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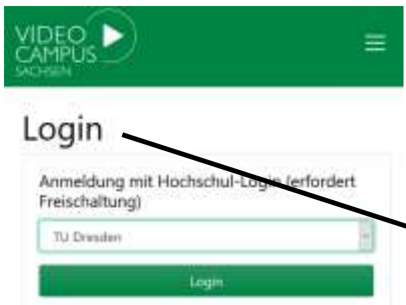

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Vacuum Technology
WS 20/21
Virtually presented
Lecture 6, Dec. 1'st, 2020

Prof. Dr. Johann W. Bartha

Inst. f. Halbleiter und Mikrosystemtechnik
Technische Universität Dresden

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“VT L06 a 06:06

TECHNISCHE UNIVERSITÄT DRESDEN

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0. Introduction

Air pressure as a force to the walls of an empty container

1. Gas kinetic

Pressure as momentum transfer, Mol & Molvolume, Pressure units Partial pressure, Boltzmann Velocity&Energy distribution,

2. Pressure Ranges

3. Vacuum technical terms

4. Vacuum generation

5. Pressure measurement

Review L5

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$$f(v) = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3}\, v^2 \exp\left(\frac{-mv^2}{2kT}\right)$$

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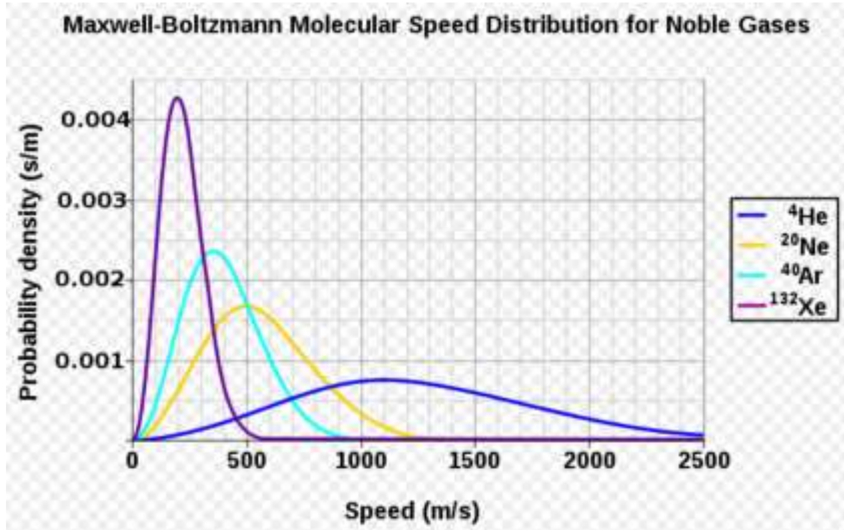

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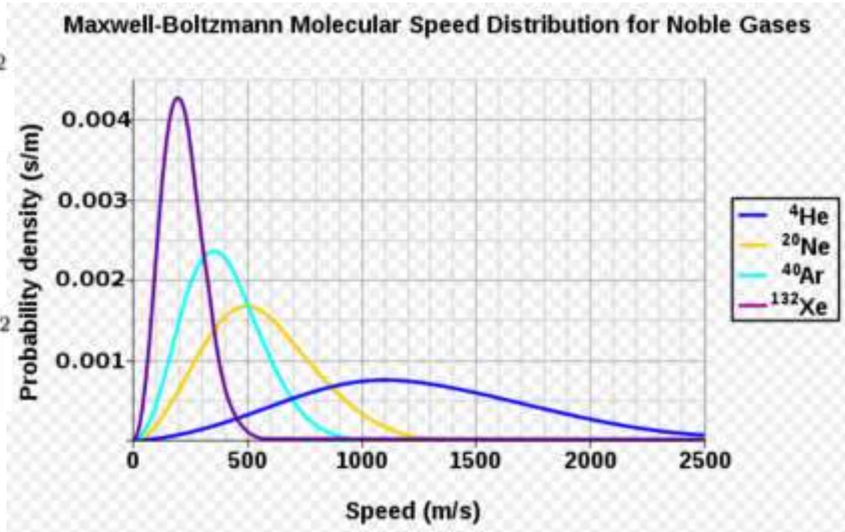

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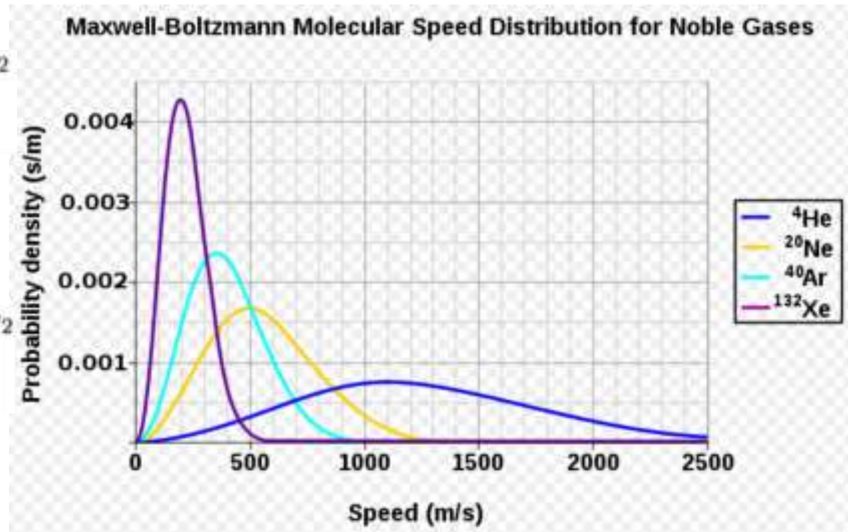

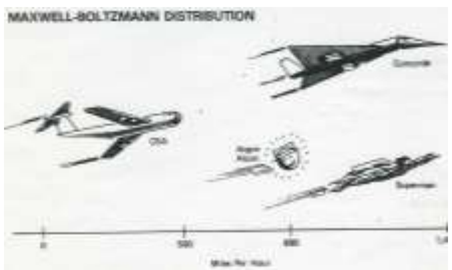

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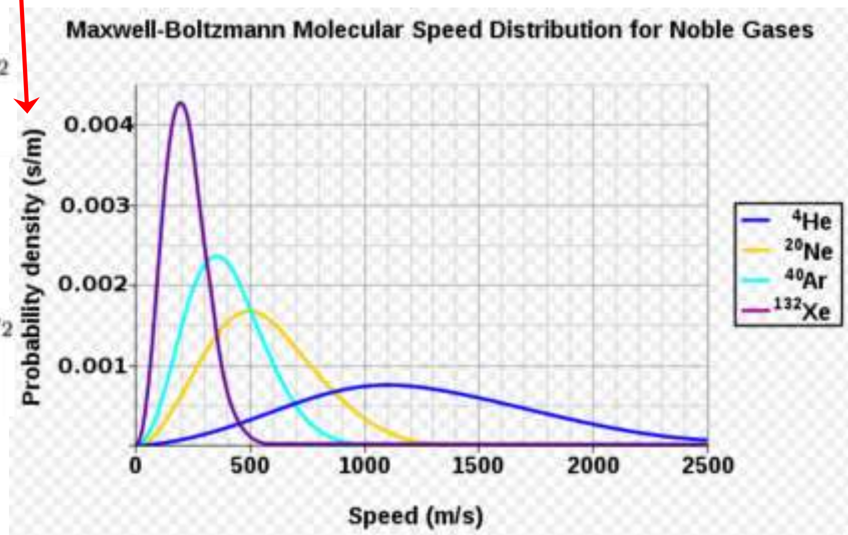

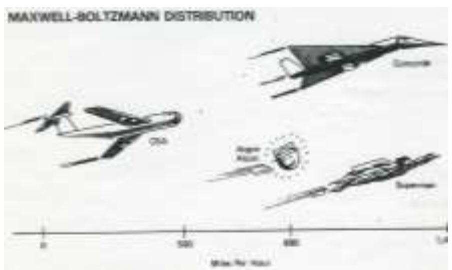

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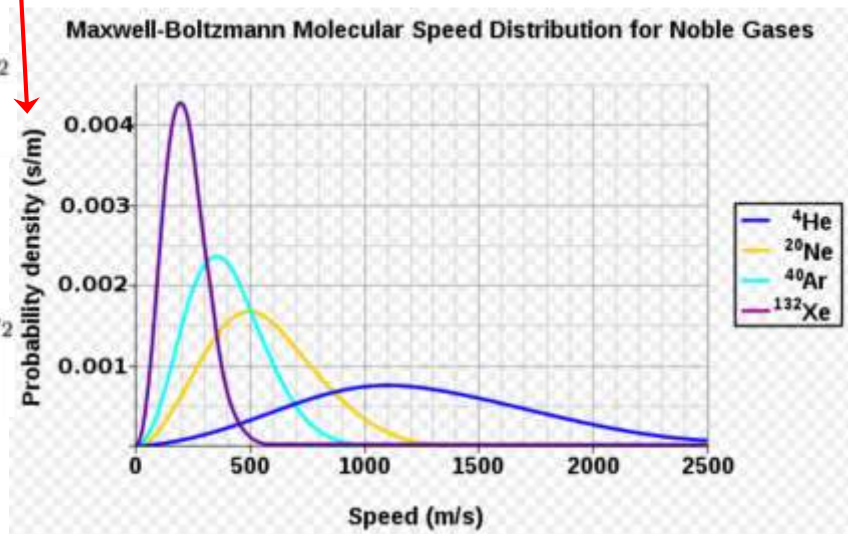

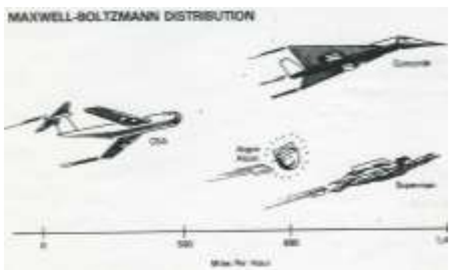

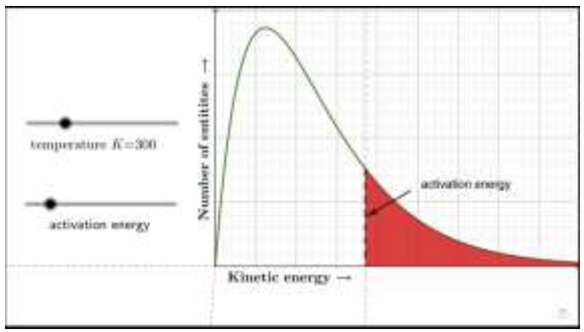

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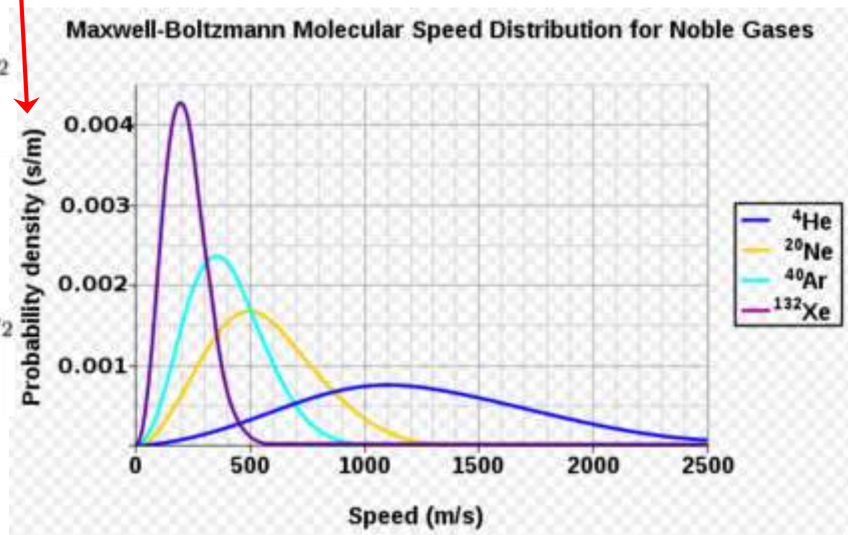

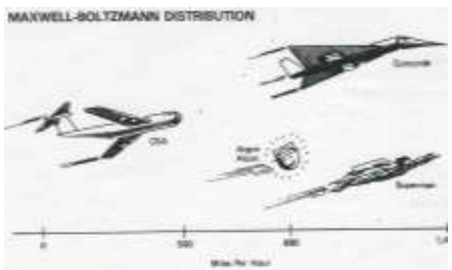

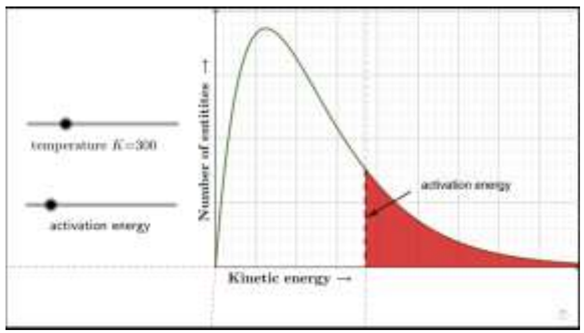

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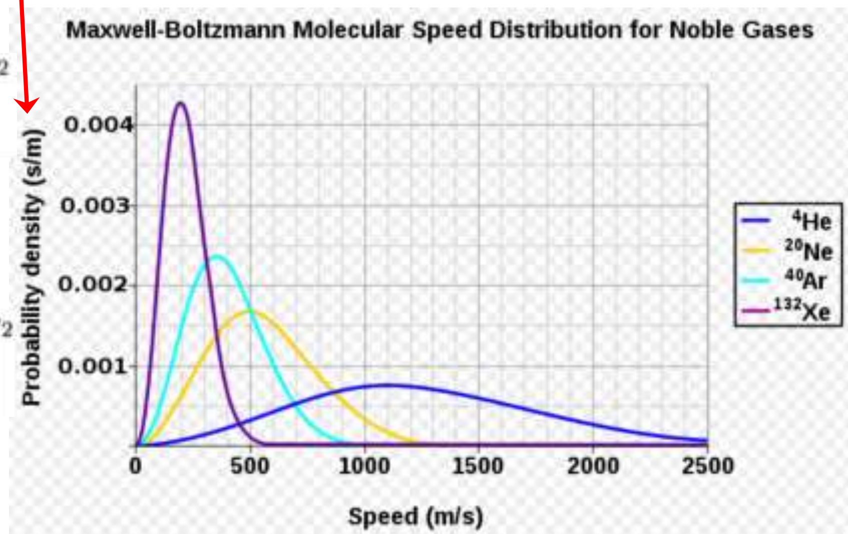

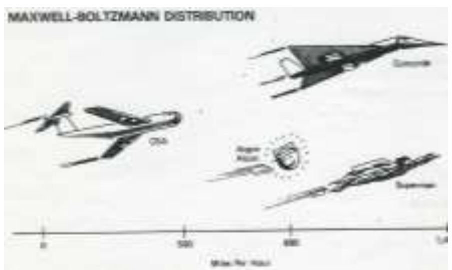

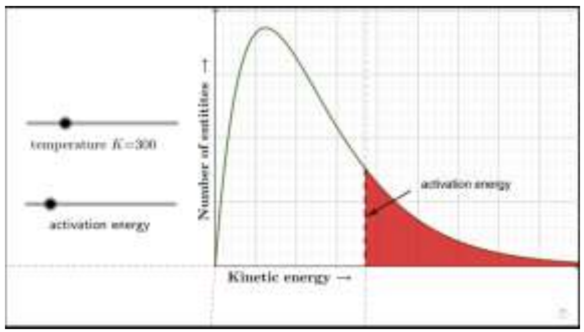

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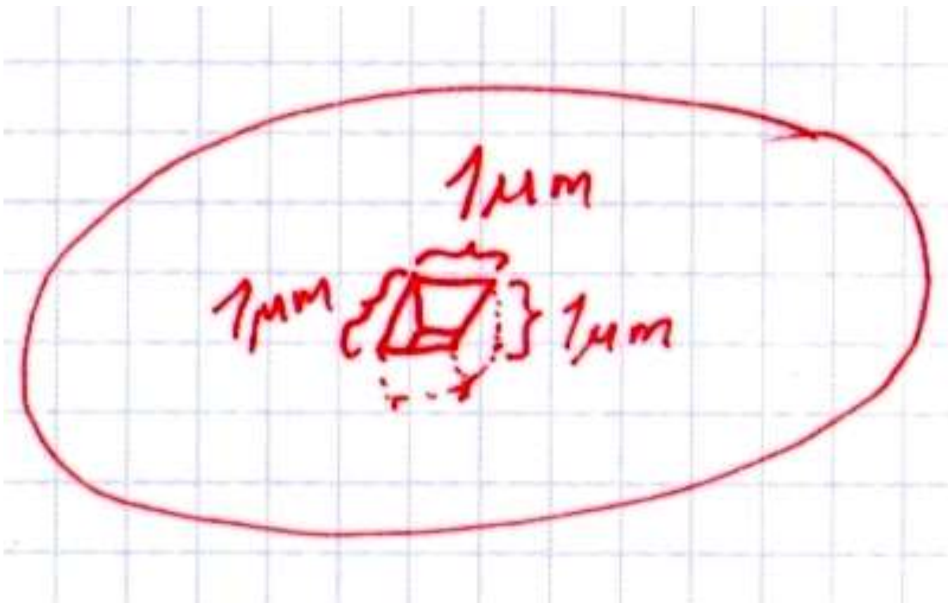

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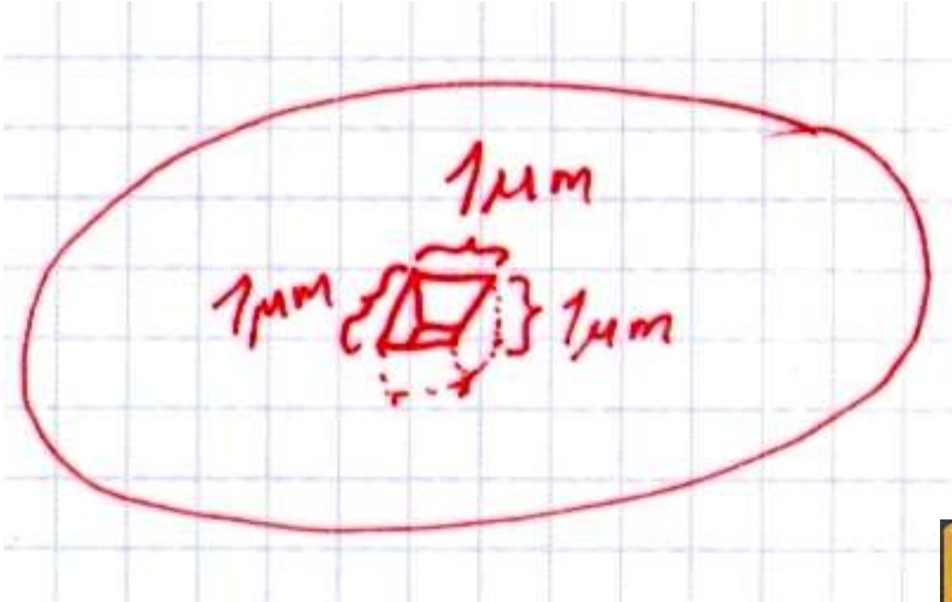

Homew

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$$P = n\,kT$$

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$$m^3 \rightarrow \mu m \sim 10^{-18}$$

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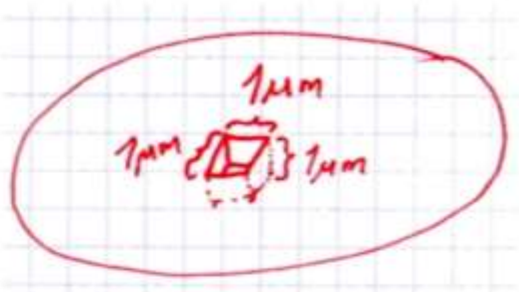
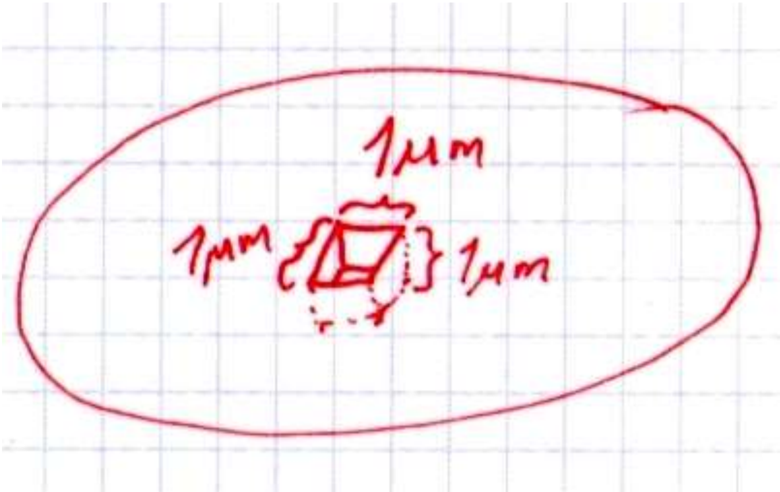


$\Rightarrow$ 25 Gas particles

Homework:



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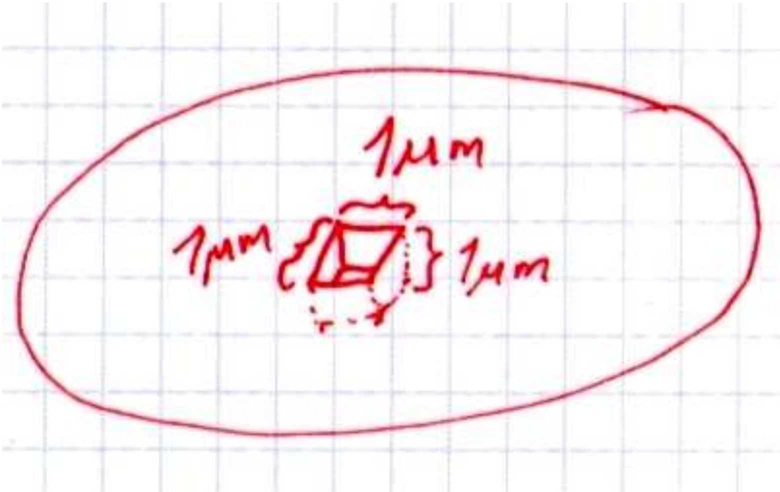

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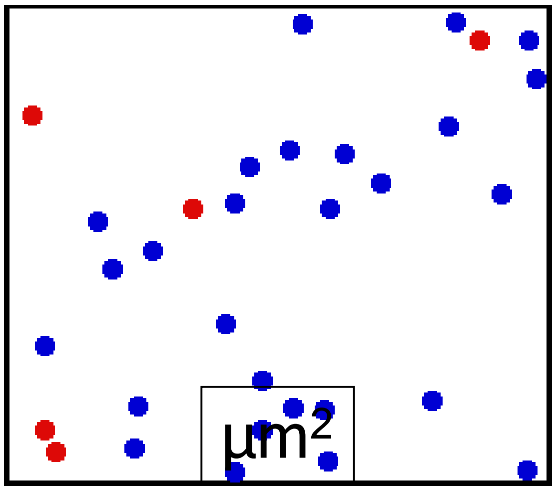
However, for an assessment concerning the etch rate, the important question is not how many gas particles are inside the trench, but how many gas particles enter the trench per time unit.



Impingement Rate Z_a / Surface collision rate

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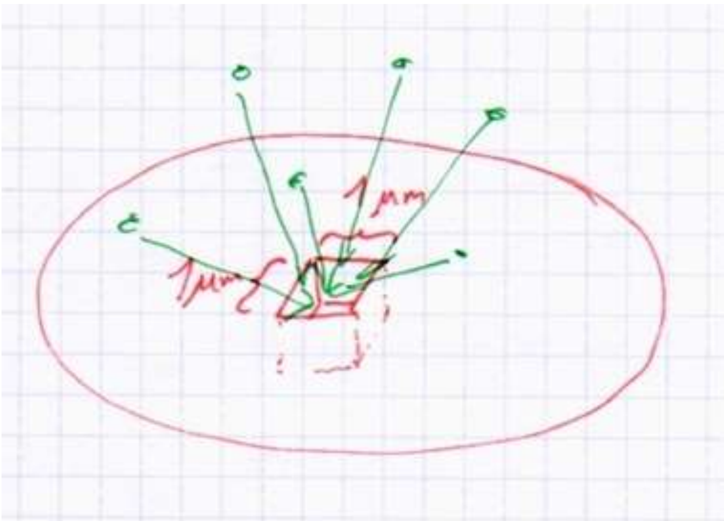

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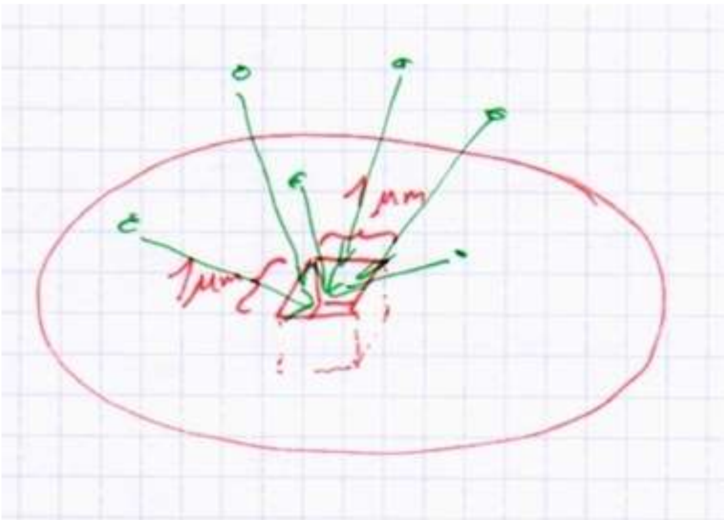

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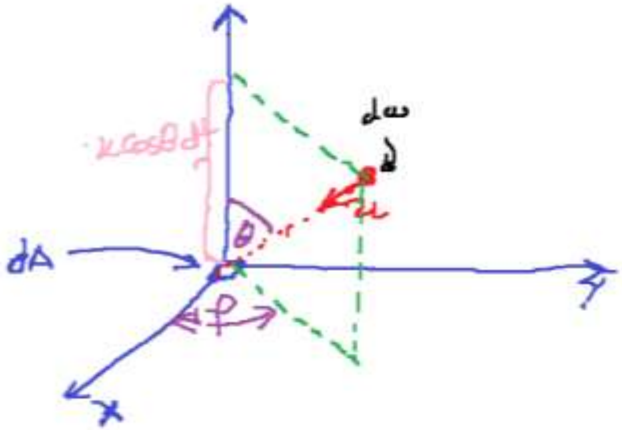

Considering the Particles dN having the velocity between u and $u+du$ moving toward dA and arriving at dA within the time dt

- within the Volume V are N particles at a density $n=\frac{N}{V}$
- With an isotropic velocity distribution ⇒ the fraction $d\omega/4\pi$ propagates towards dA
- The fraction of particles with velocity u is $f(u)du$
- Within dt only the particles closer than $u\cdot\cos\theta\, dt$ arrive at dA

$$\Rightarrow dN = n\frac{d\omega}{4\pi}\, f(u)\, du\; u\cdot\cos\theta\, dt$$

$$\frac{dN}{dt} = n\cos\theta\,\frac{d\omega}{4\pi}\, u\, f(u)\, du$$ impingement rate

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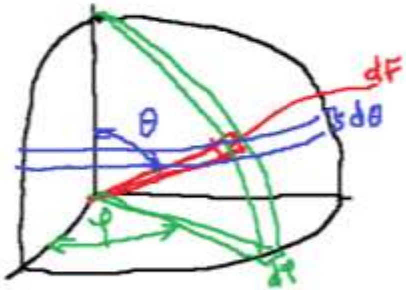
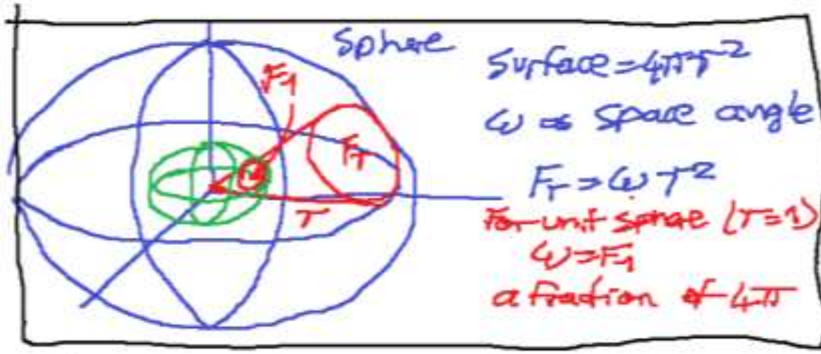
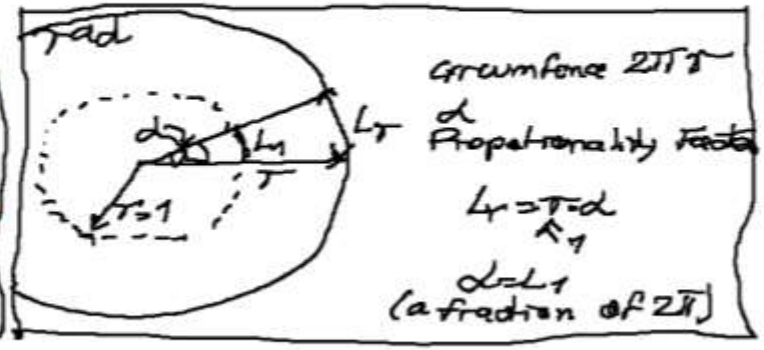
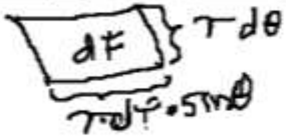








$$dF = d\omega\, r^2$$

$$d\omega = \frac{dF}{r^2} = \frac{r\,d\theta\, r\,d\varphi \sin\theta}{r^2}$$

$$d\omega = \sin\theta\, d\theta\, d\varphi$$

$$\int_0^{\pi/2} \sin\theta \cos\theta\, d\theta = \frac{1}{2}$$

$$\frac{dN}{dt} = n \cos\theta\, \frac{d\omega}{4\pi}\, u\, f(u)\, du$$

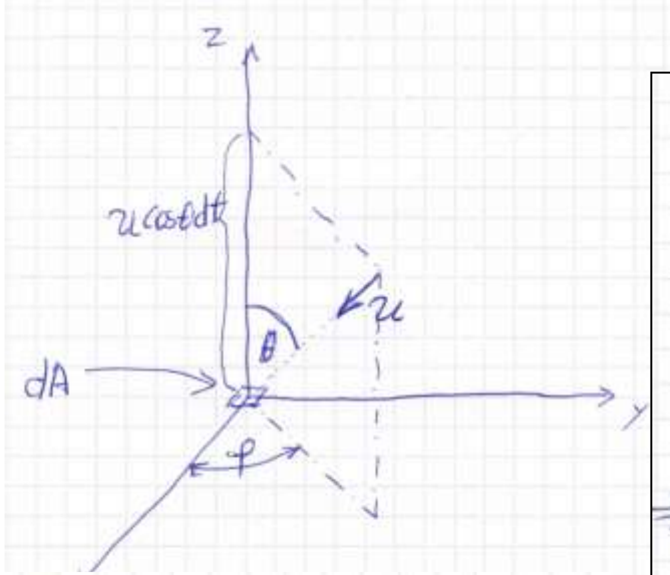
$$\frac{dN}{dt} = \frac{n}{4\pi} \cos\theta \sin\theta\, d\theta\, d\varphi \cdot u\, f(u)\, du$$

Integration over al. velocities and angles $\Rightarrow Z_a$

$$Z_a = \frac{n}{4\pi} \underbrace{\int_0^{\infty}\int_0^{2\pi}\underbrace{\int_0^{\pi/2} \cos\theta \sin\theta\, d\theta}_{1/2}\, d\varphi}_{1/2 \cdot 2\pi}\; u\, f(u)\, du = \frac{1}{4} n \underbrace{\int_0^{\infty} u\, f(u)\, du}_{\bar{u}}$$

$$\boxed{Z_a = \frac{1}{4} n \bar{u}}$$

Impingement Rate



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$$\Rightarrow dN = n \frac{d\omega}{4\pi} f(u)du \cdot u \cos\theta\, dt$$

expressed as impingement rate

$$\frac{dN}{dt} = n \cos\theta \frac{d\omega}{4\pi} u f(u) du$$

since $d\omega = \sin\theta\, d\theta\, d\varphi$

$$\frac{dN}{dt} = \frac{n}{4\pi} \cos\theta \sin\theta\, d\theta\, d\varphi \cdot u f(u) du$$

Integration over all velocities and angles yields Z_a

$$Z_a = \frac{n}{4\pi} \int_0^\infty \underbrace{\int_0^{2\pi} \underbrace{\int_0^{\frac{\pi}{2}} \cos\theta \sin\theta\, d\theta}_{1/2}\, d\varphi}_{\frac{1}{2}\cdot 2\pi}\; u f(u) du = \frac{1}{4} n \underbrace{\int_0^\infty u f(u) du}_{\bar{u}}$$

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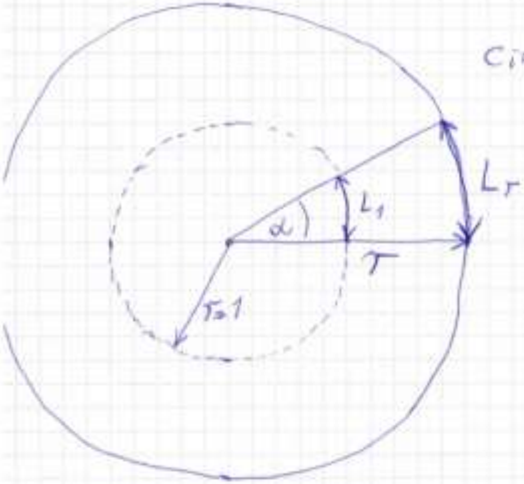
Info-Box



circle:
Circumfence $= 2\pi r$

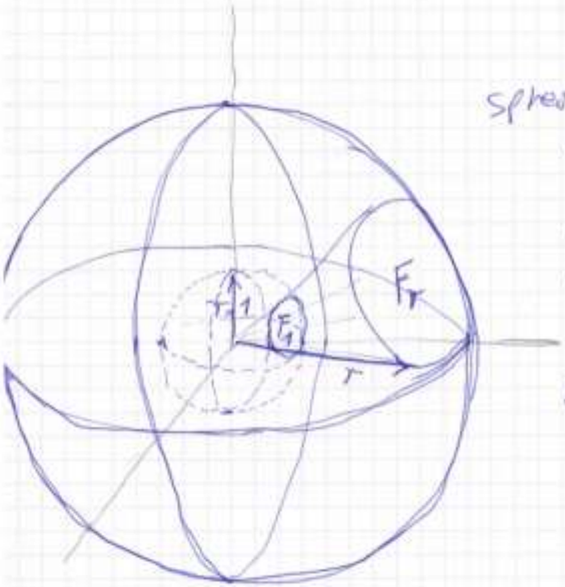
α as radian is proportionality factor between L_r and r

$L_r = r \cdot \alpha$

For the unit circle ($r=1$)

$\alpha = L_1$

(a fraction of 2π)



sphere:
Surfae $= 4\pi r^2$

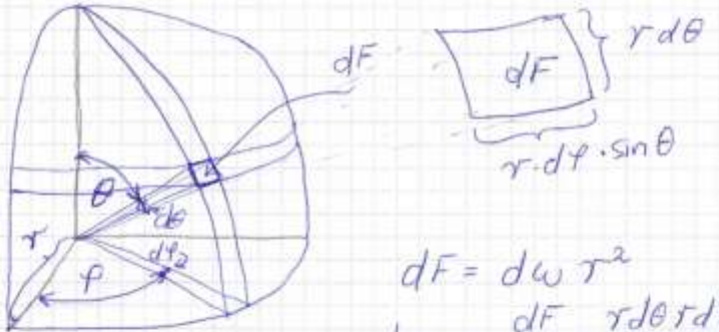
ω as proportionality factor between F_r and r^2

$F_r = \omega\, r^2$

For the unit sphere ($r=1$)

$\omega = F_1$

(a fraction of 4π)



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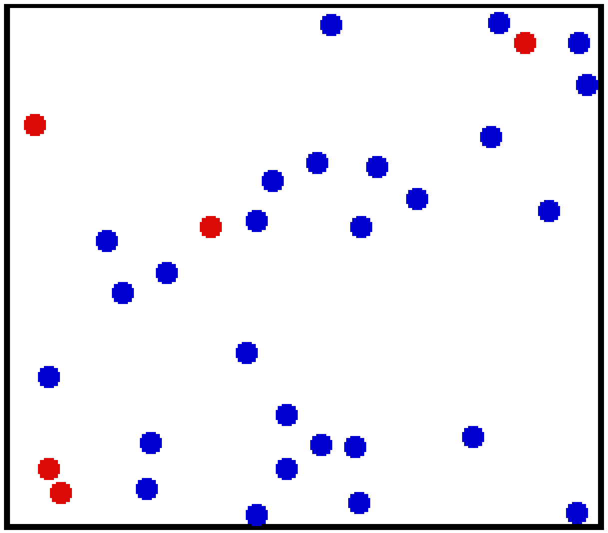
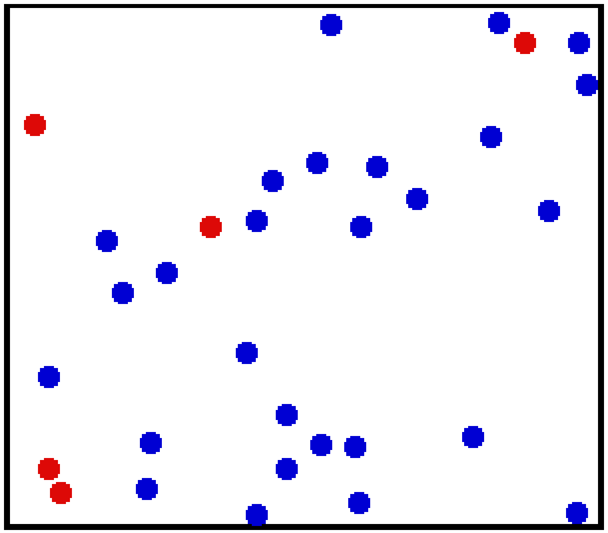
Surface collision rate



# of particles which
hit the surface
per area - and time unit

$$Z_a = \frac{1}{4}\, n\, v_{mean}$$

Surface collision rate



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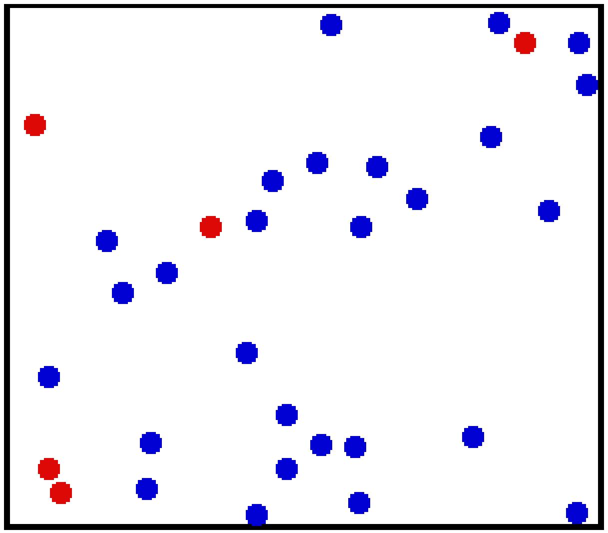
$$Z_a = \frac{1}{4}\frac{N}{V}v_{avg} = \frac{n}{4}\sqrt{\frac{8kT}{\pi m}}.$$

Surface collision rate



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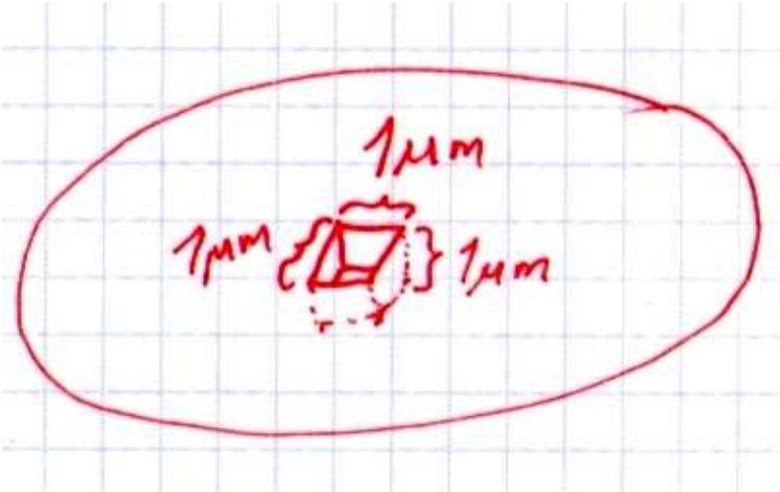
Remember?



Exercise:
Scenario: Vacuum based dry etching of a Si trench!

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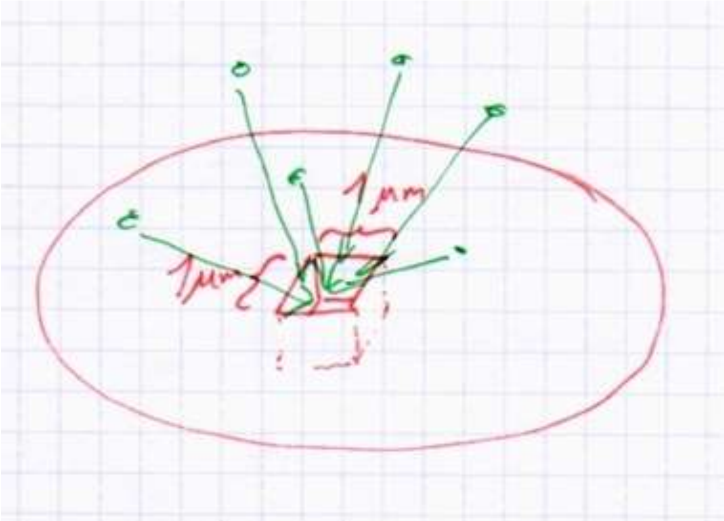
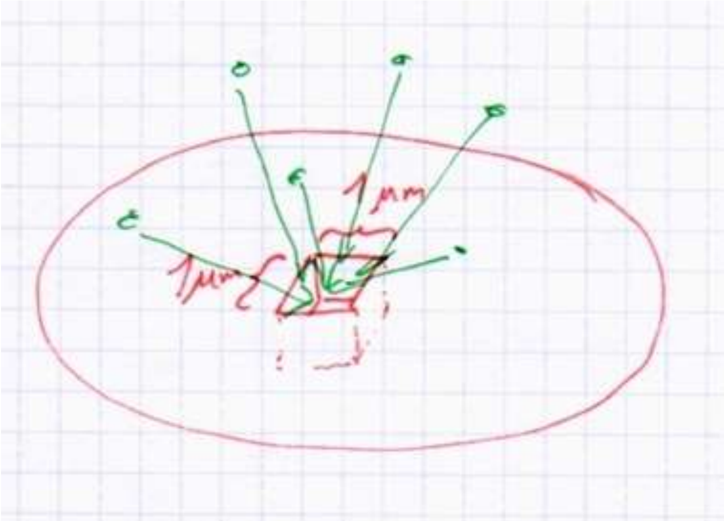


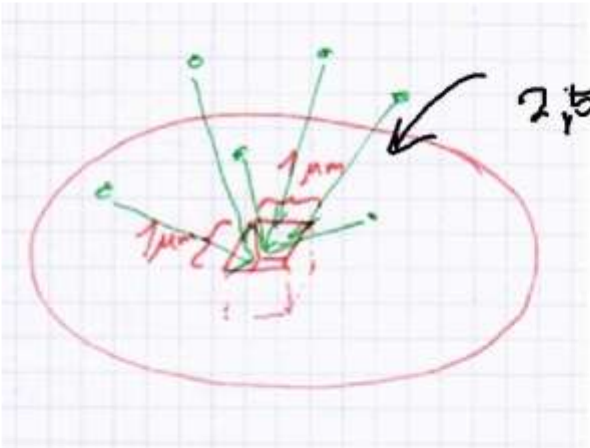
How many Ar particles approach the trench opening (1X1 μm^2) at a pressure of 0.1 Pa ($1{\cdot}10^{-3}$mBar) and a temperature of 20°C ?

Exercise:



How many Ar particles approach the trench opening ($1 \times 1\ \mu m^2$) at a pressure of 0.1 Pa ($1 \cdot 10^{-3}$ mBar) and a temperature of 20°C ?

B06d



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$2{,}5 \; 10^{9} \frac{1}{s}$

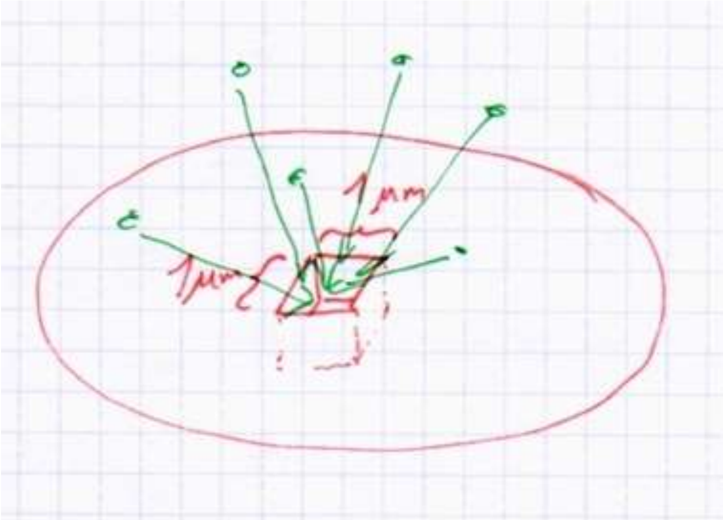
$$Z_a = \frac{1}{4} n \cdot \bar{v}$$

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}} = 394 \frac{m}{s}$$

$$n = \frac{p}{kT} = 2{,}5 \cdot 10^{18} \frac{1}{m^3}$$

$$Z_a = 2{,}5 \cdot 10^{21} \frac{1}{m^2 s} = \underline{\underline{2{,}5 \cdot 10^{9} \frac{1}{\mu m^2 s}}}$$

Back to our calculation:



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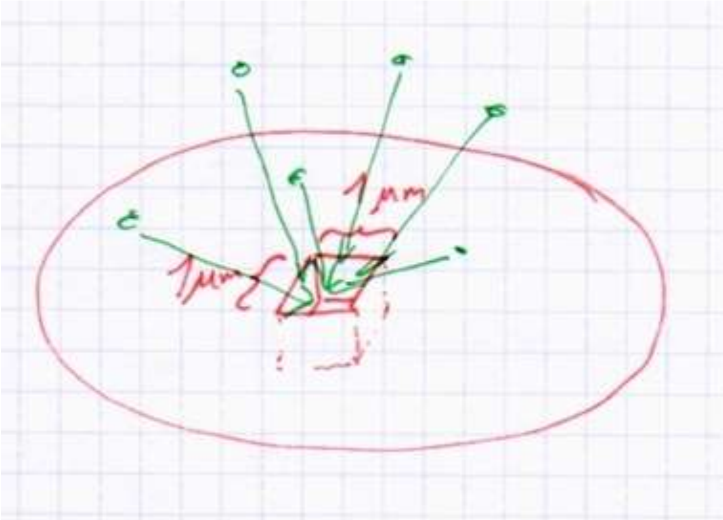

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Question: Is this much?

How to get this number into a picture?

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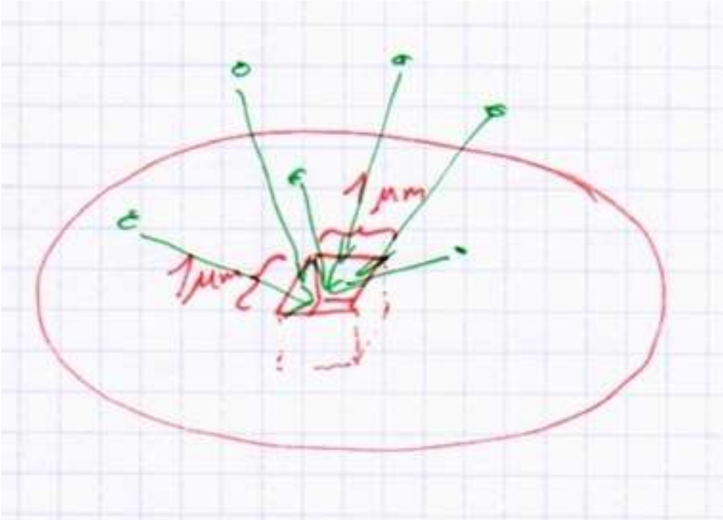

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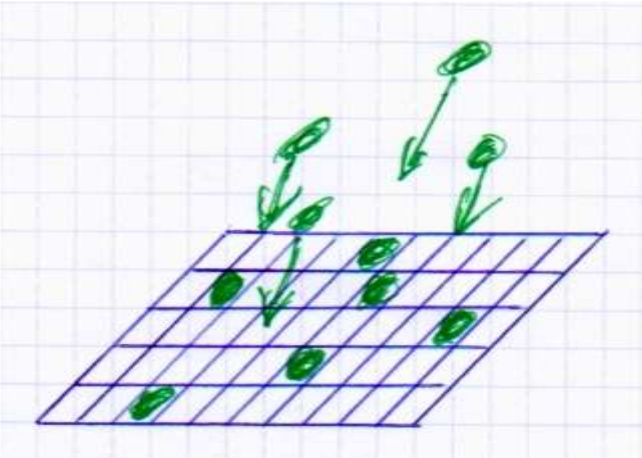
Shade balls as Monolayer

https://www.nytimes.com/2015/08/13/us/in-california-millions-of-shade-balls-combat-a-nagging-drought.html

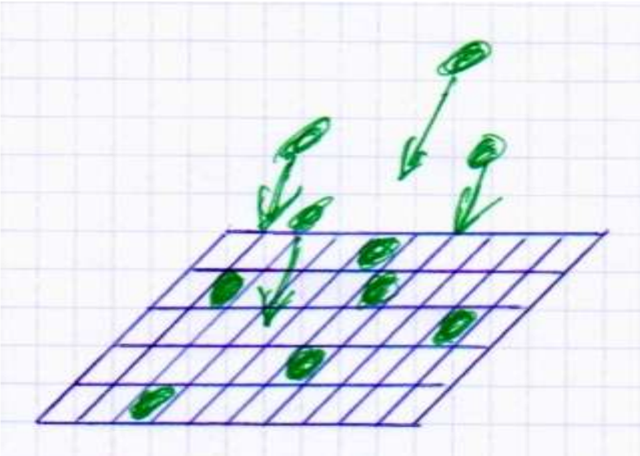
Monolayer coverage



There is a certain density of adsorption sites a at the surface.

We make the following assumptions:
i) Every arriving particle adsorbs i.e. Sticking coefficient =1 (not generally valid!)
ii) The growth in the second layer does not start before every site in the first layer is occupied (also not generally valid!)

Monolayer coverage



There is a certain density of adsorption sites **a** at the surface.

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(not generally valid!)

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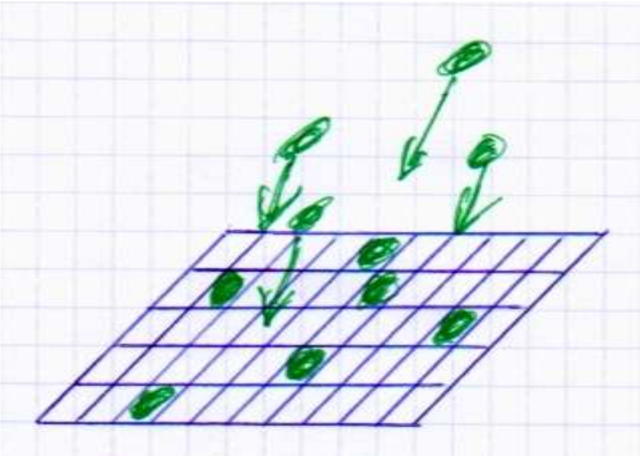
Q: Which time τ is required for the formation of a complete monolayer?

Answer: $\tau = a/Z_a = 4a/n \cdot v_{mean}$ (▸ Depends on pressure mass and temperature!)

A common "thumb value" for **a** in vacuum technology is: ?

Monolayer coverage



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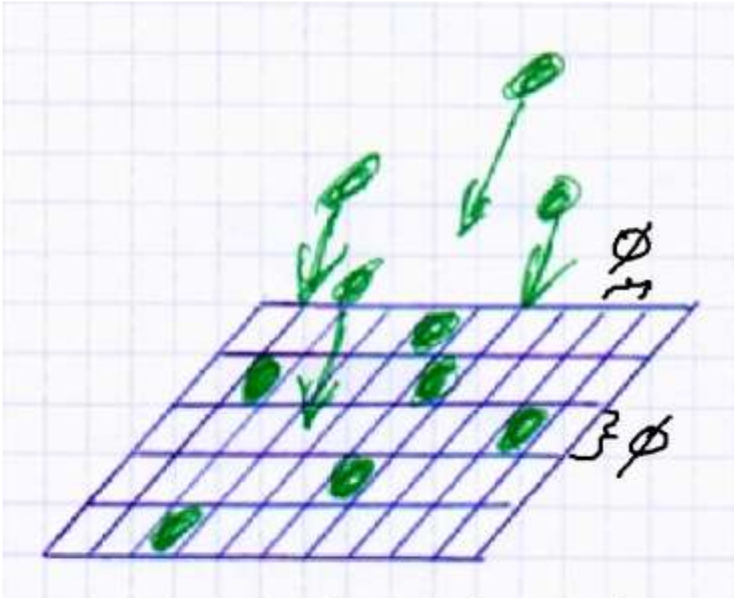
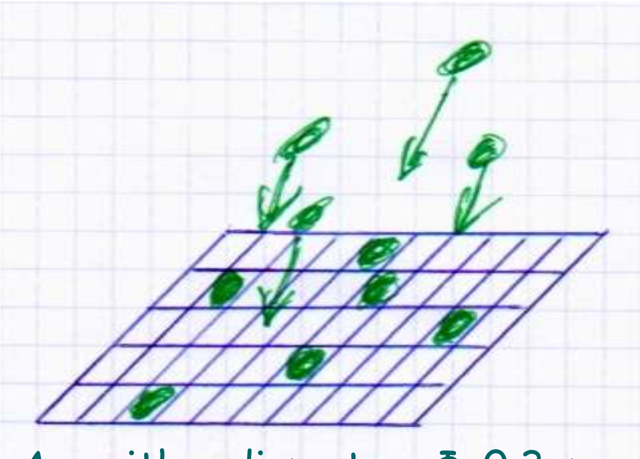


Ar with a diameter $\phi = 0.3nm$

$$a = 1/\phi^2 = \underline{\underline{1 \cdot 10^{19}\ 1/m^2}}$$

Monolayer coverage



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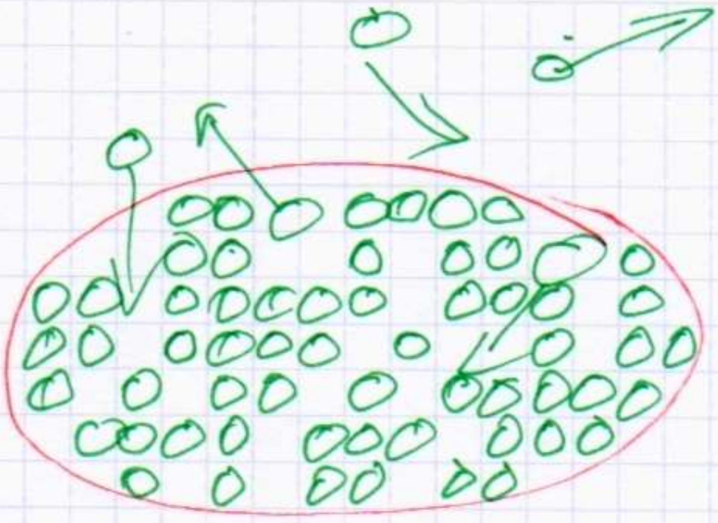
A common "thumb value" for **a** in vacuum technology is: **$a = 1 \cdot 10^{19}$ [1/m²]**

This turns out for a typical gas particle like Ar with a diameter Φ=0.3nm in a checkered arrangement $a = 1/\Phi^2 = 1 \cdot 10^{19}$ [1/m²]

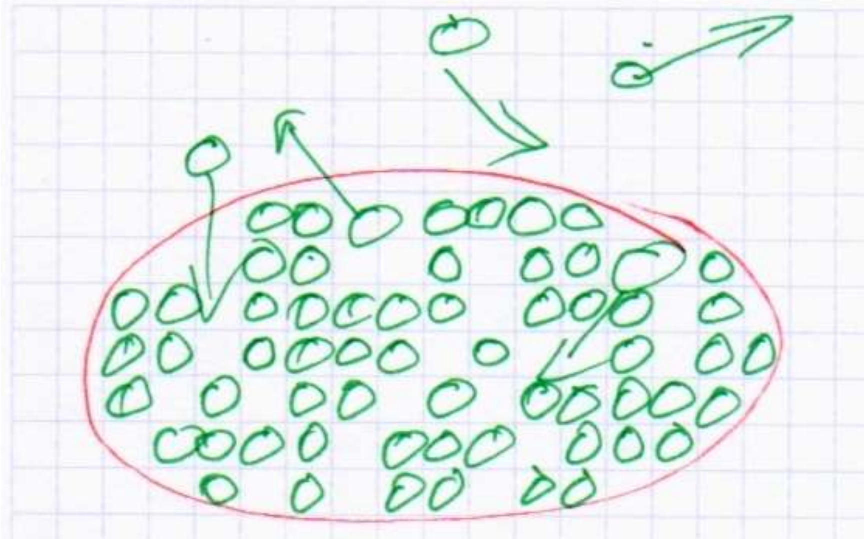
TECHNISCHE UNIVERSITÄT DRESDEN



How long is the monolayer coverage time?
Based on a pressure of 0.1 Pa ($1 \cdot 10^{-3}$mBar) and a temperature of 20°C

Hypothetically we are assuming Ar with a sticking coefficient of 1 (Non realistic, but for a “cryo-surface” possible)

TECHNISCHE UNIVERSITÄT DRESDEN



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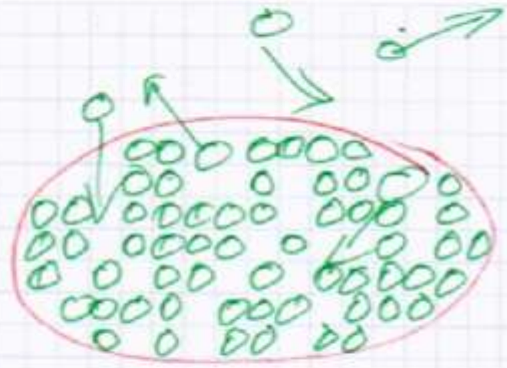

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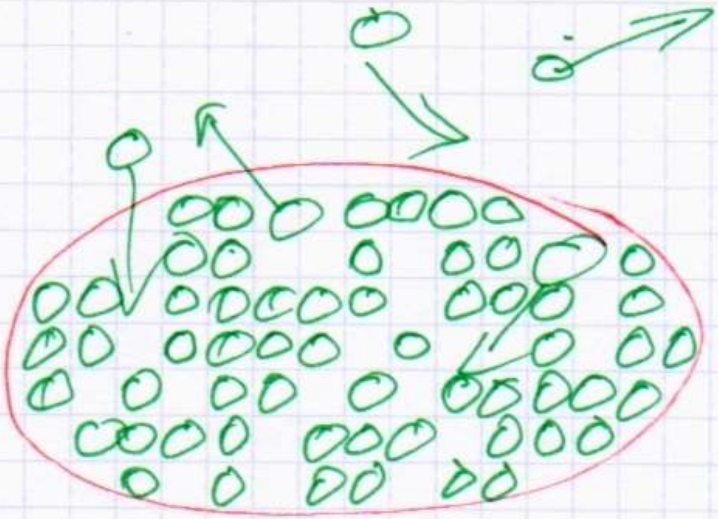
$$\tau = \frac{a}{Z_a} \qquad a \leftarrow 1\cdot10^{19}\,\frac{1}{m^2}$$

$$Z_a \leftarrow \frac{1}{4} n \bar{u} = \frac{p}{\sqrt{2\pi m k T}} \approx 2{,}5\cdot10^{21}\,\frac{1}{m^2 s}$$

$$\tau\,(0{,}1\,\text{Pa or } 10^{-3}\,\text{mBar}) = \frac{1\cdot10^{19}}{2{,}5\cdot10^{21}} = \underline{\underline{4\,\text{ms}}}$$

TECHNISCHE UNIVERSITÄT DRESDEN



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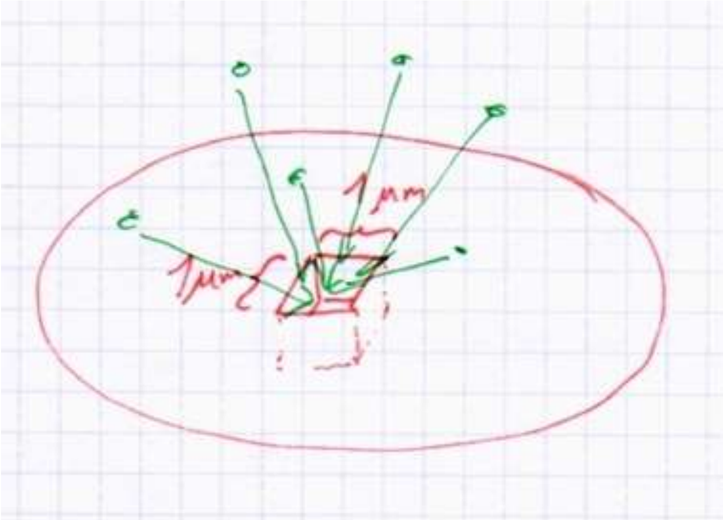

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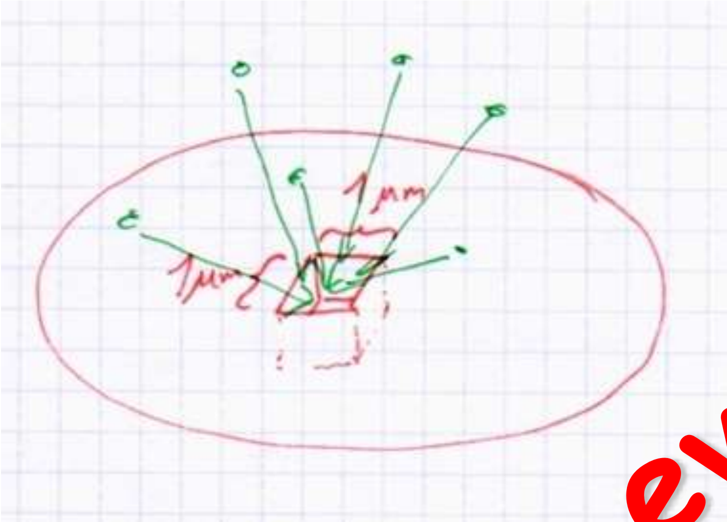

How many Ar-particles approach the trench opening (1X1 µm²) at a pressure of 0.1 Pa (1·10^{-3} mBar) and a temperature of 20°C ?

$$Z_a = \frac{1}{4} n \bar{c}$$

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It is 1ML every 4 ms!

That means 250 ML / s!

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ML coverage time and pressure:

$$\tau = \frac{a}{Z_a} = \frac{4a}{n\,\bar{u}}$$

$$p = nkT \qquad \bar{u} = \sqrt{\frac{8kT}{\pi m}}$$

$$\tau = \frac{a\,4}{\frac{p}{kT}\cdot\sqrt{\frac{8kT}{\pi m}}} = \frac{a}{p\sqrt{\frac{8}{16}\frac{kT}{(kT)^2}\frac{1}{m}}}$$

$$\tau = \frac{a}{p\sqrt{\frac{1}{2kTm}}} = \frac{a\sqrt{2kTm}}{p}$$

Or:

$$Z_a = \frac{a}{\tau} = \frac{p}{\sqrt{2\pi m kT}}$$

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At $1 \cdot 10^{-5}$ Pa we have 1 ML/40s => $P_{(1ML/s)} = 1 \cdot 10^{-5}\,\text{Pa} \cdot 40 = 40 \cdot 10^{-5}$ Pa

$= 4 \cdot 10^{-6}$ mBar

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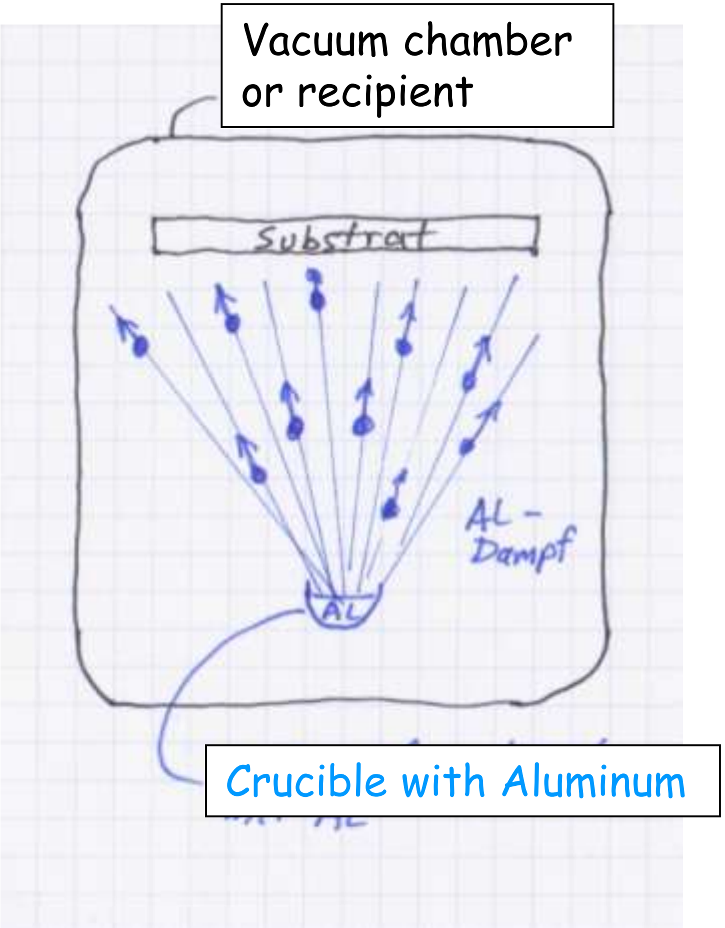
An example on the practical meaning of that


Vacuum chamber
or recipient
Substrat
AL -
Dampf
AL
Crucible with Aluminum

»Wissen schafft Brücken.«