UFSC

Federal University of Santa Catarina
Graduate Program in Engineering and Mechanical Sciences

Plasmas and electrical discharges in gases

(ECM410054)

Diego Alexandre Duarte
Laboratory of Surface Treatments

SUMMARY
Plasmas and electrical discharge in gases

- Kinetic theory of gases
- Atomic structure
- Ionization
- Deionization
- Electron emission
- Behavior of charged particles in a gas in electric fields of low E/p
- Behavior of charged particles in a gas in electric fields of high E/p
- Glow discharges
- Plasmas

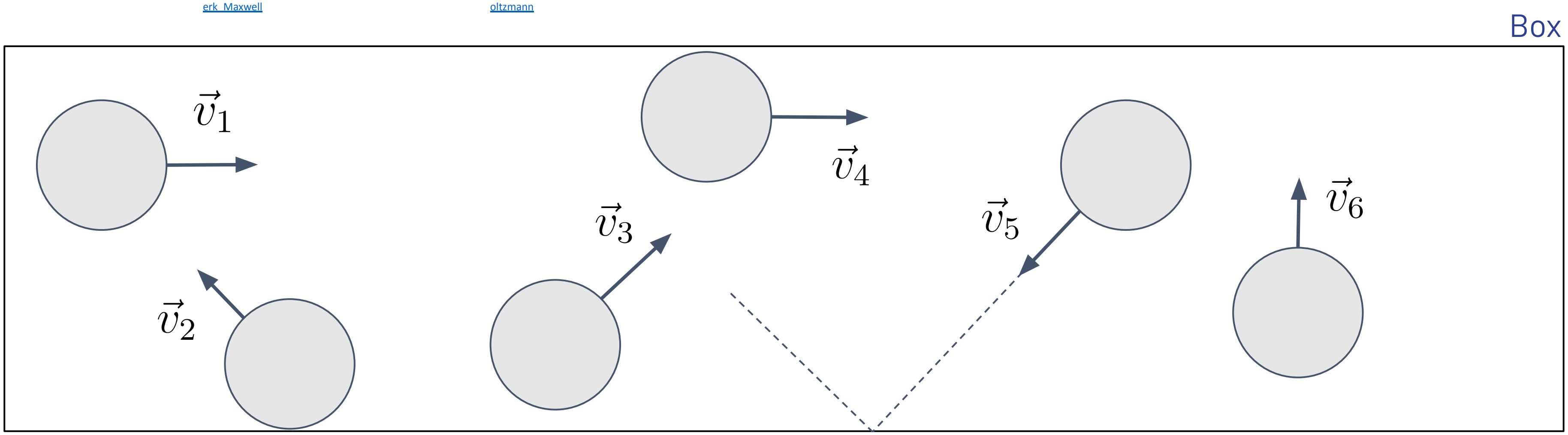
KINETIC THEORY OF GASES
Background

- The basics of the kinetic theory of gases was set by James Clerk **Maxwell** (1831-1879) and Ludwig **Boltzmann** (1844-1906):

https://pt.wikipedia.org/wiki/James_Clerk_Maxwell

https://pt.wikipedia.org/wiki/Ludwig_Boltzmann

- Condition for an ideal gas:
  - Spherical and solid particles
  - Random motion
  - Elastic collisions
  - Large mean free path
  - Linear motion between two collisions



KINETIC THEORY OF GASES

Kinetic energy, temperature and velocity distribution

- For energy stored in translational form:

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_BT$$

where m is particle mass, k_B the Boltzmann constant, T the gas temperature and $\overline{v^2}$ the mean square speed:

$$\overline{v^2} = v_{rms}^2 = \int_0^\infty v^2 f(v)dv \quad \therefore \quad v_{rms} = \sqrt{\frac{3k_BT}{m}}$$

where $f(v)$ is the velocity distribution given by the Maxwell-Boltzmann function:

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

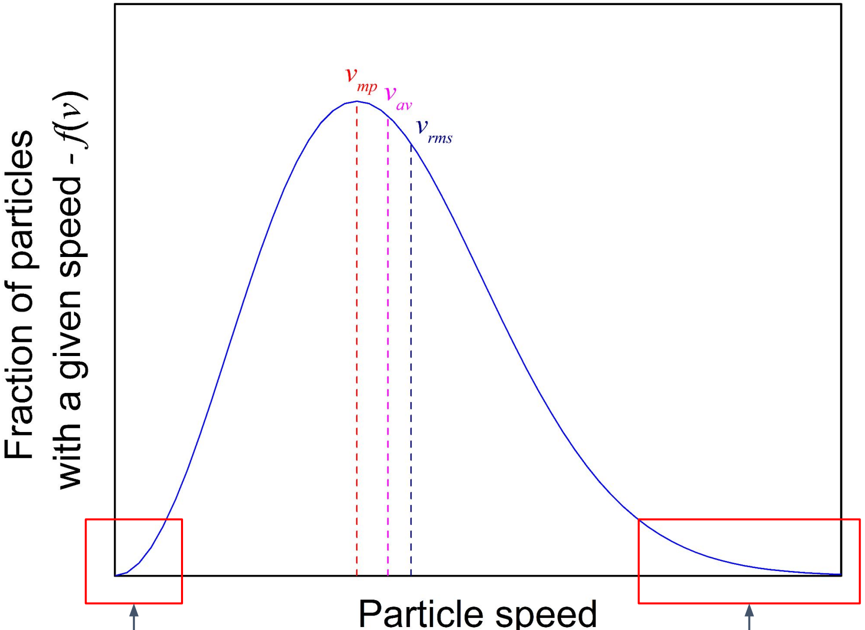
- The most probable and average speed are given by:

$$\frac{d}{dv}f(v) = 0 \quad \therefore \quad v_{mp} = \sqrt{\frac{2k_BT}{m}}$$

$$v_{av} = \int_0^\infty v f(v)dv = \sqrt{\frac{8k_BT}{\pi m}}$$

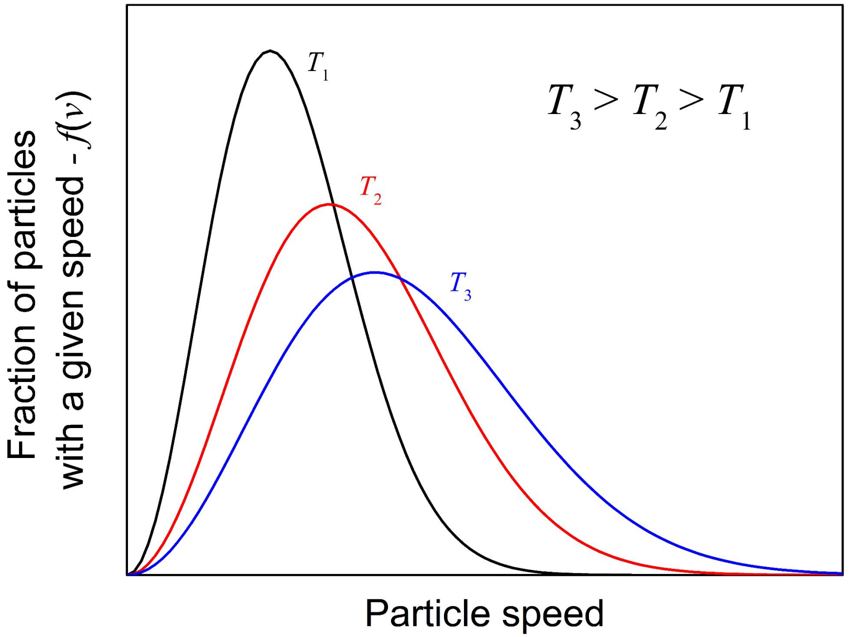
KINETIC THEORY OF GASES
Kinetic energy, temperature and velocity distribution

- The MB function calculates the fraction of particles with a given speed v for an ideal gas with temperature T:



slow particles

fast particles



Area under the curve = 1. This means that the probability to find some gas particle is 100%

KINETIC THEORY OF GASES
Kinetic energy, temperature and velocity distribution

- For a gas composed by argon atoms at 20°C (~ 293 K):

$$v_{mp} = \sqrt{\frac{2k_B T}{m}} = \sqrt{\frac{2(1.38{\times}10^{-23})(293)}{6.63{\times}10^{-26}}} = 349.2 \text{ m/s} = 1257.3 \text{ km/h}$$

$$v_{av} = 1.128 v_{mp} = 393.9 \text{ m/s} = 1418.2 \text{ km/h}$$

$$v_{rms} = 1.224 v_{mp} = 427.4 \text{ m/s} = 1538.7 \text{ km/h}$$

$$\frac{1}{2} m v_{rms}^2 = \frac{3}{2} k_B T = \boxed{6.0 \times 10^{-21} \text{ J} = 37.8 \text{ meV}} \quad \therefore \quad T \approx 293 \text{ K}$$

1 eV = 1,6×10^{-19} J

- The speed of sound is **343 m/s ≈ 1235 km/h**. So, they are fast! The distribution velocity function is given by:

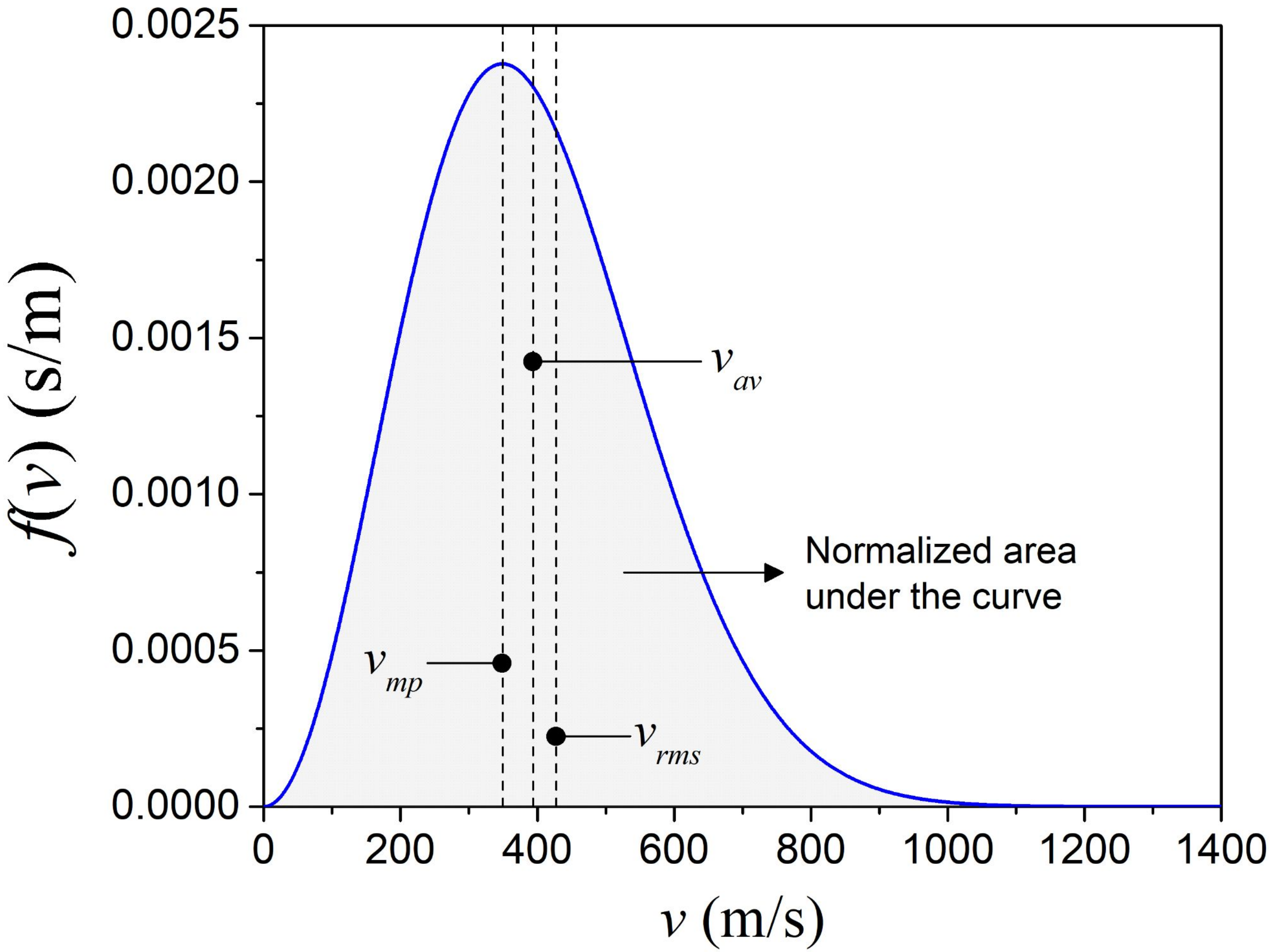
$$f(v) = (5.297 \times 10^{-8}) v^2 e^{-[(8.198\times10^{-6})v^2]} \quad (\text{s/m})$$

$$\text{Area under the curve} = \int_0^\infty f(v)dv = \boxed{1}$$

Normalized

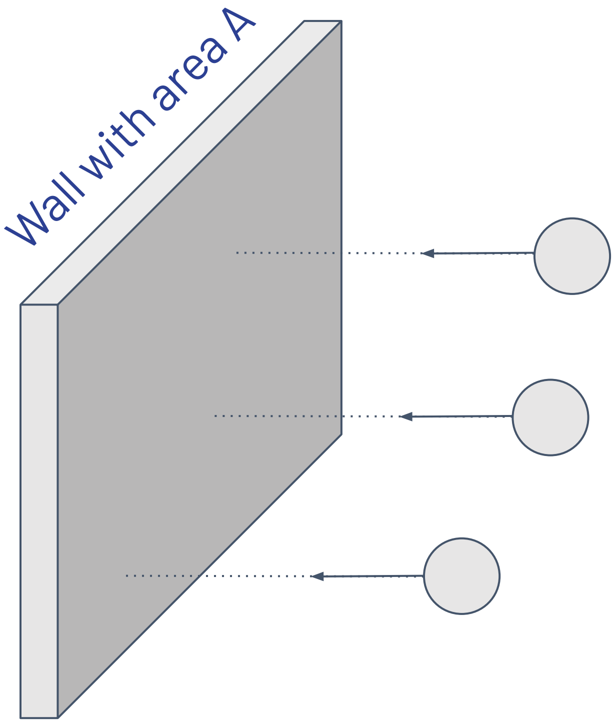
KINETIC THEORY OF GASES

Kinetic energy, temperature and velocity distribution



KINETIC THEORY OF GASES

Gas pressure



- The gas particles bounce the walls, exerting force per unit area. This property is known as **pressure**:

$$p = \frac{F}{A} = nk_BT = \frac{n}{3}mv_{rms}^2$$

where n is the gas density (particles per volume unit).

- The pressure for a gas composed by two or more particles is given by the sum of the partial pressures:

$$p = p_1 + p_2 + ... + p_N$$

where N represents the N-th gas.

- The pressure commonly used in plasmas are **torr**: 760 torr = 760 mmHg or 1 Pa = 7.5 mtorr. Many plasma processing techniques, under low pressure, operate between 1 torr and 1 mtorr. For this condition, a vacuum system is required!

KINETIC THEORY OF GASES
Gas density

- The number of particles at STP is given by:

$$p = nk_BT = \frac{N}{V}k_BT \quad \therefore \quad N = \frac{pV}{k_BT} = \frac{(1.01325\times10^5)(0.0224)}{(1.38\times10^{-23})(273)} = 6.02\times10^{23}\ \text{particles}$$

which is known as the **Avogadro's number** and is defined as **1 mole of particles**. The gas density is:

$$n = \frac{N}{V} = \frac{6.02\times10^{23}}{0.0224} = \boxed{2.7\times10^{19}\ \text{cm}^{-3}} \rightarrow \boxed{\text{Standard density}}$$

that is the same order of magnitude of atmospheric He plasmas excited by RF source:

Parameter	He low pressure plasma	He atmospheric pressure plasma
Pressure (p)	100 mTorr	760 Torr
Gas density (n)	3.2×10^{15} cm^{-3}	$\boxed{2.5\times10^{19}\ \text{cm}^{-3}}$
Electrode gap distance (d)	10 cm	1 cm
Angular excitation frequency (ω)	13.56 MHz	13.56 MHz
Electron temperature (T_e)	3 eV	1 eV
Electron-neutral collision frequency (ν)	150 MHz	1 THz
pd	~1 Torr cm ($\leqslant pd_{min}$)	~760 Torr cm ($\gg pd_{min}$)
E/n	10–100 Td	10–100 Td
ω_{rf}/ν	~0.1	10^{-5}($\ll 1$)

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https://doi.org/10.1088/1361-6595/aa97af

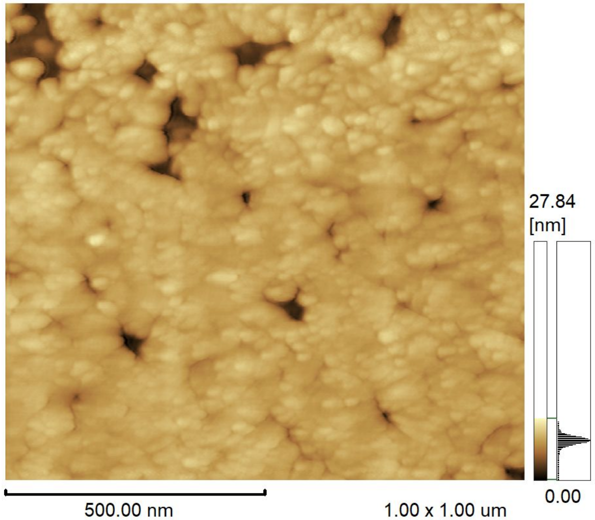
KINETIC THEORY OF GASES
Impingement flux

- The particle flux f on the walls per unit area and time for argon at STP is given by:

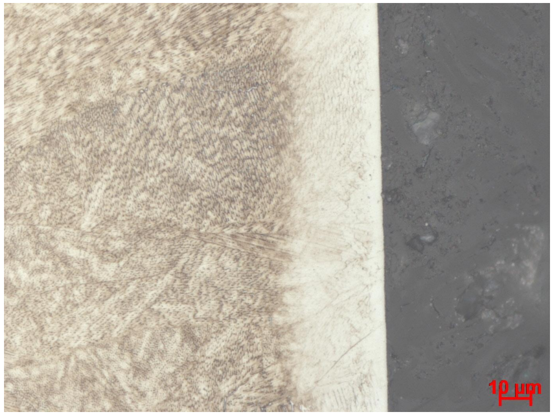
$$f = \frac{1}{4} n v_{av} = \frac{1}{4}\left(\frac{p}{k_B T}\right)\sqrt{\frac{8k_B T}{\pi m}} = \frac{p}{\sqrt{2\pi k_B m T}} = \frac{1.01325\times 10^5}{\sqrt{2\pi(1.38\times 10^{-23})(6.63\times 10^{-26})(273)}}$$

$$f = 2.6\times 10^{23}\ \mathrm{cm}^{-2}\cdot \mathrm{s}^{-1}$$

- The gas-surface interaction plays a fundamental role in plasmas-assisted process, such as for film deposition, thermal treatment and etching.

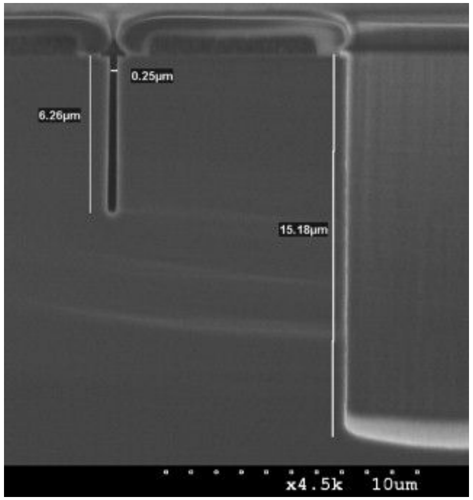


Thin film deposition by sputtering



Plasma nitriding

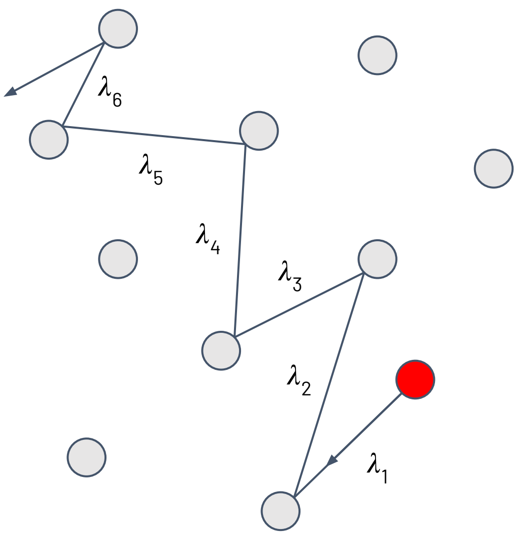
Surface and Coatings Technology, 466 (2023) 129688
https://doi.org/10.1016/j.surfcoat.2023.129688



Silicon etching

Sensors and Actuators A: Physical Volume 144, 2008, 109-116
https://doi.org/10.1016/j.sna.2007.12.026

KINETIC THEORY OF GASES
Mean free path



$$\lambda = \sum_{i=1}^{N} \lambda_i$$

where N is the number of individual free paths.

- The average distance travelled by a particle between two successive collisions:

$$\lambda = \frac{1}{4\sqrt{2}\pi r^2 N} = \frac{k_B T}{4\sqrt{2}\pi r^2 p}$$

where r is the particle radius. For the previous example:

$$\lambda = \frac{k_B T}{4\sqrt{2}\pi r^2 p} = \frac{(1.38\times10^{-23})\boxed{(273)}}{4\sqrt{2}\pi(1.82\times10^{-10})^2(1.01325\times10^5)} = \boxed{6.3\times10^{-8}\ \mathrm{m}} = 63\ \mathrm{nm}$$

Table 1.1 Values of the Mean Free Path λ_g of Some Gas Molecules, Their Mean Velocity $\bar{v}$ and Their Collision Frequency $\bar{\nu}_c$ Calculated from the Kinetic Theory of Gases at $\boxed{T = 288°K}$ and $p = 760$ torr[5].

Gas	Molecular weight	λ_g 10^{-8}m	$\bar{v}$ m/sec	$\bar{\nu}_c$ 10^9sec^{-1}	Diameter Å
H_2	2.016	11.77	1,740	14.8	2.74
He	4.002	18.62	1,230	6.6	2.18
H_2O	18.000	4.18	580	13.9	4.60
Ne	20.180	13.22	550	4.2	2.59
N_2	28.020	6.28	467	7.4	3.75
O_2	32.000	6.79	437	6.4	3.61
A	39.940	6.66	391	5.9	3.64
CO_2	44.000	4.19	372	8.8	4.59
Kr	82.900	5.12	271	5.3	4.16
Xe	130.200	3.76	217	5.8	4.85

E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics, New York: Wiley, 1971.

KINETIC THEORY OF GASES
Probability and frequency of collisions

- The probability of collision for a gas particle is given by:

$$P = e^{-x/\lambda}$$

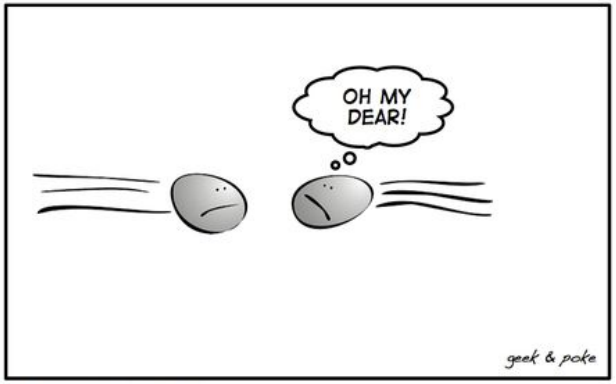
where x is the travelled distance without colliding. The probability of a particle travels 100 nm without colliding, for the previous example, is:

$$P = e^{-\frac{100\times10^{-9}}{6.3\times10^{-8}}} = 0.204 \quad \therefore \quad P_{\%} = 20.4\%$$

- The number of collisions per second (frequency of collisions) is:

$$f = \frac{v_{av}}{\lambda} = \frac{1}{\lambda}\left[1.128\sqrt{\frac{2k_BT}{m}}\right]$$

$$f = \frac{1}{(6.3\times10^{-8})}\left[1.128\sqrt{\frac{2(1.38\times10^{-23})(273)}{6.63\times10^{-23}}}\right] = 6.0\text{ GHz}$$



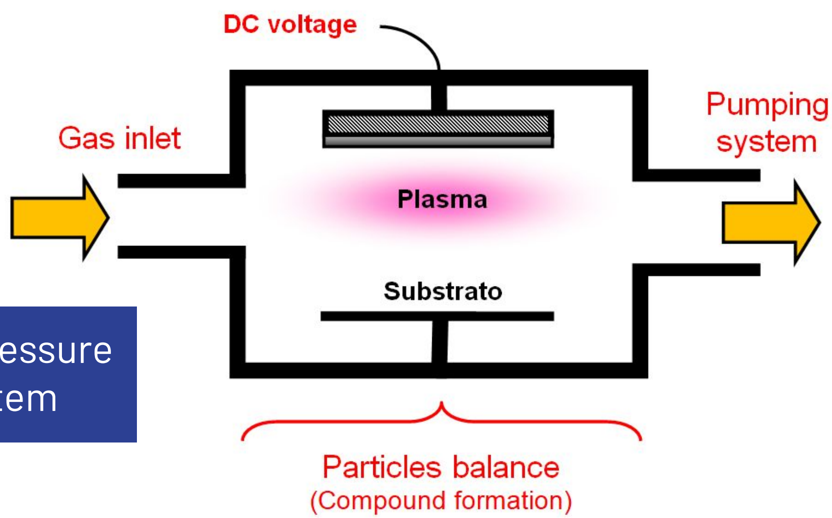
KINETIC THEORY OF GASES

Gas flow

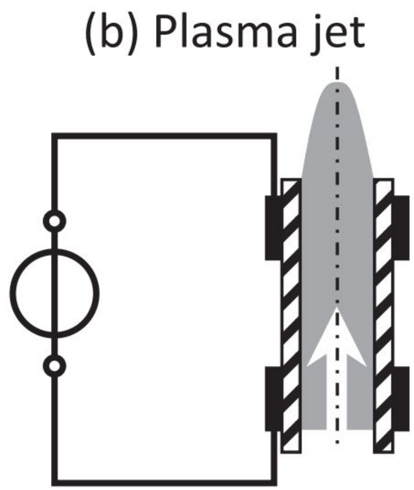
- The inlet rate of a gas flowing in a plasma assisted experiment is known as **flow rate** and measured in **sccm** (standard cubic centimeter per minute). This unit is defined at STP as:

$$1 \text{ sccm} = \frac{N}{V} = \frac{p}{k_B T} = \frac{1.01325\times10^5}{(1.38\times10^{-23})(273)} = 2.7\times10^{19} \text{ cm}^{-3} \text{ per minute}$$

- The flow rate depends on working pressure, gas type etc, ranging from units (low pressure gases) to thousands* (high pressure gases) of sccm.
- For low pressure plasmas, the use of a vacuum system is required.



Low pressure system



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https://doi.org/10.1088/1361-6595/aa97af

High pressure system

*Consider changing to other units, such as litres/minute.

KINETIC THEORY OF GASES
Reading

- Chapter 1 – E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics.
- Chapter 1 – B. Chapman, Glow Discharge Processes: Sputtering and Plasma Etching.

See you next topic!

Diego A. Duarte
diego.duarte@ufsc.br
https://lats.ufsc.br