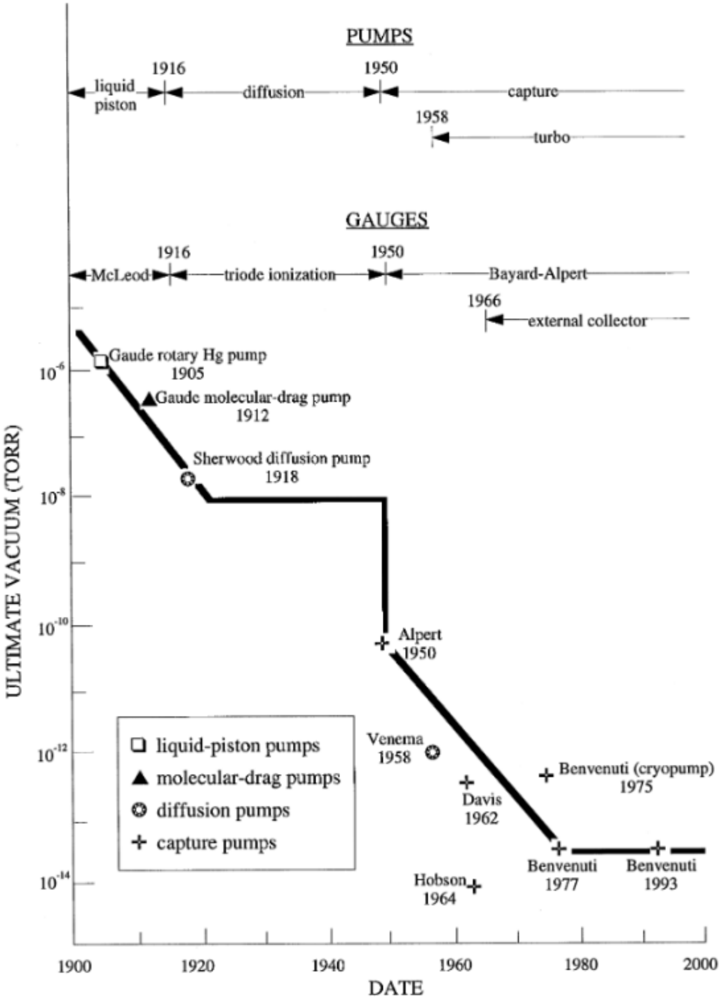


Modulated BA gauge

P. A. Redhead et al, Can. J. Phys. 40,1814 (1962)

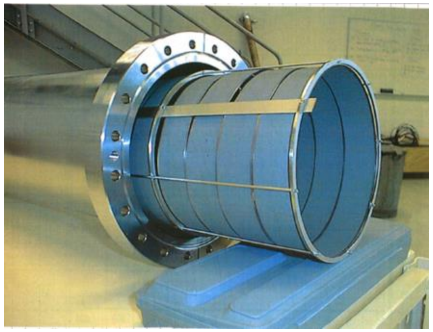


J.P Hobson P.A Redhead



P. A. Redhead, Vacuum 53 (1999) 137-149

1993: ~ 10^{-14} Torr
Passively activated NEG at 350 °C



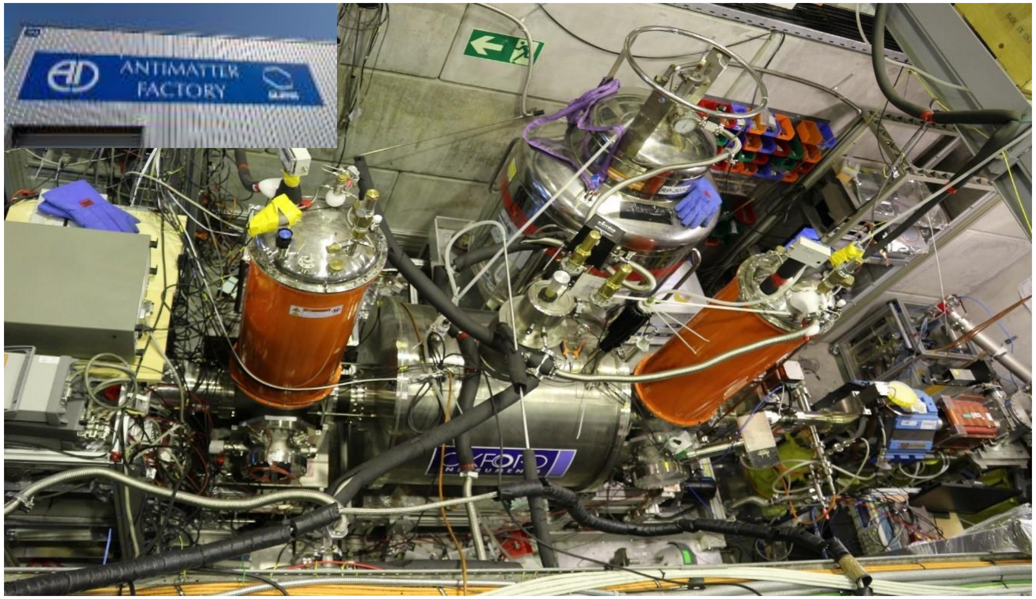
ST707 NEG mounted on
a frame & Helmer gauge

C. Benvenuti et al, Vacuum 44,511-13 (1993)

C. Benvenuti

Lowest (measured, *derived*) pressure

- Recently obtained at the BASE experiment (the Baryon-Antibaryon Symmetry Experiment)



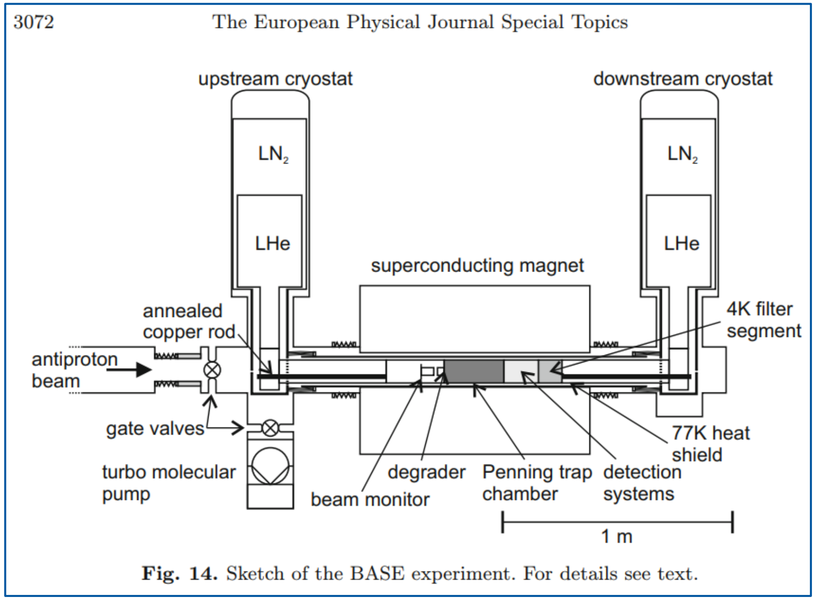

3072 The European Physical Journal Special Topics

Fig. 14. Sketch of the BASE experiment. For details see text.

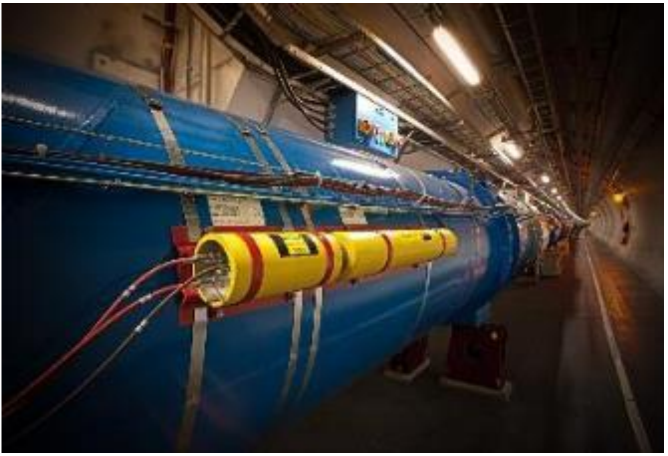
BASE experiment implemented at the CERN AD/ELENA Antimatter Factory

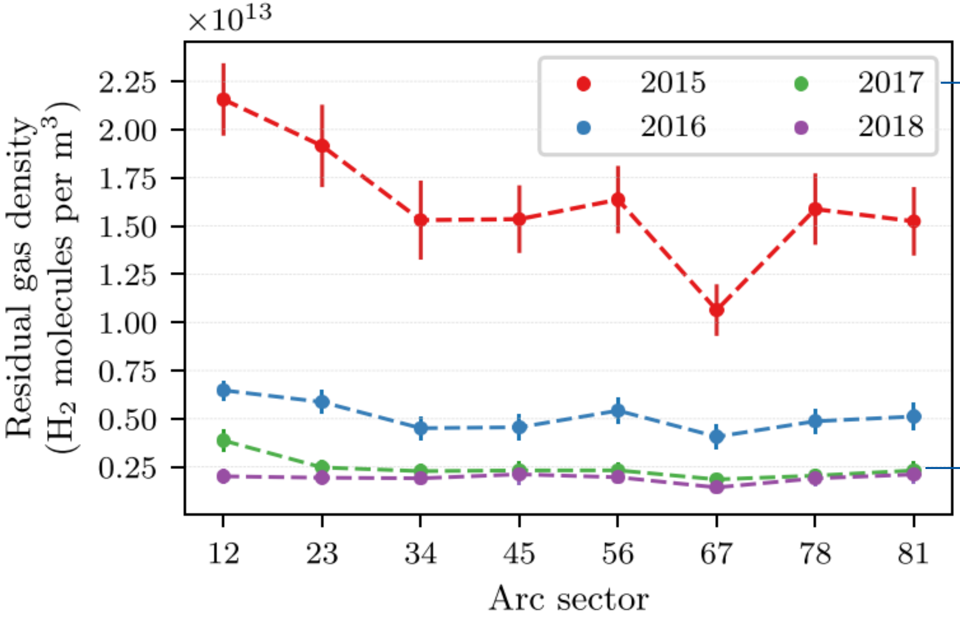
BASE, Eur. Phys. J. Special Topics 224, 3055-3108 (2015)

- By measuring the annihilation of *anti-protons* due to beam-gas scattering, the estimated pressure in the cryogenic Penning trap is **~10^{-19} mbar** i.e. 2400 molecules/m^3 (equivalent, at room temperature, 160k at 4.5ºK)

Pressure in the LHC arcs during RUN2

- Measure of beam-gas scattering, using *beam loss monitors* (used to estimate the pressure (molecular density) along the path of the p beam)





$2\ 10^{-10}$ mbar

$2\ 10^{-11}$ mbar

$$\frac{dI}{dt} = -I\,n\,v\,\sigma$$

$$\boxed{I = I_o\,e^{-\frac{t}{\tau}}}$$

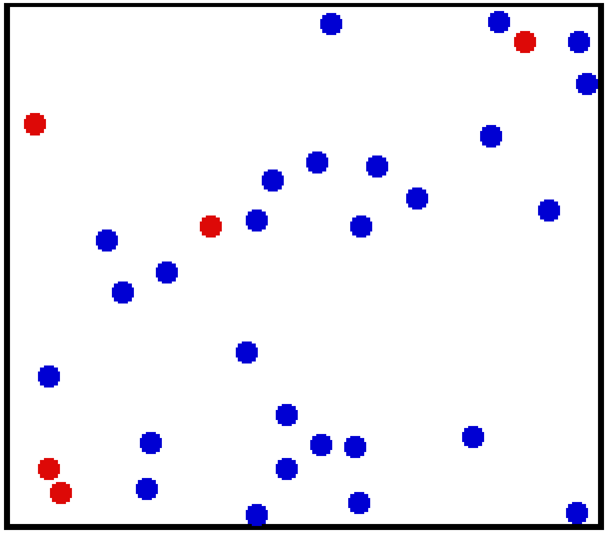
$$\tau = \frac{1}{n\,\sigma\,v}$$

	Design	2015	2018
Life time	100 h	185 days	4,5 years !!

2. Gas kinetic theory

Introduction

- Assume a large number of molecules, always moving in a disordered manner
- The size of molecules is very small as compared to the intermolecular distance
- Molecules move in a rectilinear uniform manner between successive collisions
- Collisions (elastic) are intra-molecular or against the surrounding walls



http://www.matierevolution.fr

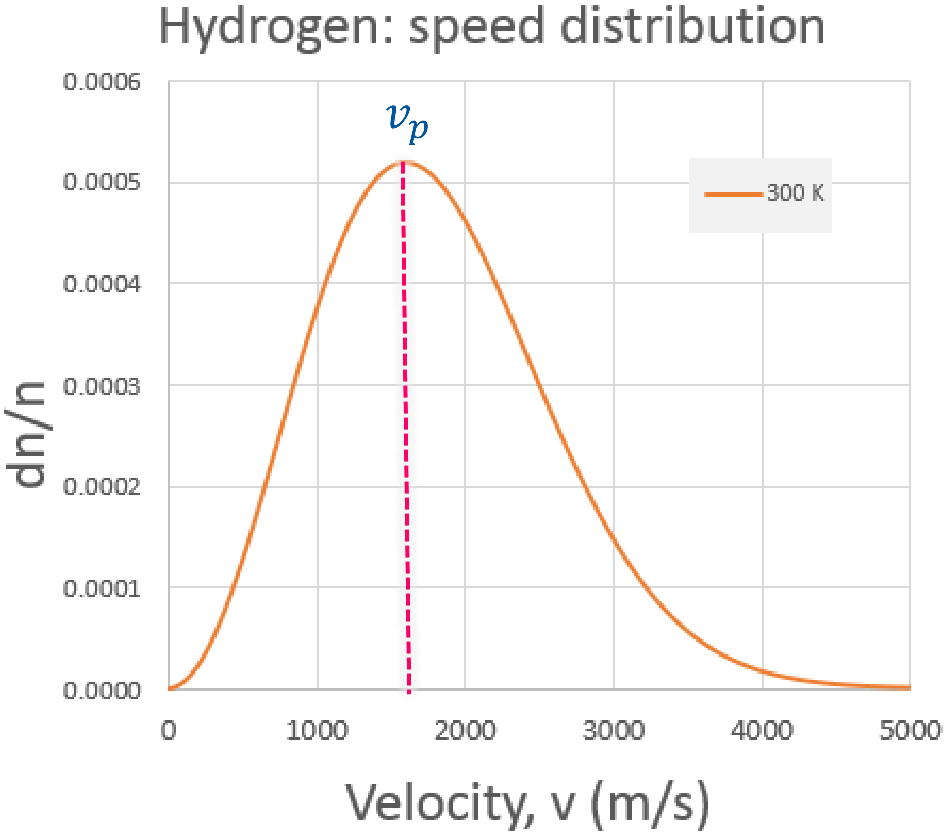
Maxwell Boltzmann Distribution

- Assume a pure gas, in thermal equilibrium and enclosed in an isothermal volume
- In this case:
  - The molecular density is constant in the volume and does not vary in time
  - The direction of the molecules' speed is isotropic
  - The speed distribution is stationary

$$\boxed{\frac{dn}{n} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} v^2\, e^{-\frac{mv^2}{2kT}}\, dv}$$

- The speed of the molecules follows the Maxwell-Boltzmann distribution

- Most of the molecules have a speed around the maximum, v_p
- Less than 1/1000 of molecules have speed:
  v<0.1 v_p or v>3 v_p



J.C. Maxwell 1860

L. Boltzmann 1870

Maxwell Boltzmann Distribution

- The most probable speed is given at the maximum of the distribution: d(dn/n)/dv =0. It equals

$$v_p = \sqrt{\frac{2kT}{m}}$$

- The mean thermal speed equals:

$$\bar{v} = \frac{1}{n}\int_0^{\infty} v\,\frac{dn}{dv}\,dv = \sqrt{\frac{8kT}{\pi\,m}}$$

$$\boxed{\begin{gathered}\bar{v} = 1.1284 \cdot v_p \\ {v_q}^2 = 1.2247 \cdot v_p\end{gathered}}$$

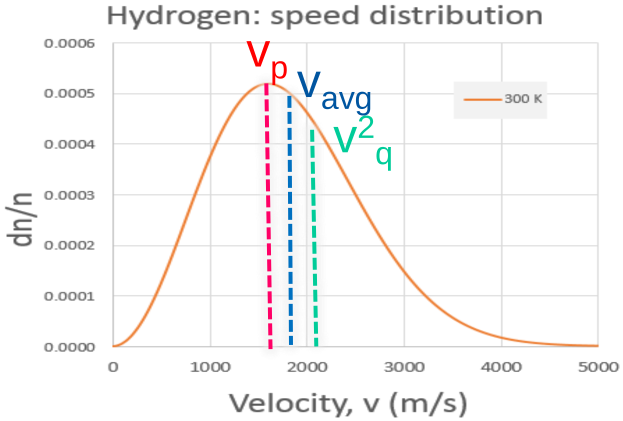
- The average quadratic speed (rms) equals:

$${v_q}^2 = \overline{v^2} = \frac{1}{n}\int_0^{\infty} v^2\,\frac{dn}{dv}\,dv$$

$$v_q = \sqrt{\frac{3kT}{m}}$$

- The corresponding kinetic energy is:

$$\frac{1}{2} m\,{v_q}^2 = \frac{3}{2} kT$$



All molecular speeds scale like ~ √(T/m)

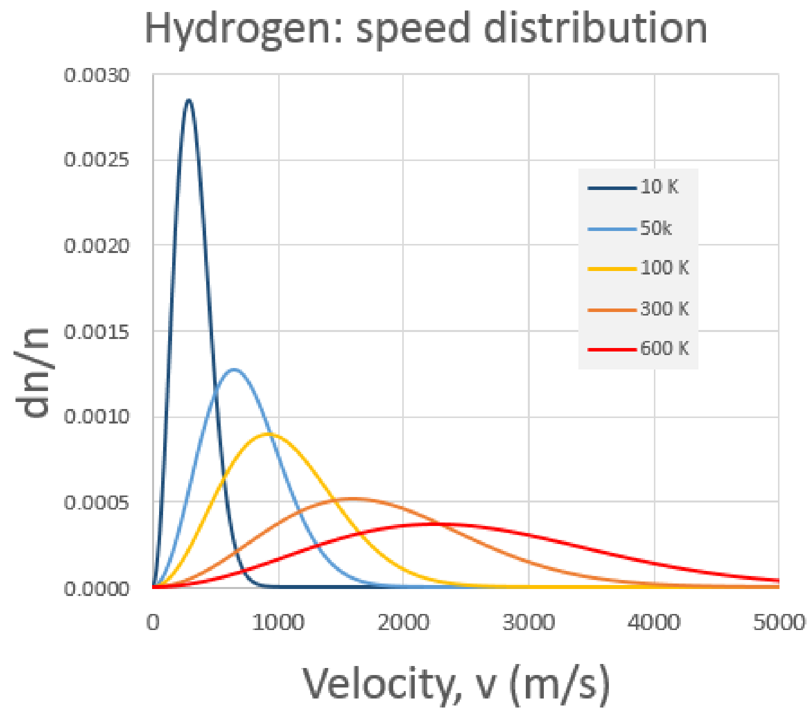
T in degrees Kelvin not (Celsius), m in kg, v in m/s

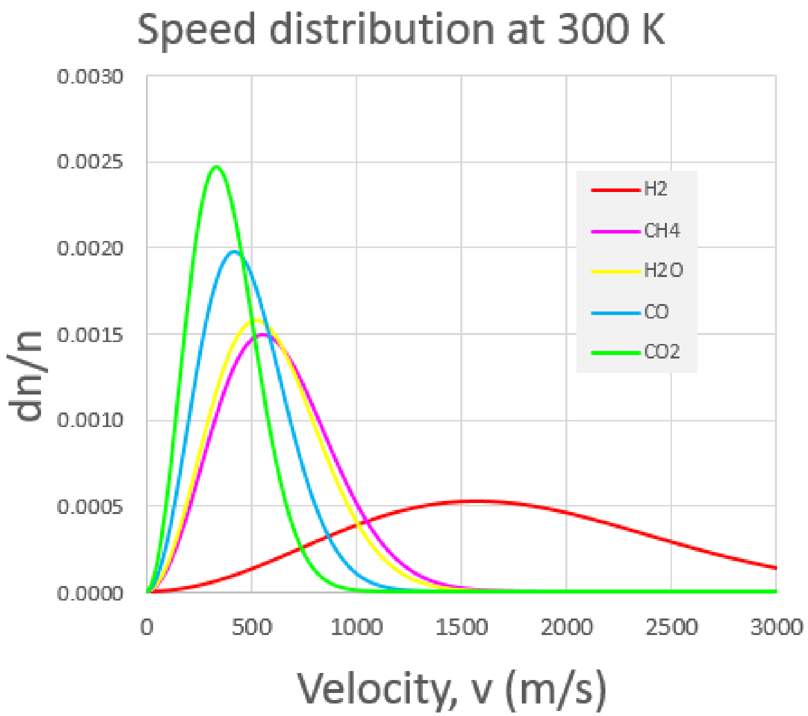
Maxwell Boltzmann Distribution

- The gas velocity:
  - increases with increasing temperature
  - it is larger for light molecules
  - Atomic Mass Unit (often called “a.m.u.”): 1/12 of the weight of a ^{12}C atom

$\sim \sqrt{(T/m)}$

Gas	H_2	He	CH_4	H_2O	CO	N_2	O_2	Ar	CO_2
AMU	2	4	16	18	28	28	32	40	44


Hydrogen: speed distribution


Speed distribution at 300 K

Average velocity

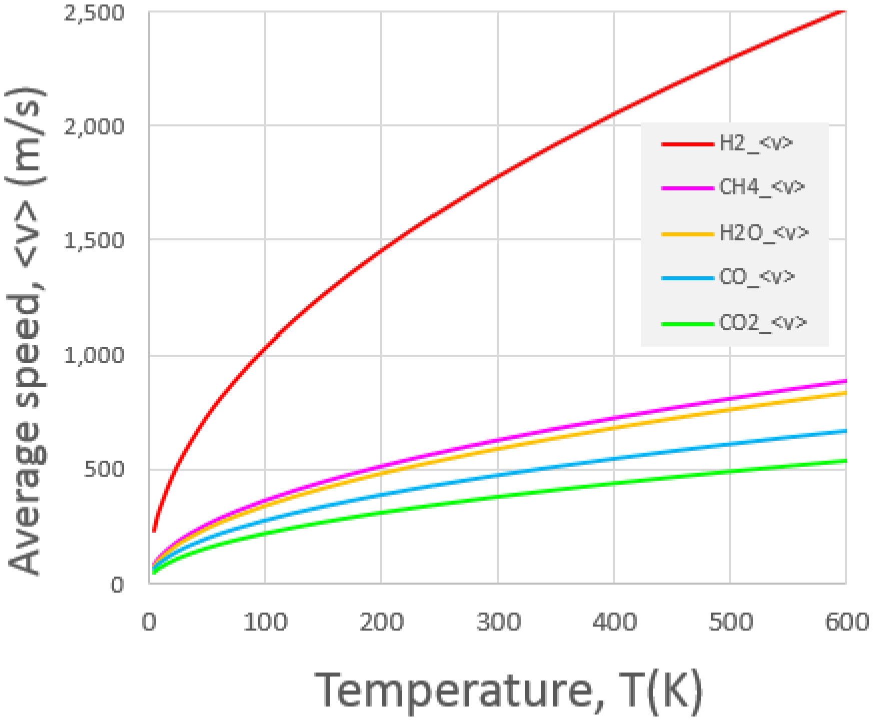
- The mean thermal speed range from ~ 50-100 m/s to several 1000s m/s:

  The traveled distance in a second is much larger than the vacuum chamber dimensions!

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}} = 145\sqrt{\frac{T}{M}}$$

T (K)	He	Air	Ar
4.2	150	55	50
300	1300	470	400
600	1800	660	560

$\sim \sqrt{(T/m)}$



Collision rate on the wall

- The molecular collision rate on the wall (the impingement (or *incidence*) rate), ν, can be derived from the Maxwell Boltzmann distribution

$$\boxed{\nu = \frac{number\ of\ collisions\ with\ the\ wall}{area\ of\ wall\ \cdot\ time} = \frac{1}{4}\, n\, \bar{v}}$$

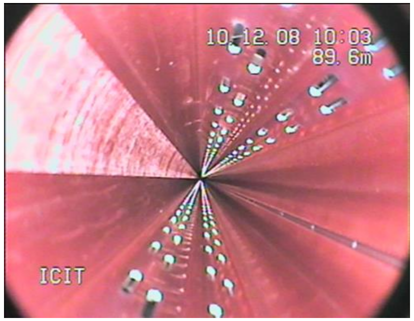
- Monolayer formation time

~10^{15} molecules/cm^2

- At room temperature, a monolayer is formed in ~1 s at 10^{-6} Torr **:** Langmuir formation time
- Langmuir unit definition: 1 L = 10^{-6} Torr·1 s ; It is the product pressure and time that matters, e.g. 1 L = 10^{-8} Torr·100 s; In practical terms, 1 L ~ 1 monolayer/s);
- Very low pressure is preferred to minimize surface contamination,

A monolayer is formed in:
1 ns at 1 atm
1 s at 10^{-6} mbar
1 day at 10^{-11} mbar !!!

Ice formed at atm pressure



LHC beam screen under vacuum

Pressure & Ideal gas law

- Molecules which collide on a wall of area A, generate a force, F, onto it.
- The pressure P, exerted on the wall by the molecules is defined by the ratio of the force to the surface:

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

- It can be shown that, for <u>any particle velocity distribution</u>, the pressure is given by the mass density ρ and the quadratic speed (equipartition theorem):

$$P = \frac{1}{3}\,\rho\,{v_q}^2$$

- If the particle velocity distribution follows a Maxwell-Boltzmann distribution (e.g. at <u>thermodynamic equilibrium</u>), the pressure is given by the IDEAL GAS LAW:

$$P = n\,k\,T$$

- For such a gas, the pressure, P [Pa], is defined by the gas density, n [molecules·m^{-3}] , the temperature of the gas, T [K] and the Boltzmann constant k , (1.381·10^{-23} J/K)

- The pressure increases <u>linearly</u> with the gas temperature

Ideal gas law: illustration

$$P = n\,k\,T$$

- Ultra-High Vacuum
  - take LHC design
  - n= 10^{15} molecules/m^3
    - k = 1.38 10^{-23} J/K
    - T = 300 K *i.e.* room temperature
    - ➔ P = 10^{15} x 1.38 10^{-23} x 300 = 4 10^{-6} Pa

- The ideal gas law relation is another expression on the Avogadro's law:
  - The occupied volume by one mole in standard condition equals 22.4 ℓ (*i.e.* 22.4 10^{-3} m^3)
    - ➔ n = N / V = 6.02 10^{23} / 0.0224 m^3 = 2.7 10^{25} molecules/m^3
  - Standard conditions (STP): 0 °C (273.15 K), 1 atm
    - P = 101 300 Pa,
    - k = 1.38 10^{-23} J/K
    - T = 273 K *i.e.* 0°C
    - ➔n = 101 300 / (1.38 10^{-23} x 273) = 2.7 10^{25} molecules/m^3

Pressure Units

- The pressure is the force exerted on the wall by the molecules per unit of surface:

1 Pa = 1 N/m^2 [SI unit] (CERN uses mbar)

→	Pa	kg/cm^2	Torr	mbar	bar	atm
1 Pa	1	$10.2\ 10^{-6}$	$7.5\ 10^{-3}$	10^{-2}	10^{-5}	$9.81\ 10^{-6}$
1 kg/cm^2	$98.1\ 10^{3}$	1	735.5	980	0.98	0.96
1 Torr	133	$1.35 \cdot 10^{-3}$	1	1.33	$1.33 \cdot 10^{-3}$	$1.31\ 10^{-3}$
1 mbar	100	$1.02\ 10^{-3}$	0.75	1	10^{-3}	$9.869\ 10^{-4}$
1 bar	$1.0\ 10^{5}$	1.02	750	10^{3}	1	$9.869\ 10^{-1}$
1 atm	101,325	1.03	760	1,013.25	1.01325	1

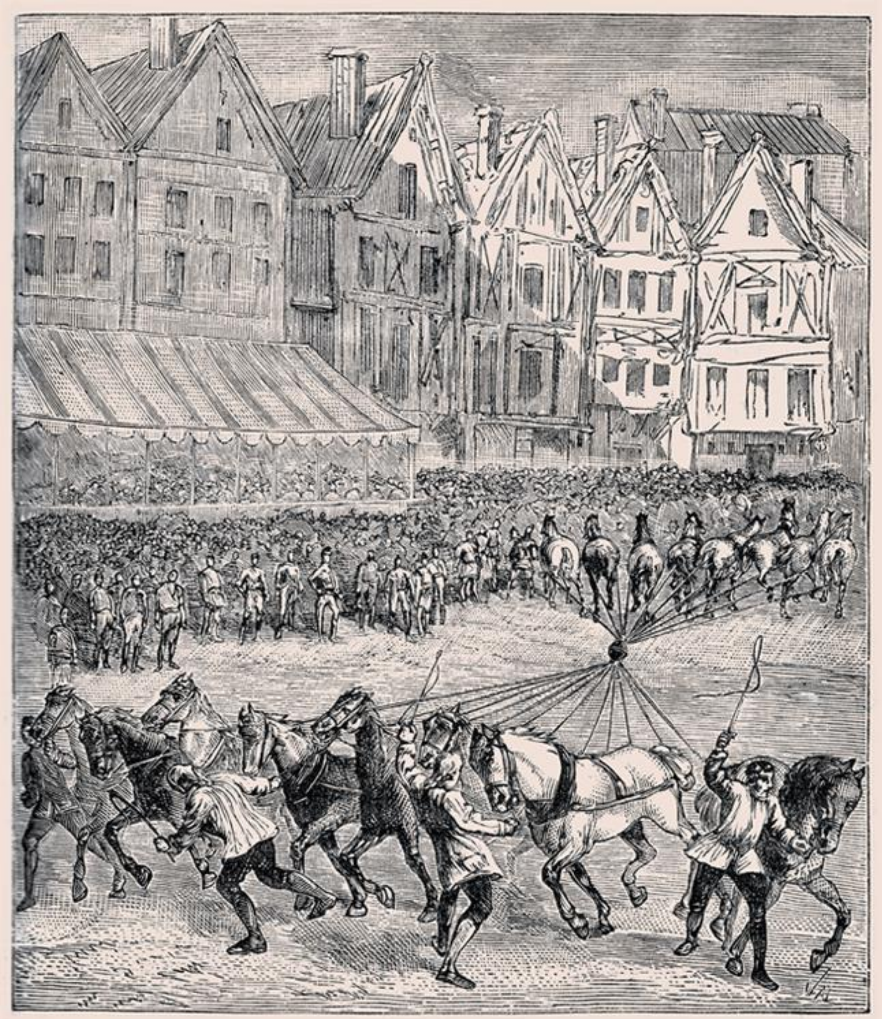
E. Torricelli, 1644

B. Pascal, 1647

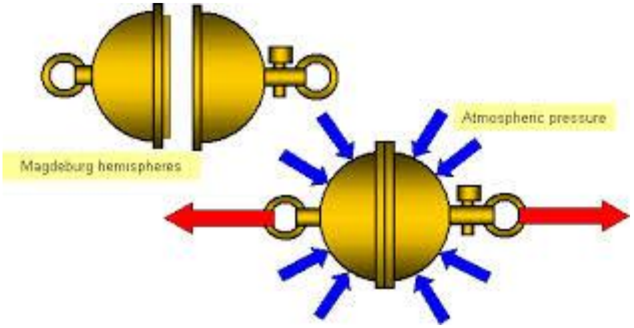
- Examples:
  - 10^{-6} Torr is equivalent to $1.33 \times 10^{-6} = 1.3\ 10^{-6}$ mbar
  - 10^{-6} Torr is equivalent to $133 \times 10^{-6} = 1.3\ 10^{-4}$ Pa
  - $4\ 10^{-6}$ Pa is equivalent to $4\ 10^{-6} / 133 = 3\ 10^{-8}$ Torr
  - $4\ 10^{-6}$ Pa is equivalent to $4\ 10^{-6} / 100 = 4\ 10^{-8}$ mbar

“Vacuum force”: Magdeburg hemisphere

- 1654, Magdeburg



Expérience des *Hémisphères de Magdebourg*,
exécutée par Otto de Guéricke devant l'empereur Ferdinand III, à la diéte de Ratisbonne



55 cm diameter ➔ ~2.4 Tons

Otto von Guericke

Force applied on a vacuum vessel

- When the vacuum vessel is evacuated, a force is applied onto it (atmospheric pressure)
- It amounts to 1 kg/cm^2

- Example: force applied on a blank flange

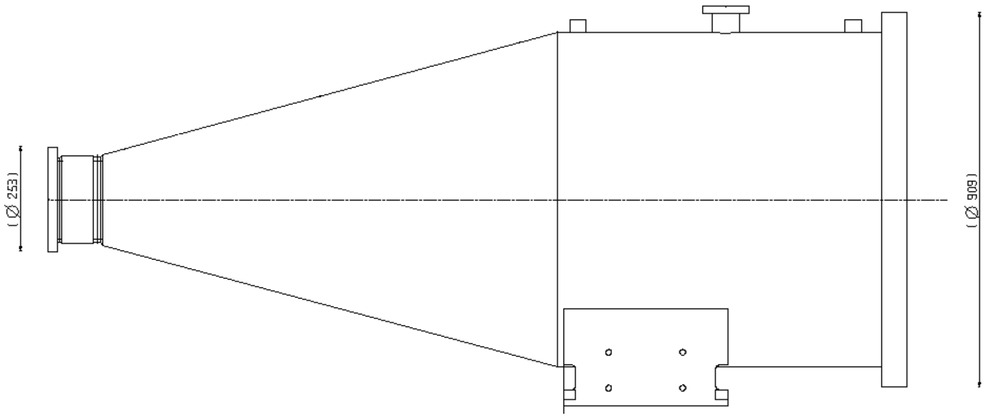
Picture Kurt J. Lesker

D (mm)	16	35	63	80	100	130	150	212
kg	2	10	32	52	81	137	182	363

As a consequence of the « vacuum force » …

Work with the Mechanical Design Office !

0.5 ton →



← **6.6 tons**

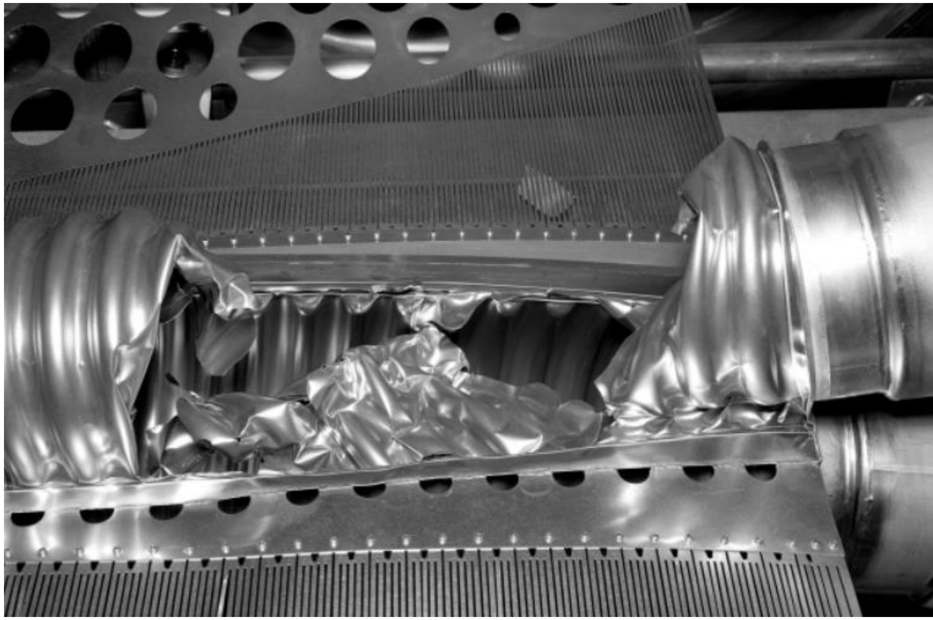
60

Otherwise… damage to supports and chambers may result!

Typical accidents with UHV!

- Case of the CERN ISR in the 70’s :

“spontaneous” breaking of a bellow (either due to a bad design or to a fixed point not well attached)



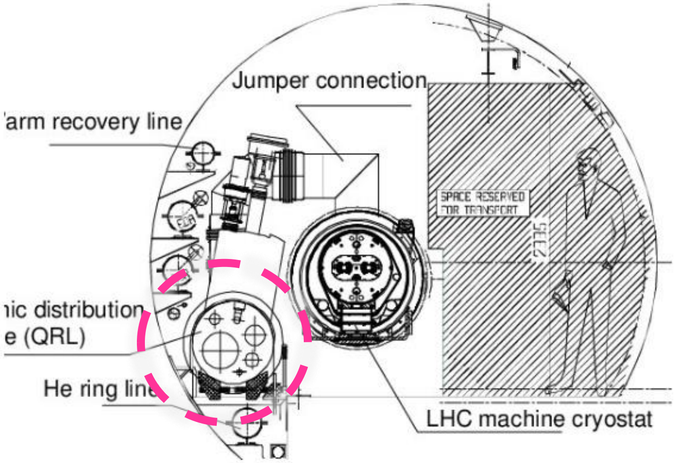
Imploded “flat fish” at an ISR intersection

Even in modern times …

- Accident still possible nowadays <u>even</u> with modern computing tools …

- Case of the QRL's bellows in the LHC deformed during pump down, (QRL=cryogenic distribution line in the LHC tunnel)

- Origin attributed to a non-conformal bellow with a too small corrugation height



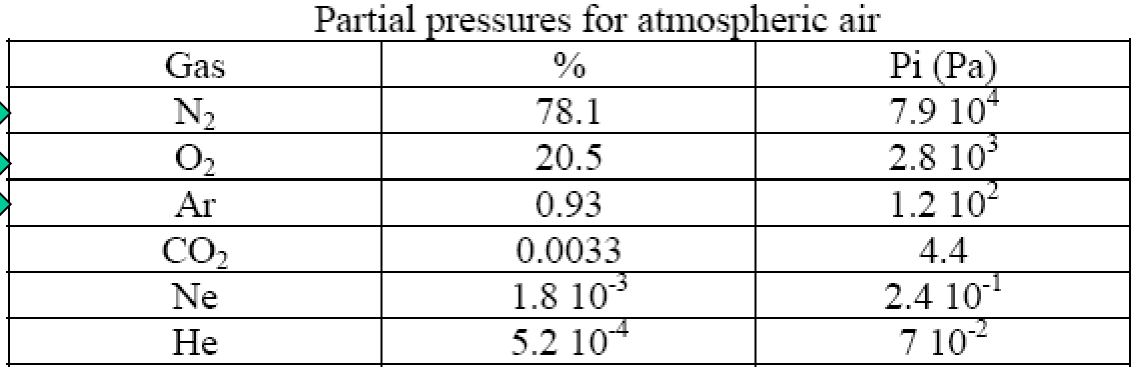
Total Pressure and Partial Pressure

- The gas is usually composed of several types of molecules (ex : air, residual gas in vacuum systems)

- The **total pressure,** P_{Tot}, is the sum of all the **partial pressures,** P_i (**Dalton's law**)

$$\boxed{P_{Tot} = \sum P_i = k\,T \sum n_i}$$

John Dalton, 1801



Partial pressures for atmospheric air

Gas	%	Pi (Pa)
N_2	78.1	$7.9\ 10^4$
O_2	20.5	$2.8\ 10^3$
Ar	0.93	$1.2\ 10^2$
CO_2	0.0033	4.4
Ne	$1.8\ 10^{-3}$	$2.4\ 10^{-1}$
He	$5.2\ 10^{-4}$	$7\ 10^{-2}$

3. Gas flow

Mean free path

- It is the path length that a molecules traverse between two successive impacts with other molecules. It was derived by Clausius.

- It is a function of the pressure, *P*, of the temperature, *T*, and of the molecular diameter, σ.

$$\lambda = \frac{1}{\sqrt{2}\pi n \sigma^2} = \frac{1}{\sqrt{2}\pi}\frac{kT}{P}\frac{1}{\sigma^2}$$

$$\boxed{\lambda_{air}[cm] = \frac{5\,10^{-3}}{P[Torr]}}$$

R. Clausius

➔ Increasing mean free path when decreasing pressure

- Air at room temperature

P (Torr)	λ	Size	Regime
760	70 nm	Coronavirus	Atmosphere
1	50 μm	Human hair	Rough vacuum
10^{-3}	5 cm	Flower	Medium vacuum
10^{-7}	500 m	Stadium	High Vacuum
10^{-10}	500 km	Geneva-Paris	Ultra High Vacuum
10^{-12}	50,000 km	Earth circumference	Extreme High Vacuum

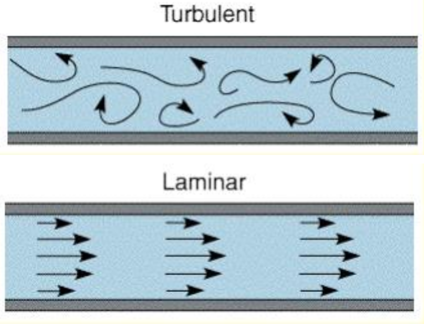
accelerators

Classification of vacuum

- From atmospheric pressure to very low pressure, the **mean free path** varies over more than 15 orders of magnitude!

Low or Rough vacuum	10^5 to 10^2 Pa ;	10^3 to 1 mbar
Medium vacuum	10^2 to 10^{-1} Pa ;	1 to 10^{-3} mbar
High vacuum (HV)	10^{-1} to 10^{-5} Pa ;	10^{-3} to 10^{-7} mbar
Ultra-high vacuum (UHV)	10^{-5} to 10^{-10} Pa ;	10^{-7} to 10^{-12} mbar
Extreme-high vacuum (XHV) (below actual limit of “standard” instrumentation)	$<10^{-12}$ Pa ;	$<10^{-14}$ mbar

Flows



- The turbulent flow is established around the atmospheric pressure

- In the low vacuum (10^3-1 mbar), the flow is viscous and laminar.

- In the high vacuum (10^{-3} – 10^{-7} mbar) and ultra-high vacuum (10^{-7}–10^{-12} mbar), the flow is molecular. The mean free path is much larger than the vacuum chamber diameter. Molecules interact only with the vacuum chamber walls

The molecular flow is the main regime of flow to be used in vacuum technology for particle accelerators

In this regime, the vacuum vessel has been evacuated , and molecular collisions are very rare, or totally absent

The pressure inside the vessel is dominated by the nature of **the surface,** which makes things a lot more interesting but difficult to describe

Molecular Flow: domain of application

$$\text{Molecular flow: } \overline{\mathrm{P}} \cdot \mathrm{D} < 2.0\ 10^{-2}\ [mbar \cdot cm]$$

- Assume an accelerator ring operating under UHV:
  - vacuum chamber diameter D ~ 10 cm
  - average pressure 10^{-8} mbar
    - ➔ $P \cdot D = 1.0 \cdot 10^{-8} \times 10 = 1.0 \cdot 10^{-7}$ mbar·cm ➔ molecular regime
  - mean free path:
    - ➔ $\lambda = 5 \cdot 10^{-4} / 1.0 \cdot 10^{-8} = 50$ km

$$\lambda_{N_2}[cm] \approx \frac{5 \cdot 10^{-2}}{P[mbar]}$$

- Assume a large vacuum vessel, *e.g.* a large cryostat, operating under HV:
  - vacuum chamber diameter ~ 10 m (=1000 cm)
  - average pressure 10^{-5} mbar
    - ➔ $P \cdot D = 1.0 \cdot 10^{-5} \times 1000 = 1.0 \cdot 10^{-2}$ mbar·cm ➔ molecular regime
  - mean free path:
    - ➔ $\lambda = 5 \cdot 10^{-4} / 1.0 \cdot 10^{-5} = 50$ m

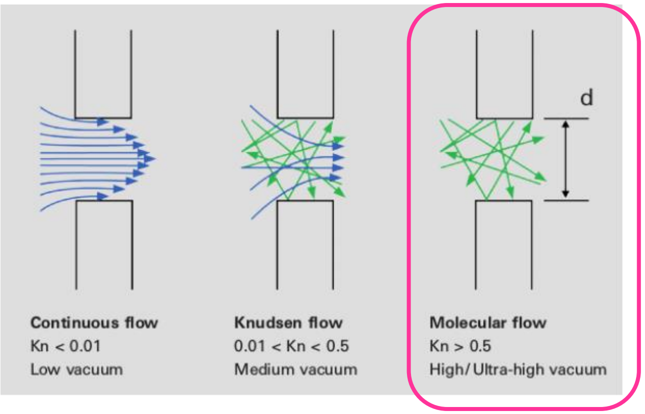
Molecular interaction with the wall

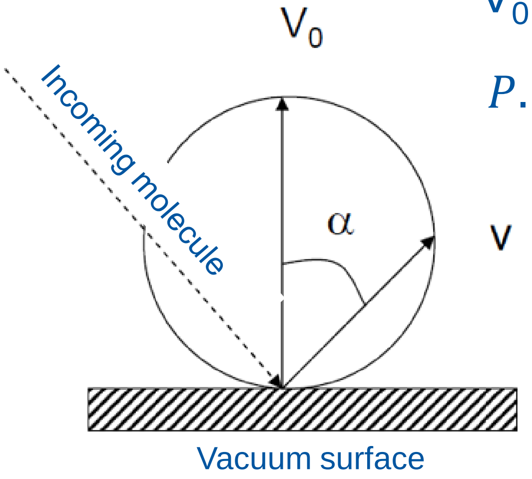
- In the molecular regime, Knudsen observed that the flow of the molecules is altered due to interactions with the pipe
- Following the collision on the wall, the molecule is randomly re-emitted in a diffused way (partly due to the roughness of the surface) into the vacuum system according to the Beer-Lambert law (also called “cosine distribution law”)

Knudsen number

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

λ = mean free path; d = tube diameter





V_0: normal vector

$$P.D.F:\ f(\alpha) = V_0 \cos\alpha$$

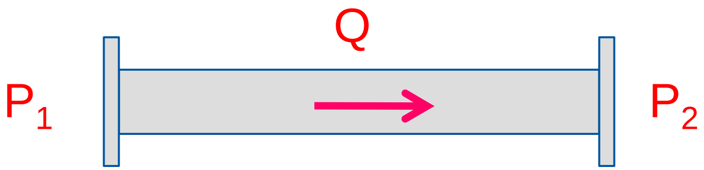
- This observation introduced the concept of conductance (Dushman)

Saul Dushman (1883–1954)

Conductance

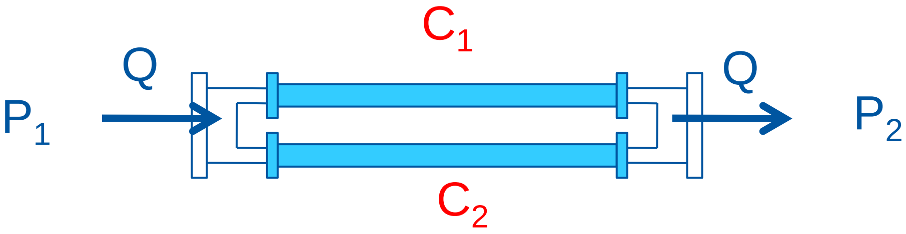
- It is a volumetric flow rate
- It is defined as the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel.
- It is a function of the shape of the vessel, the nature of the gas and its temperature.

$$\boxed{C = \frac{Q}{(P_1 - P_2)}}$$



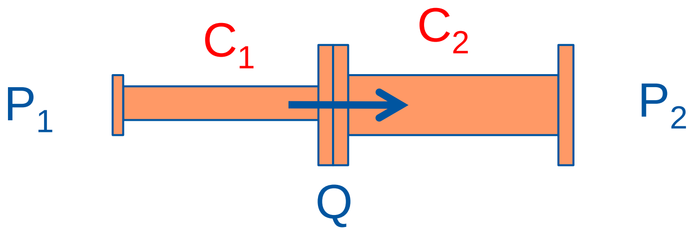
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$



Conductance calculation in molecular regime

- Customary units for C are in ℓ/s or m^3/s.

- **For a (thin) orifice:**

$$C = \sqrt{\frac{kT}{2\pi\,\mathrm{m}}}\,A = \sqrt{\frac{RT}{2\pi\,M}}\,A;\; C_{\mathrm{air},\,20^\circ}[l/s] = 11.6\,A[cm^2]$$

(with R=k·N$_A$, N$_A$ =Avogadro number (6.0221·10^{23} molecules/mole); R= 8.3145 J/K/mole; M=molecular weight in kg/mole, 29 g/mole for air).

➔ The conductance of an orifice of 10 cm diameter is ℓ/s

- **For a tube :**

$$C = \frac{1}{6}\sqrt{\frac{2\pi\,RT}{M}}\,\frac{D^3}{L};\quad C_{\mathrm{air},\,20^\circ}[l/s] = 12.1\,\frac{D[\mathrm{cm}]^3}{L[\mathrm{cm}]}$$

➔ The specific conductance (conductance of a tube of unit length) for a tube of 10 cm diameter is ~ ℓ·m/s

!! Note the units: conductance is in ℓ/s; specific conductance in ℓ·m/s

To increase the conductance of a vacuum system, it is better to have a vacuum chamber with large diameter and short length

Scaling of conductances

- The conductance scales like:

$$\boxed{C \sim \sqrt{\frac{T}{M}}}$$

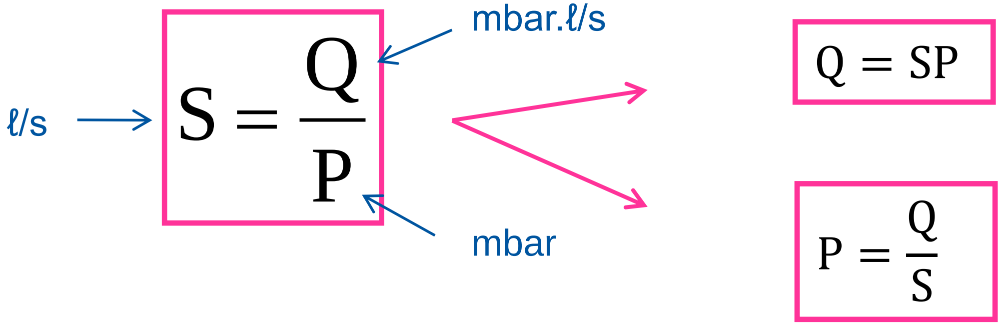
Gas	M	C_orifice [l/s]	C_tube [l·m/s]
Air	29	900	120
H_2	2		
CH_4	16		
CO	28		
CO_2	44		

10 cm ID tube or 10 diameter orifice,
at room temperature (20 °C)

- ***Orifice***: defined as a zero-length tube, like a hole in a very thin wall dividing two volumes

Pumping Speed

- The pumping speed, S, is the ratio of the flux, Q, of molecules pumped to the pressure, P



$$S = \frac{Q}{P}$$

$$Q = SP$$

$$P = \frac{Q}{S}$$

- S can range from 10 to 20 000 l/s (or even more in e.g. neutral-beam injectors for tokamaks or large space simulation chambers)

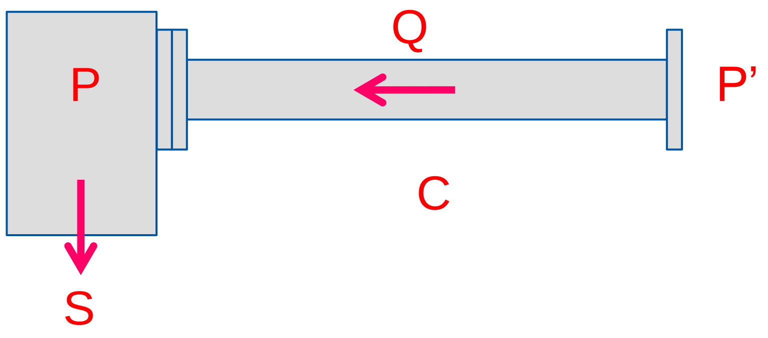
- Q = A q, with q specific outgassing rate (in e.g. mbar.ℓ/s/cm^2)
- q range from 10^{-14} mbar.ℓ/s/cm^2 for metallic tubes to 10^{-5} – 10^{-4} mbar.ℓ/s/cm^2 for polymers

~3 orders of magnitude for pumping
vs
~10 orders of magnitude for outgassing

Outgassing MUST be minimised to achieve UHV

Effective pumping speed

- It is the pumping speed seen from P’ through the pipe of conductance, C



Pumping speed

$$\begin{cases} Q = P\,S \\ Q = C\,(P' - P) \end{cases} \Rightarrow Q = \frac{SC}{S+C}P' = S_{eff}P'$$

Conductance

$$S_{eff} = \frac{SC}{S+C}$$

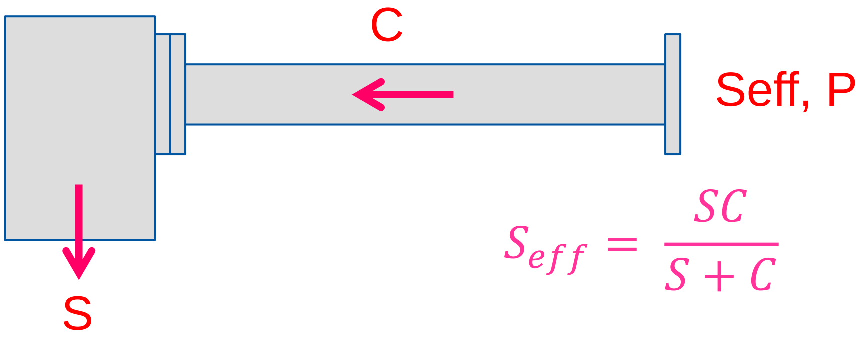
- This is the result of **adding in series the conductance C with the pumping speed S**

- If:
  1) C = S then S_{eff} = S/2
  2) C >> S then S_{eff} = S
  3) C << S then S_{eff} = C, the system is “conductance-limited”

Maximisation of the conductances improves the efficiency of the pumping system

Effective pumping speed

- Assume a 10 m long 10 cm diameter vacuum pipe evacuated by a turbomolecular pump of 60 l/S



$$S_{eff} = \frac{SC}{S + C}$$

- C = 120 / 10 = 12 l/s
- S = 60 l/S

- Seff = (12x60)/(12+60) = 10 l/s

- The system is conductance limited and the (effective) pumping speed, hence pressure, at the upstream part is defined by the conductance of the pipe!

CONDUCTANCE LIMITATION IS A COMMON FEATURE OF ALL ACCELERATORS !!

Summary

- The kinetics of gas molecules is described by the Maxwell-Boltzmann distribution

- The pressure is defined by the ideal gas law. Partial pressures contribute as per Dalton's law.

- As a function of mean free path, several flow regimes exist.

- Molecular flow is the operational regime of particle accelerator vacuum systems: the molecules interact only with the vacuum chamber wall.

- The conductance characterizes the pressure drop along a vacuum component

- The pressure in a large vessel is defined by the ratio of the gas flow to the pumping speed.

- Effective pumping speed must be calculated (and used in place of the nominal one) in conductance-limited vacuum systems e.g. for lumped-pumping system of particle accelerators

  ➔ Distributed pumping schemes are preferable to reduce further the pressure in particle accelerators, see next lectures.

Some References

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- *The physical basis of ultra-high vacuum*, P.A. Redhead, J.P. Hobson, E.V. Kornelsen, American Vacuum Soc.
- *Scientific foundations of vacuum technique*, S. Dushman, J.M Lafferty. J. Wiley & sons.
- *Handbook of Vacuum Technology*, K. Jousten (ed.), Wiley VCH
- *Vacuum Technology*, A. Roth. Elsevier Science
- *Foundations of vacuum science and technology*, Ed by J.M. Lafferty. J. Wiley & sons.

Some Journals Related to Vacuum Technology for Particle Accelerators

- Journal of vacuum science and technology A and B
- Vacuum
- Nuclear Instruments and Technology (A and B)
- Review Modern Instruments
- Applied Physics
- Fusion Engineering and Design

Thank you for your attention !!!


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