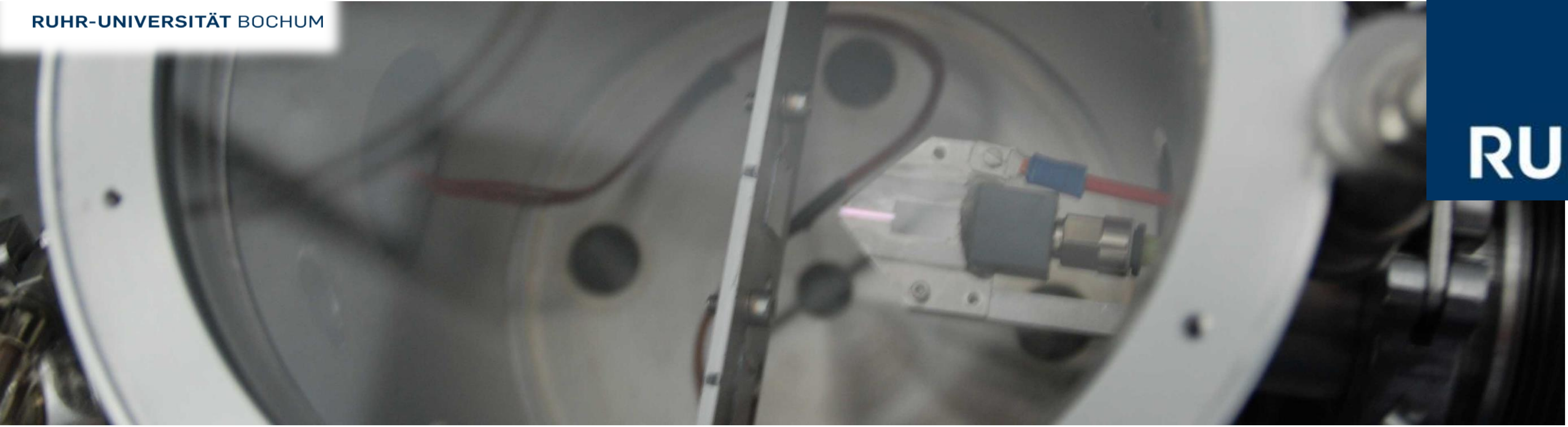


Introduction to plasma science for life science applications

Achim von Keudell

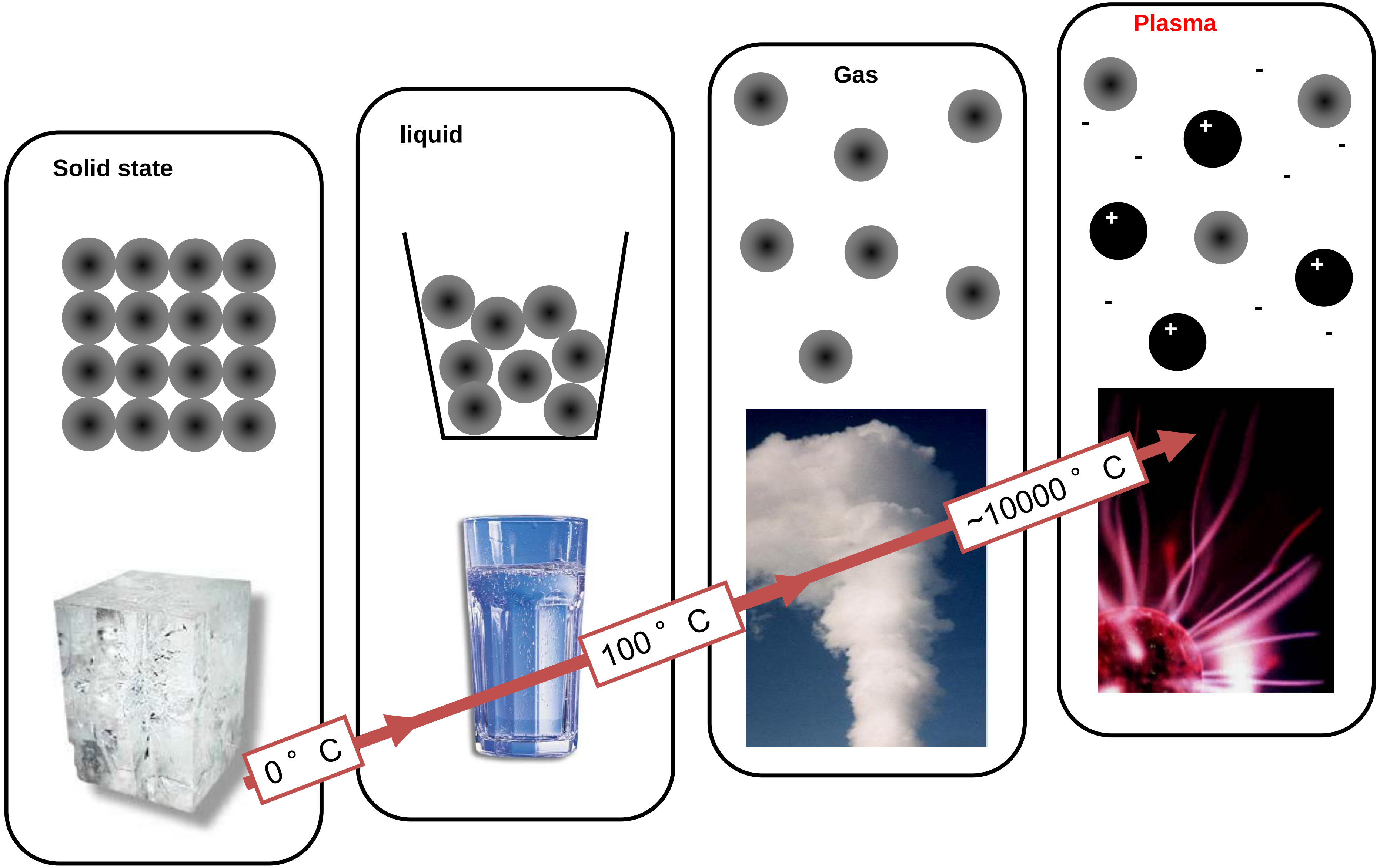
Research Department Plasmas with Complex Interactions
Ruhr-Universität Bochum

Foundations of low-temperature plasma physics—an introduction
A von Keudell and V Schulz-von der Gathen 2017 *Plasma Sources Sci. Technol.* **26** 113001

Youtube Playlist of This lecture: https://www.youtube.com/playlist?list=PLgXZ2UeRnGhDOXYebt-L9CRWQ53fFCOeV

Physics/Plasma animations at youtube channel Achim von Keudell

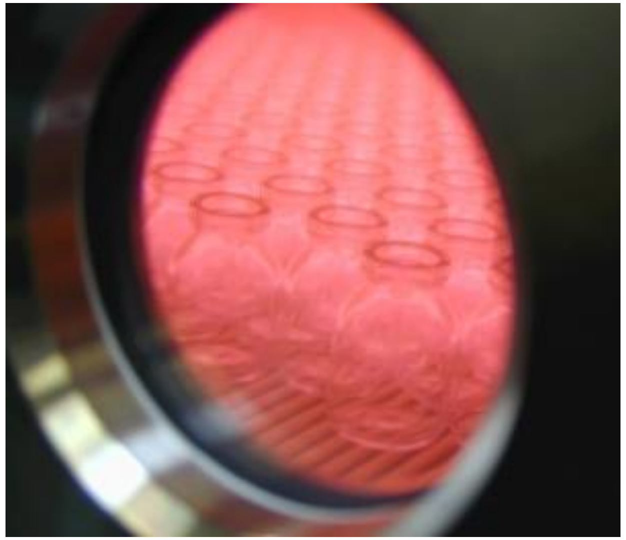
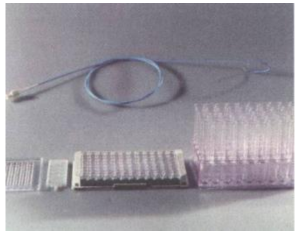
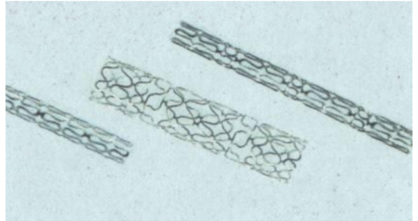
Plasma as the fourth state of matter



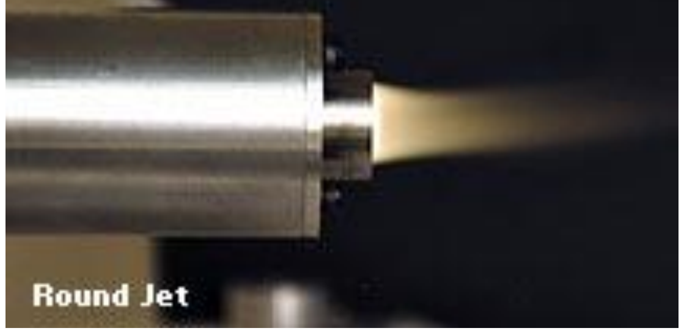
Plasma in the biomedical sector

- Artifical knee – plasma coated
- Catheders – plasma coated
- Stents – plasma coated
- Artifical hips –plasmaspraying
- Sterilisation in Hospitals
- Drugs – plasma treated
- Sterilisation of vials

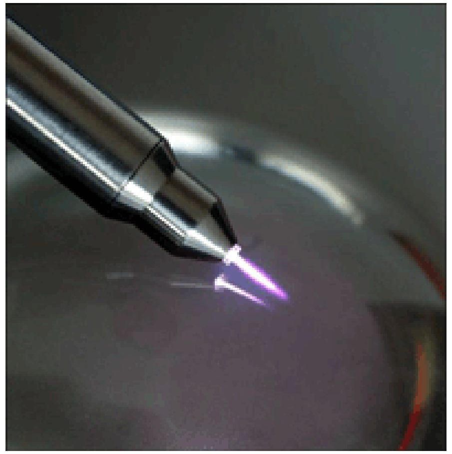


Plasmajets for biological applications



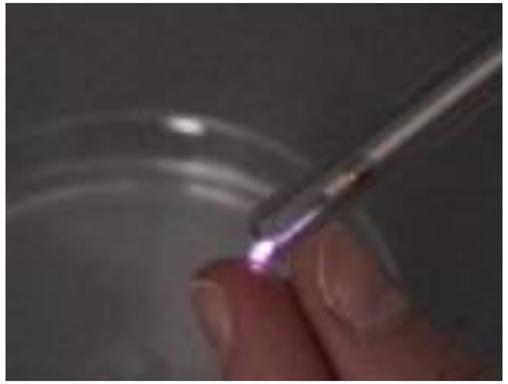
Plasma Jet
(APJJet, G. Selwyn)



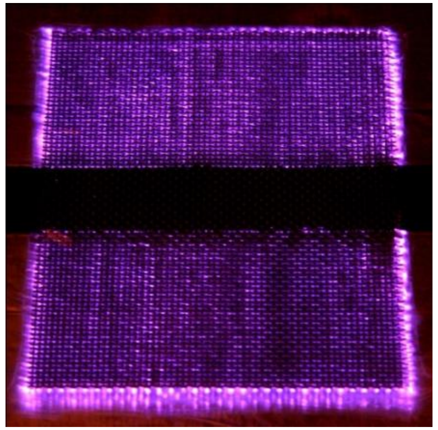
Plasma Jet (INP)

Plasma Pencil etc.
(kHz,kV)
(JE Consult)

Plasma Pen
(PVA TePla)



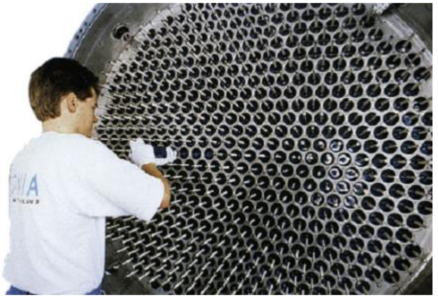
Plasma needle (rf)
(E. Stoffels)

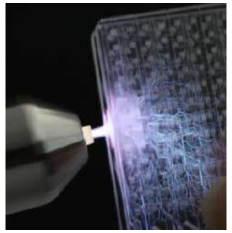


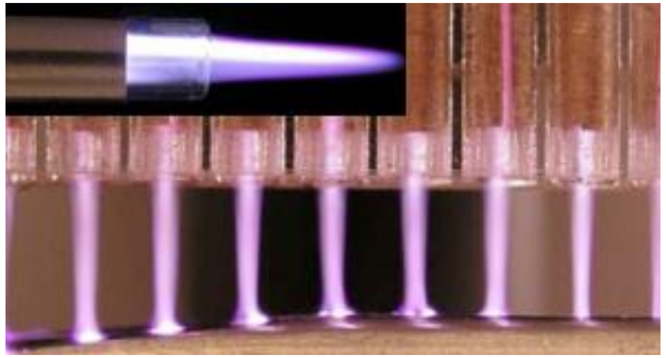
plasma brush
(Rheinhausen)

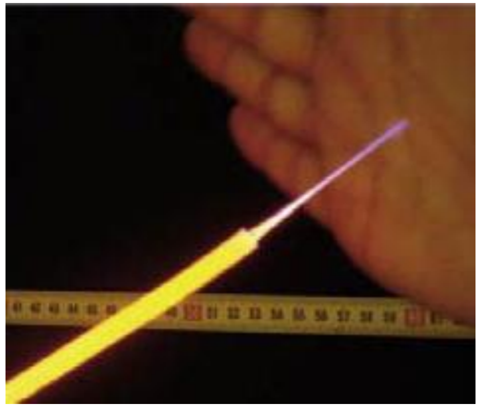
Environmental Applications

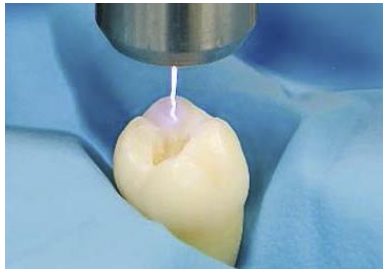
- Waste treatment
- Water and air cleaning
- Plasma medicine

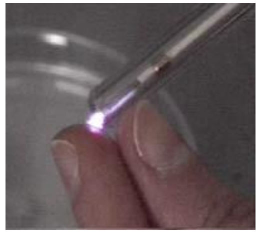


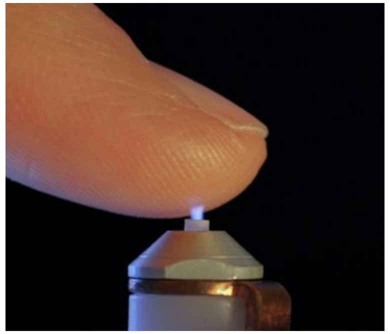




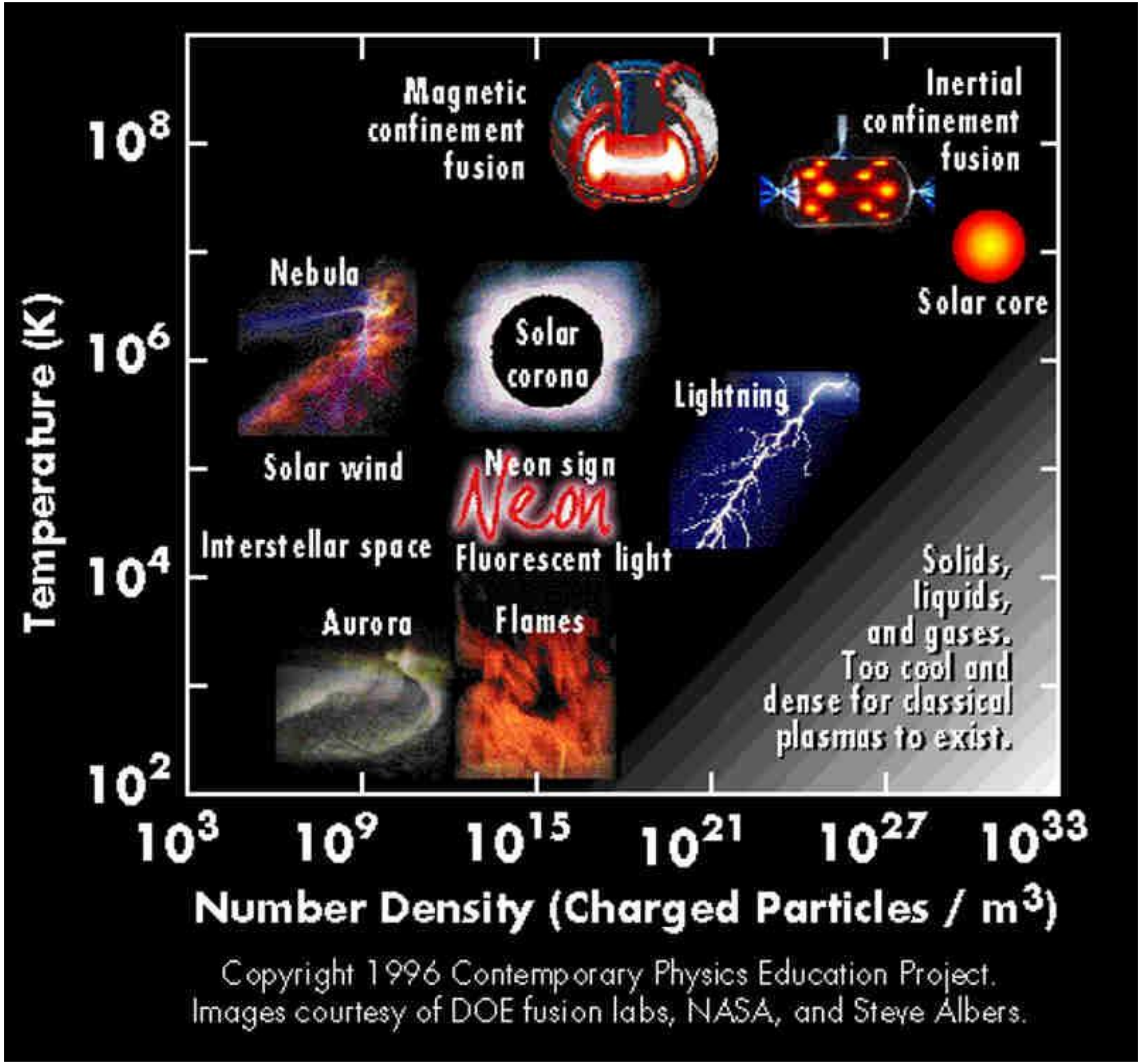




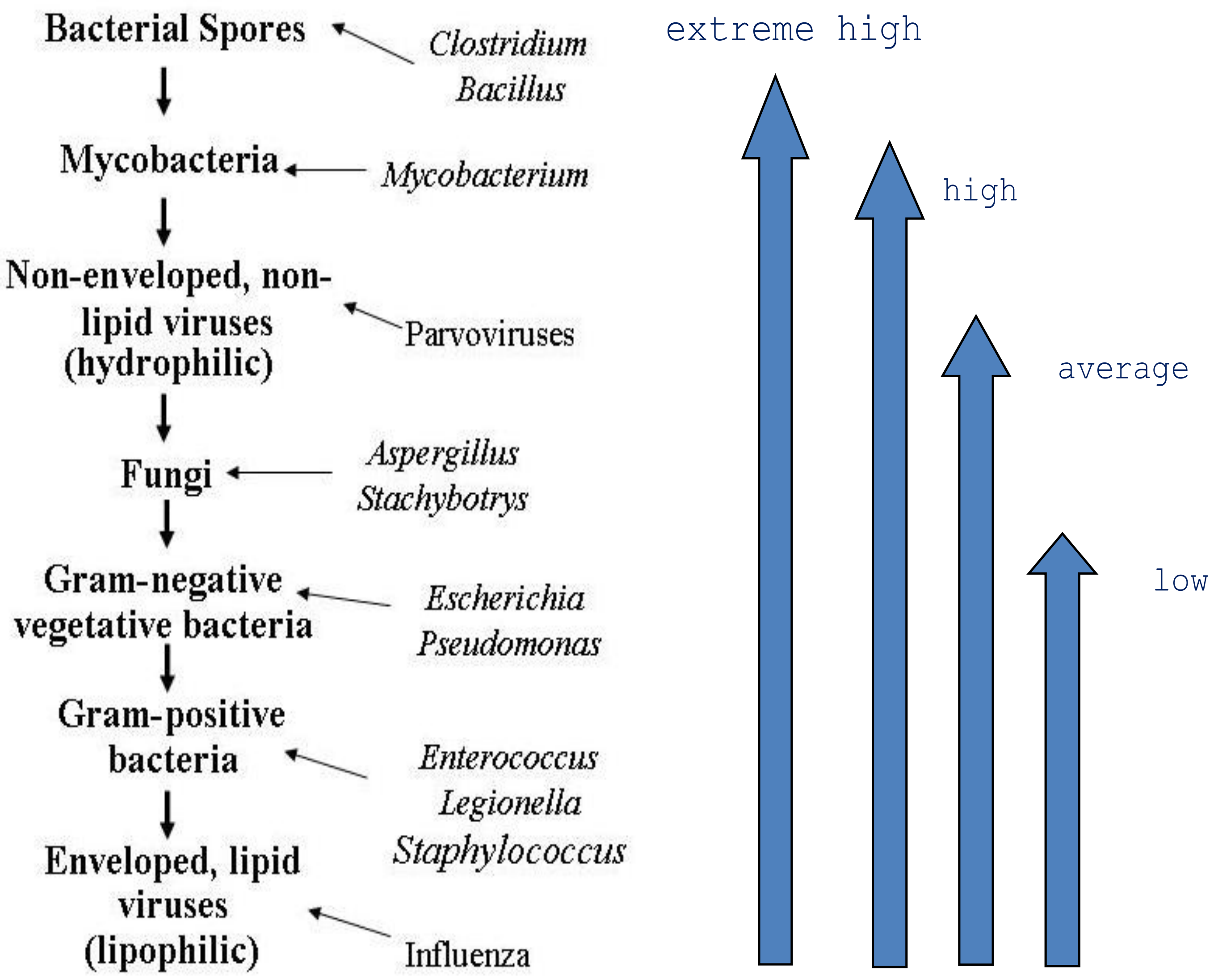




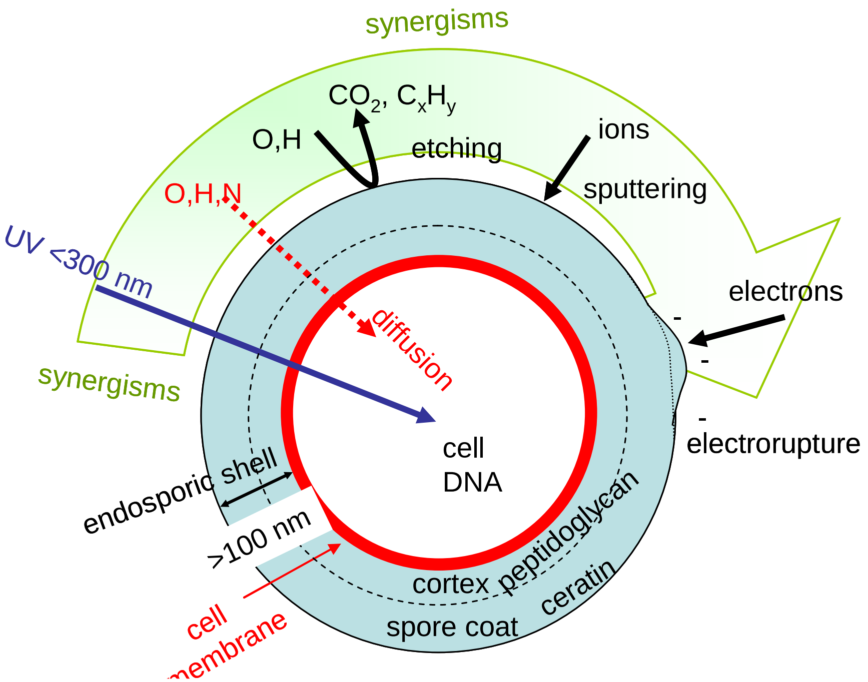
Plasma vs. n_e and T_e



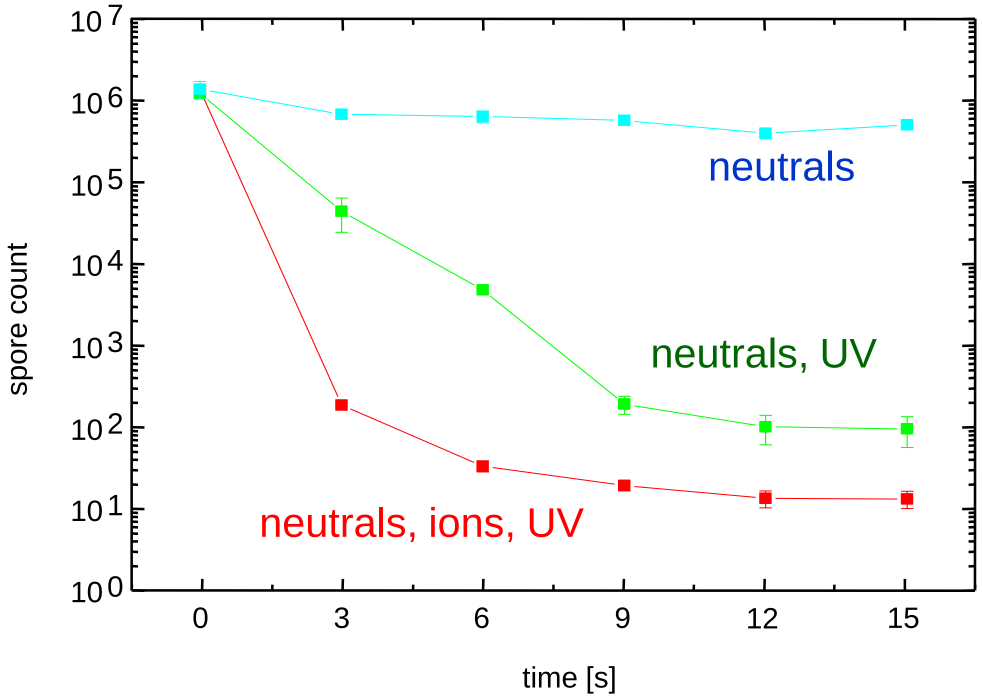
The resistance of biological systems against inactivation mechanisms



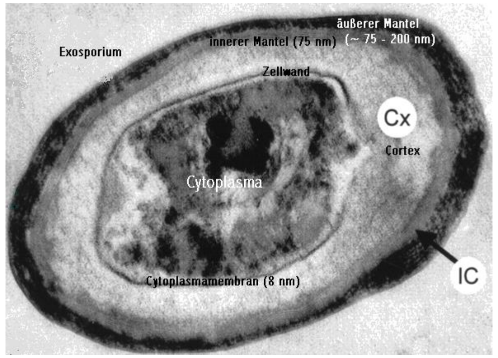
Possible Mechanisms of Bacteria Inactivation

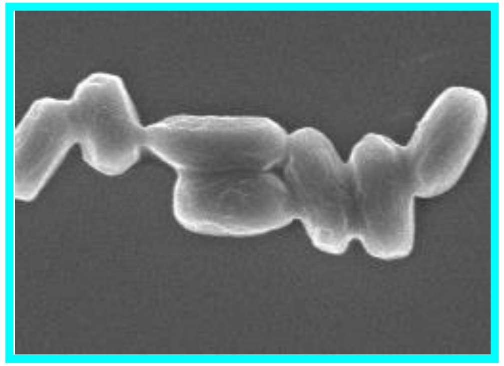


bac. subtilis in an **Ar/H_2** plasma

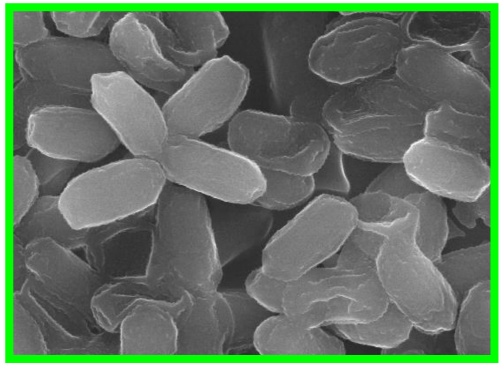


T. Gans et al., Plasma Phys. Control. Fusion **47** (2005) A353

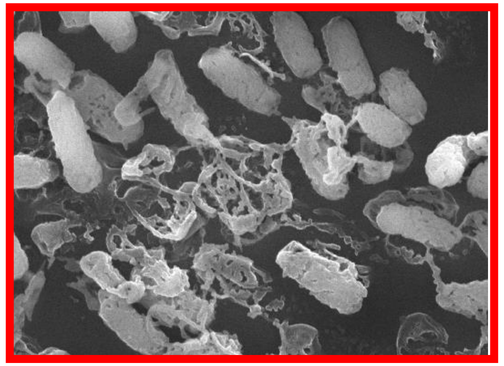




UV, gas



plasma



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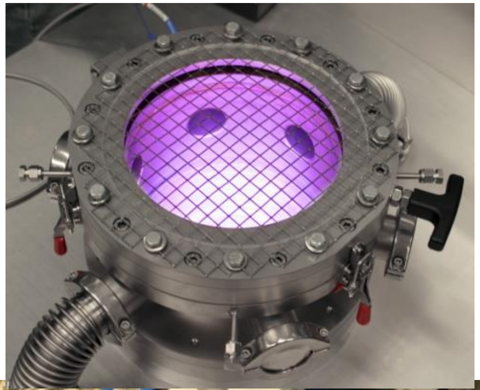
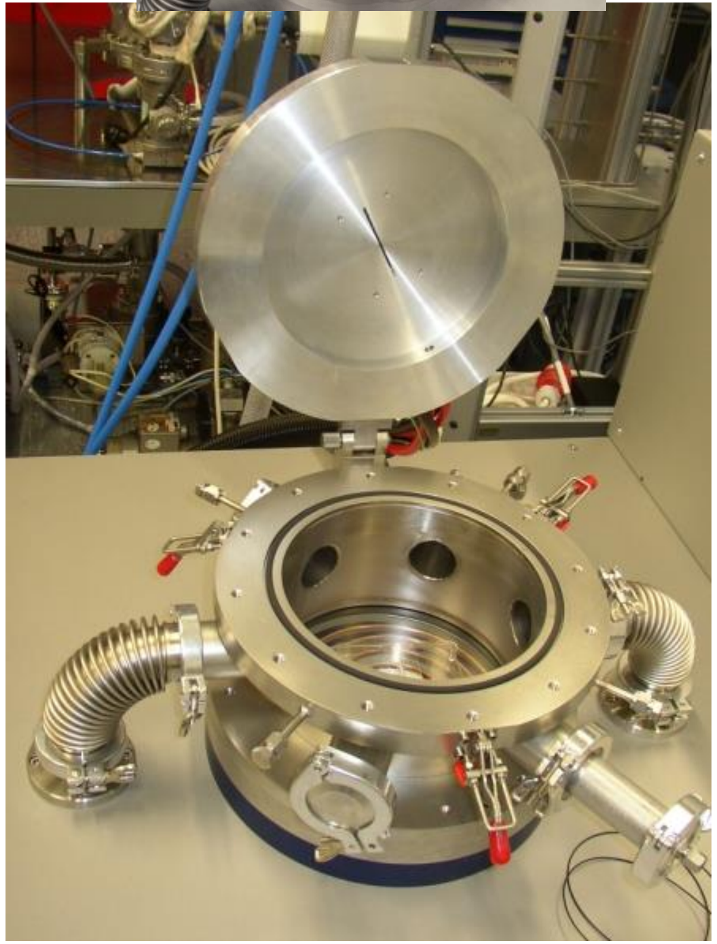
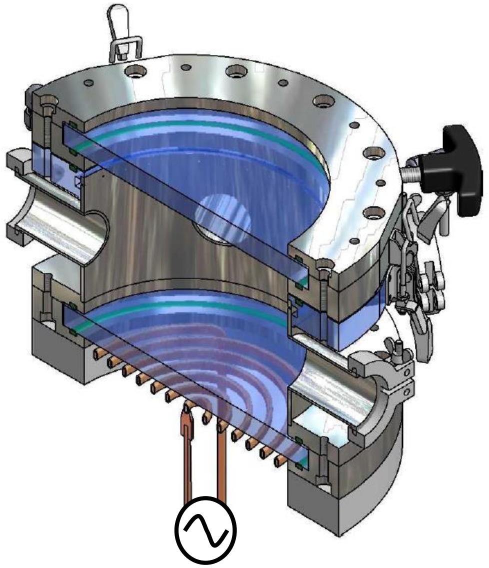
A flexible low pressure ICP system for decontamination





Low pressure system:
Inductively Coupled Plasma
Pressures 0.5...30 Pa
Reactor volume ~ liters
Power up to 600 W
Gases Ar, He, O_2, N_2, H_2

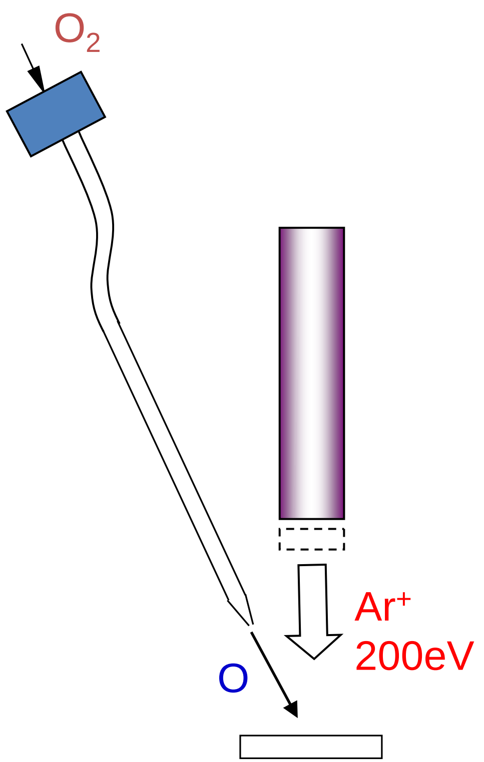
Fully computer controlled
On mobile platform
Only 230 V plug needed



Steam Sterilisation
Subtil Crepieux

Inactivation of spores

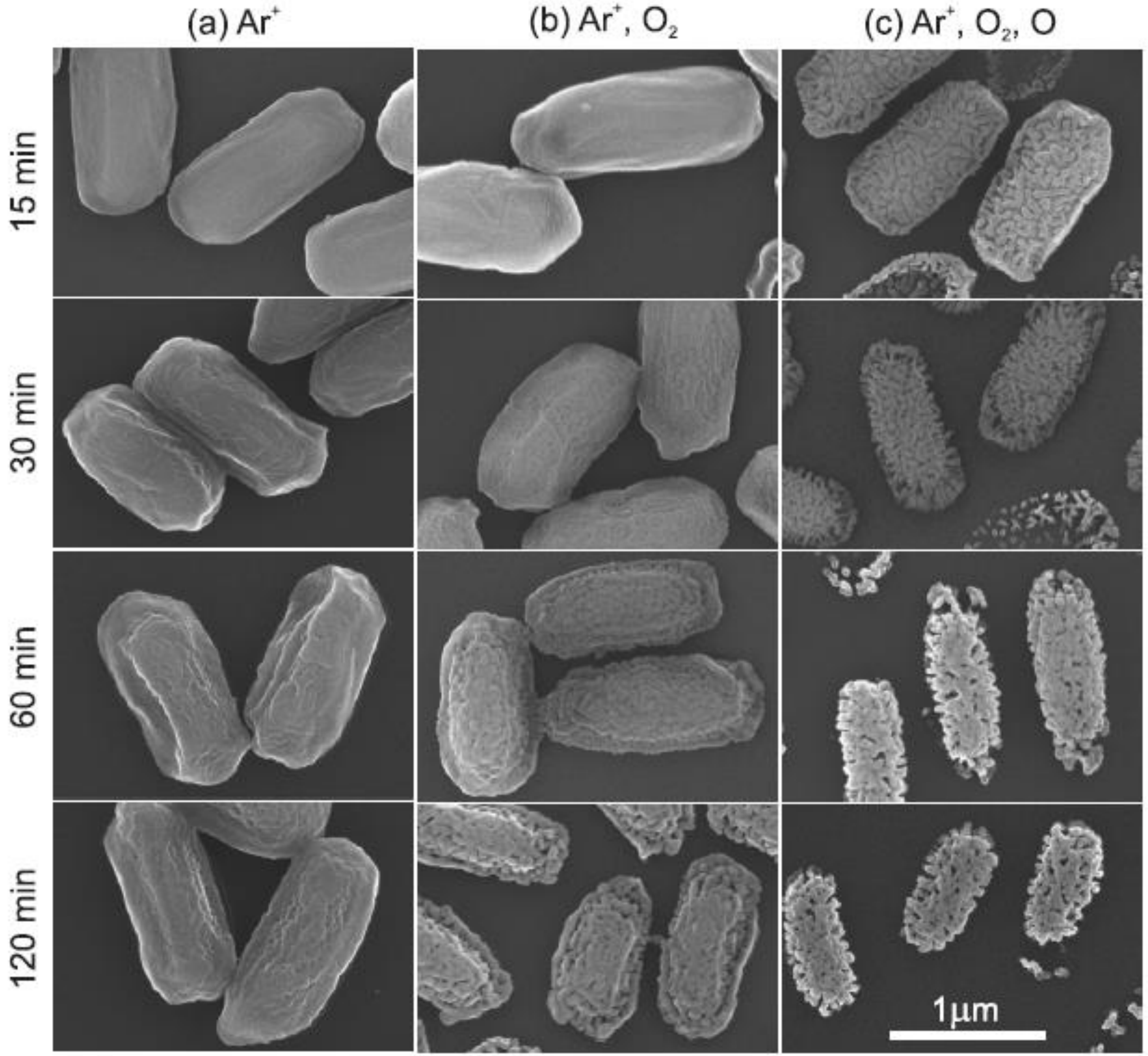
Raballand et al.
J. Phys. D 41,
115207 (2008)



$j_{Ar^+} = 1.8 \times 10^{14}\ cm^{-2}s^{-1}$

$j_{O2} = 1.5 \times 10^{17}\ cm^{-2}s^{-1}$

$j_O = 2.4 \times 10^{15}\ cm^{-2}s^{-1}$



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groninger
MWU 010
Manual Debagger

Plasma Fundamentals - Outline

1. What is a plasma ?
   - Temperature
   - Debye shielding
   - Plasma frequency

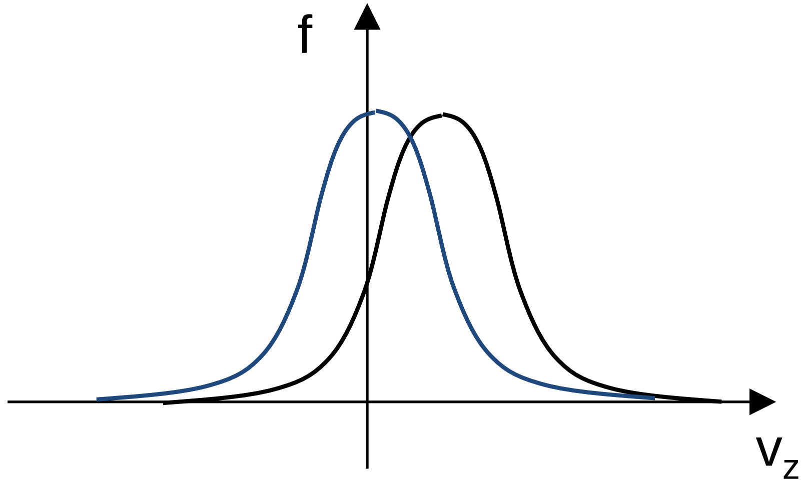
2. The edge of a plasma
   - Sheath physics

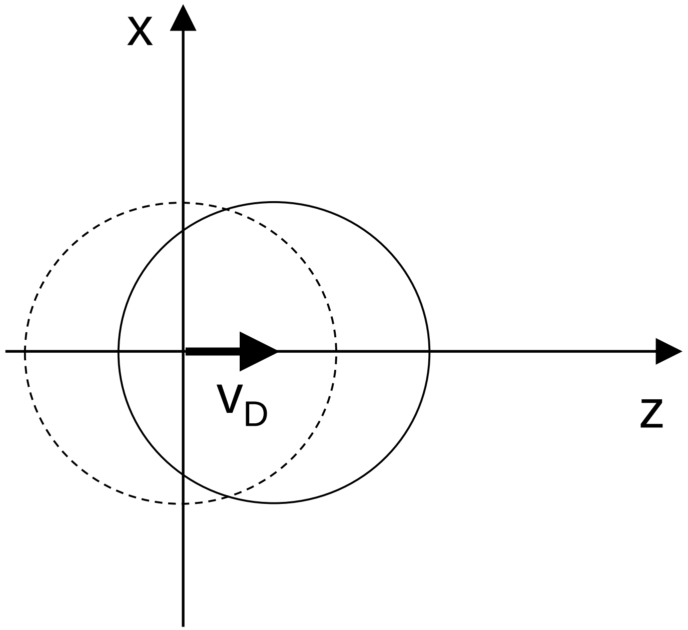
3. How to ignite a plasma
   - Ignition, Paschen curve
   - Streamer
   - RF-ignition

4. Transport in a plasma
   - Particle motion
   - Plasma as a fluid
   - Drift and diffusion

5. How to sustain a plasma
   - DC plasma
   - Rf-plasmas
   - Plasma heating

What is a plasma ? Concept 1 - temperature

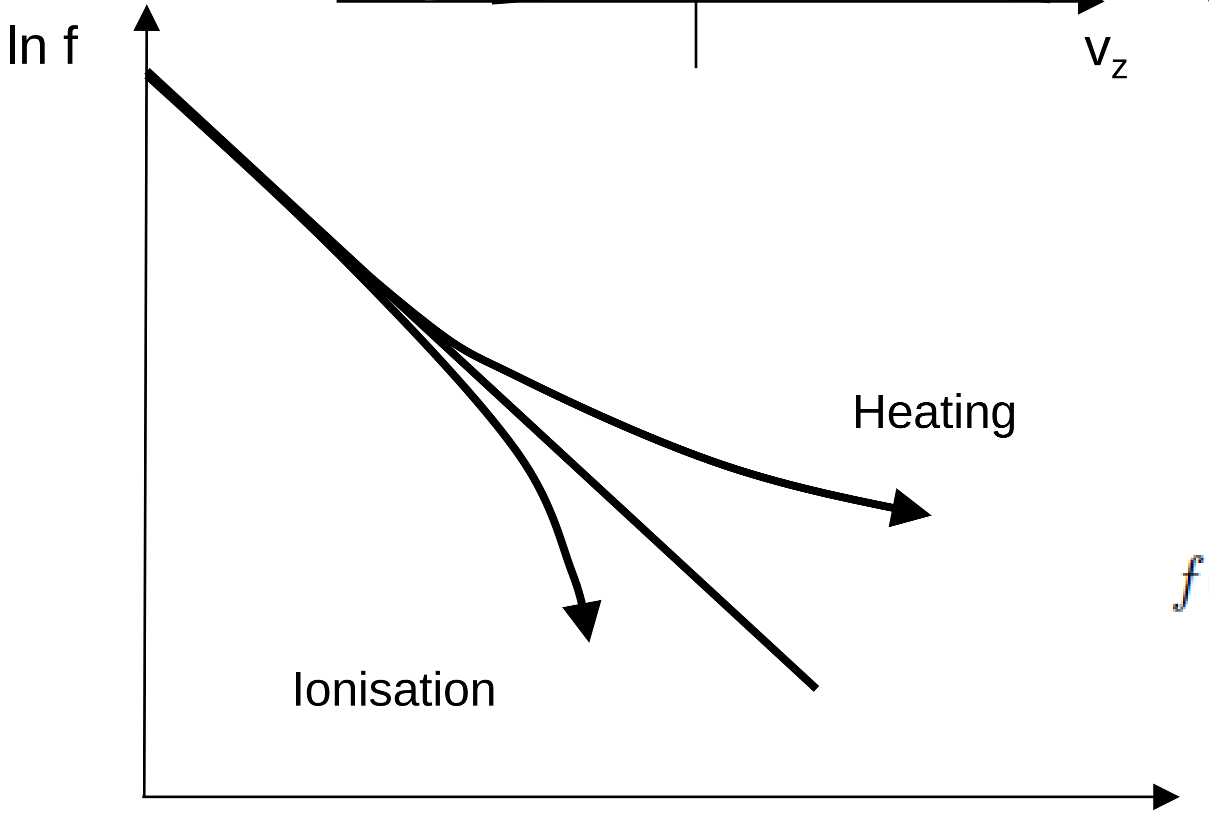




What is the best plasma for life science applications?

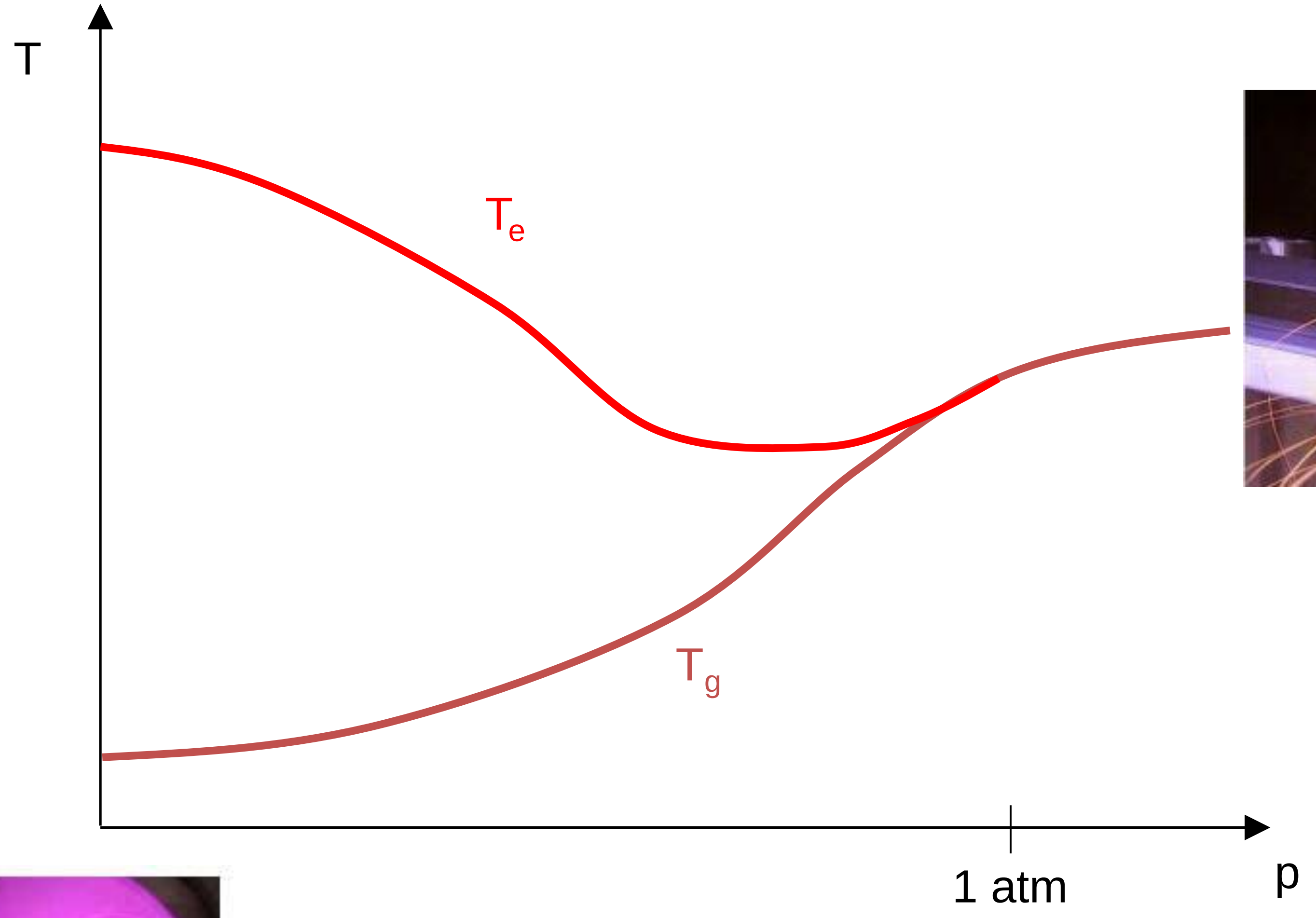
DBD – barrier discharges
cold, high electric fields
Energy inefficient

Microwave discharges
Hot, low electric field
Energy efficient



$$f(v) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} e^{\frac{-\frac{1}{2}mv^2}{k_B T}}$$

What is a plasma ? Concept 1 - temperature

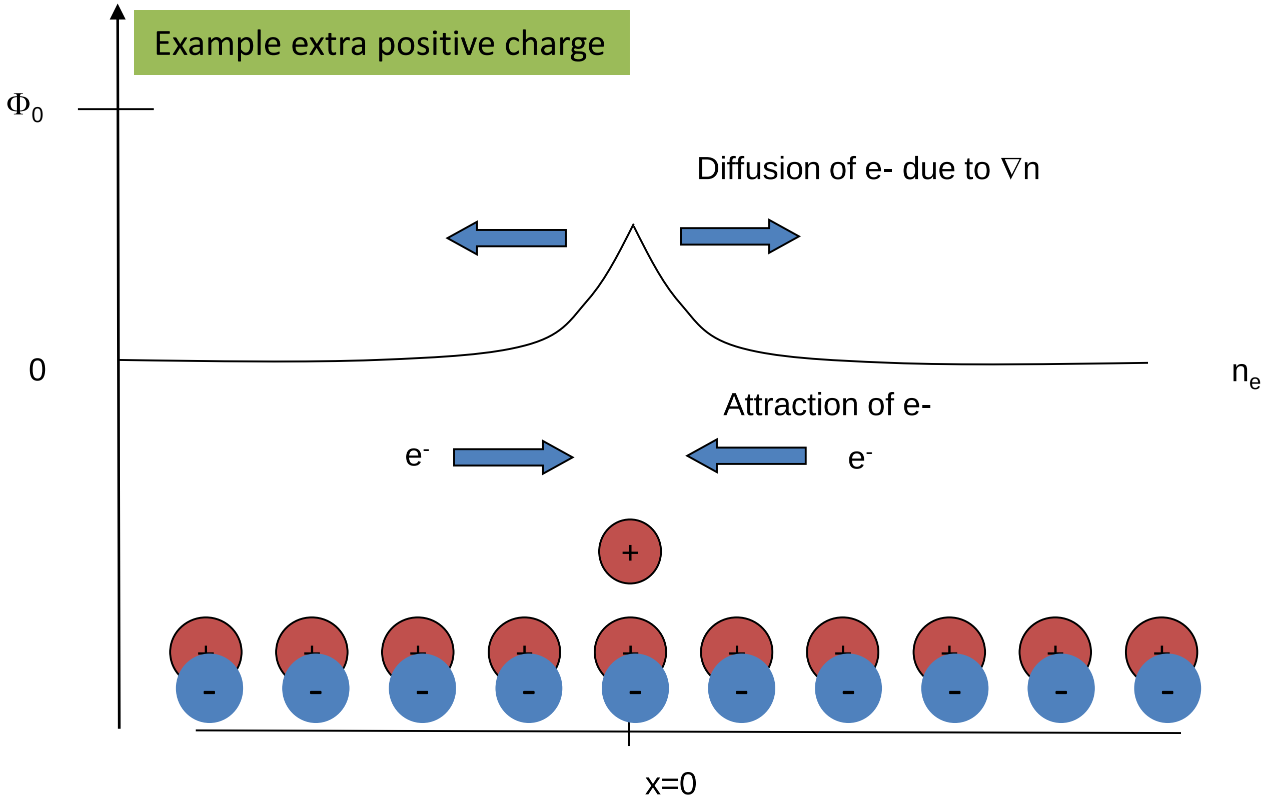


What is the best
pressure/equilibrium
for life science applications?

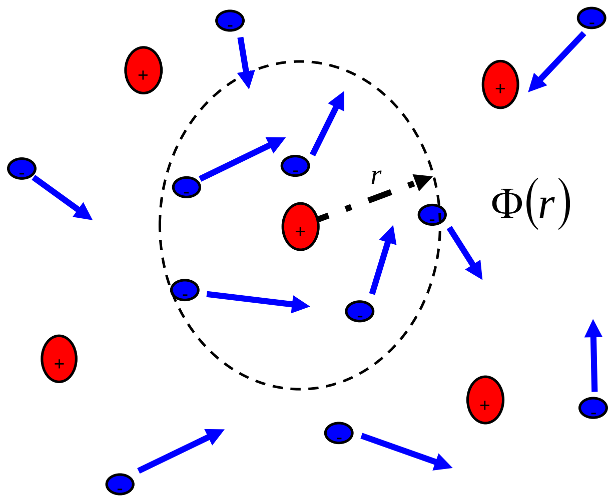
Low pressure
Cold plasmas,
only electrons are hot

High pressure,
All species equilibrate
OR
Pulsing,
Fast gas flows

What is a plasma ? - Concept 2 – Debye shielding, quasineutrality



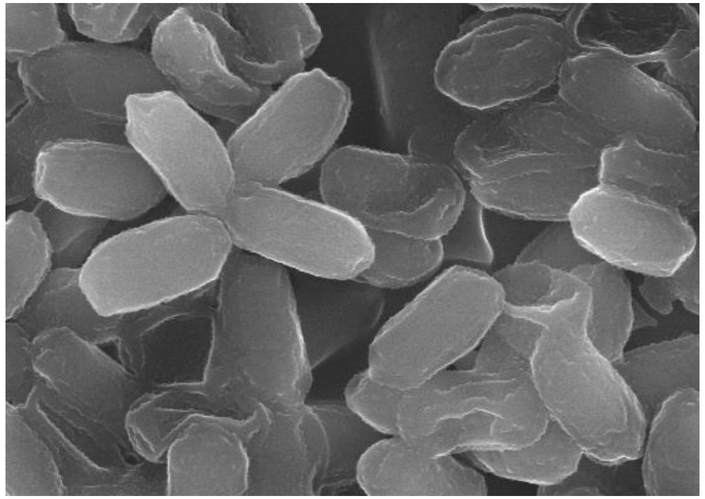
$$n_e = n_0 e^{\frac{e\Phi(x)}{k_B T}}$$



$$\lambda_D = \left(\frac{\epsilon_0 k_B T}{n_0 e^2}\right)^{1/2}$$

What is the best plasma for life science applications?

High electron densities, Plasma can penetrate into small pores



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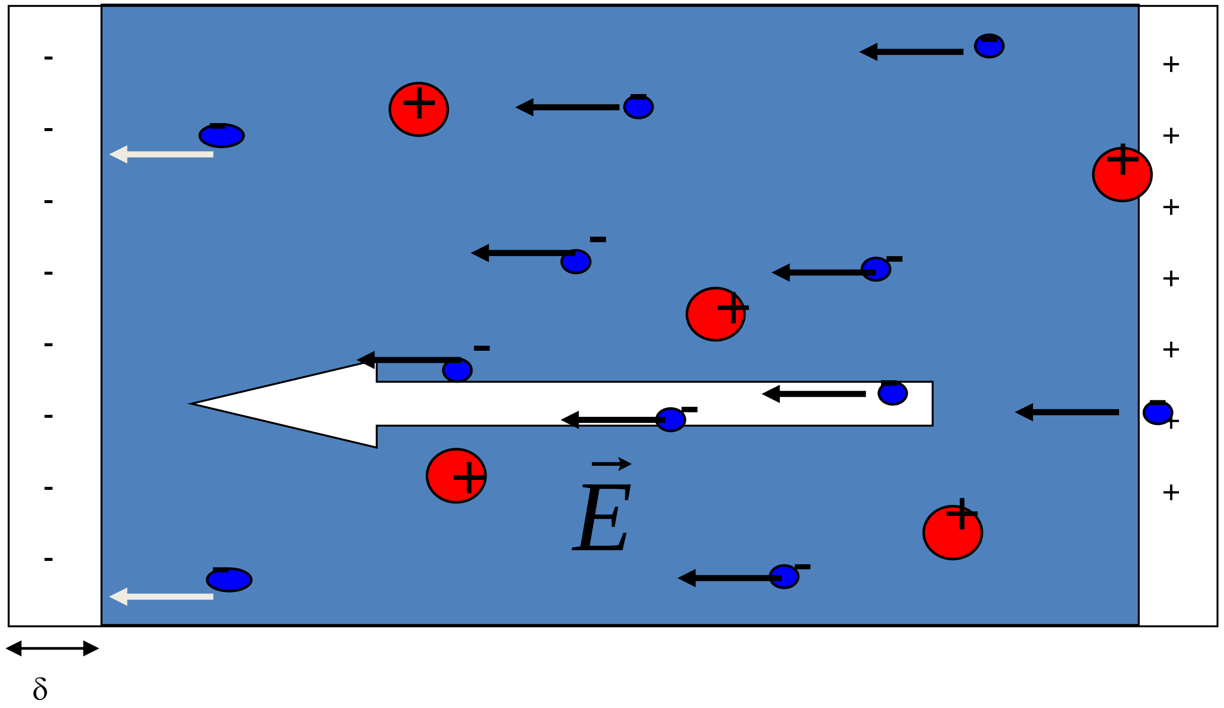
What is a plasma ? - Concept 4 –the plasma frequency (formulas)



$$E = \frac{1}{\epsilon_0} e n \delta$$

$$m_e \frac{d\delta^2}{d^2 t} = -eE$$

$$\frac{d^2\delta}{dt^2} + \frac{ne^2}{\epsilon_0 m}\delta = 0$$

$$\omega_p = \left(\frac{ne^2}{\epsilon_0 m}\right)^{1/2}$$

What is the best plasma
for life science applications?

How to get the energy
Into the plasma?

Use high frequency fields
To keep heavy species cold

Parameter of a plasma – Nick Braithwaites Plasma Calculator

Web version at
wwww.plasma-school.org

HOME PROGRAM REGISTER SPONSORS CONTACT HISTORY MATHS

Plasma Calculator

This is an online version of the original Nick Braithwaite Plasmacalculator Excel-Sheet.

Input Parameter

T_g	300	K
T_e	3.00	eV
n_e	1.00e+17	m^{-3}
Pressure *p*	100000.00	Pa
Mass Neutrals/Ions *m*	40	amu
Cross Section neutrals *sigma*	1.00e-19	m^2
System Dimension *L*	0.10	m
Magnetic field *B*	0.10	T
Microwave *f*	2.45	GHz

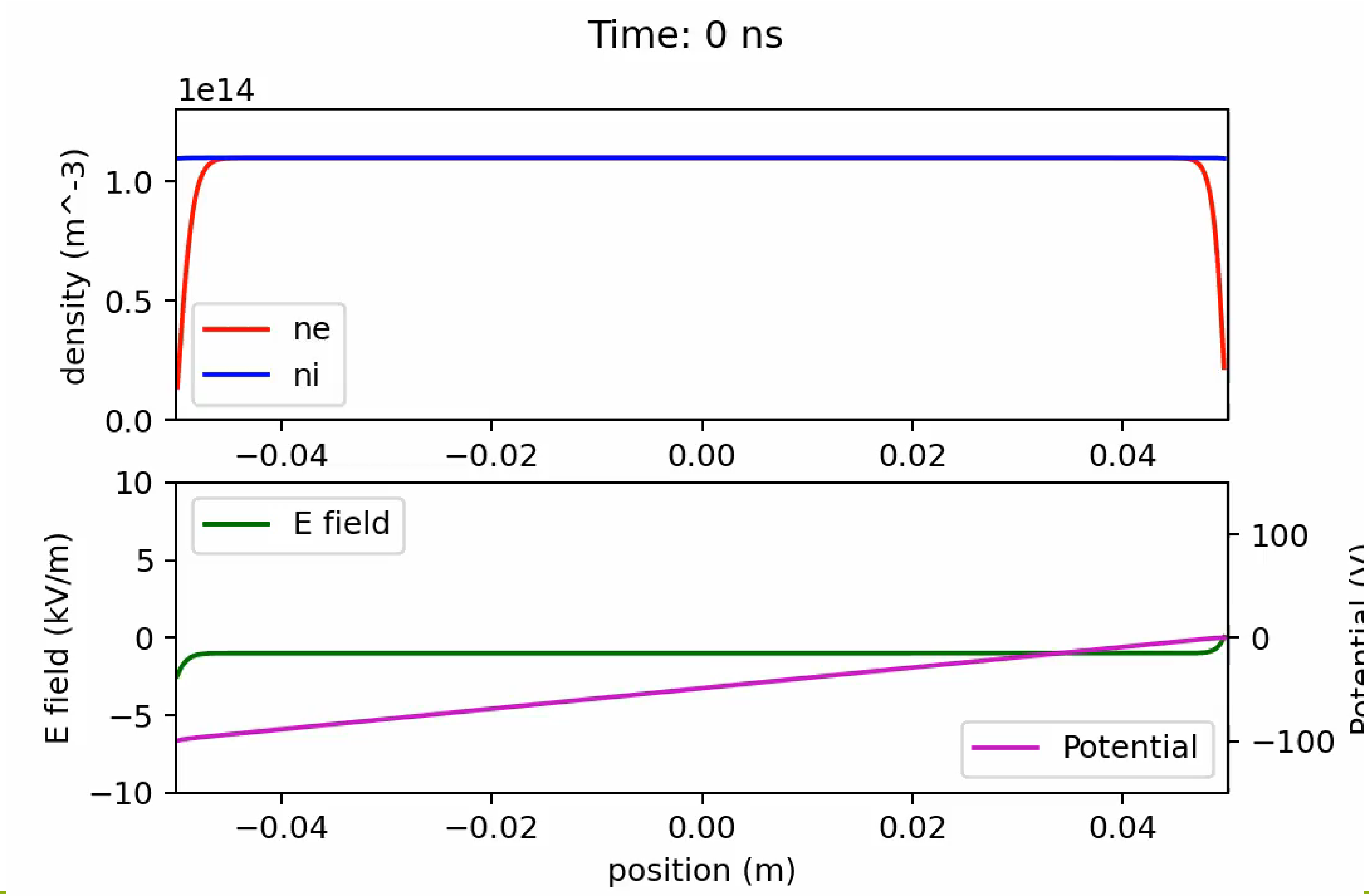
Calculate

Output Parameter

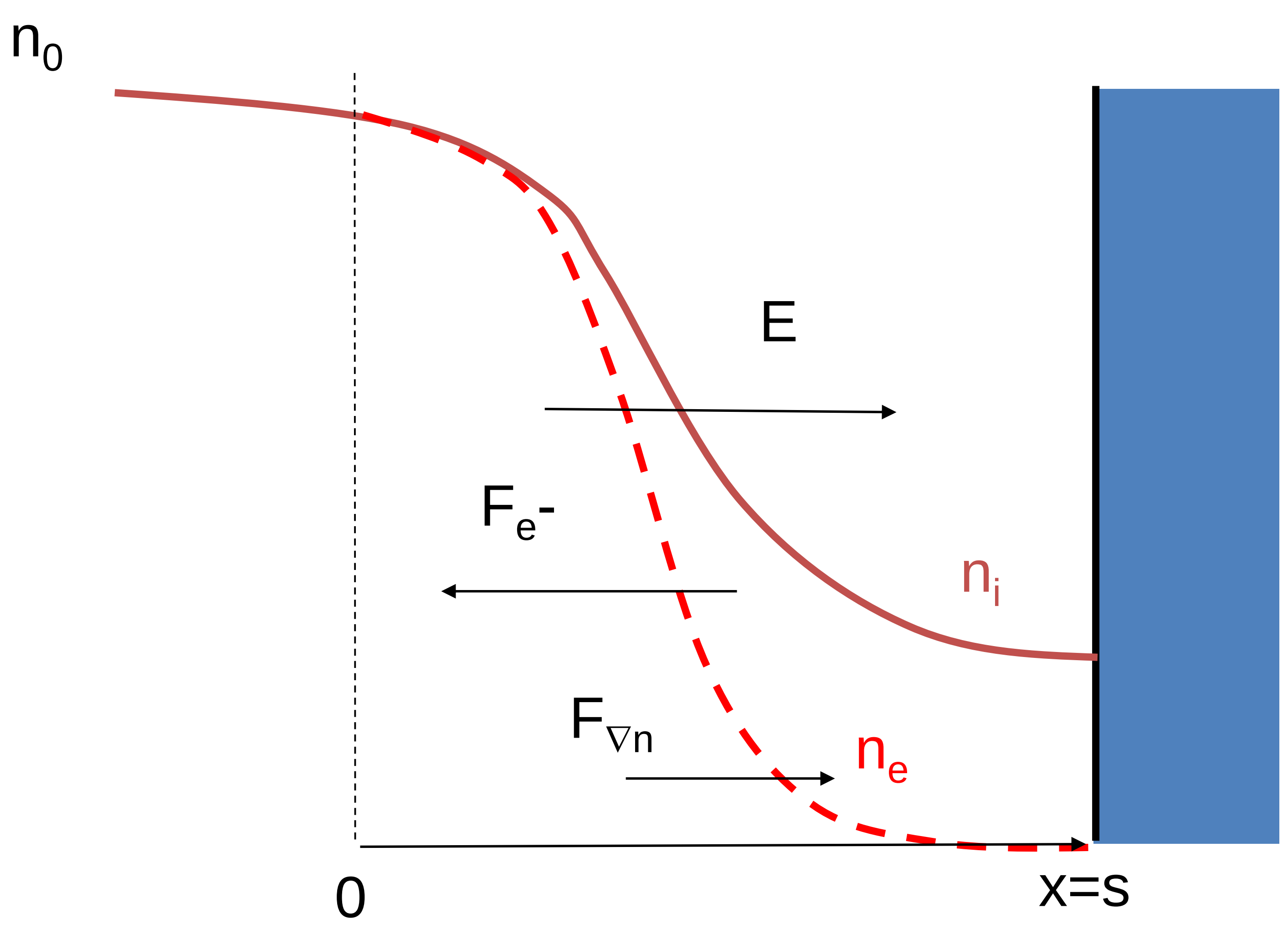
Parameter	Value	Unit
Distances		
Neutral-Neutral	3.46e-9	m
Mean Free Path	4.14e-7	m
Debye Length	4.07e-5	m
Densities		
Neutrals	2.42e+25	m^{-3}

The edge of a plasma

A plasma in front of a wall – sheath physics



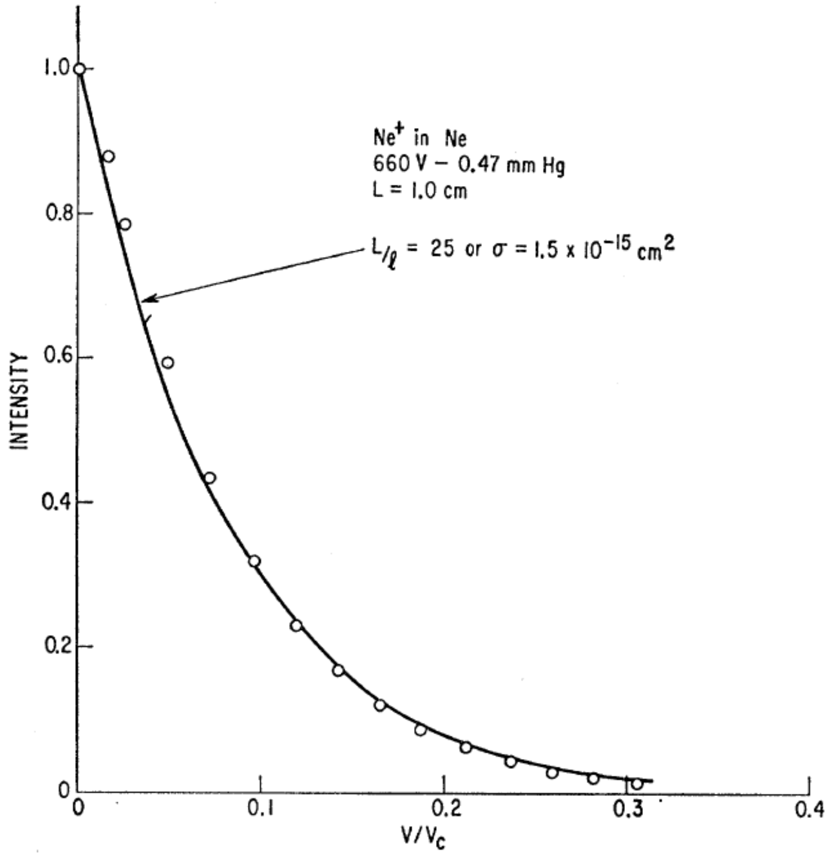
A plasma in front of a wall – sheath physics



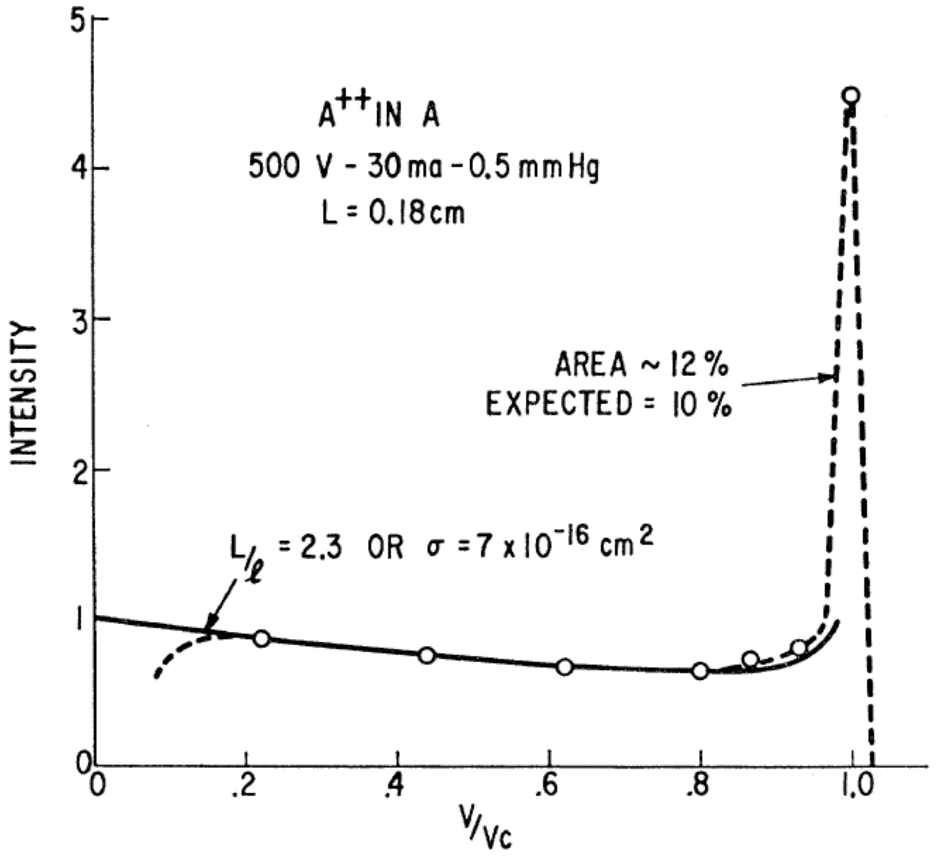
$$v_0 > \sqrt{\frac{k_B T_e}{M}} = v_B$$

A plasma in front of a wall – sheath physics – ion energy distributions - collisions

many collisions in the sheath

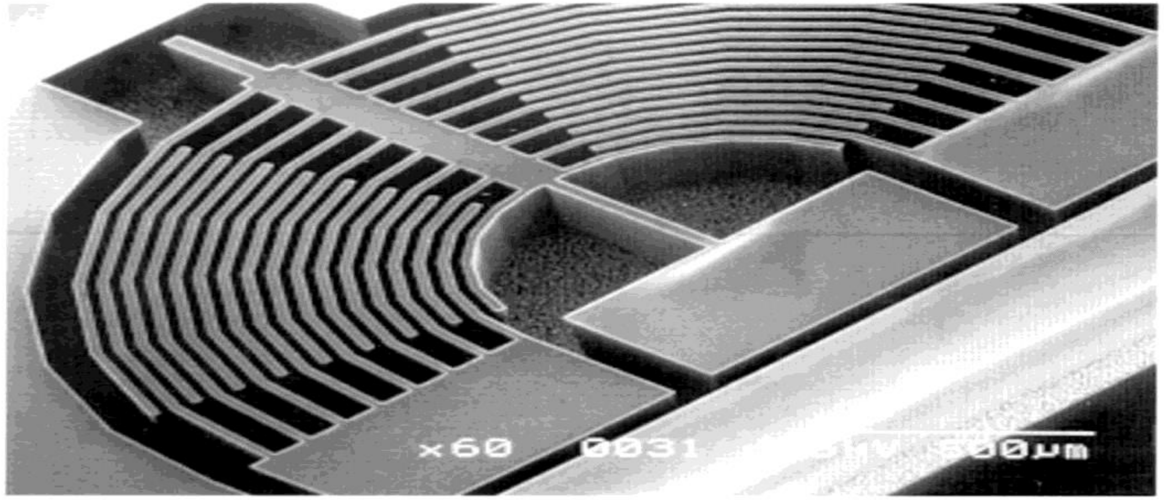


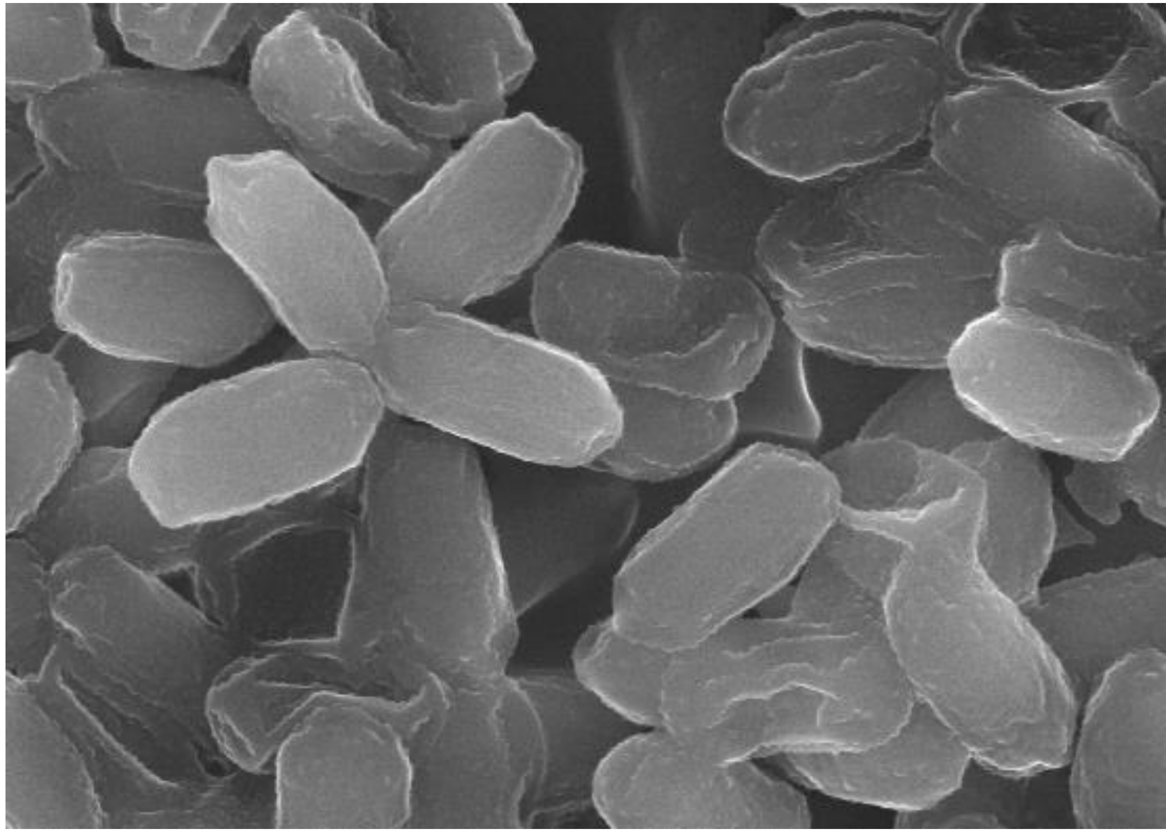
Few collisions in the sheath

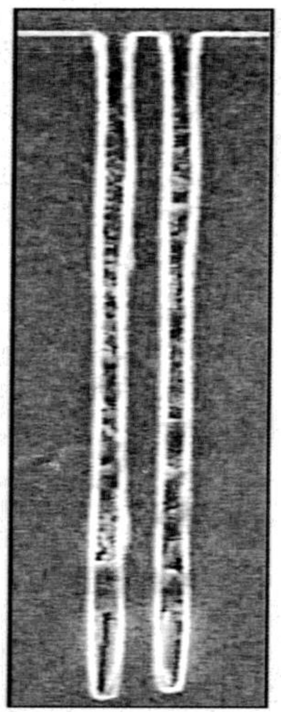


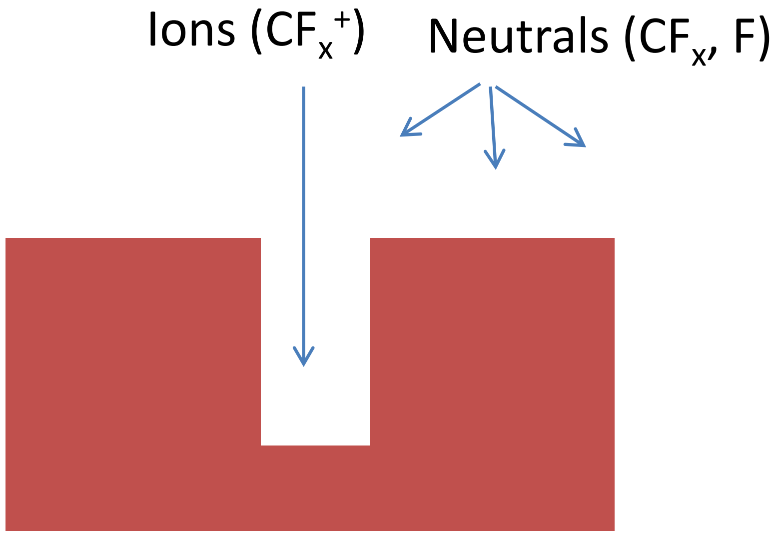
mbar) [T. Davis, T. Vanderslice *Ion energies at the cathode of a glow discharge*, Phys. Rev. 131, 219 (1963)]

A plasma in front of a wall – sheath physics – applications in microelectronics

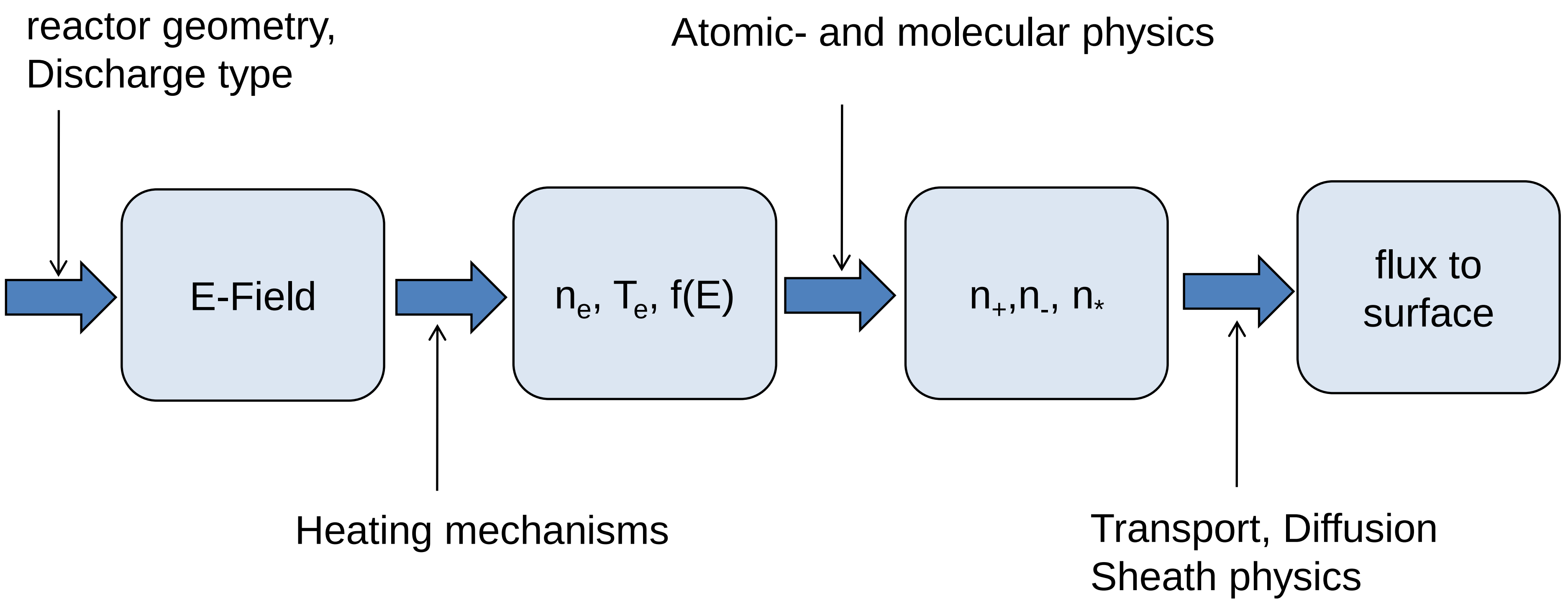




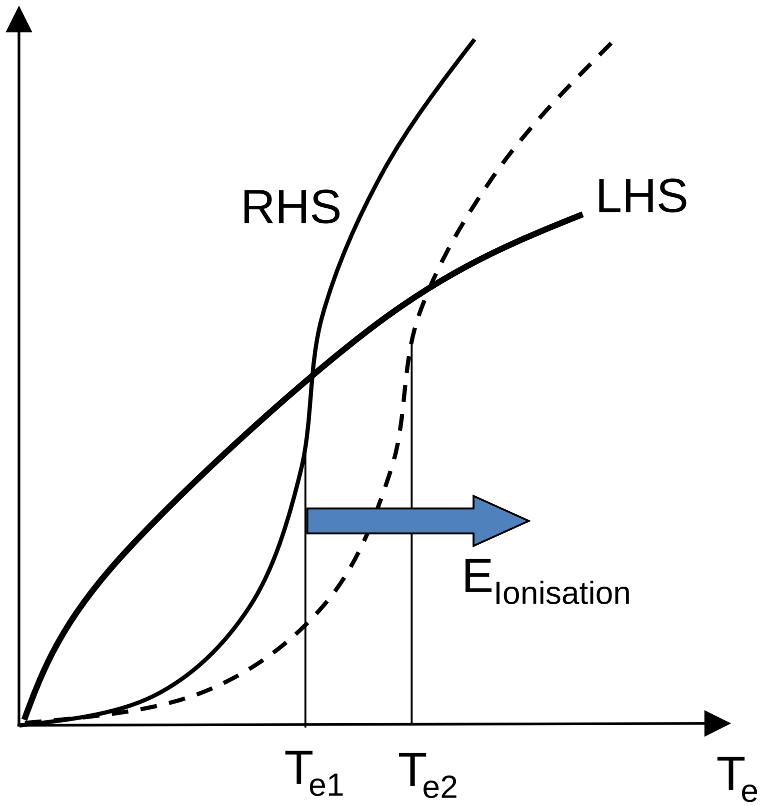


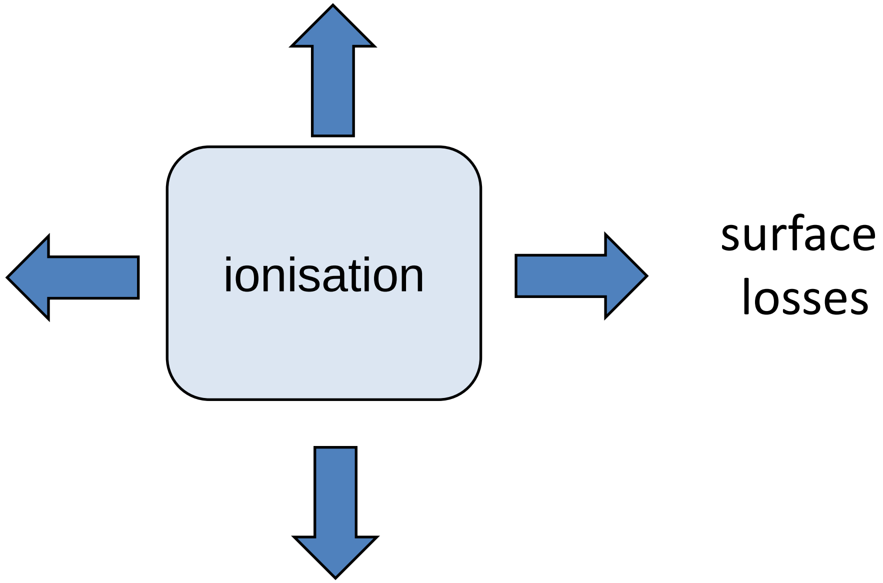


Working point of a Plasma – global model



Working point of a Plasma – global model





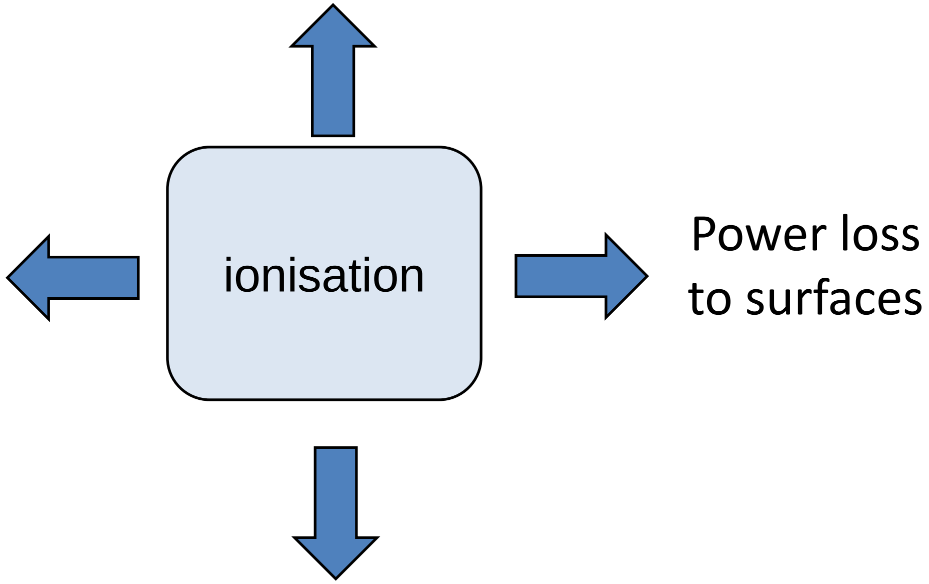
$$A n_0 v_B = n_g n_0 k_{Ionisation} V$$

$$k_{Ionisation} = k_0 e^{-\frac{E_{Ionisation}}{k_B T_e}}$$

$$A n_0 \sqrt{\frac{k_B T_e}{M}} = n_g n_0 k_0 e^{-\frac{E_{Ionisation}}{k_B T_e}} V$$

Particle balance determines Electron temperature

Working point of a Plasma – global model



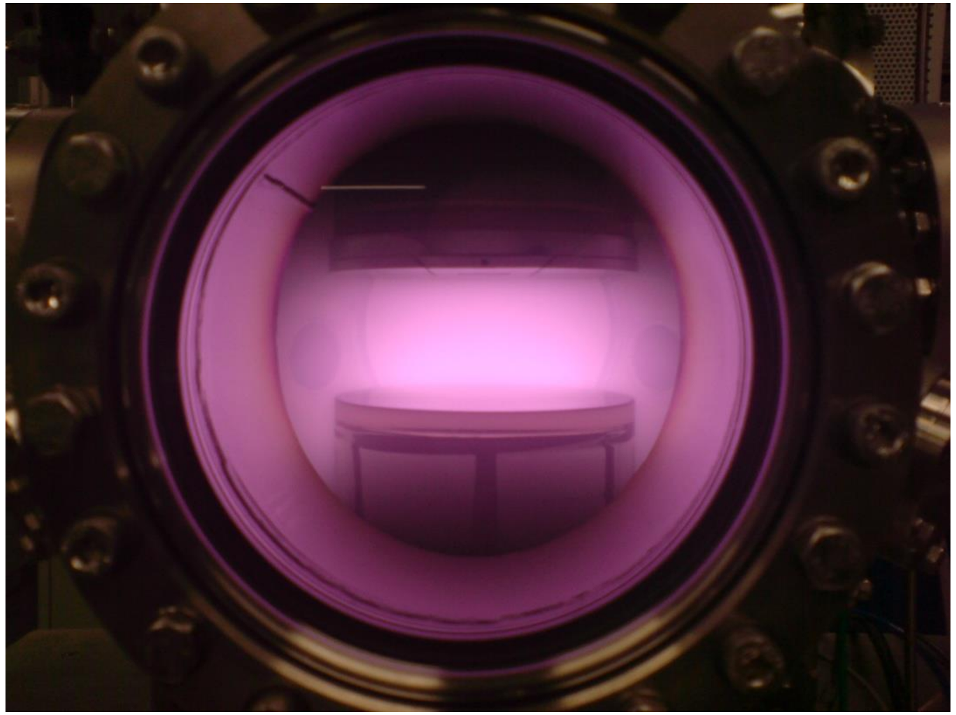
Absorbed power is a
complicated function
of electon density

$$P_{abs} = P_{\text{Verlust}} = n_0 v_B A \left(E_{Ionisation} + E_{Randschicht} \right)$$

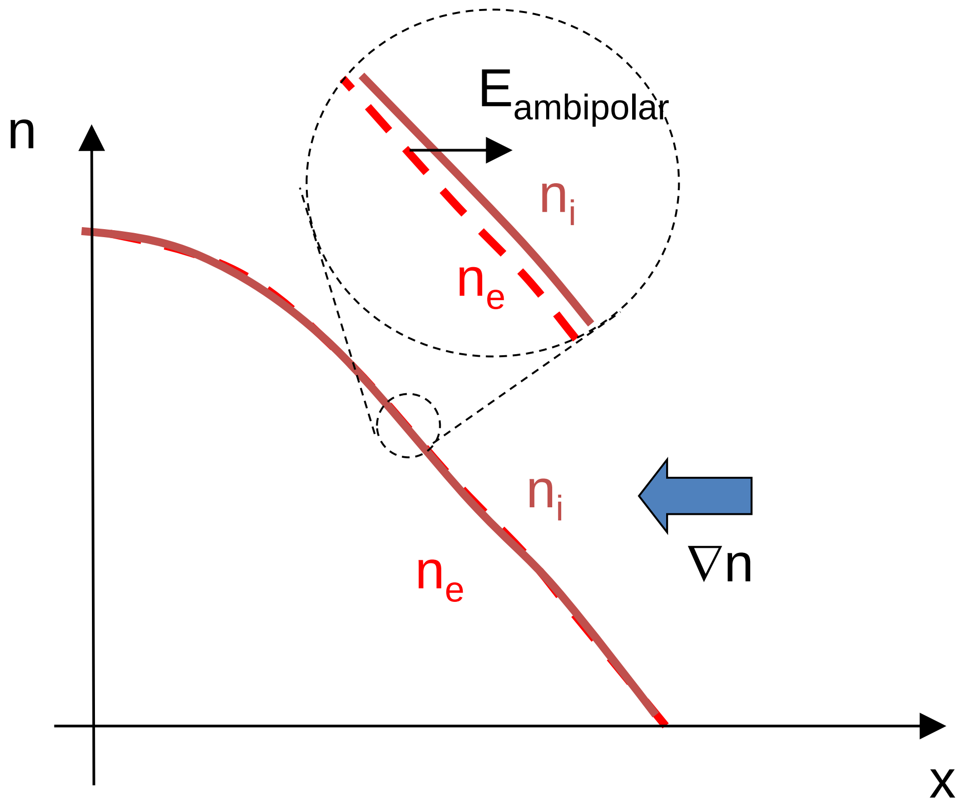
+ excitation,
+ electron loss to surfaces

Power balance determines
Electron density

Transport in a plasma



Transport in a plasma – motion as a fluid – ambipolar diffusion



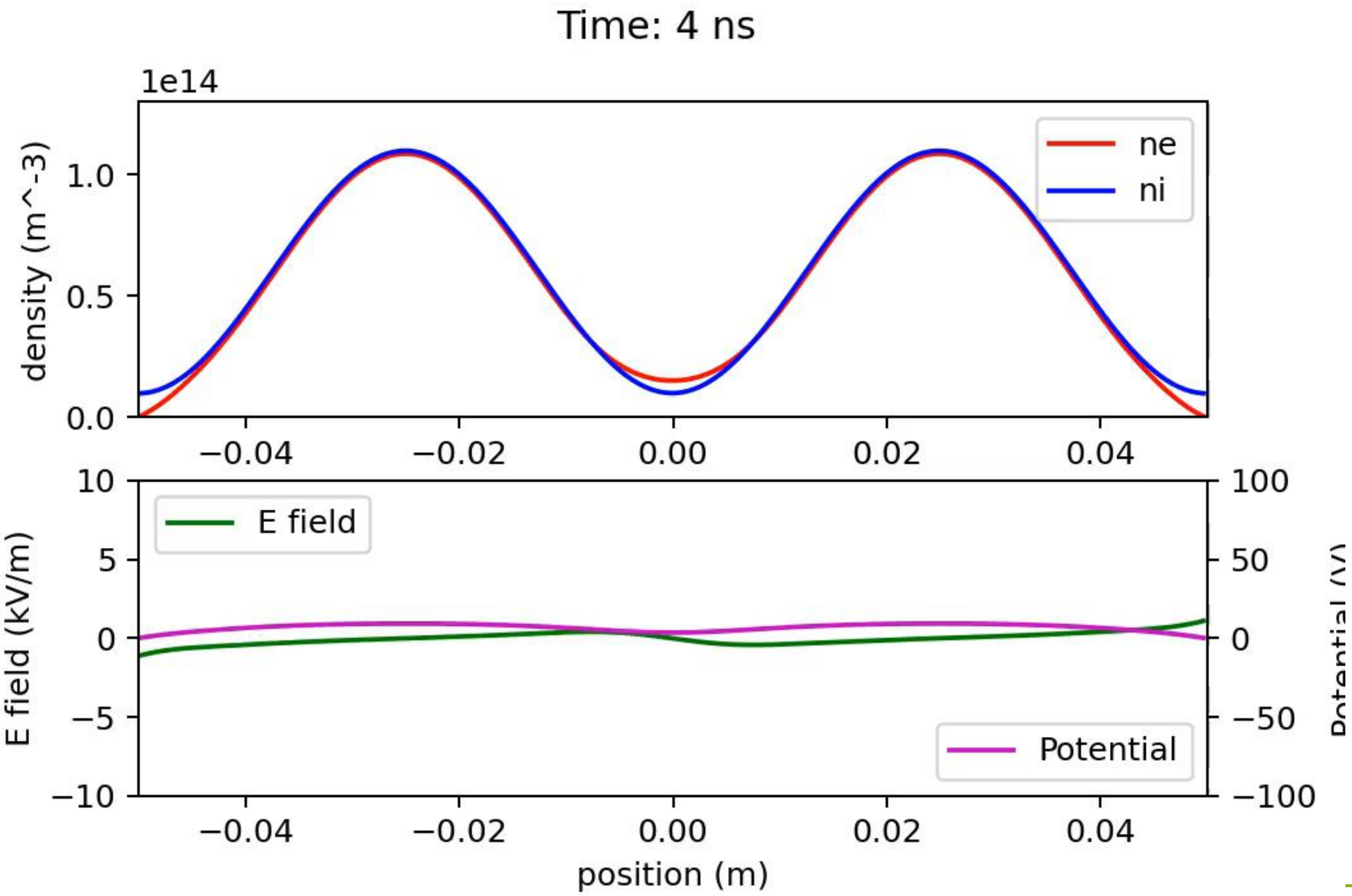
for $j_i = j_e,\ n_e = n_i$ $\quad \nabla n_e = \nabla n_i$

for $\mu_e \gg \mu_i .$ and Te>>Ti

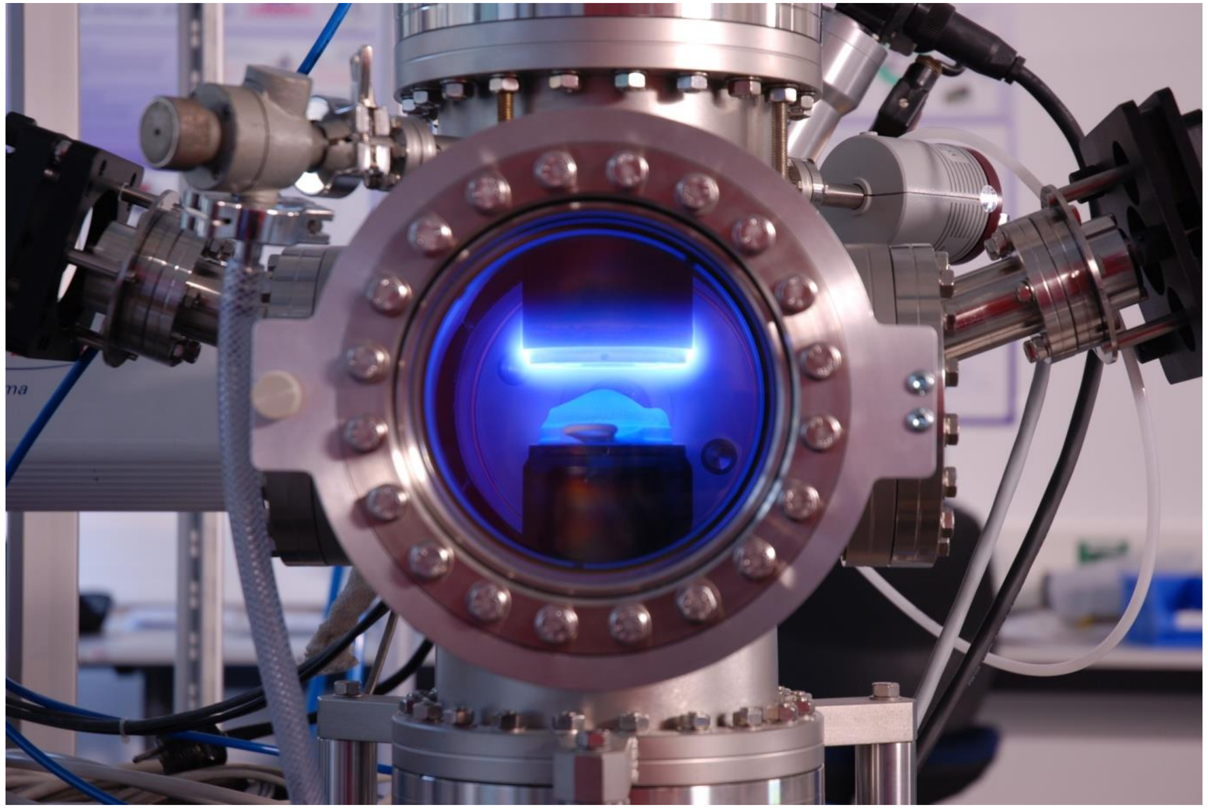
$$D_{amb} = D_i \frac{T_e}{T_i} = \frac{k_B T_e}{M \nu_{m,Ionen}}$$

$$\vec{E}_{amb} = \frac{D_i - D_e}{\mu_i + \mu_e} \frac{\nabla n}{n}$$

Transport in a plasma – motion as a fluid – ambipolar diffusion



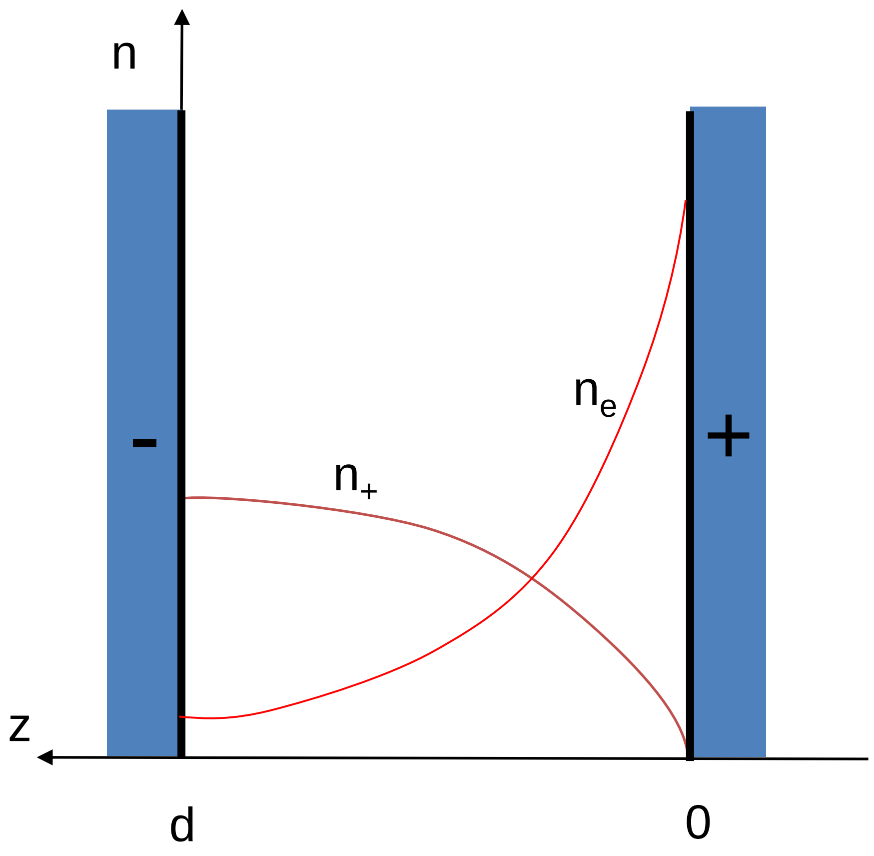
Ignition of a plasma

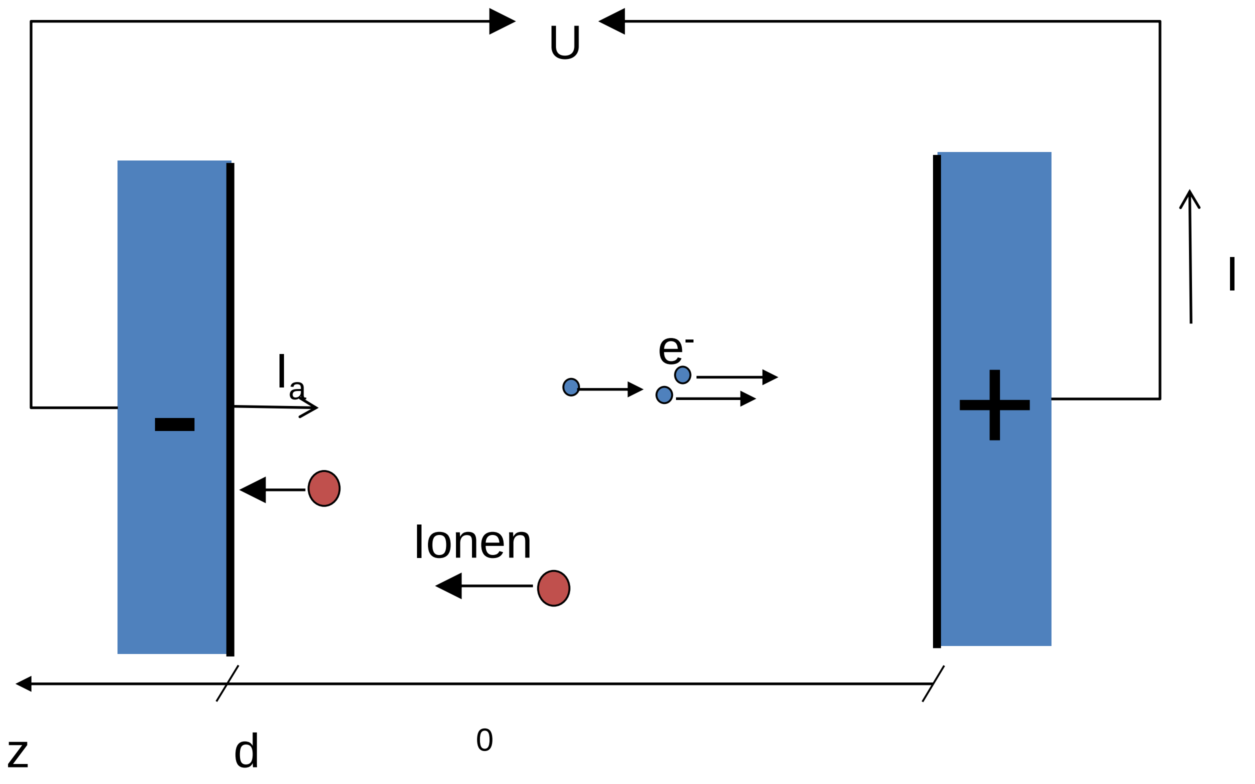


Ignition of a plasma – Townsend regime

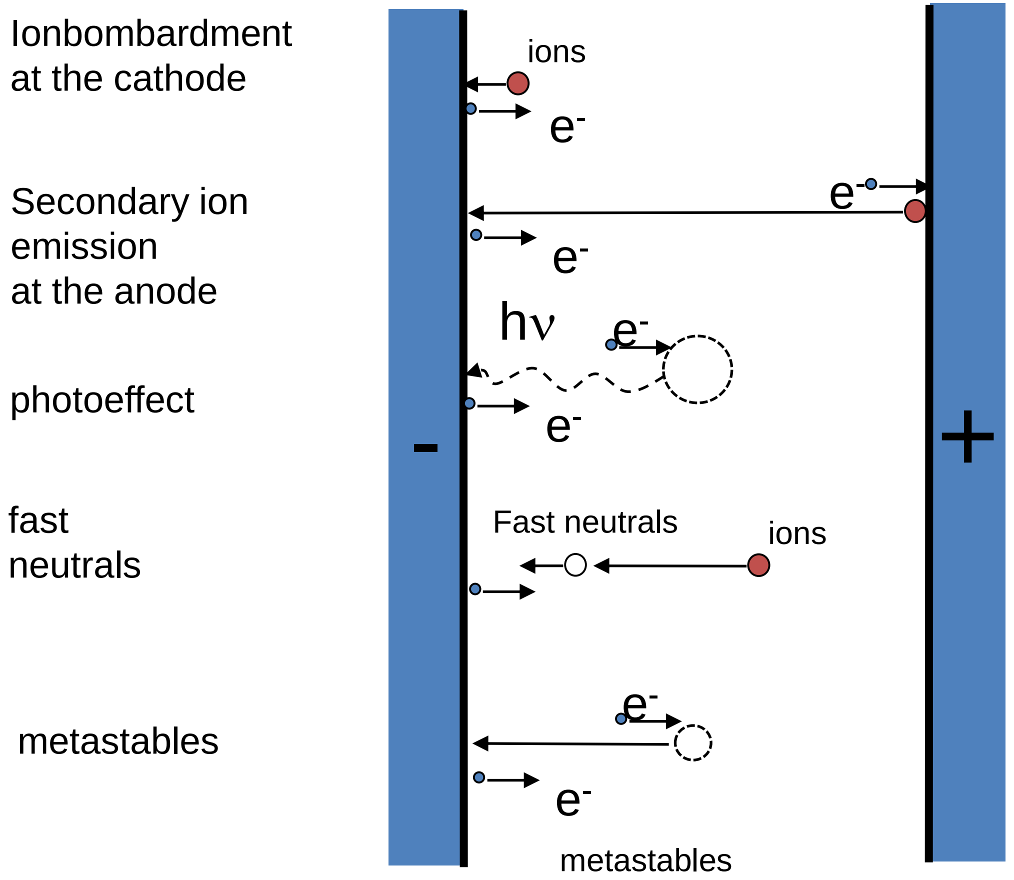
1. Townsend coefficient
gas amplification

$$\alpha = Ap\exp\left[-B\frac{pd}{V}\right]$$





Ignition of a plasma – Townsend regime – Secondary effects



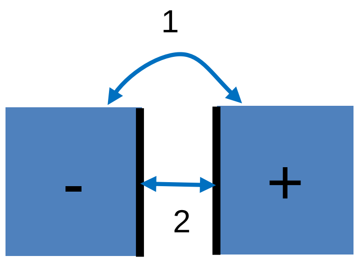
$$I = \underbrace{I_a e^{\alpha d}}_{\text{primary amplification}} \underbrace{\frac{1}{1-\gamma_i\left(e^{\alpha d}-1\right)}}_{\text{secondary amplification}}$$

$$\gamma\left(e^{\alpha d}-1\right) \equiv 1$$

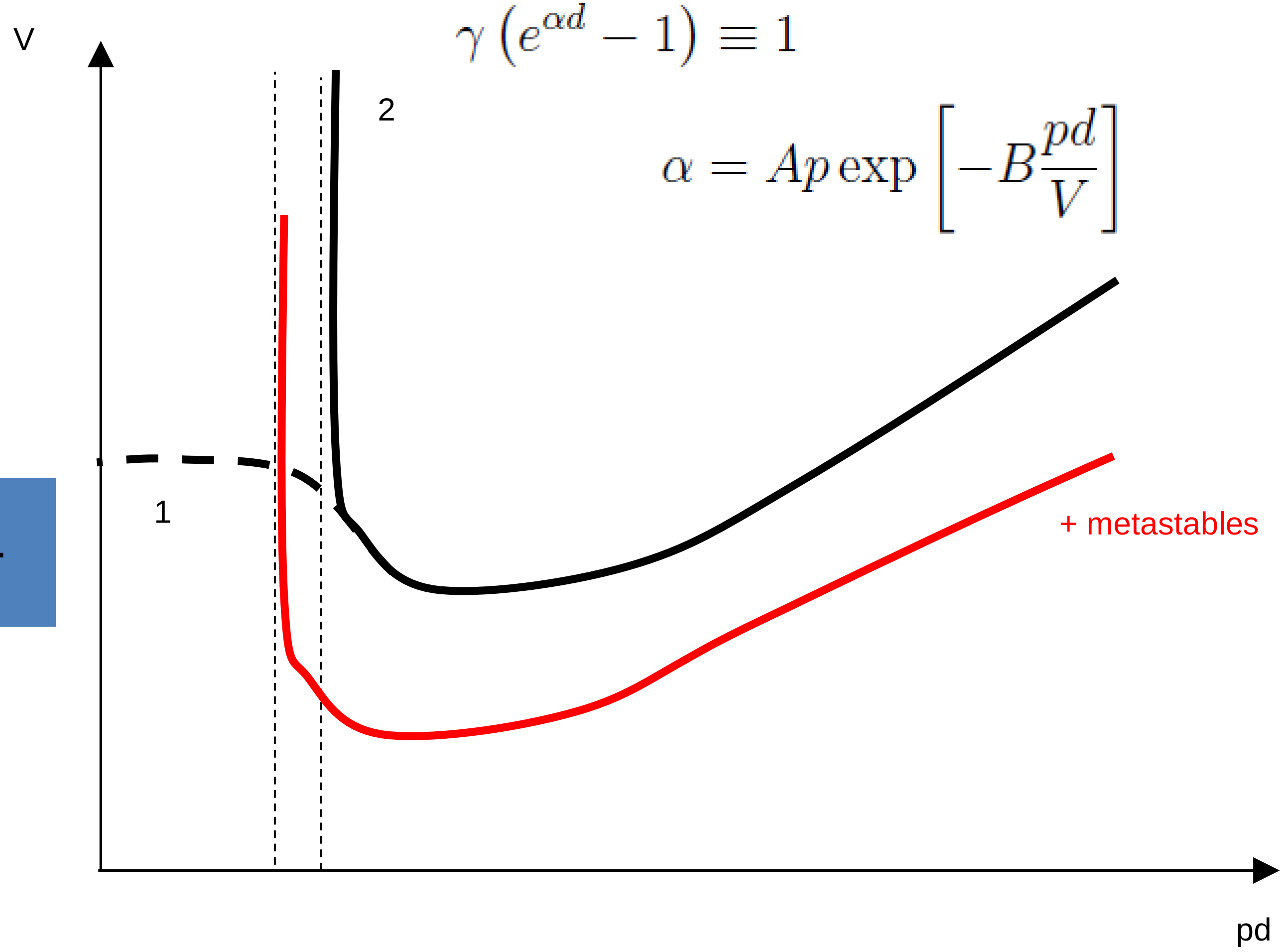
Ignition of a plasma – the Paschen curve

$$\gamma\left(e^{\alpha d}-1\right)\equiv 1$$

$$\alpha = Ap\exp\left[-B\frac{pd}{V}\right]$$



long path
breakdown

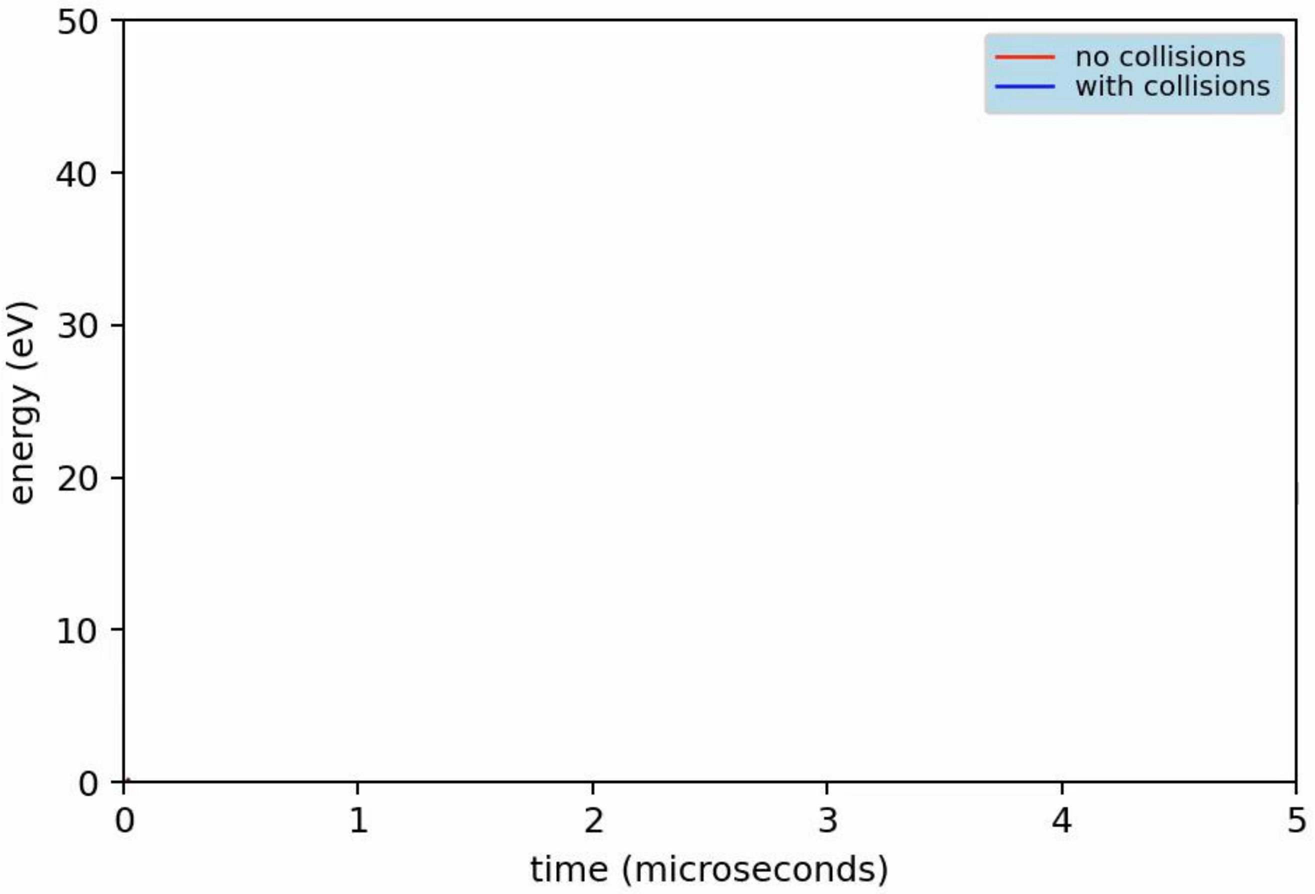


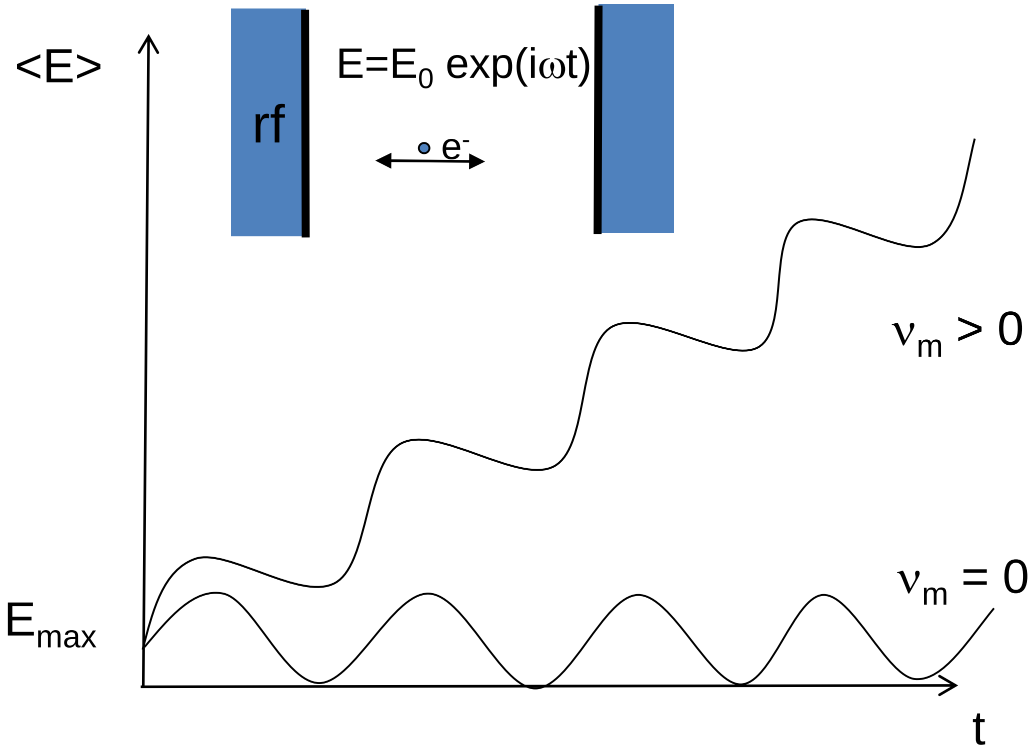
	$A[\mathrm{cm}^{-1}\mathrm{Torr}^{-1}]$	$B[\mathrm{V\ cm}^{-1}\mathrm{Torr}^{-1}]$	$e\frac{B}{A}$ [eV]
He	1.8	50	27.5
Ar	12	200	16.7
H_2	10.6	350	33
CO_2	20	466	23.3

$$V = \frac{Bpd}{\ln(Apd) - \ln[\ln(1+\gamma^{-1})]}$$

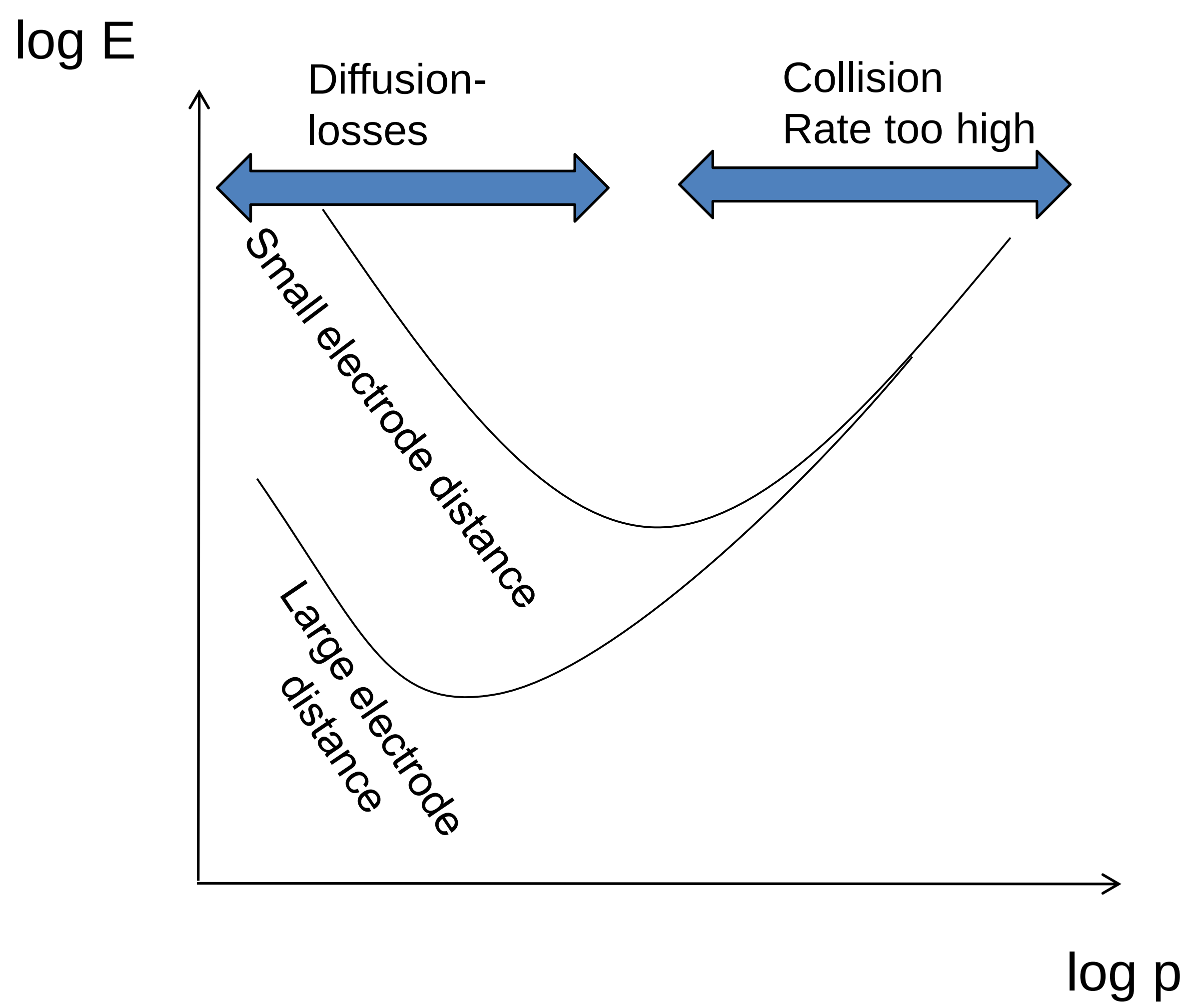
Ignition of a plasma – rf-voltages

Collisions are essential to heat a high frequency plasmas

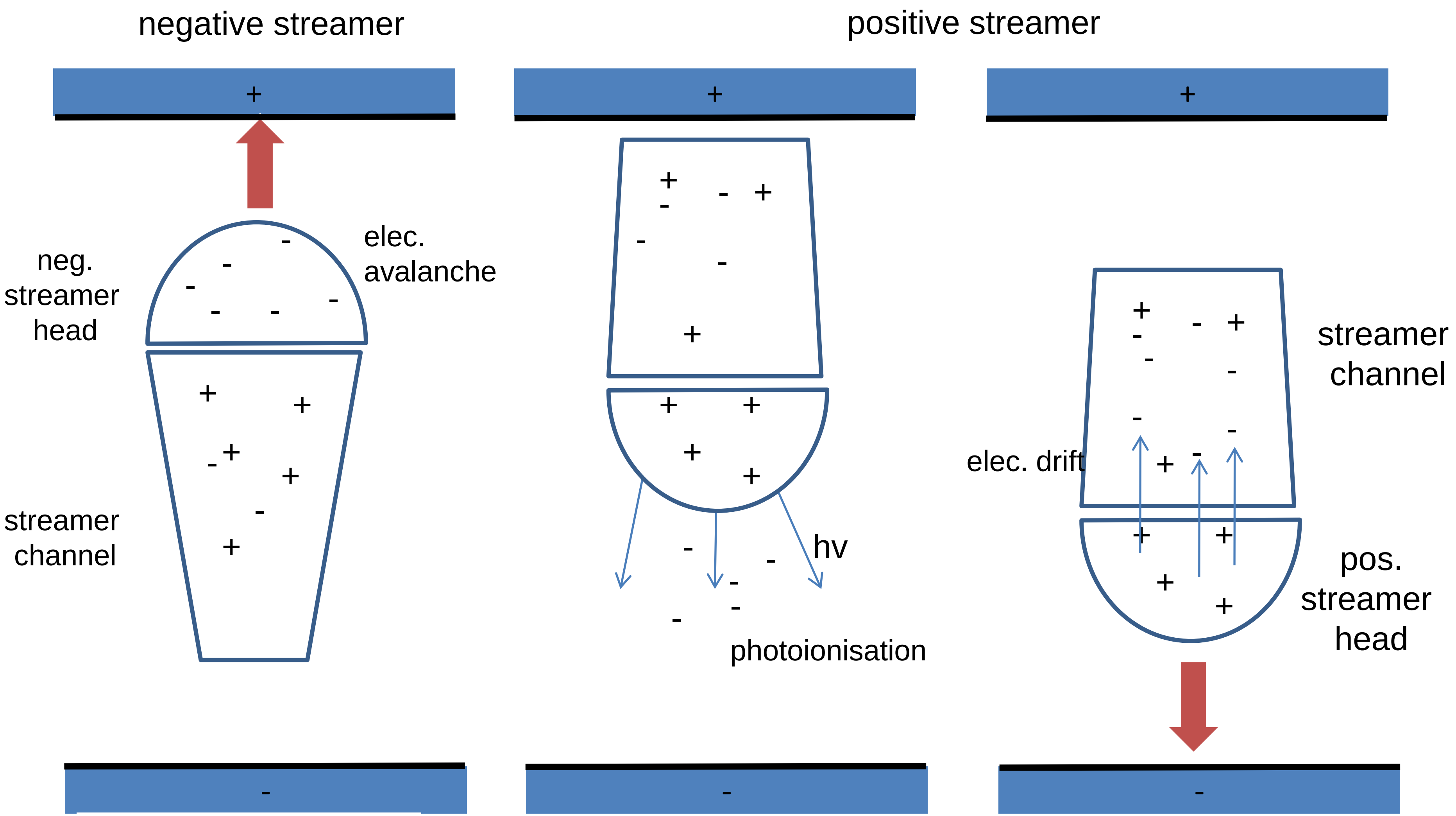


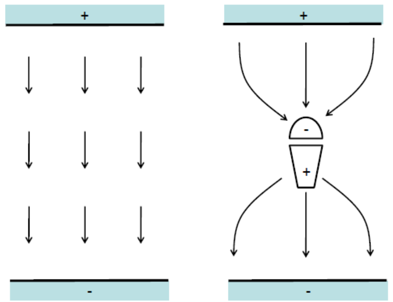


Ignition of a plasma – Paschen curve for rf-voltages



Ignition of a plasma – High presssure - streamers





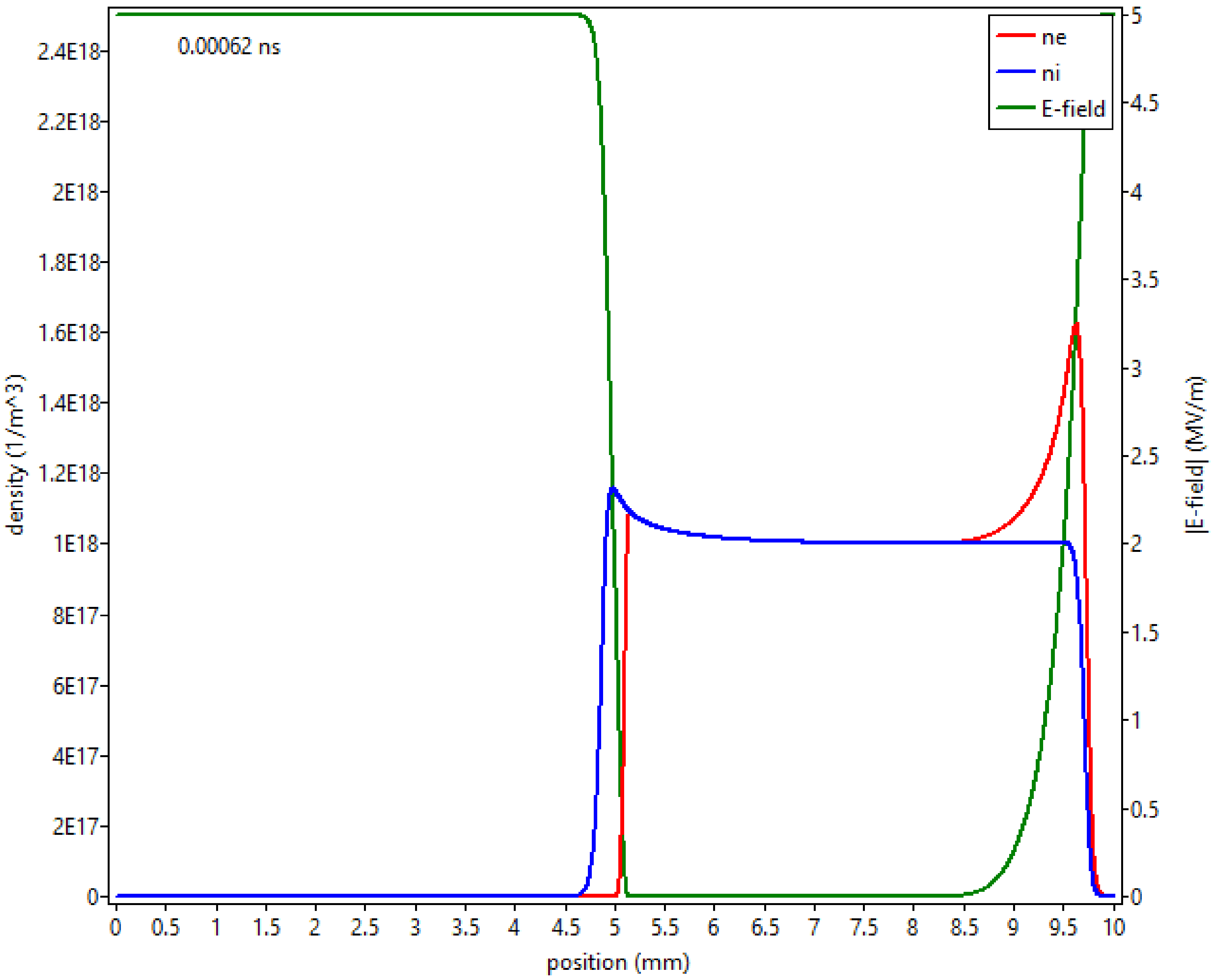
$$E_a = \frac{e}{4\pi\epsilon_0 R^2} e^{\alpha d}$$

$$R = \frac{1}{\alpha}.$$

$$\alpha d = \ln \frac{4\pi\epsilon_0 E_0}{e\alpha^2} \approx 20$$

Meek criterion

Ignition of a plasma – High presssure - streamers



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Ignition of a plasma – High presssure - streamers

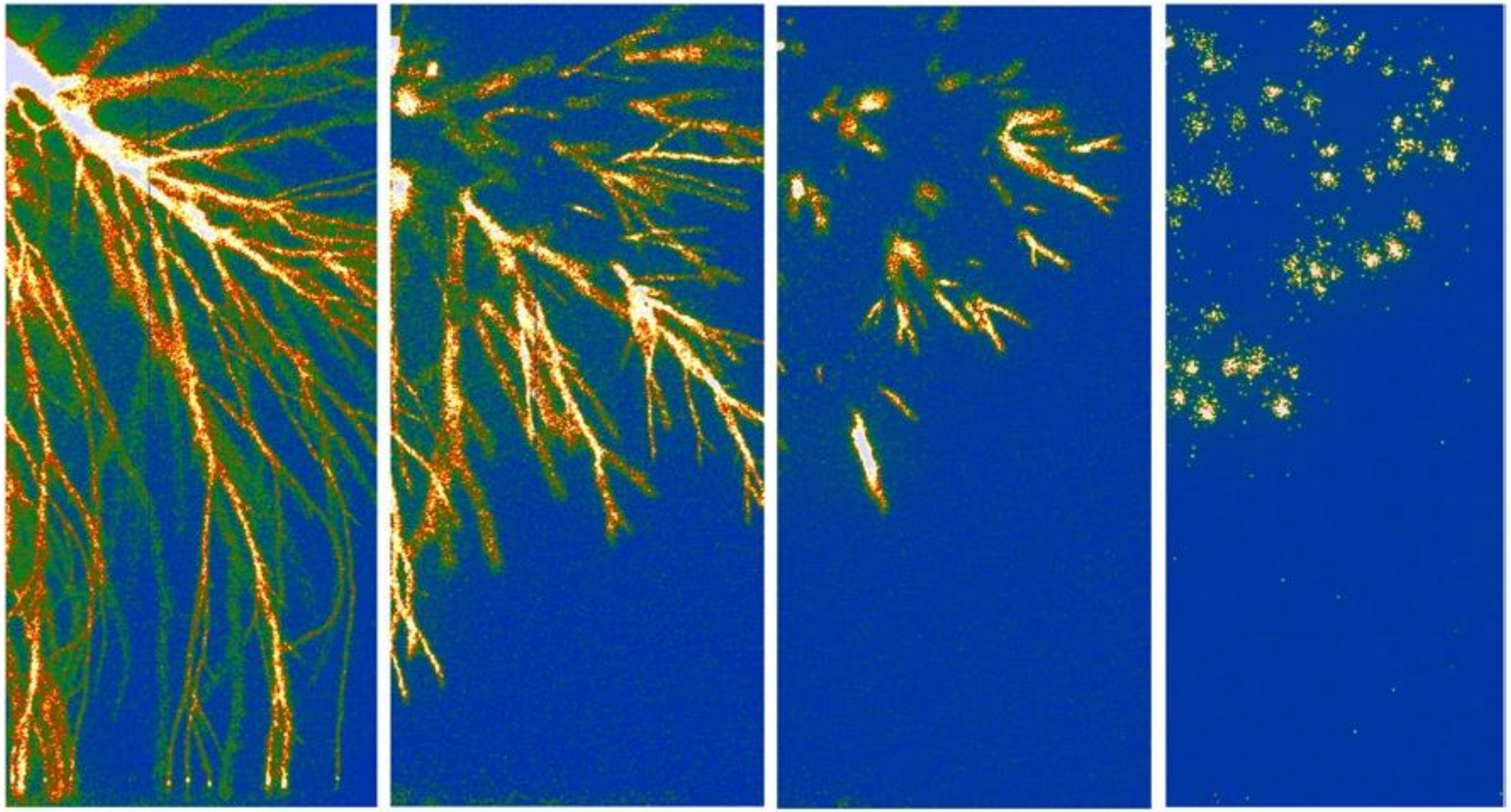
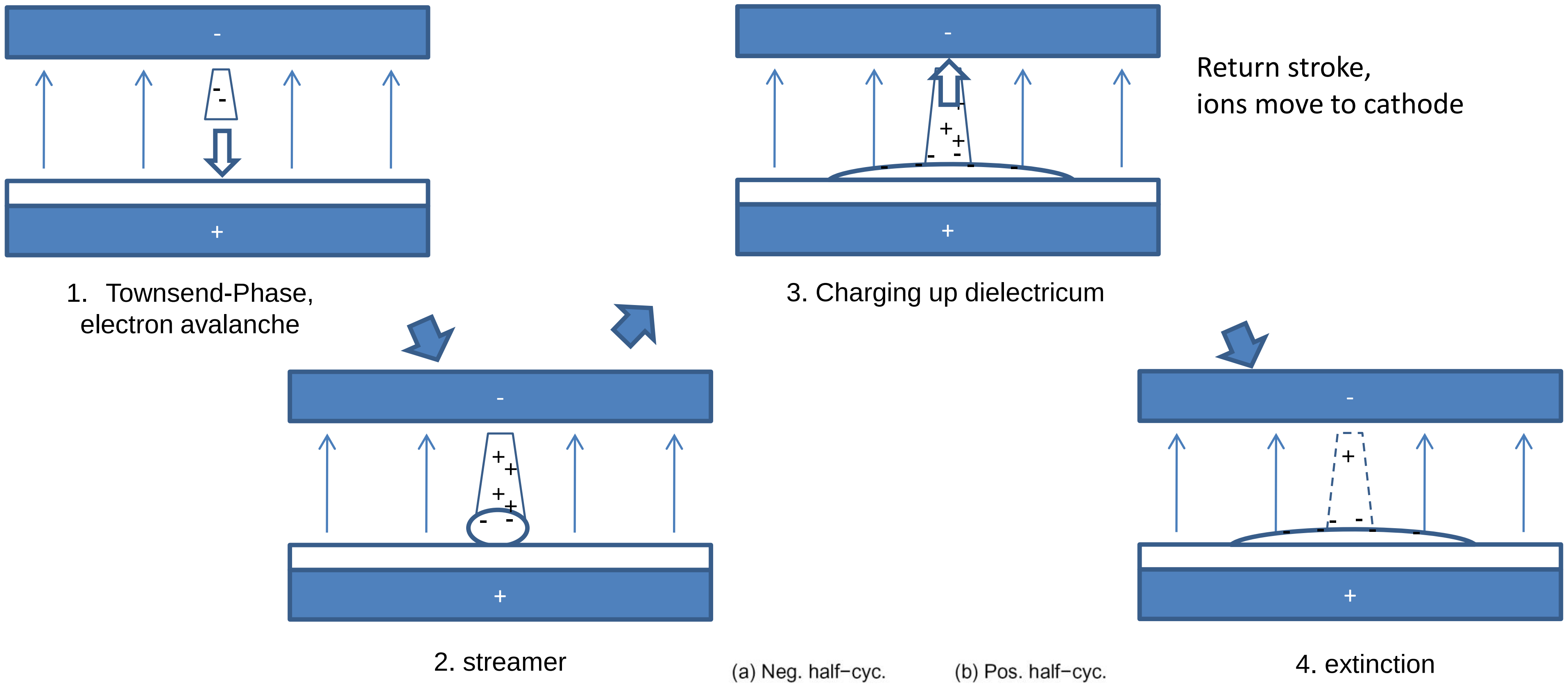
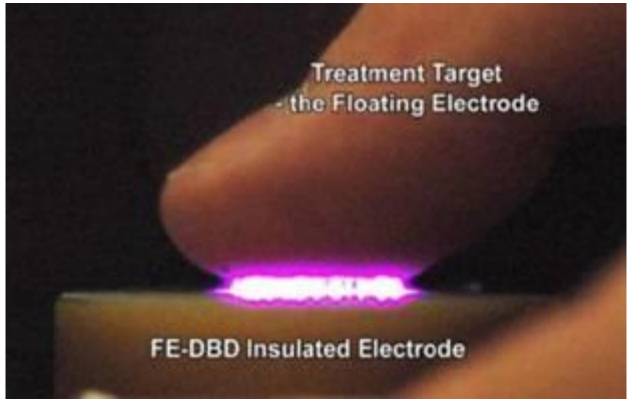
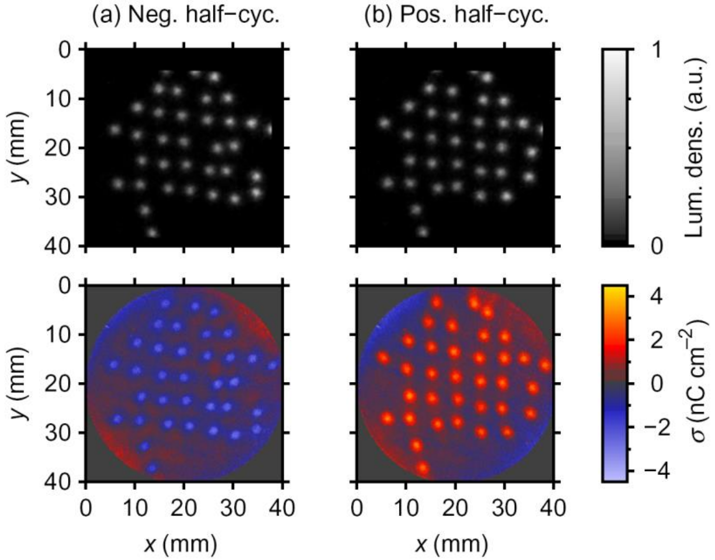


Abbildung 2.14: Photographie einer Streamerentladung bei unterschiedlichen Belichtungszeiten. [U. Ebert et al. *The multiscale nature of streamers*, Plasma Sources Science and Technol. 15, S118 (2006)]

Sustaining a plasma – barrier discharges







from L. Stollenwerk,
New Journal of Physics 11,
103034 (2009)

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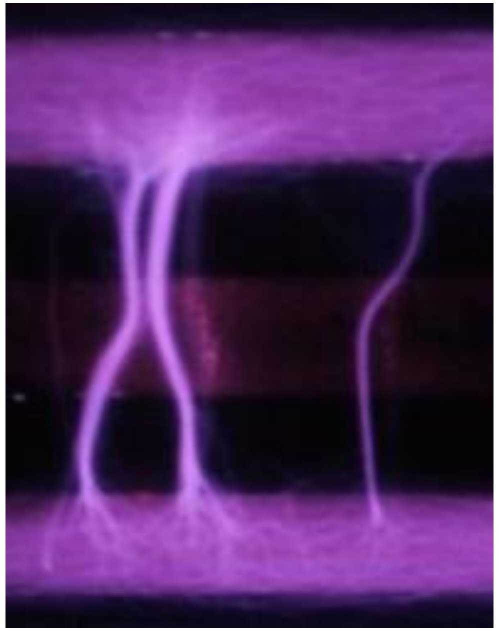
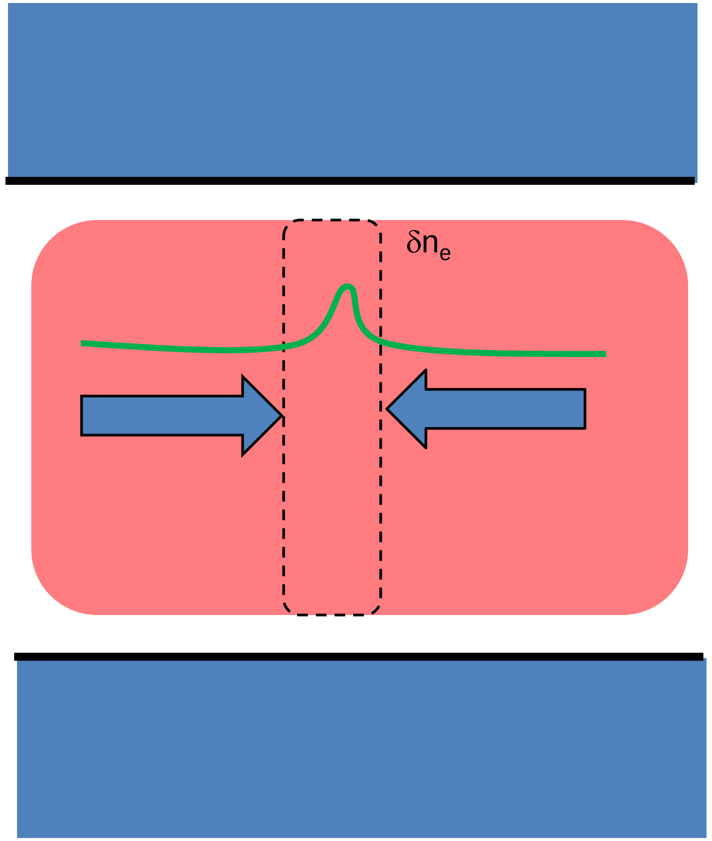
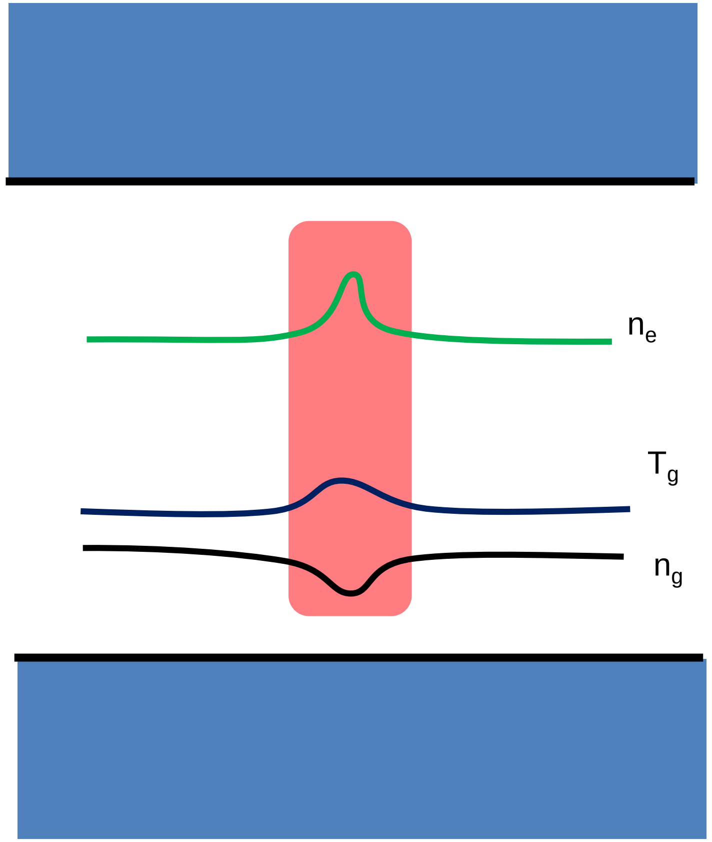
Sustaining a plasma – high pressure discharges - filamentation







Summary

1. What is a plasma ?

- Temperature
- Debye shielding
- Plasma frequency

$$f(v) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} e^{\frac{-\frac{1}{2}mv^2}{k_B T}} \qquad \omega_p = \left(\frac{ne^2}{\epsilon_0 m}\right)^{1/2} \qquad \lambda_D = \left(\frac{\epsilon_0 k_B T}{n_0 e^2}\right)^{1/2}$$

2. The edge of a plasma

- Sheath physics

$$v_0 > \sqrt{\frac{k_B T_e}{M}} = v_B$$

3. Transport on a plasma

- Particle motion
- Plasma as a fluid
- Drift and diffusion

$$\vec{j} = \mu_i n_i \vec{E} - D_i \nabla n_i$$

4. How to ignite a plasma

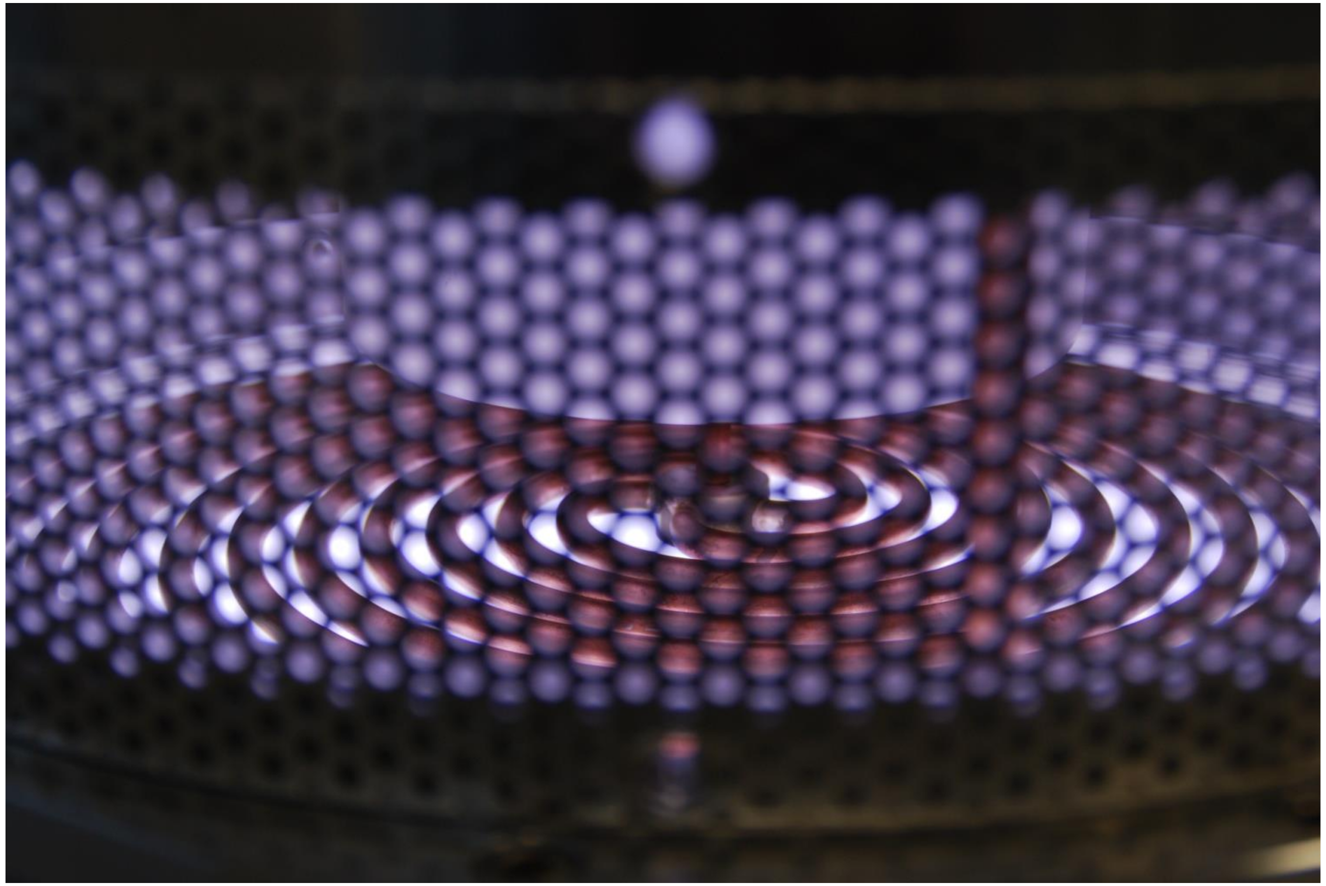
- Ignition, Paschen curve
- Streamer
- RF-ignition

$$V = \frac{Bpd}{\ln(Apd) - \ln[\ln(1+\gamma^{-1})]}$$

5. How to sustain a plasma

- DC plasma
- Rf-plasmas
- Plasma heating

Sustaining a plasma

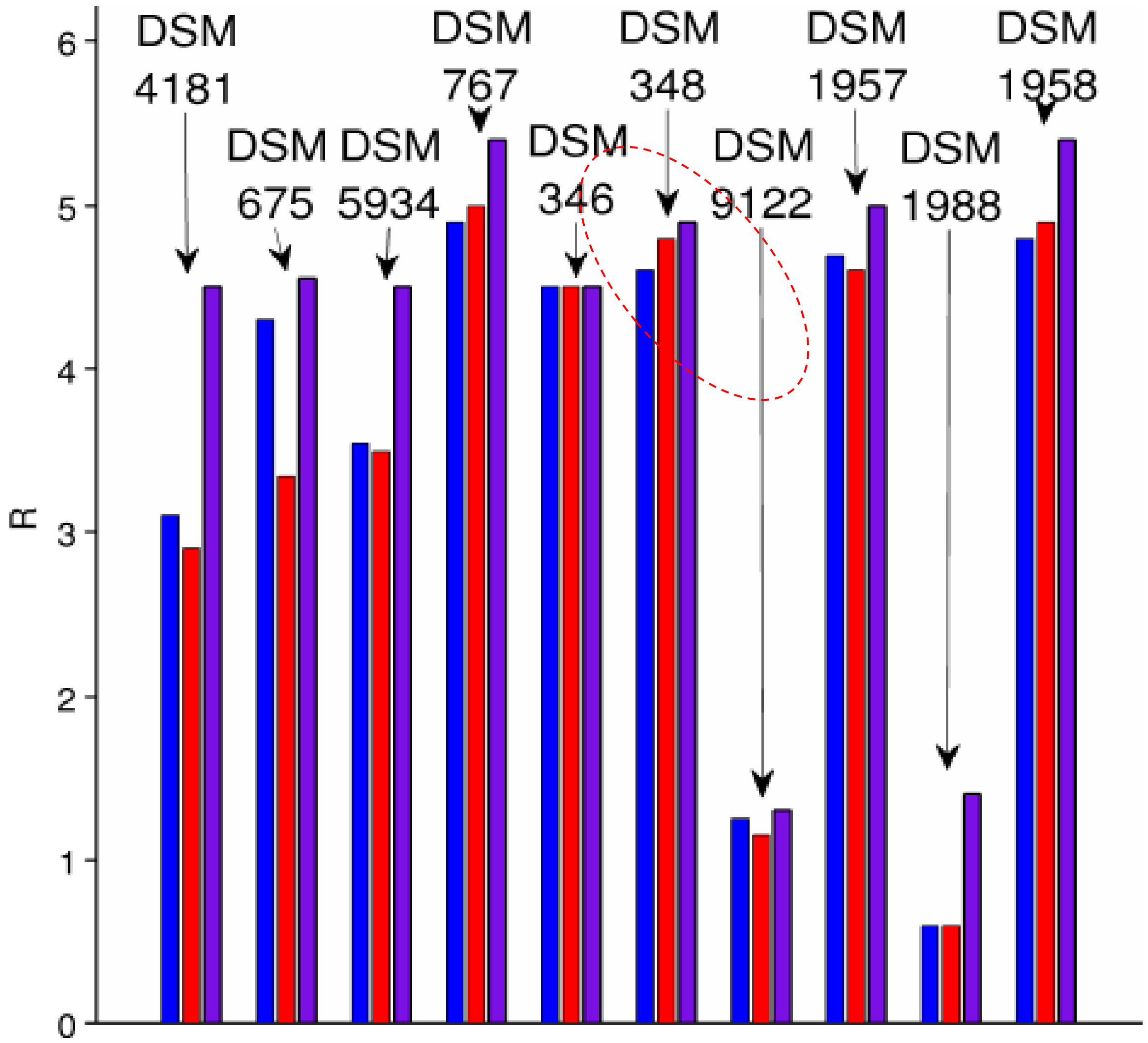


Sterilisation of bacteria and fungi

Plasma optimisation:
Study of effects of different plasmas on bacteria

10 s plasma treatment

Logaritmic reduction after 10s of plasma treatment

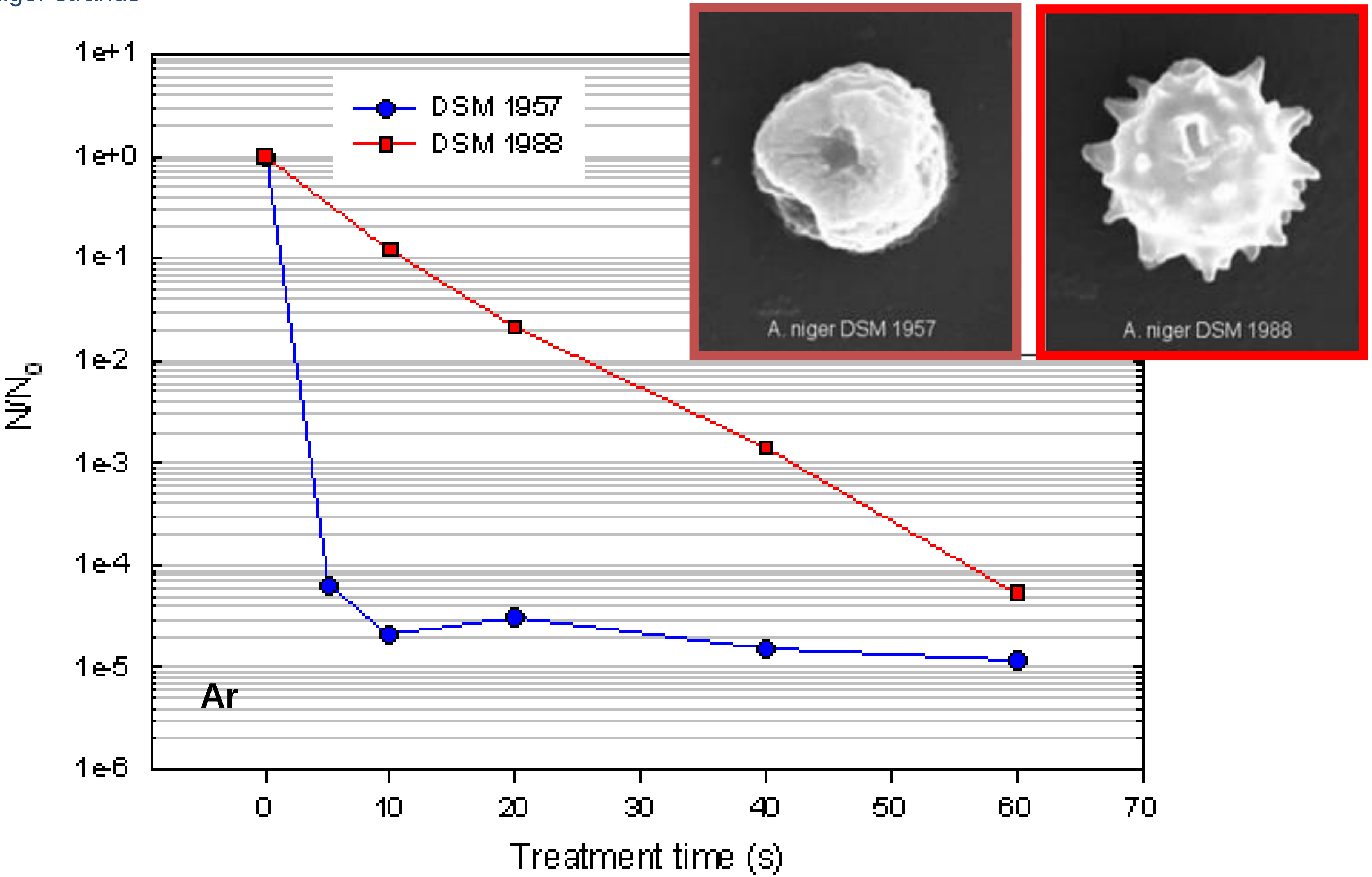


BioDecon-Plasma parameter:
P=150 W; p=10 Pa; t=10 s
Ar Ar:H2 Ar:O2

DSM 4181: *B. subtilis SA22* (sp.)
DSM 675: *B. atrophaeus* (sp.)
DSM 5934: *Geob. stearothermophilus* (sp.)
DSM 767: *Clostridium sporogenes* (sp.)
DSM 346: *Styphylococcus aureus* (veg.)
DSM 348: *Kocuria rhizophila* (veg.)
DSM 9122: *Scopulariopsis brevicaulis* (sp.)
DSM 1957: *A. niger* (fungi)
DSM 1988: *A. niger* (fungi)
DSM 1958: *A. terreus* (fungi)

Sterilisation of Aspergillus Niger

Survival curves of different aspergillus niger strands



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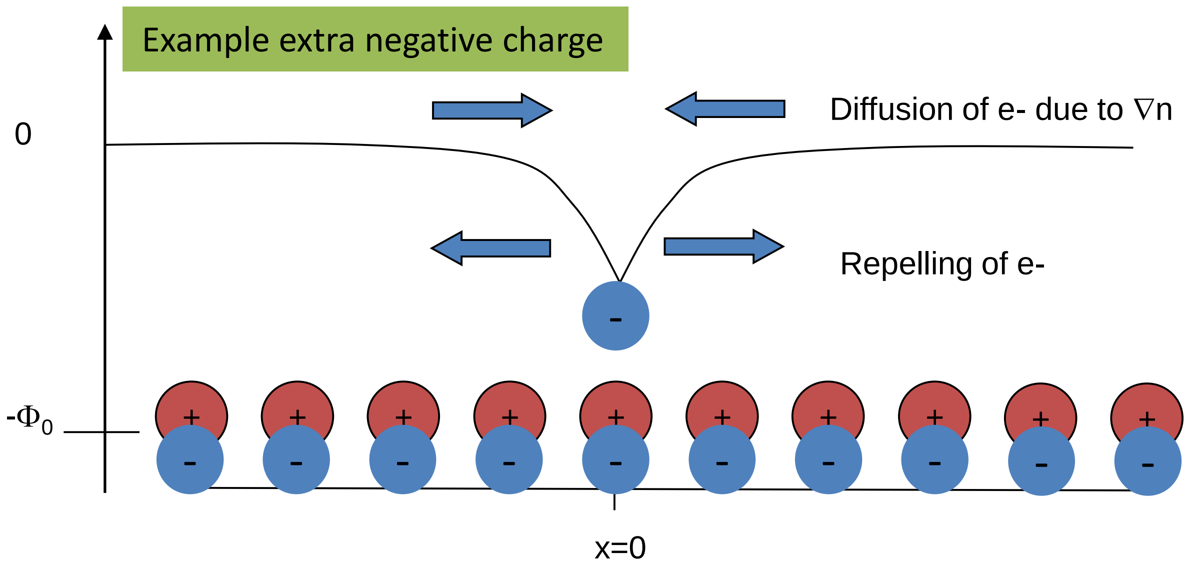
What is a plasma ? - Concept 2 – Debye shielding (in formulas)



$$n_e = n_0 e^{\frac{e\Phi(x)}{k_B T}}$$

$$\epsilon_0 \frac{d^2\Phi}{dx^2} = e n_0 \left(e^{\frac{e\Phi(x)}{k_B T}} - 1 \right)$$

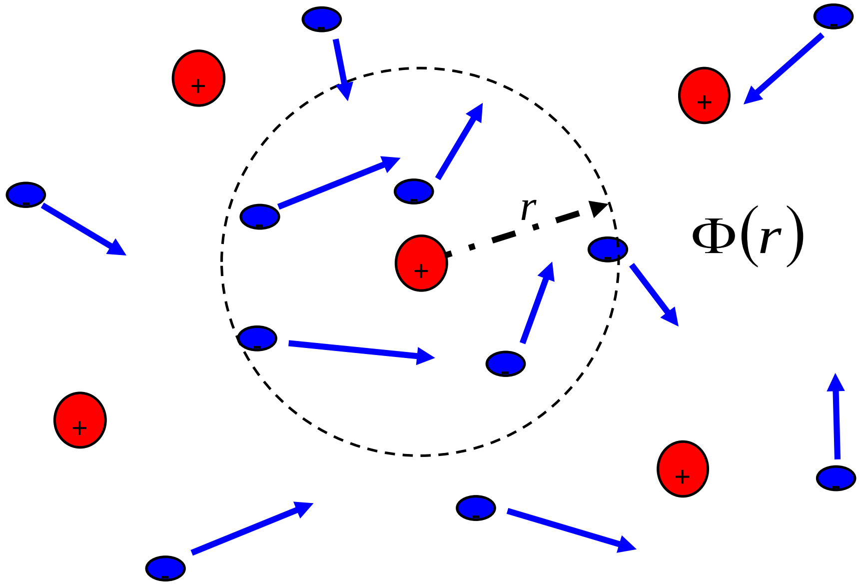
with $\frac{e\Phi}{k_B T} \ll 1$

$$\epsilon_0 \frac{d^2\Phi}{dx^2} = e n_0 \left(1 + \frac{e\Phi(x)}{k_B T} + ... - 1 \right) \simeq e n_0 \frac{e\Phi}{k_B T}$$

$$\frac{d^2\Phi}{dx^2} = \frac{n_0 e^2}{\epsilon_0 k_B T} \Phi \quad \rightarrow \quad \Phi = \Phi_0 e^{-\frac{|x|}{\lambda_D}}$$

What is a plasma ? - Concept 3 – Collective phenomena – the plasma parameter

$$N_D = \frac{4\pi}{3}\lambda_D^3 n \gg 1$$



What is a plasma ? - Concept 4 –the plasma frequency (numbers)

electrons

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \simeq 60\sqrt{n_e\,[10^{16} m^{-3}]}$$

$$f_{pe} \simeq 9\sqrt{n_e\,[10^{16} m^{-3}]}$$

ions

$$\omega_{pi} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_i}} \simeq 1.4\sqrt{\frac{n_e\,[10^{16} m^{-3}]}{A\,[amu]}}$$

$$f \simeq 0.2\sqrt{\frac{n_e\,[10^{16} m^{-3}]}{A\,[amu]}}$$

Assume:
100 MHz RF plasma in Ar
$n_e = 10^{16}$ m^{-3}

$$f_{pe} \simeq 9 \times 10^8 s^{-1} \rightarrow \tau = 1.1 \times 10^{-9} s$$

$$f_{pi} \simeq 3 \times 10^6 s^{-1} \rightarrow \tau = 0.3 \times 10^{-6} s$$

Electrons can easily follow the RF cycle,

ions can NOT !!