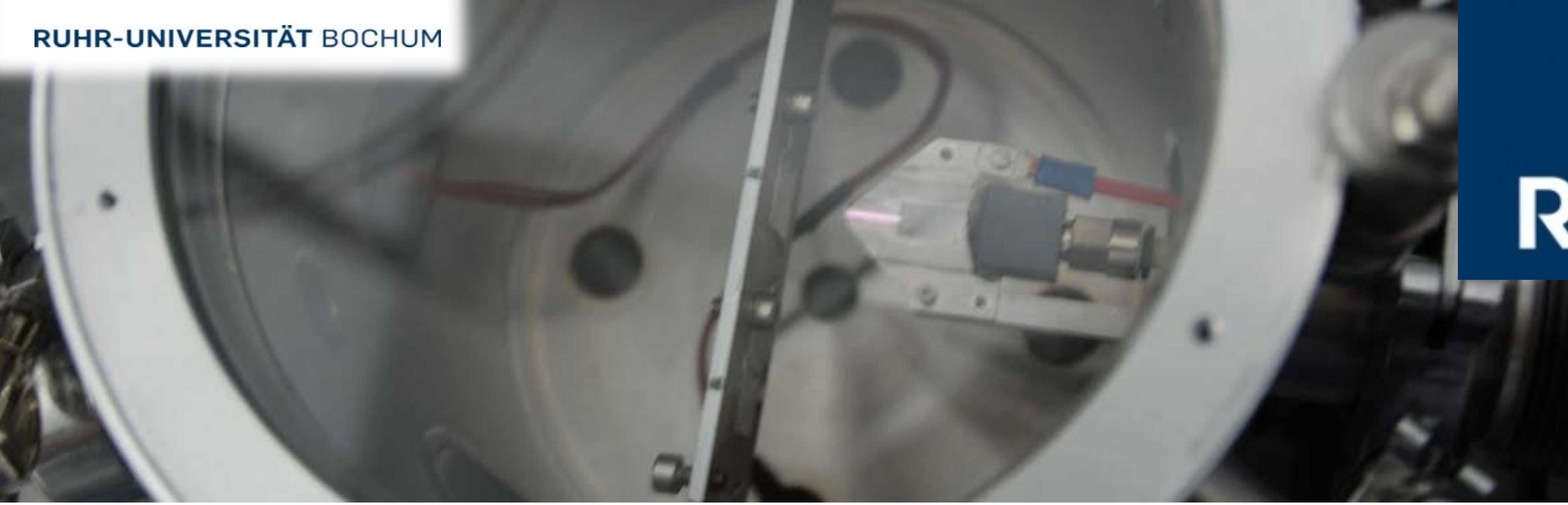

Fundamentals of Plasmas

Achim von Keudell

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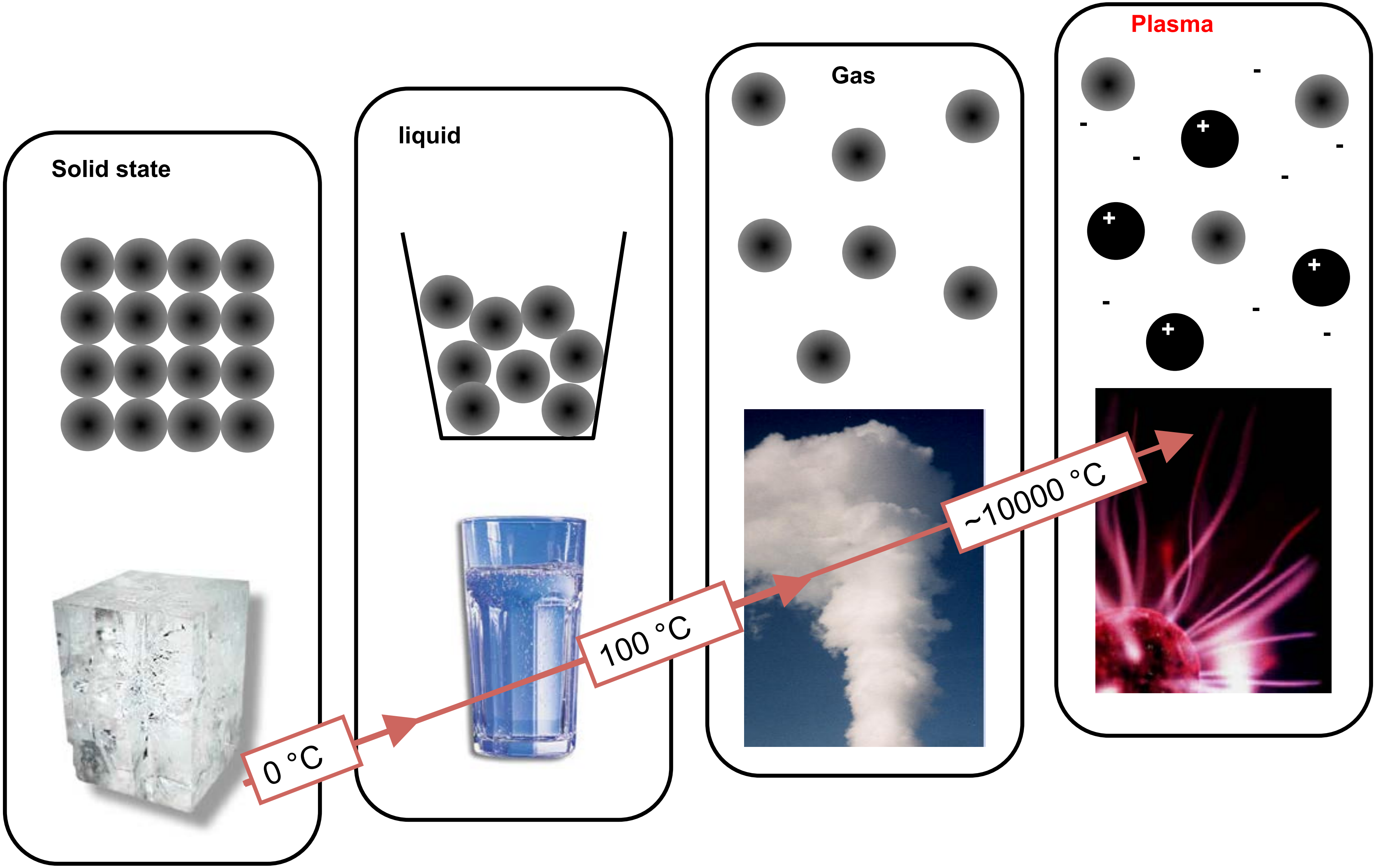
Ruhr-Universität Bochum

RESEARCH DEPARTMENT
Plasmas with Complex Interactions

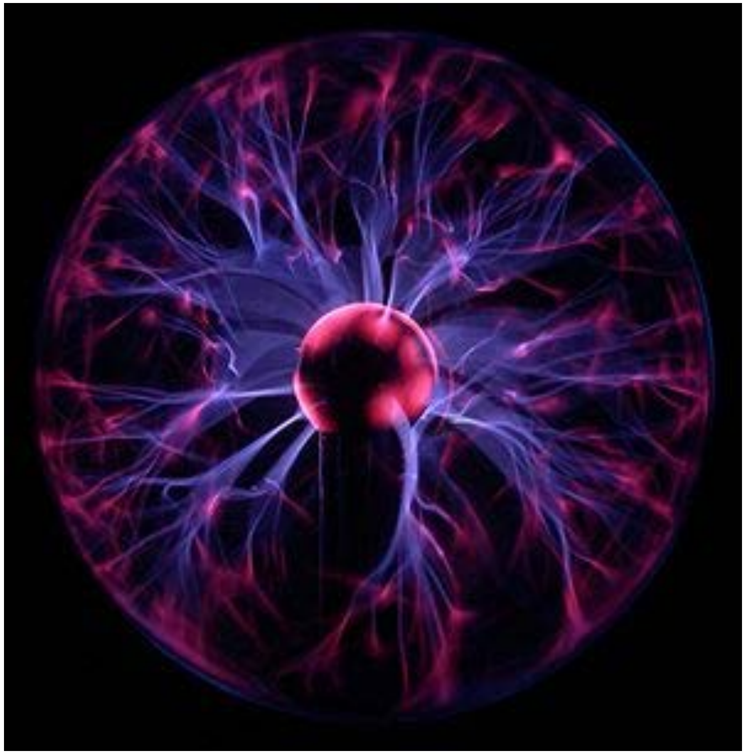
DFG FORSCHERGRUPPE 1123
Physics of Microplasmas

Plasma as the fourth state of matter



Definition

Plasma is a (hot) ionized gas with reactive particles like electrons, ions, and radicals.



More than 99% of visible matter is plasma.

Plasmas in the universe

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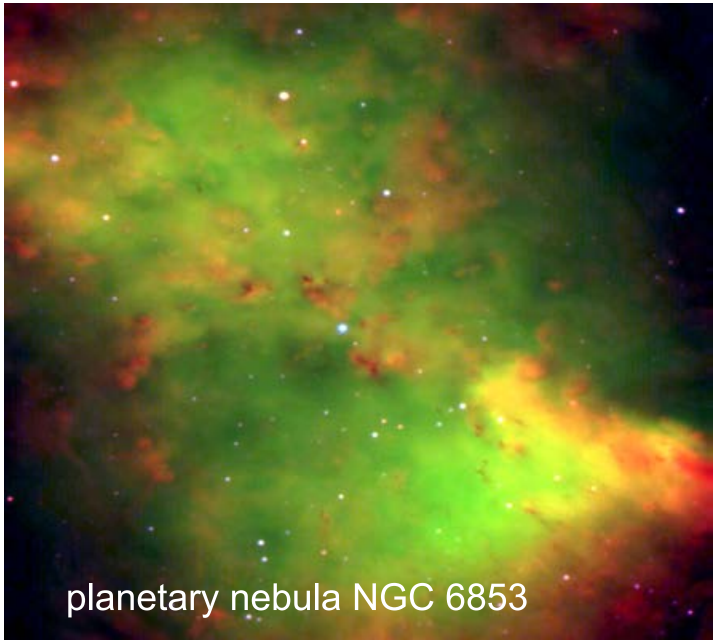
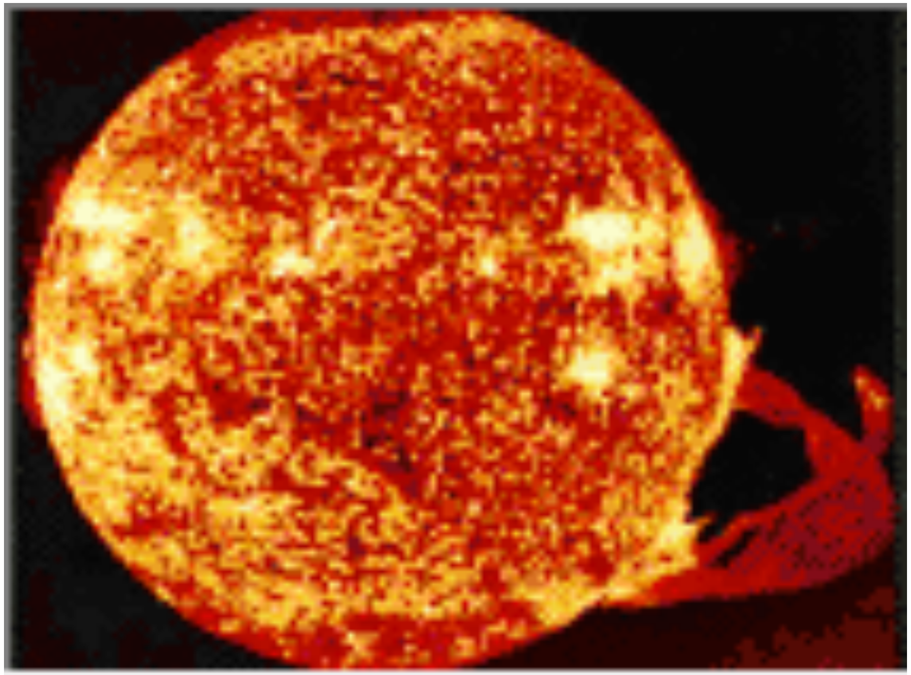
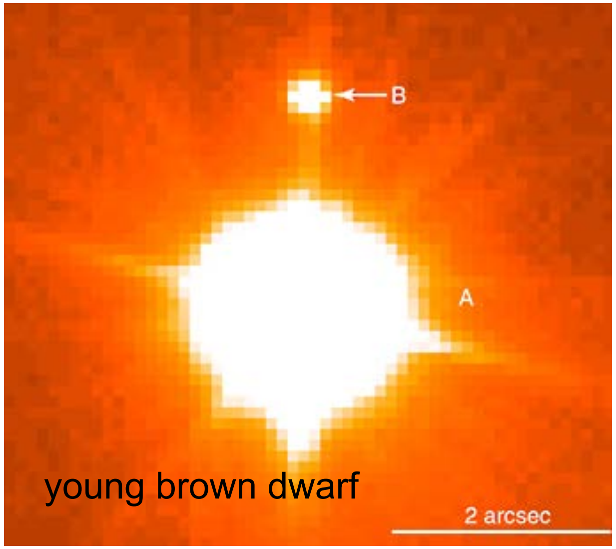
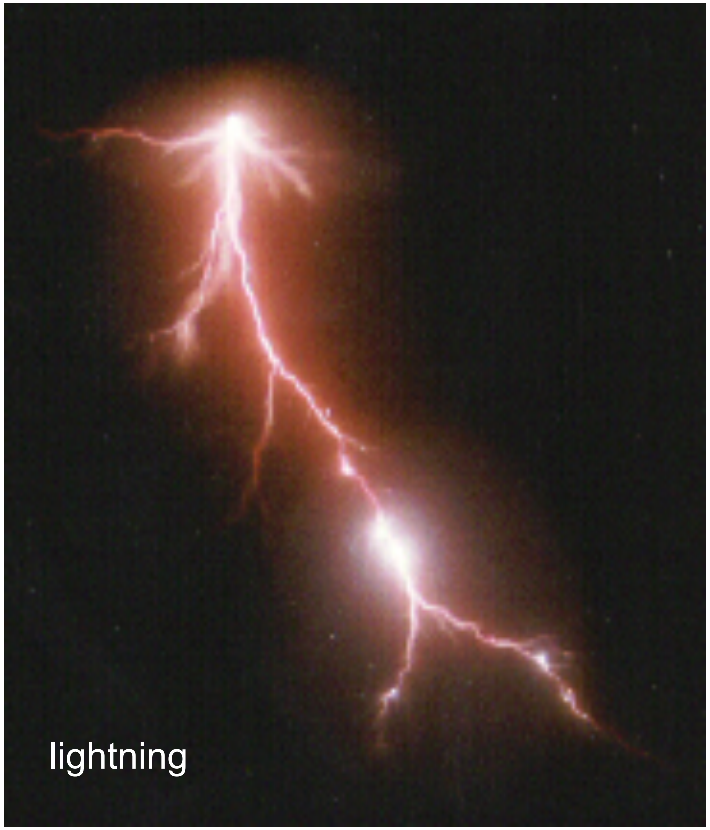
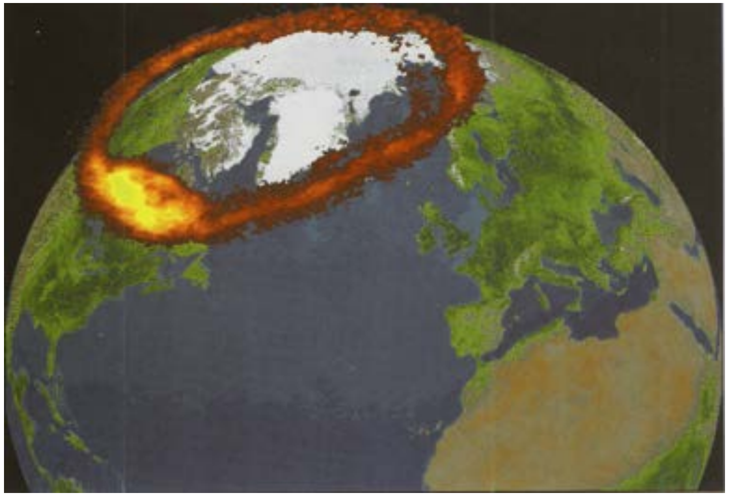






Natural plasmas on earth





Low temperature plasmas for our daily lifes

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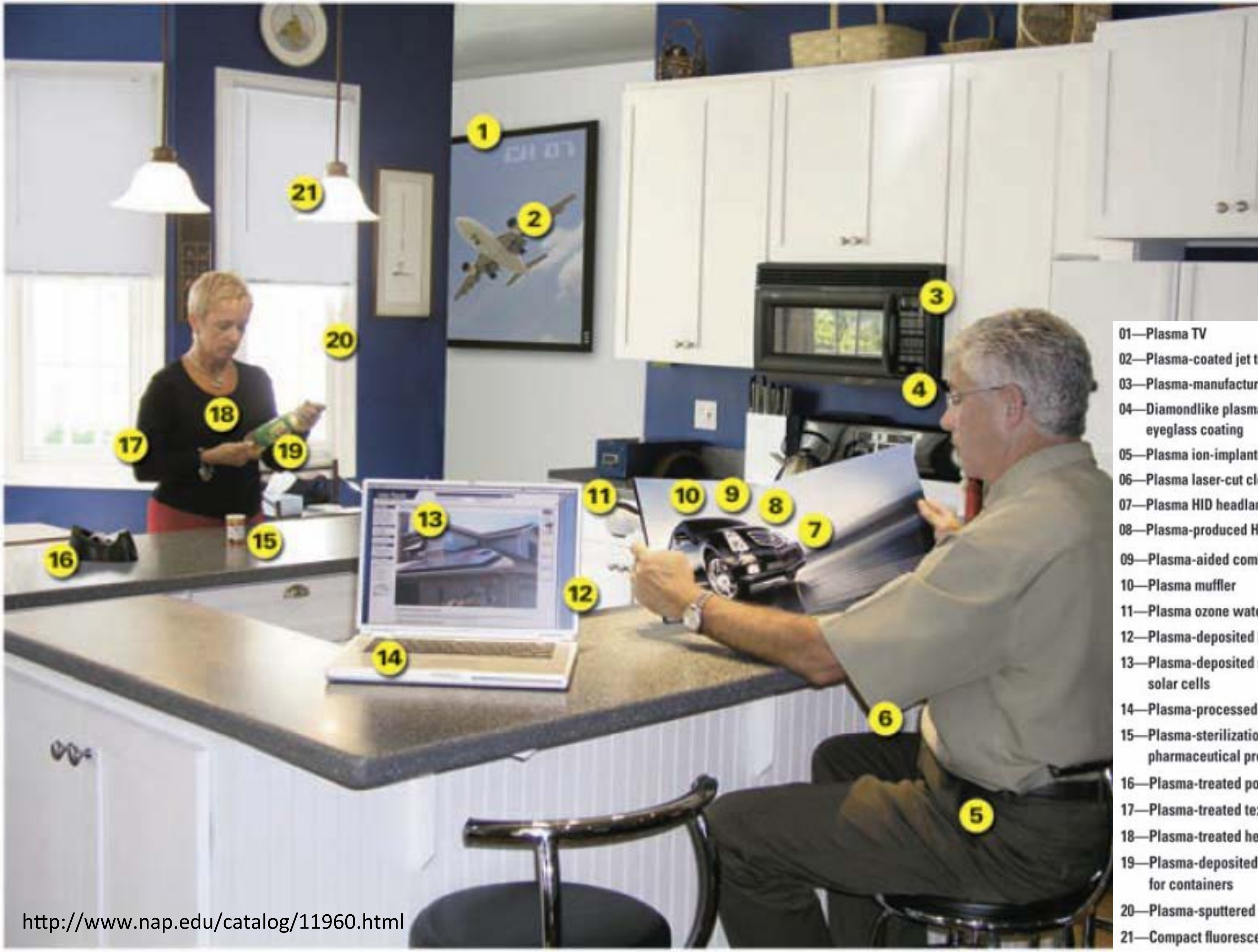

01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

http://www.nap.edu/catalog/11960.html


seat covers
welding
surface hardening
automotive
soot removal
colored plastic parts
pasting
lamps
ignition

Plasma methods

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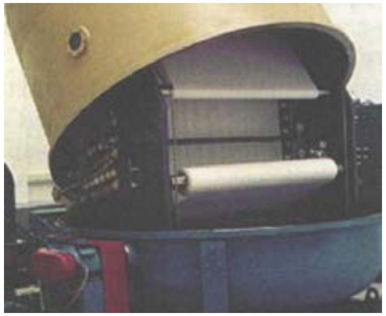
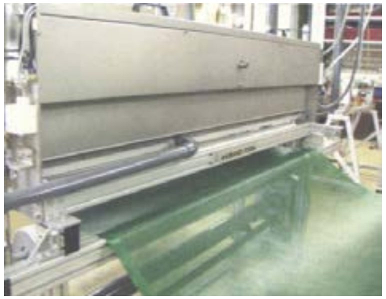
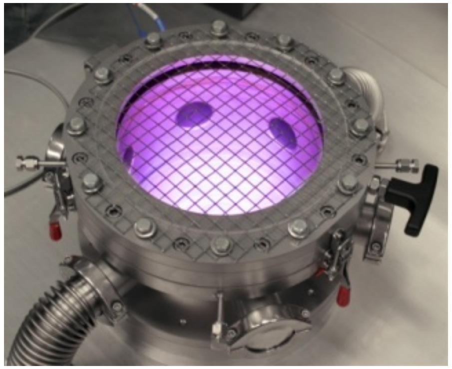
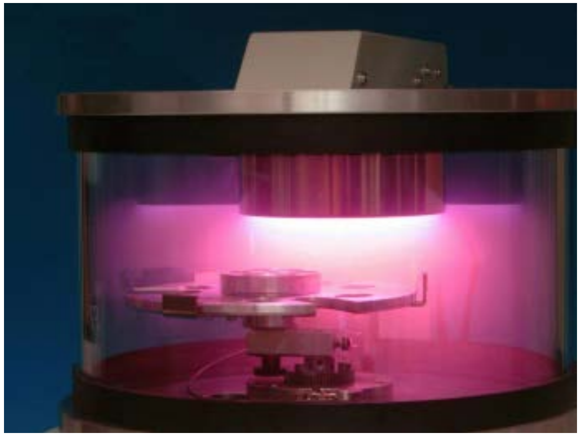
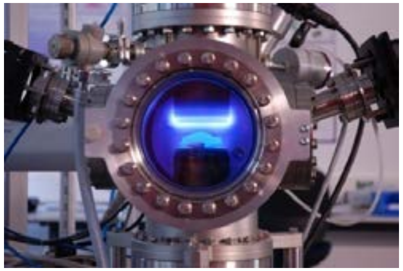
- Light generation (Plasmalamps)
- Plasmaetching in Microelectronics (Computerchips)
- Plasma based deposition (PECVD)
- Plasma spraying
- Surface modification (z.B. Hardening of metals, textiles and polymers)
- Surface sterilisation (z.B. inactivation of germs)

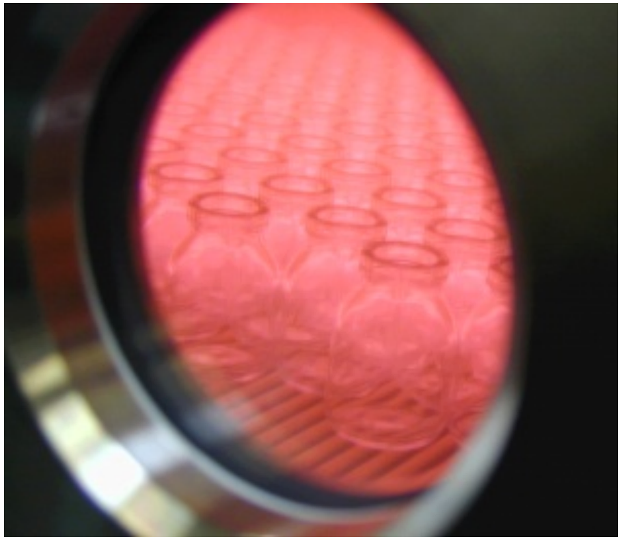
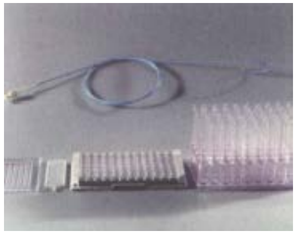
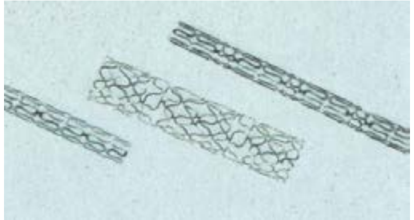





Plasma in the biomedical sector

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



Plasma for energy research

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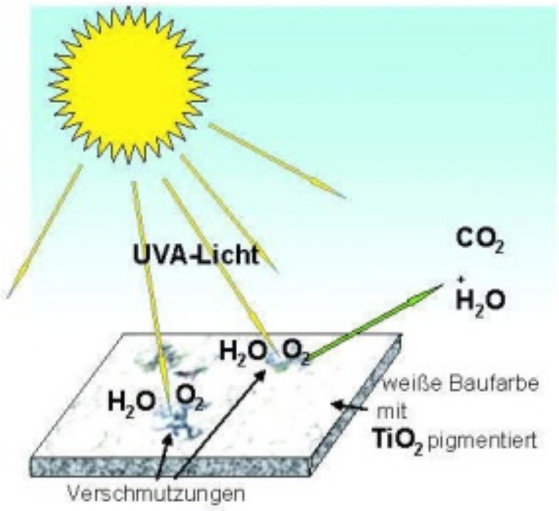
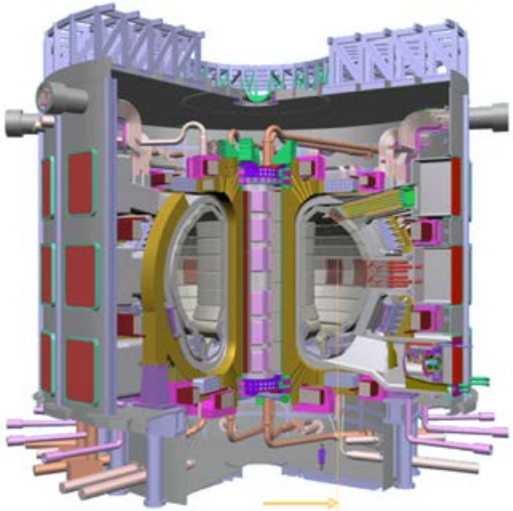
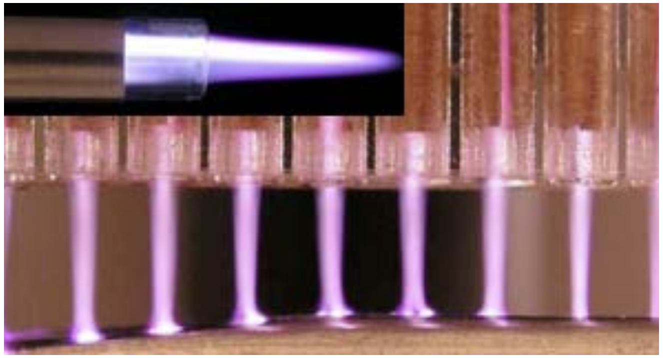
- Energy Storage (photocatalytic processes)
- Plasma switches (power plants)
- Solar panels
- Nuclear fusion
    - W 7-X, IPP Greifswald
    - ITER, Cadarache (Frankreich)

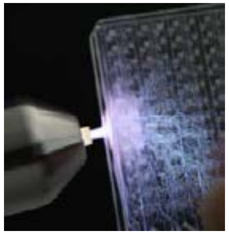


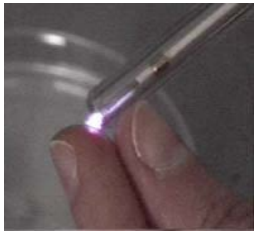


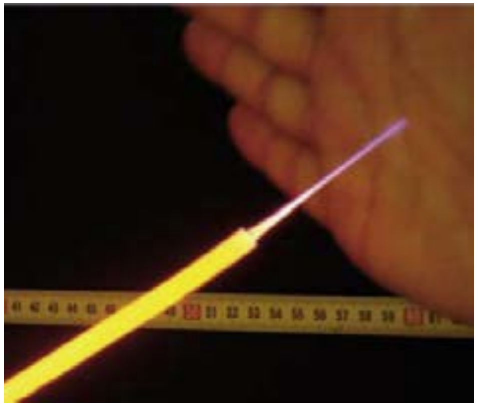
Envorinmental

- Waste treatment
- Water and air cleaning
- Plasma medicine

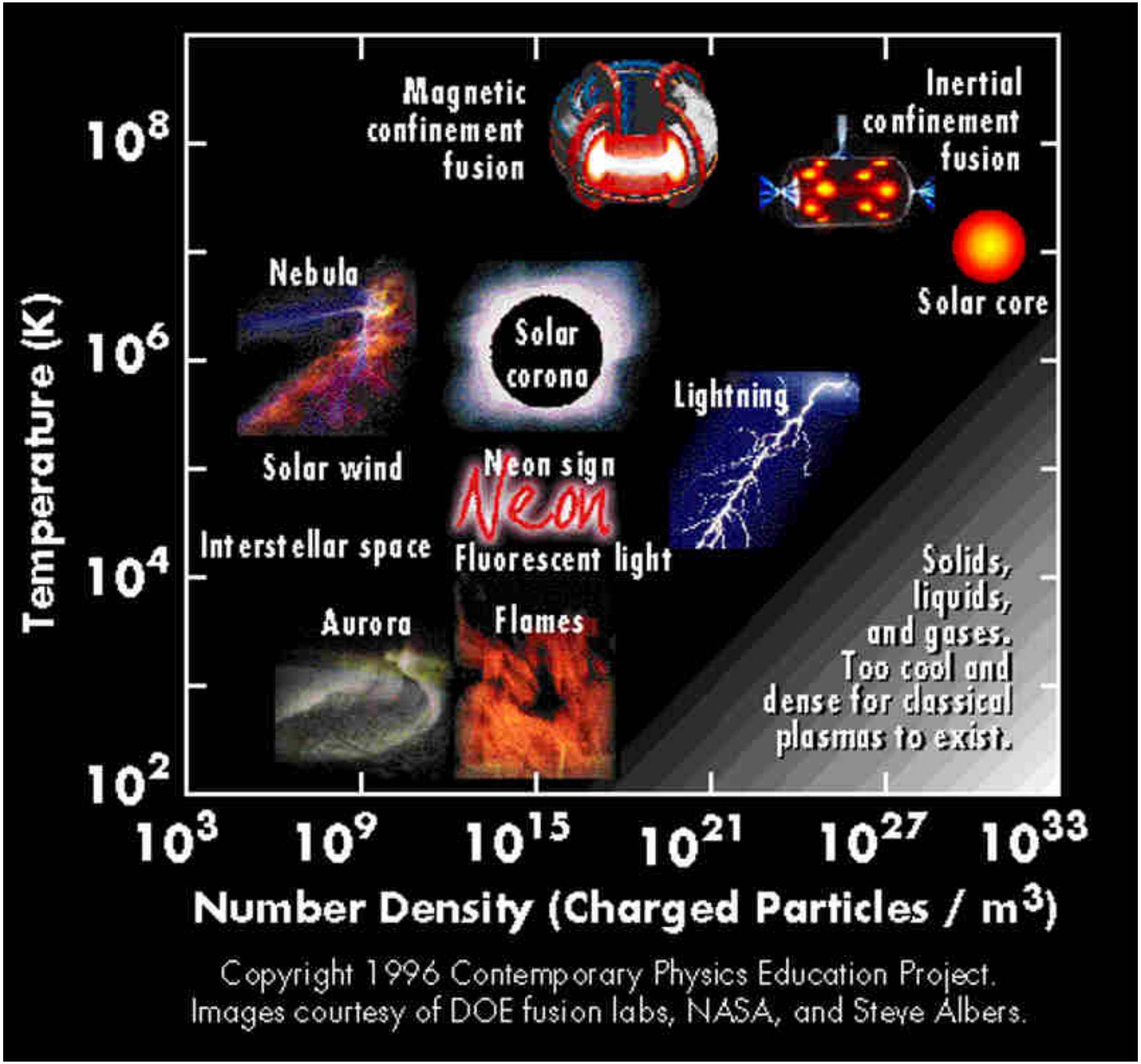








Plasma vs. n_e and T_e



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

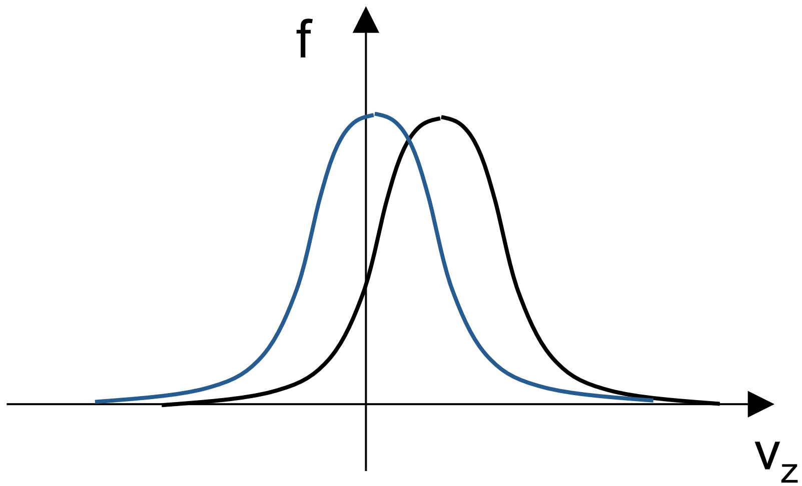
4. Transport in a plasma

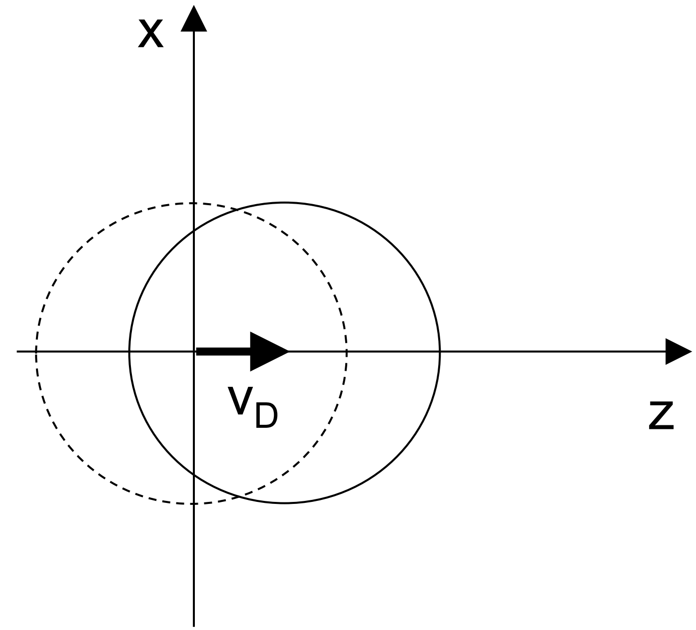
   - Particle motion
   - Plasma as a fluid
   - Drift and diffusion

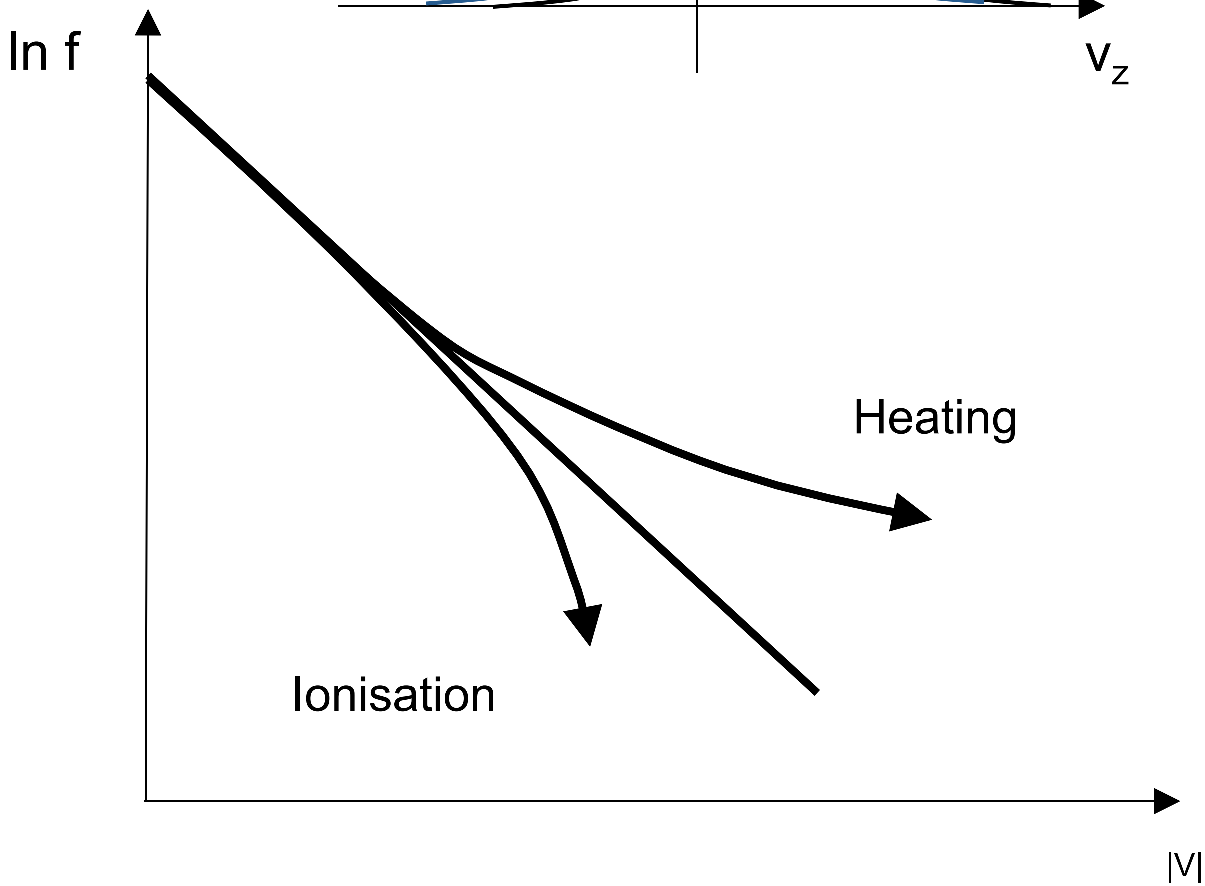
5. How to sustain a plasma

   - DC plasma
   - Rf-plasmas
   - Plasma heating

What is a plasma ? Concept 1 - temperature



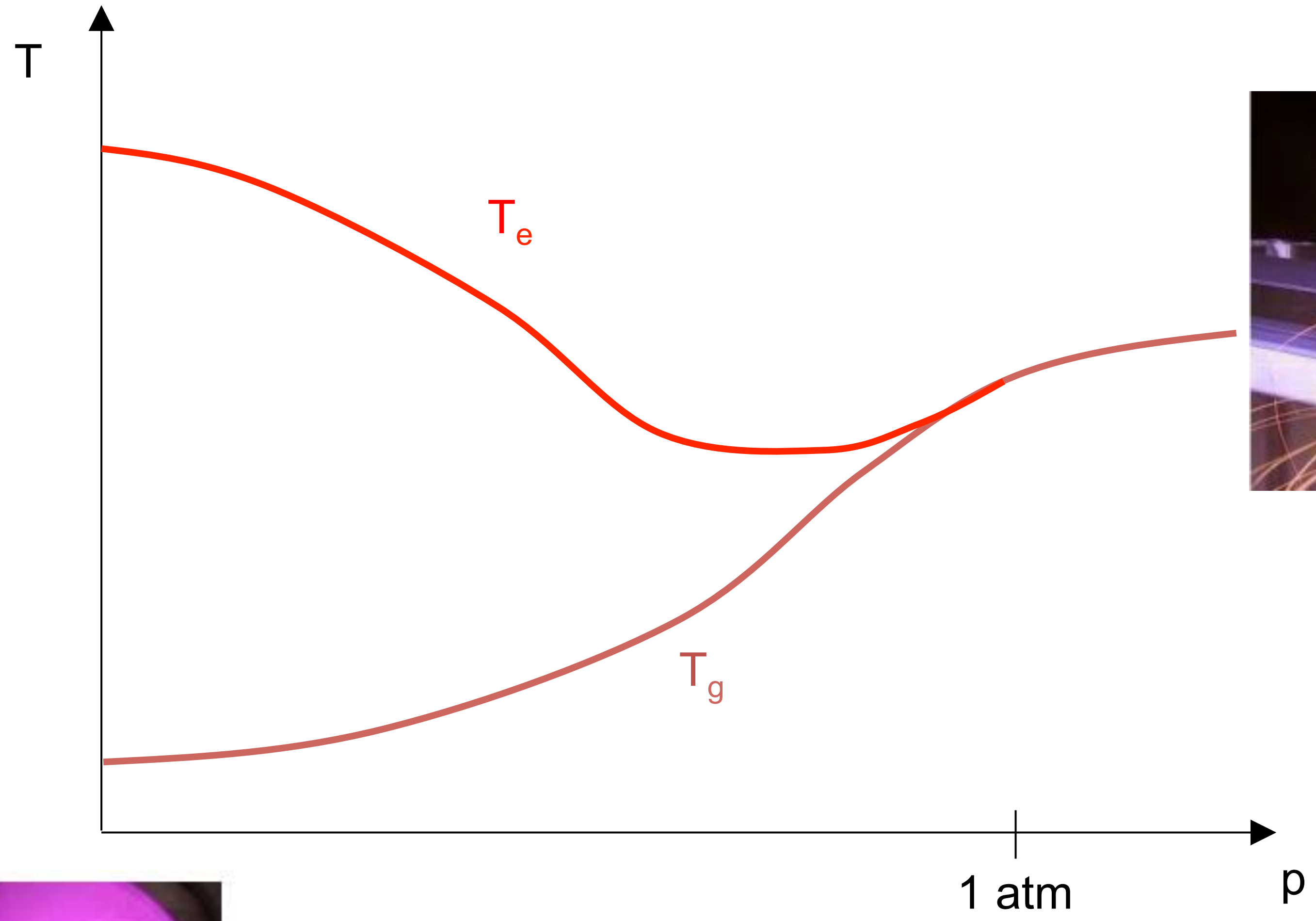




$$f(v) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} e^{\frac{-\frac{1}{2}mv^2}{k_B T}}$$

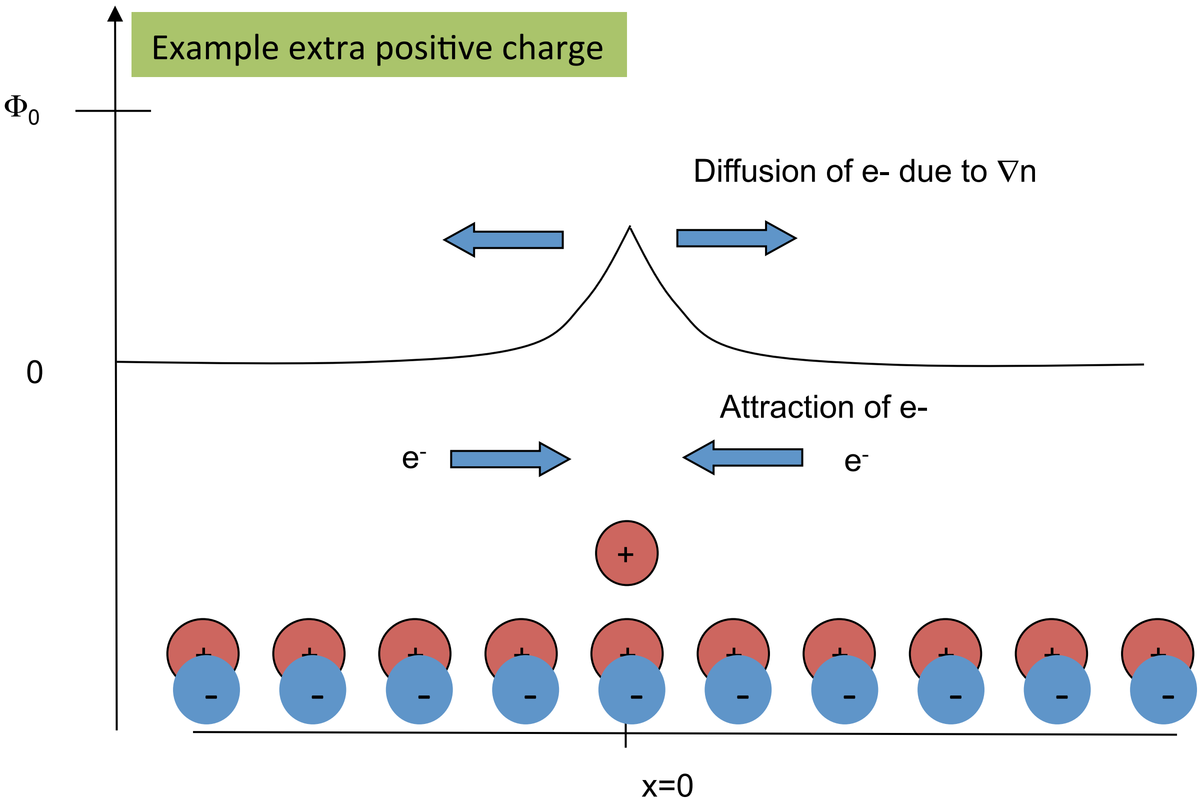
More details in the lecture
on kinetics, see also master class

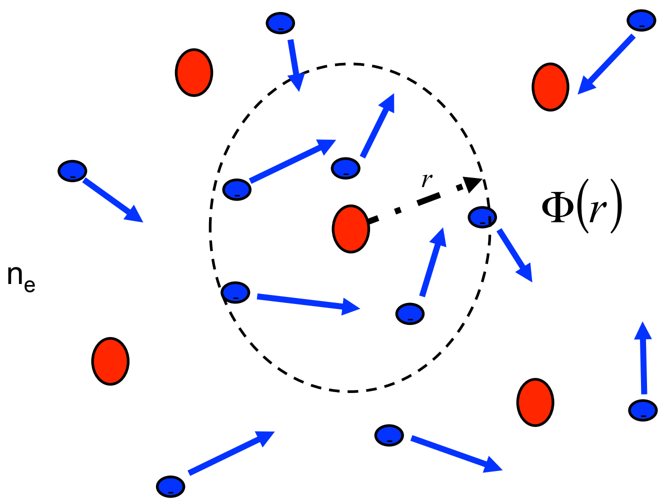
What is a plasma ? Concept 1 - temperature

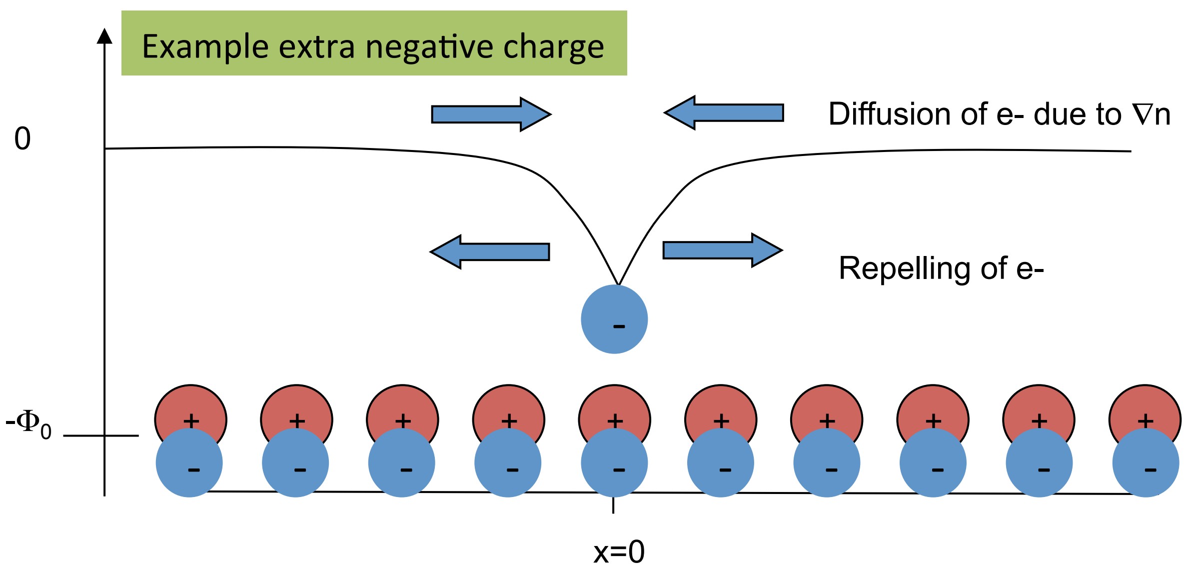


However, the concept of temperature is only an approximation.
Most plasmas are dominated by non-equilibrium.
Distribution function are needed rather than temperatures.
See also lectures on kinetics

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

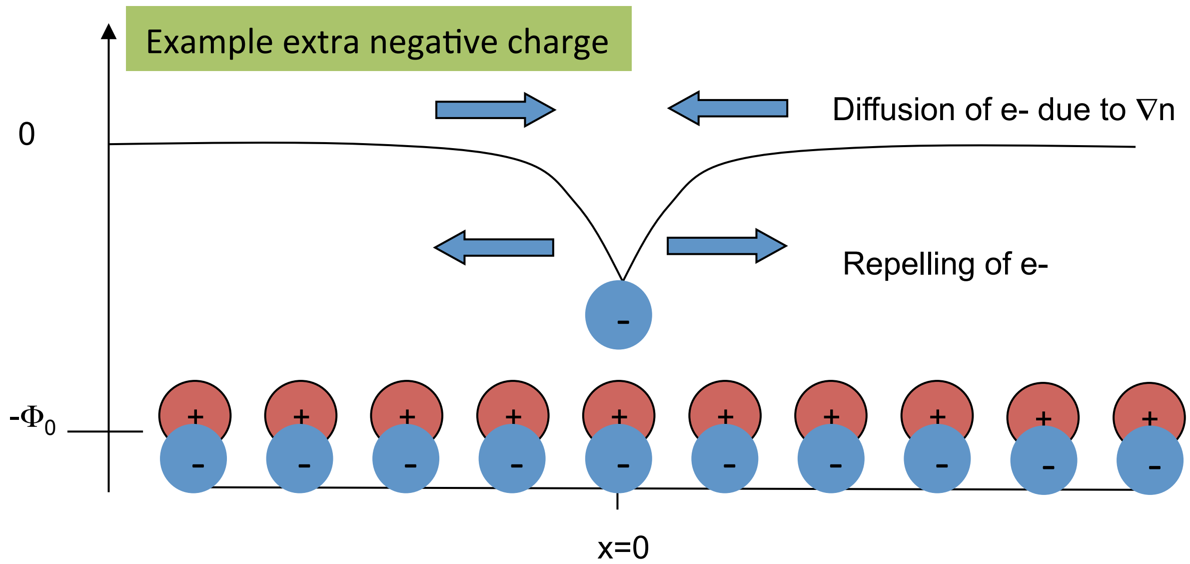






$$n_e = n_0 e^{\frac{e\Phi(x)}{k_B T}}$$

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

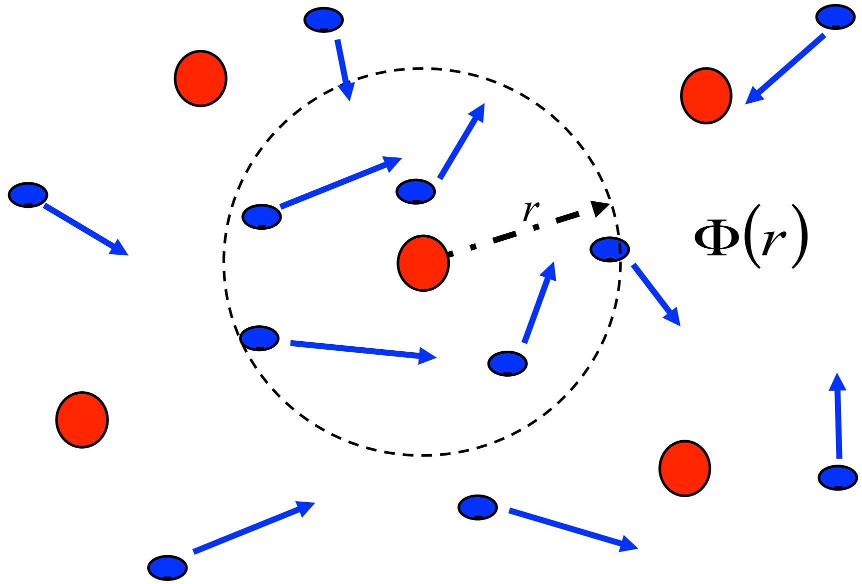
$$\epsilon_0 \frac{d^2\Phi}{dx^2} = e n_0 \left(1 + \frac{e\Phi(x)}{k_B T} + ... - 1 \right) \simeq e n_0 \frac{e\Phi}{k_B T}$$

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

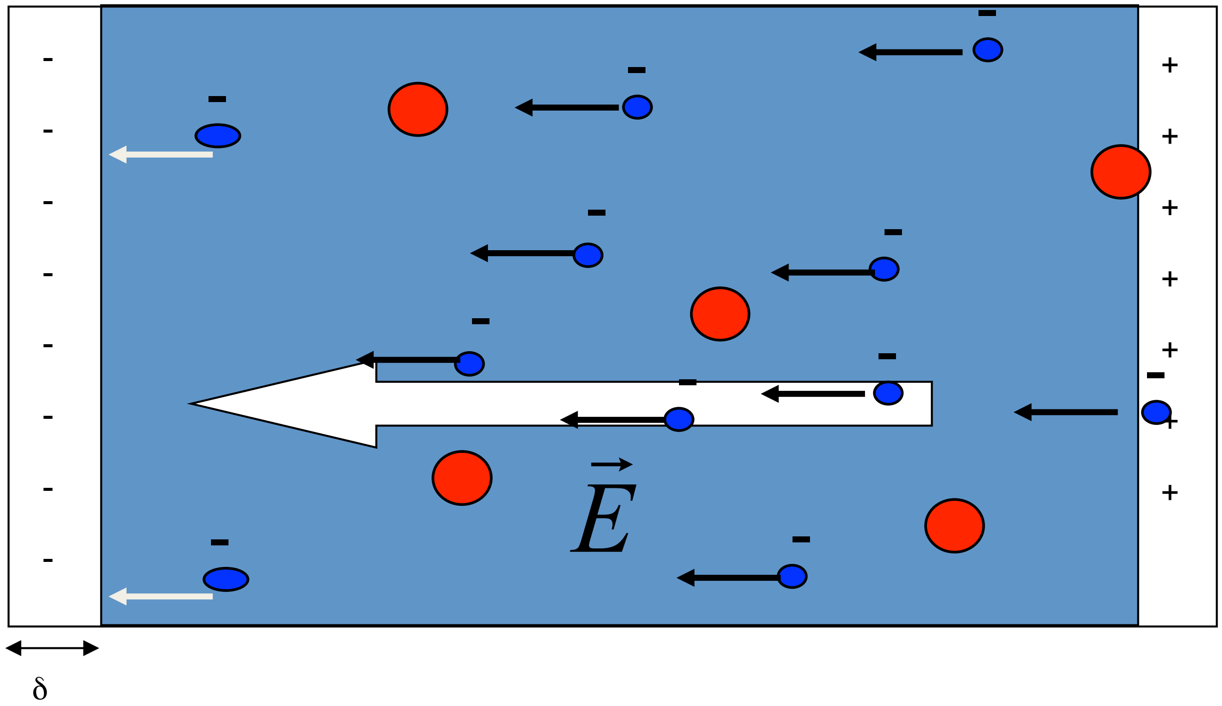
$$\frac{d^2\Phi}{dx^2} = \frac{n_0 e^2}{\epsilon_0 k_B T} \Phi \longrightarrow \Phi = \Phi_0 e^{-\frac{|x|}{\lambda_D}}$$

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

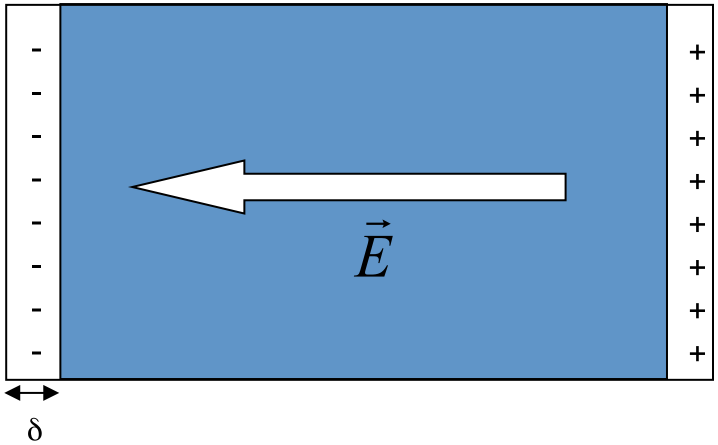
$$N_D = \frac{4\pi}{3}\lambda_D^3 n \gg 1$$



What is a plasma ? - Concept 4 – the plasma frequency



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

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electrons

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

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

ions

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

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

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

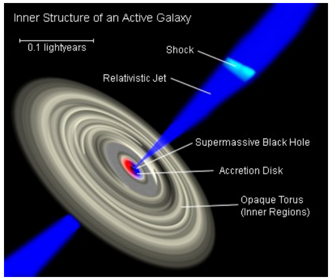
$$f_{pe} \simeq 9 \times 10^8 s^{-1} \rightarrow \tau = 1.1 \times 10^{-9} s$$

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

Electrons can easily follow the RF cycle,

ions can NOT !!

What is a plasma ? – Concept 5 – ideal and non-ideal plasmas

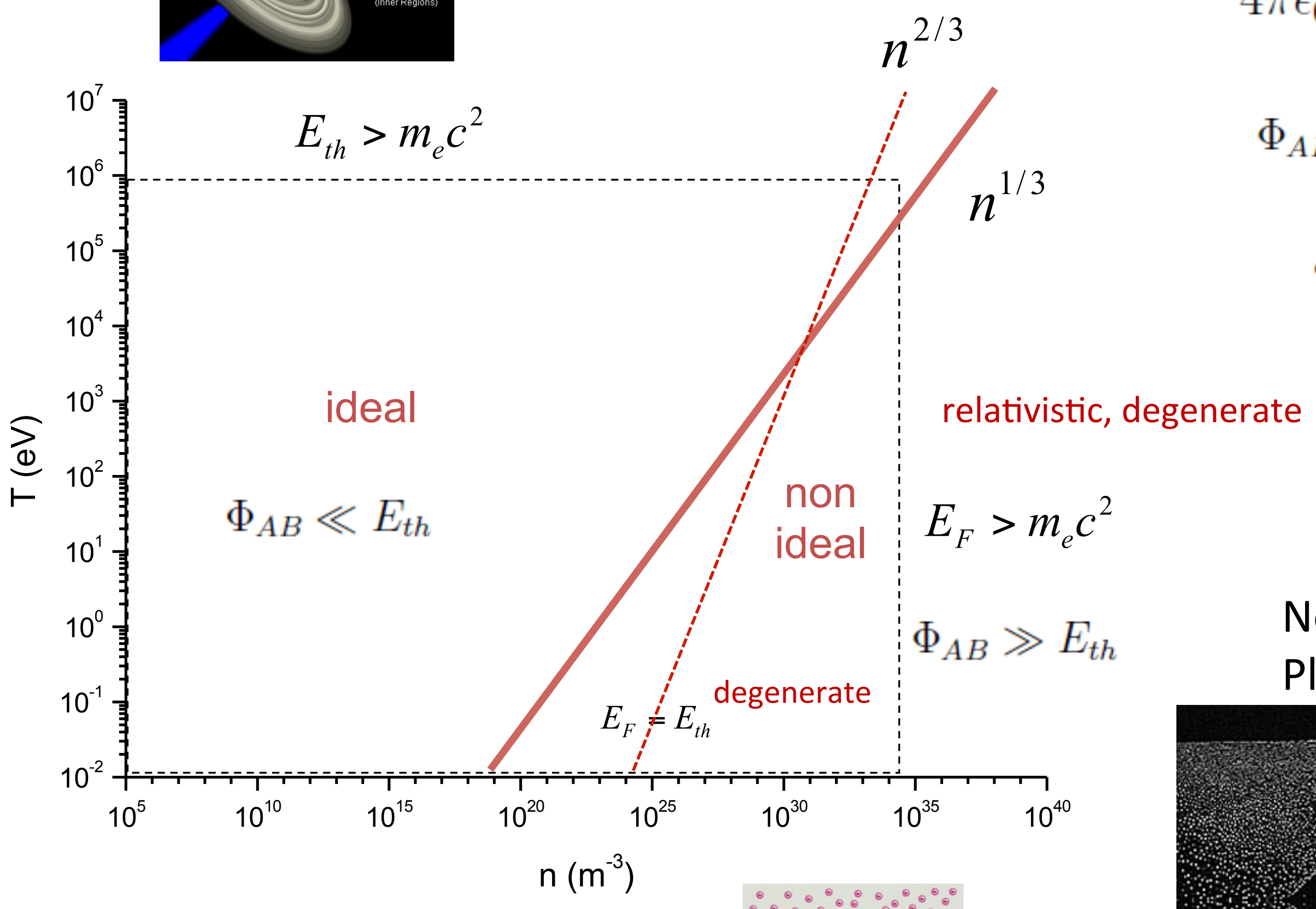


relativistic

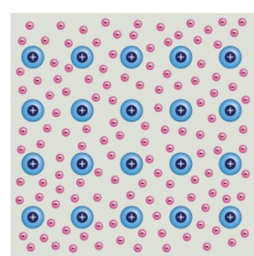
$$\frac{e^2}{4\pi\epsilon_0 b_0} = k_B T_e$$

$$\Phi_{AB} = \frac{q_A q_B}{4\pi\epsilon_0 r_{AB}}$$

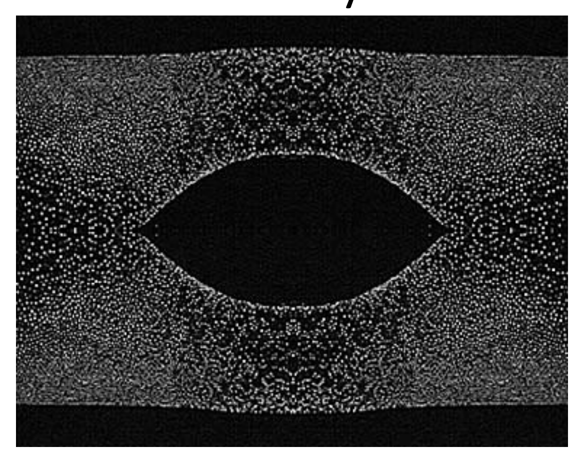
$$\Phi_{AB} \ll E_{th}$$



degenerate plasma:
electrons in a metal



Non-ideal plasma:
Plasma crystal



What is a plasma ? – Concept 5 – ideal and non-ideal plasmas

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Ideal plasma – plasma larger than the Debye length:

$$L \gg \lambda_d$$

Ideal plasma - many electrons in Debye sphere: fluid approach possible

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

$$\lambda_d \gg \frac{1}{n_e^{1/3}}$$

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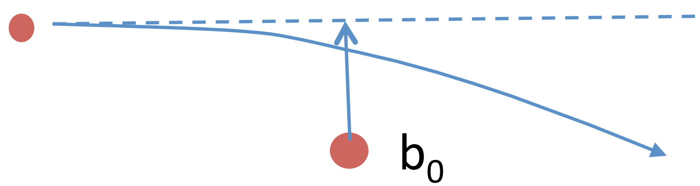
Ideal plasma – thermal energy must be larger than the Coloumb energy

$$\frac{e^2}{4\pi\epsilon_0 b_0} = k_B T_e$$

$$b_0 = \frac{e^2}{4\pi\epsilon_0 k_B T_e} = \frac{0.5\times 10^{-9}[m]}{T_e\,[eV]}$$



Relation between collision parameter and Debye length

$$\lambda_d = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = 7.45\times 10^3 \sqrt{\frac{T_e\,[eV]}{n_e\,[10^{16} m^{-3}]}}$$

$$\frac{\lambda_d}{b_0} \simeq 1.5\times 10^{13}\frac{T_e^{3/2}}{n_e^{1/2}}$$

Parameter of a plasma – Nick Braithwaites Plasma Calculator

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PLASMA CALCULATOR (N St J Braithwaite, European Summer School)

Physical Constants

e/C	k/J_K^-1	me/kg	Mp/kg	epsi0/F_m^-1	mu0/H_m^-1	c0/m_s^-1
1.60E-19	1.38E-23	9.00E-31	1.67E-27	8.85E-12	1.26E-06	3.00E+08

Gas data

p/Pa	Tg/K	Mg/amu	X-Sectn/m^2
6.00E+00	3.00E+02	4.00E+01	1.00E-19

Plasma data

kTe/eV	ne/m^-3
2.00E+00	1.00E+16

Instructions

Adjust gas, plasma and system data

(data boxes in this band are not protected)

Plasma parameters are immediately updated

System data

L/m	RF/MHz	B/T	muwave/MHz	rho_Cu/ohm_m
1.00E-01	1.36E+01	1.00E-01	2.45E+03	2.00E-08

Plasma / **System**

Lengths/m

inter-neutral	inter-ch	mfp	Debye	dskin	dskin_Cu	L
8.84E-08	4.64E-06	6.90E-03	1.05E-04	2.48E-01	1.93E-05	1.00E-01

Frequencies/rad_s^-1

wpe	wpi	wce	wRF	wm
5.67E+09	2.08E+07	1.78E+10	8.52E+07	1.54E+10

Frequencies/MHz

fpe	fpi	fce	nu	RF	muwave
9.03E+02	3.31E+00	2.83E+03	8.64E+01	1.36E+01	2.45E+03

Speeds/m_s^-1

ce	ve	cs	cg
9.52E+05	5.96E+05	2.19E+03	3.97E+02

Fluxes/m^-2_s^-1

Gi	Gg
2.19E+19	1.44E+23

Conductivity/ohm^-1_m^-1

sigDC	Re[sigRF]	Im[sigRF]
3.29E+00	1.67E+00	-1.65E+00

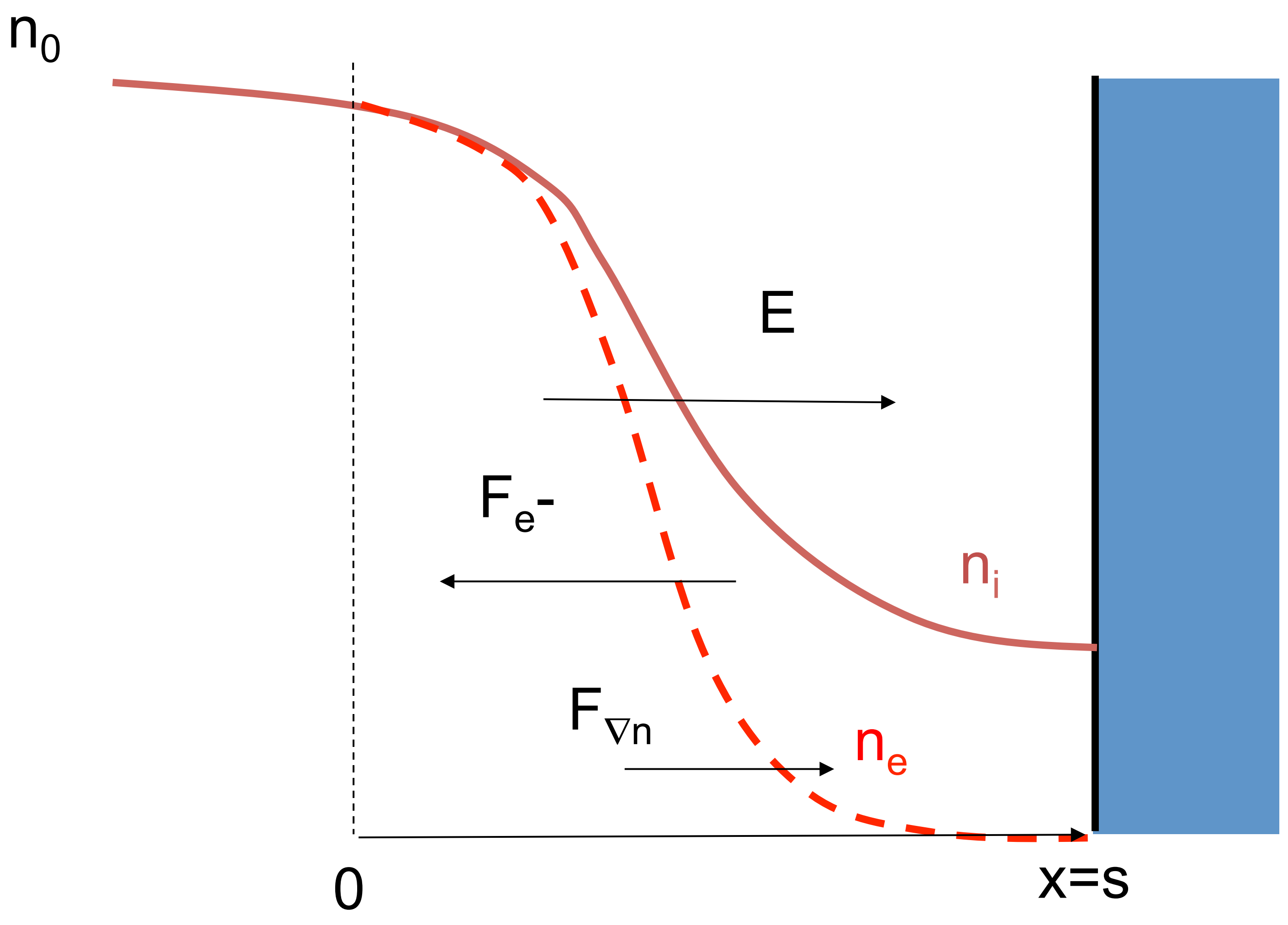
Densities/m^-3

ng	ne	% ionisation
1.45E+21	1E+16	0.00069

Comments to n.s.braithwaite@open.ac.uk

The edge of a plasma

A plasma in front of a wall – sheath physics



A plasma in front of a wall – sheath physics (formula)

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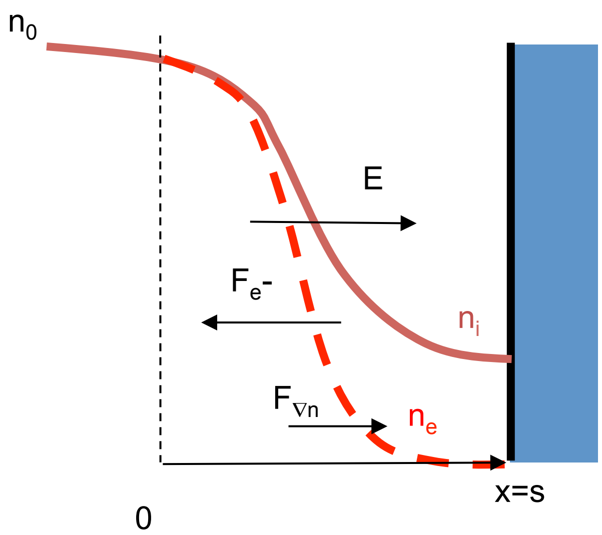


$$\frac{1}{2}Mv_i^2(x) + e\Phi(x) = \frac{1}{2}Mv_0^2$$

$$n_i(x)v_i(x) = n_0v_0$$

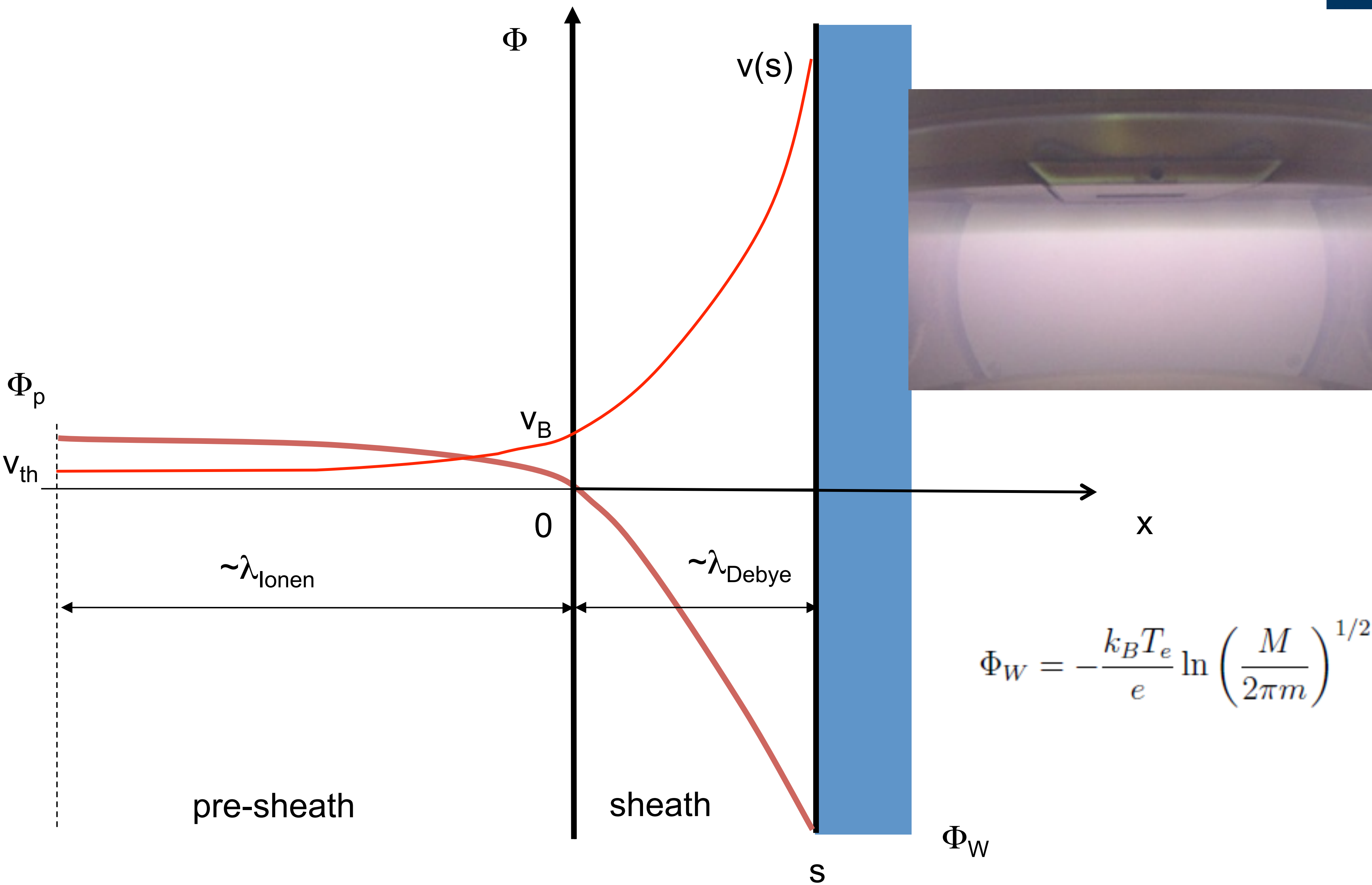
$$n_e(x) = n_0 e^{\frac{e\Phi(x)}{k_BT_e}}$$

$$n_i(x) = n_0\left(1 - \frac{2e\Phi(x)}{Mv_0^2}\right)^{-1/2} = n_0\left(1 - \frac{e\Phi(x)}{E_0}\right)^{-1/2}$$

$$\frac{d^2\Phi(x)}{dx^2} = e\frac{n_0}{\epsilon_0}\left[\exp\left(\frac{e\Phi(x)}{k_BT_e}\right) - \left(1 - \frac{e\Phi(x)}{E_0}\right)^{-1/2}\right]$$

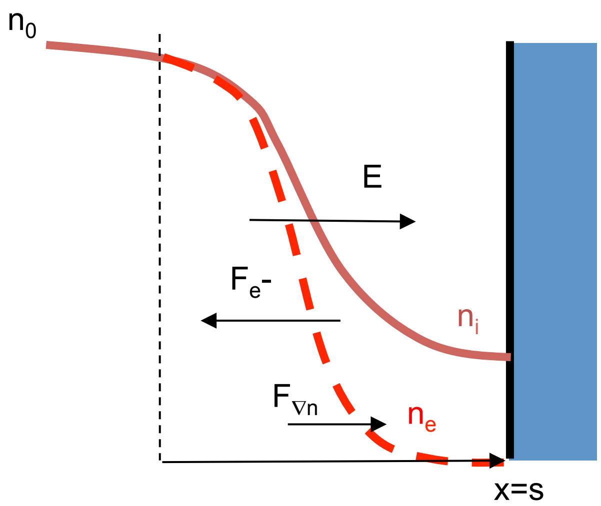
$$v_0 > \sqrt{\frac{k_BT_e}{M}} = v_B$$

A plasma in front of a wall – sheath physics – potential, ion velocity



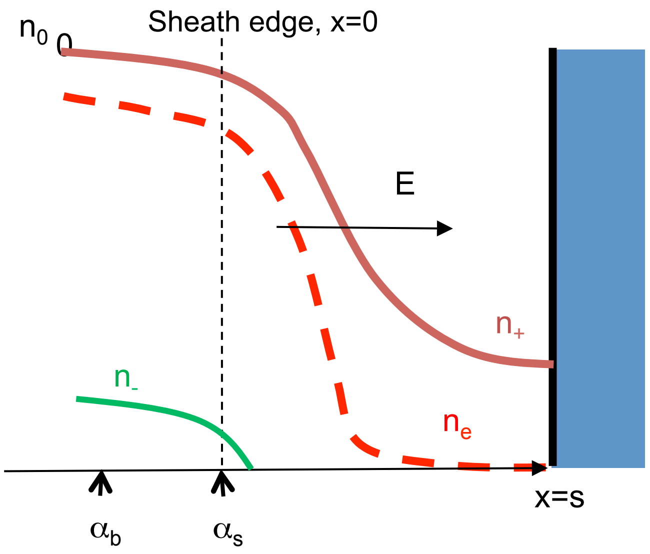
$$\Phi_W = -\frac{k_B T_e}{e} \ln\left(\frac{M}{2\pi m}\right)^{1/2}$$

RUB



Multiple ions

$$\sum_j \frac{e n_j}{m_j v_j^2} \leq \frac{e n_e}{k_B T_e}$$

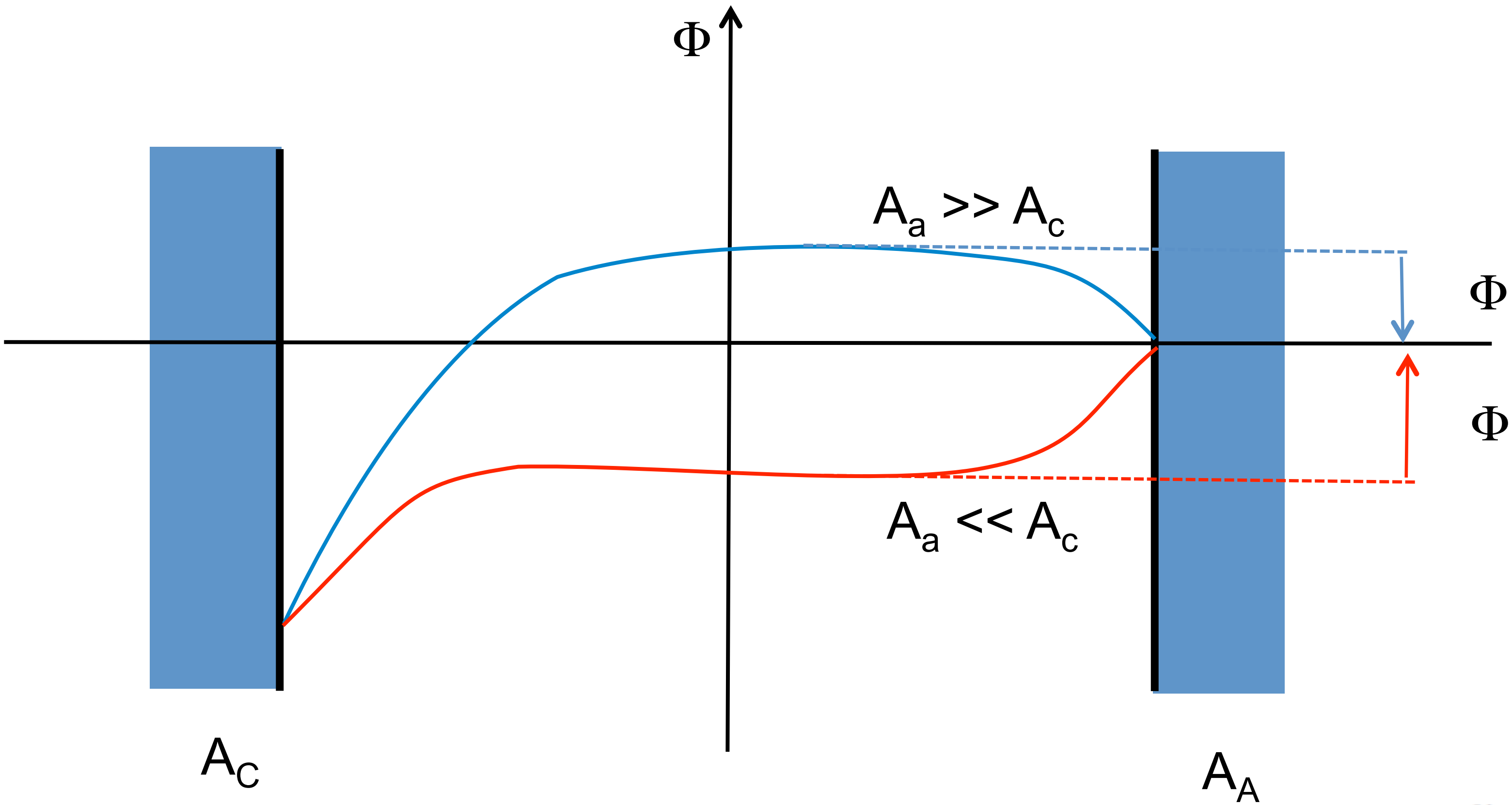


Electronegative plasmas

$$v_b > \left(\frac{k_B T_e}{M} \frac{1+\alpha}{1+\alpha\gamma} \right)^{1/2}$$

with $\gamma = \frac{T_e}{T_i}$ $\alpha = \frac{n_-}{n_e}$

A plasma in front of a wall – sheath physics – plasma potential



$v_{th} \gg v_B$

Flux balance ions and electrons

$$I_{Ionen} = n_0 v_B \left(A_c + A_a\right)$$

$$\Phi = \frac{k_B T_e}{e} \ln\left[\frac{4 v_B}{v_{th}} \frac{A_c + A_a}{A_a}\right]$$

$$I_{e-} = \frac{1}{4} v_{th} n_0 e^{\frac{e\Phi_P}{k_B T}} A_a$$

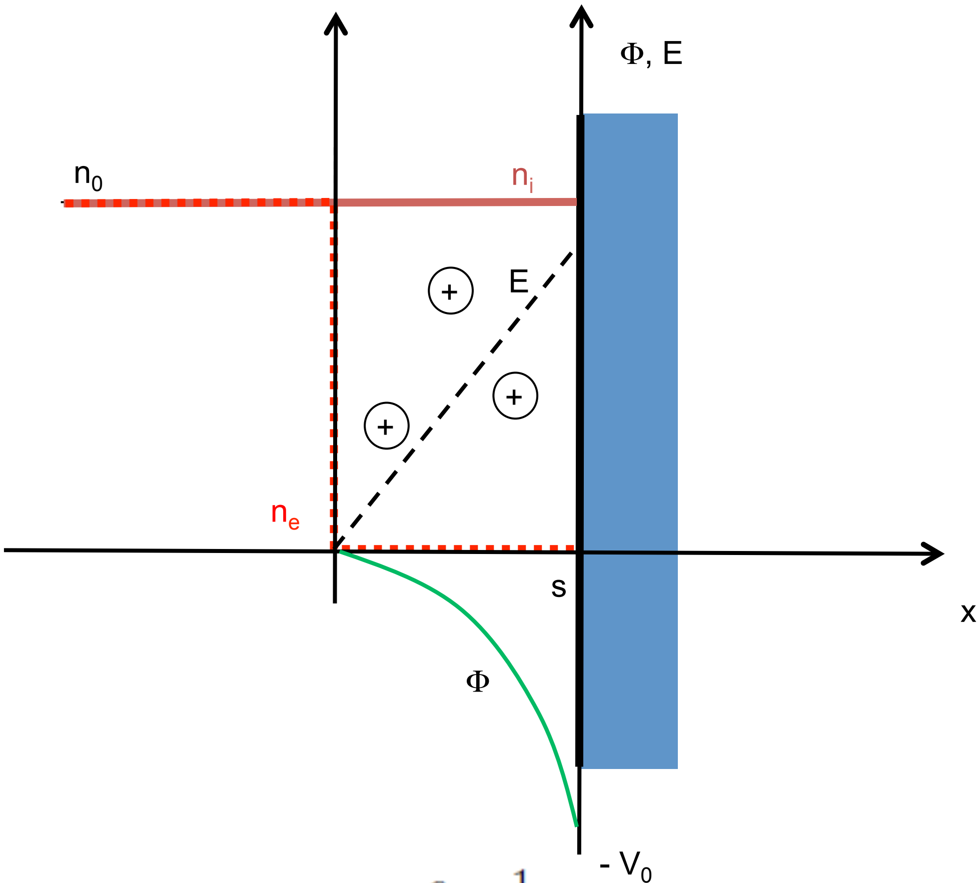
Plasma potential

$A_a \gg A_c$ $$\Phi \simeq \frac{k_B T_e}{e} \ln\left[\frac{4 v_B}{v_{th}}\right] < 0$$

$A_a \ll A_c$ $$\Phi \simeq \frac{k_B T_e}{e} \ln\left[\frac{4 v_B}{v_{th}} \frac{A_c}{A_a}\right] > 0$$

A plasma in front of a wall – sheath physics – applying a voltage to an electrode

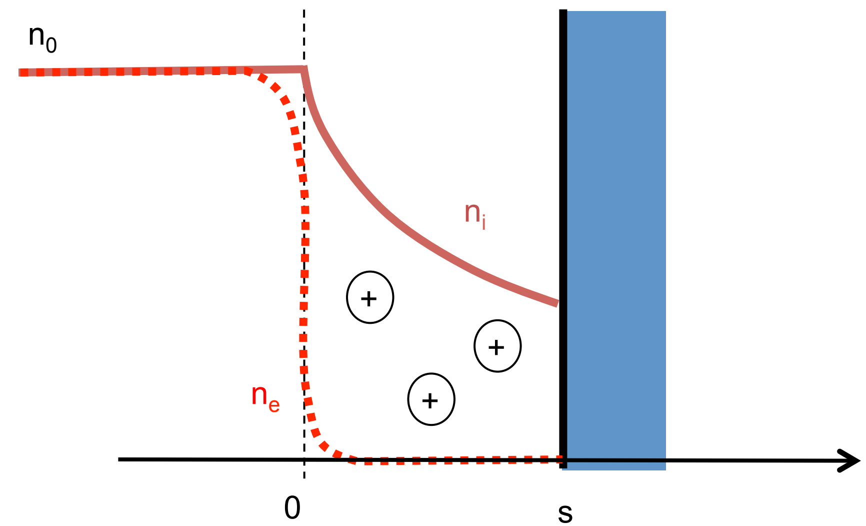
Matrix sheath



$$\Phi(x) = -\frac{e}{\epsilon_0} n_0 \frac{1}{2} x^2$$

$$s = \left(\frac{2\epsilon_0 V}{e n_0}\right)^{1/2} = \lambda_D \left(\frac{2eV}{k_B T_e}\right)^{1/2}$$

Child Langmuir sheath



$$e n(x) v(x) = j_0$$

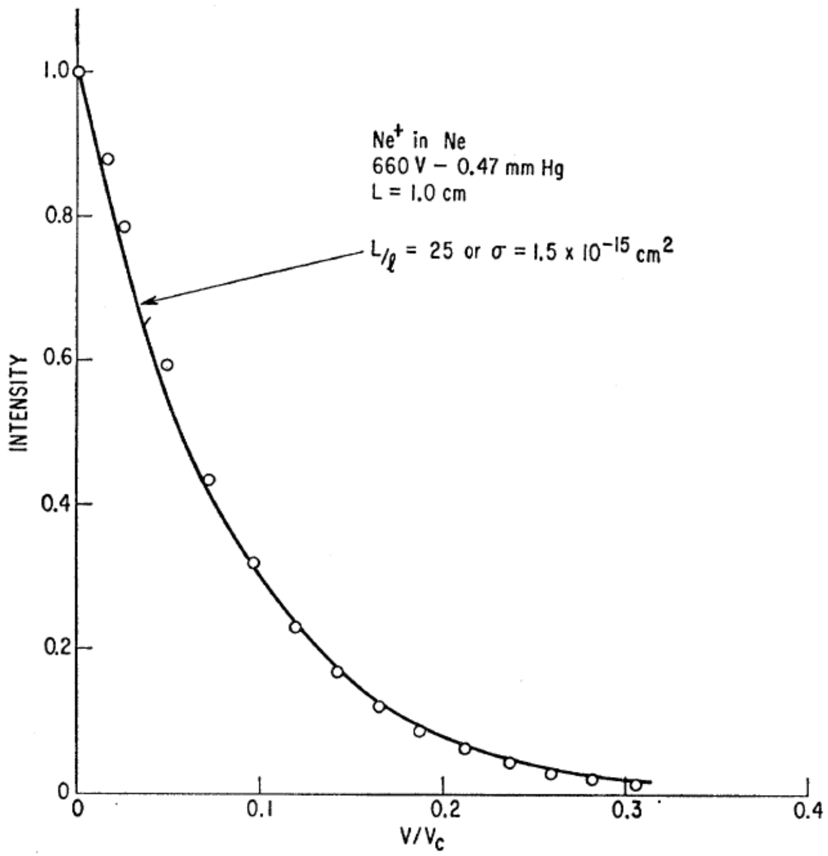
$$\frac{1}{2} M v^2(x) = -e\Phi(x) + \underbrace{\frac{1}{2} M v_0^2}_{\ll}$$

$$j_0 = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{V^{3/2}}{s^2}$$

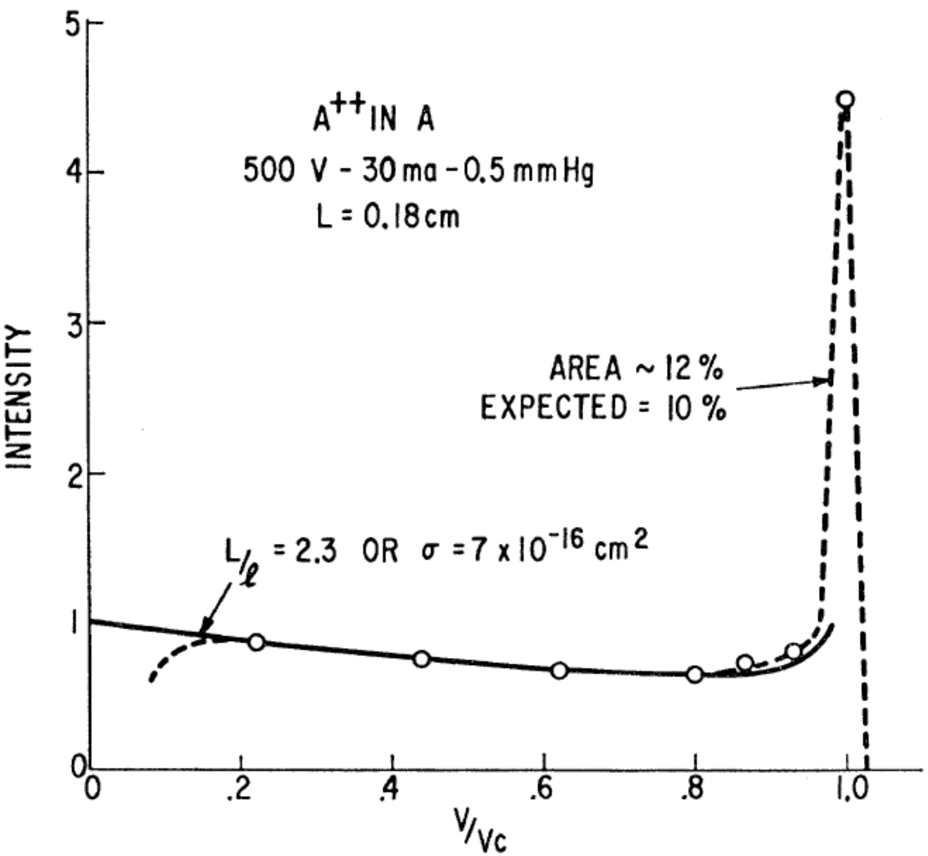
$$s = \frac{\sqrt{2}}{3}\lambda_D \left(\frac{2eV}{k_B T_e}\right)^{3/4}$$

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

many collisions in the sheath

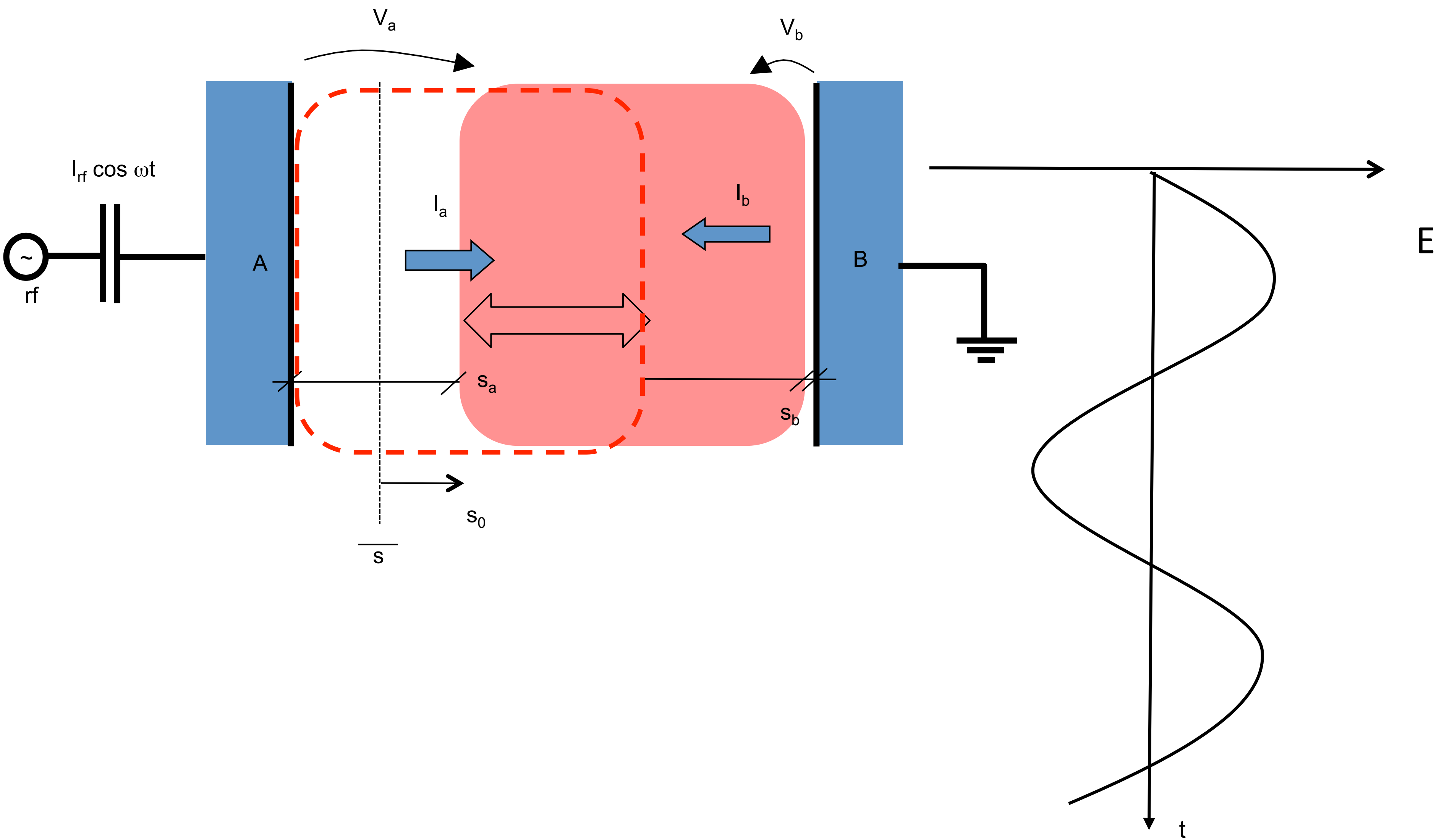


Few collisions in the sheath



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

RUB



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

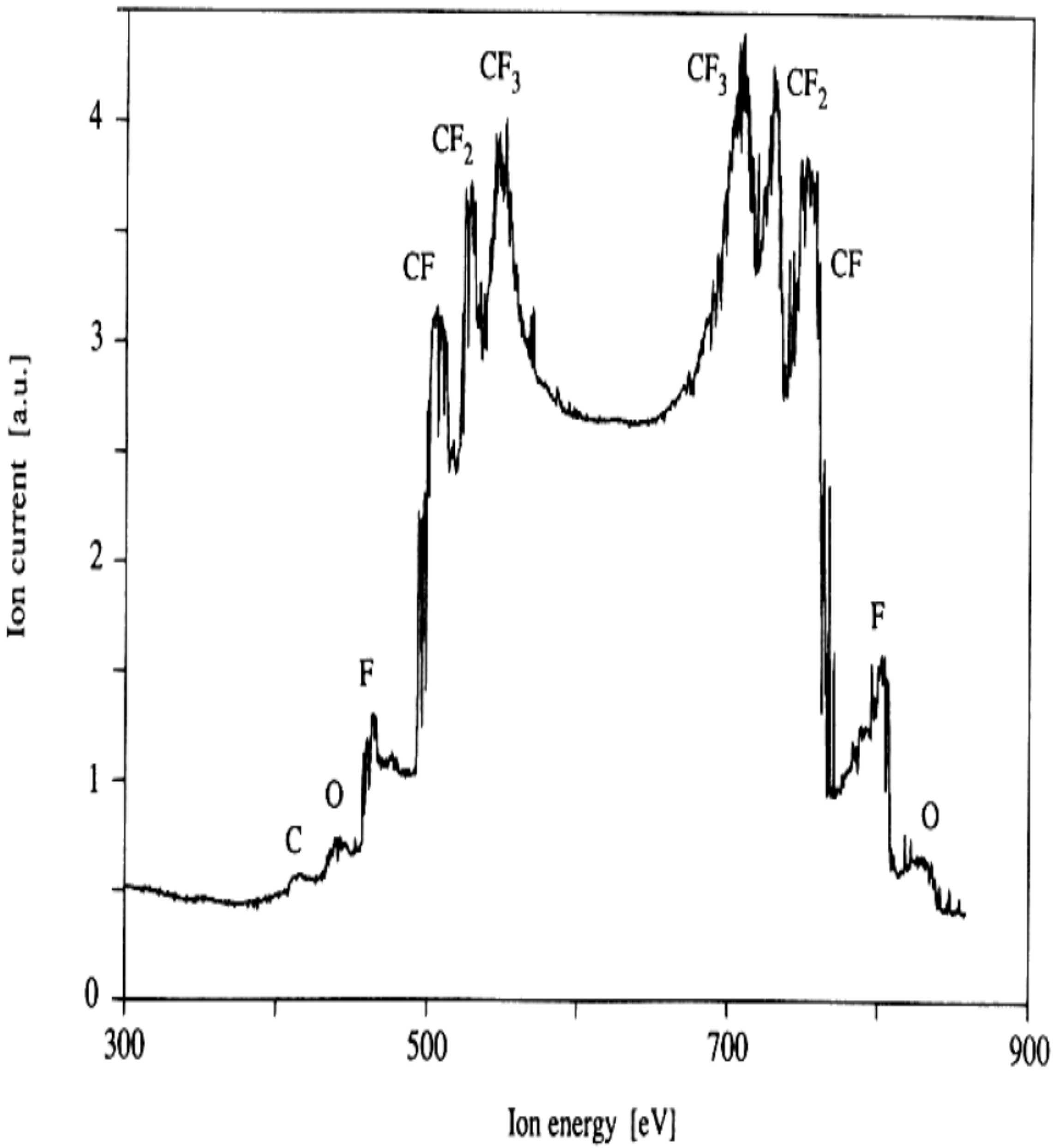
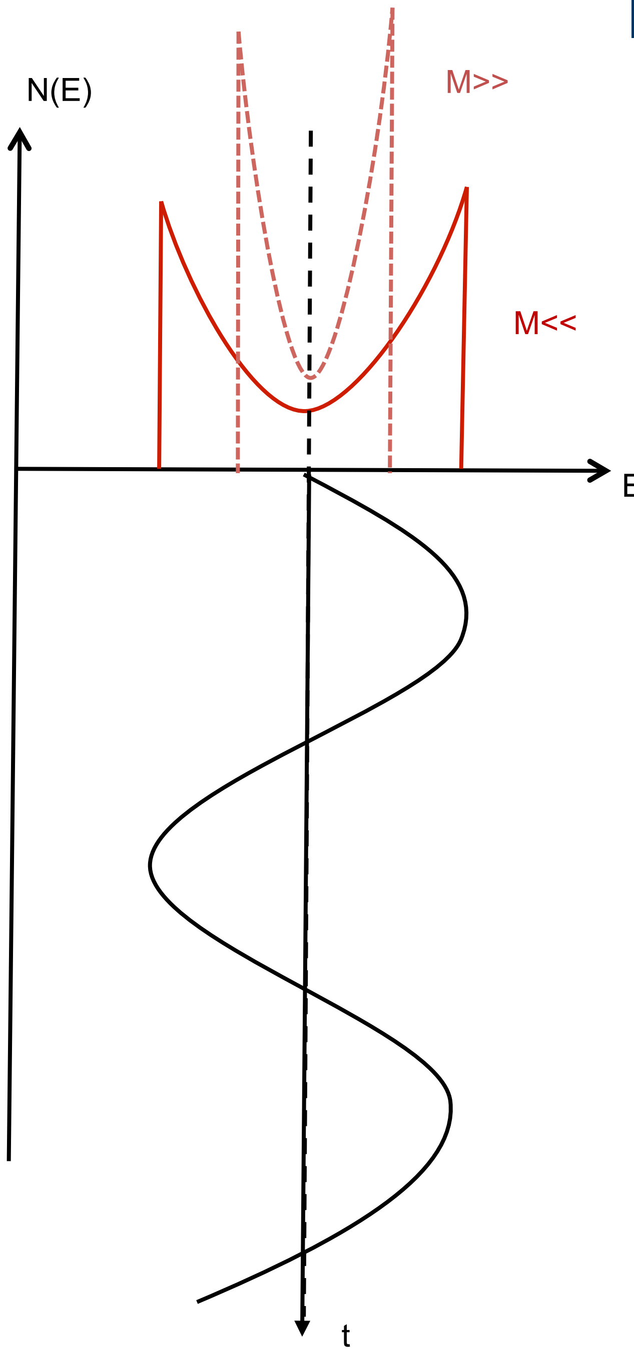


Abbildung 3.13: Messung der Ionenenergieverteilung in einem CF-rf-Plasma [A. Kuypers, H. Hopman *Measurement of ion energy distributions an the powered rf electrode in a variable magnetic field*, J. Appl. Phys. 67, 1229 (1990)]



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

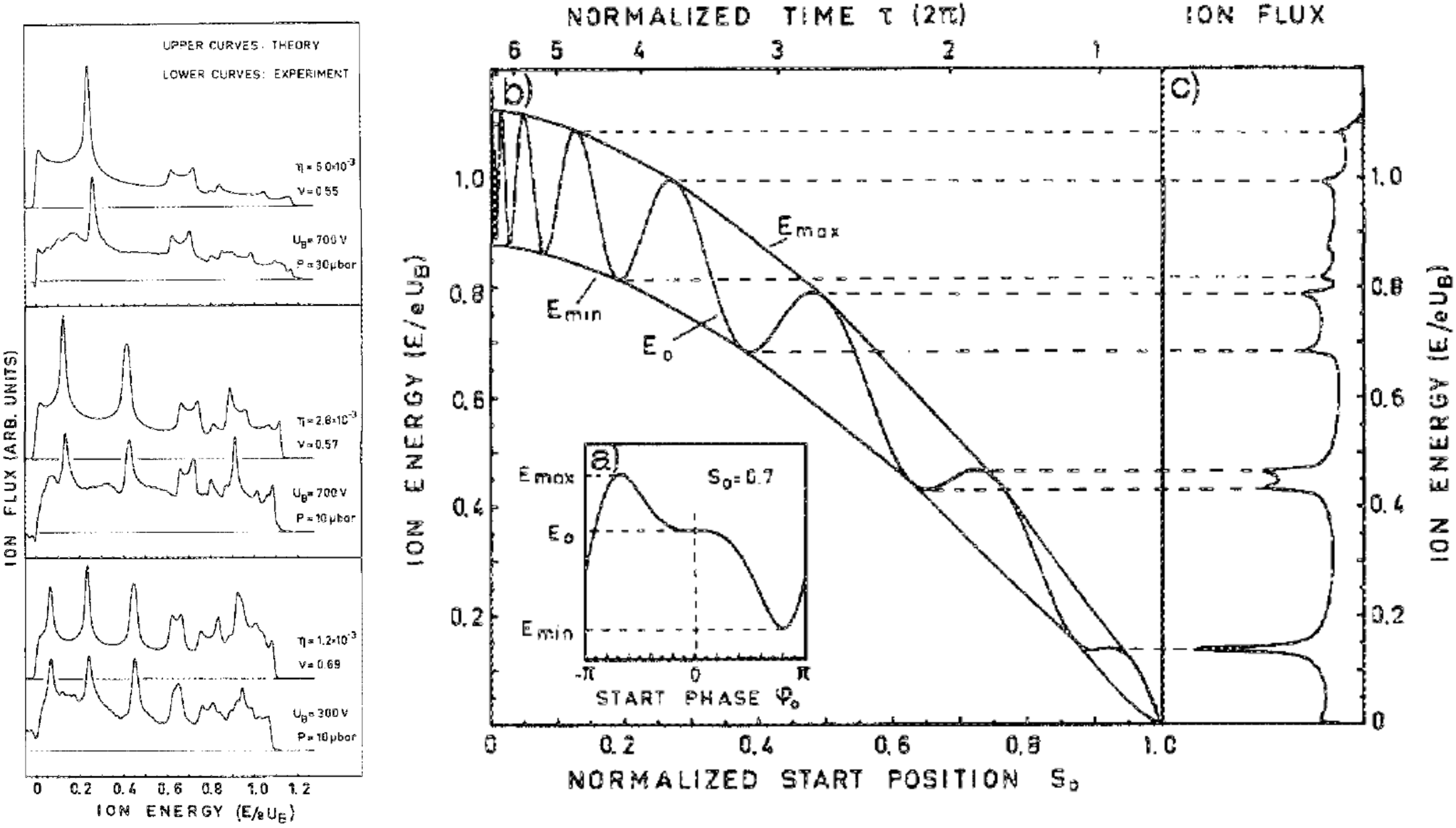
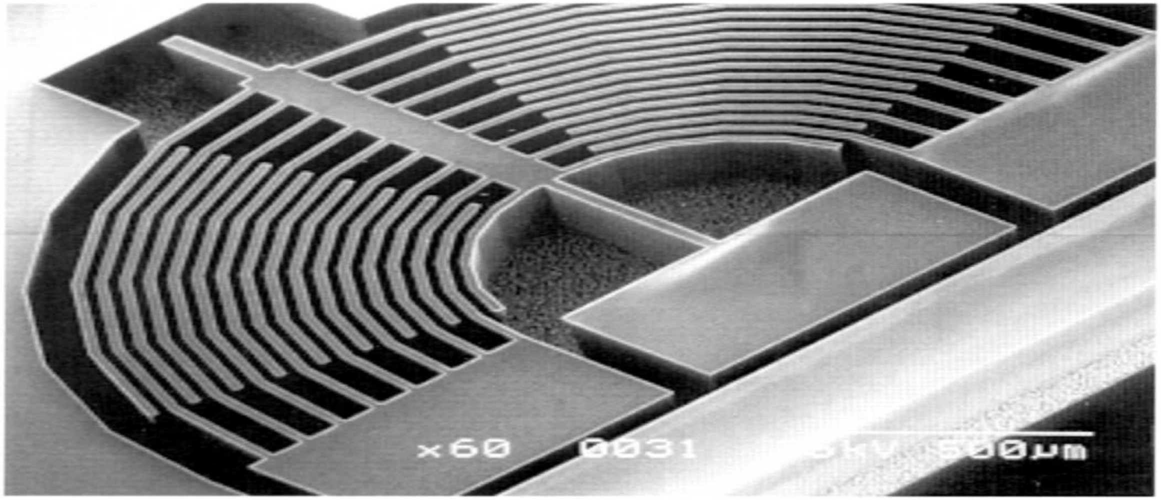
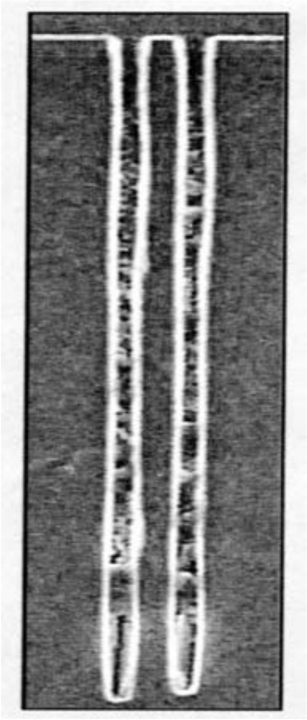
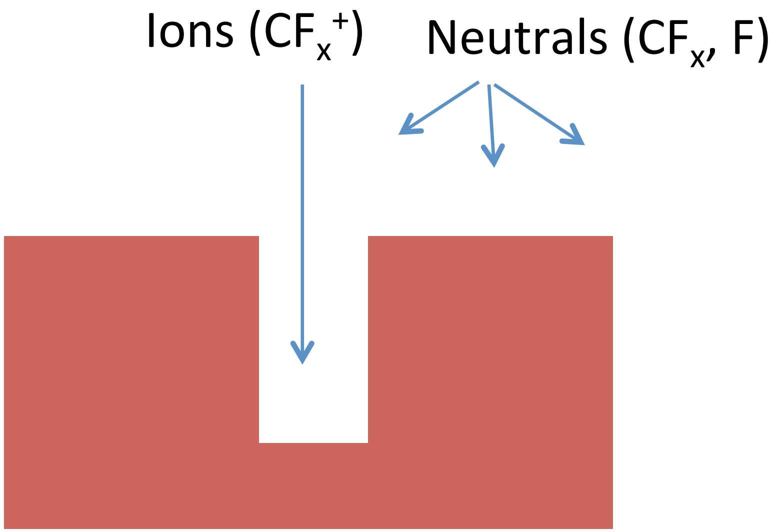


Abbildung 3.14: Stoßbestimmte Ionenergieverteilungen in einer rf-Randschicht, [C. Wild, P. Koidl *Structured ion energy distribution in radio frequency glow-discharge systems* Appl. Phys. Lett. 54, 505 (1989)]

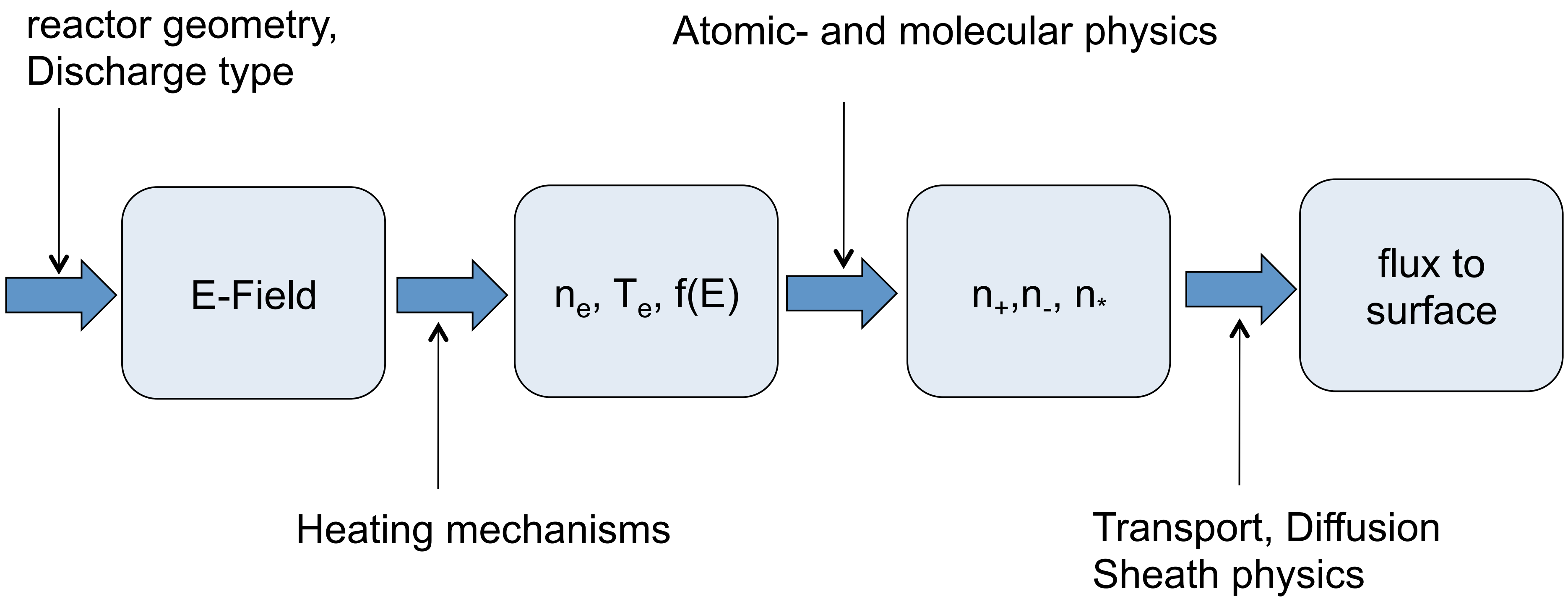
A plasma in front of a wall – sheath physics – applications in microelectronics





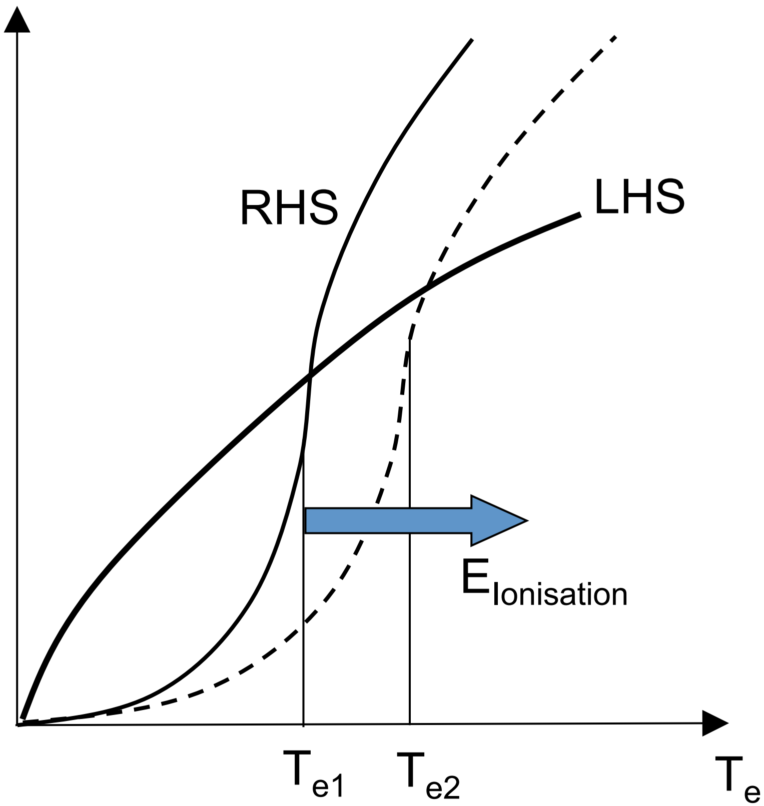


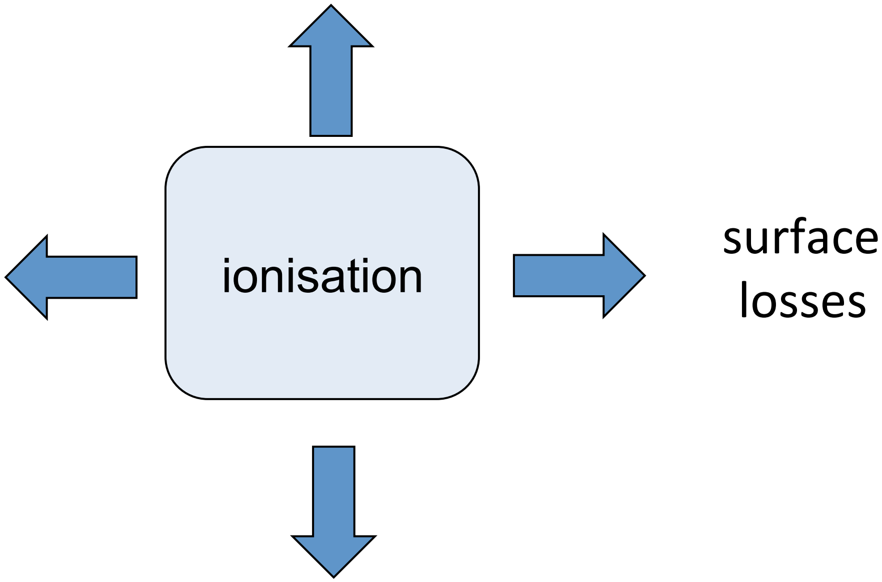
Working point of a Plasma – global model



Working point of a Plasma – global model

RUB





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

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

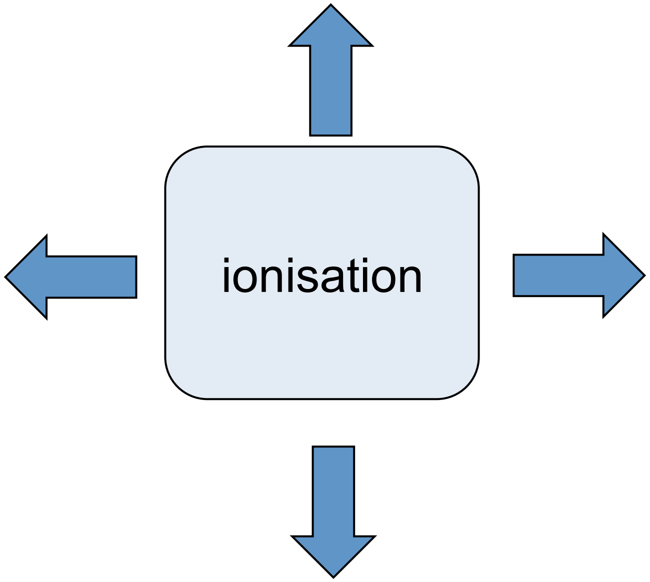
$$A n_0 \sqrt{\frac{k_B T_e}{M}} = n_g n_0 k_0 e^{-\frac{E_{Ionisation}}{k_B T_e}} V$$

Particle balance determines Electron temperature

Working point of a Plasma – global model

RUB

Absorbed power is a complicated function of electon density



Power loss to surfaces

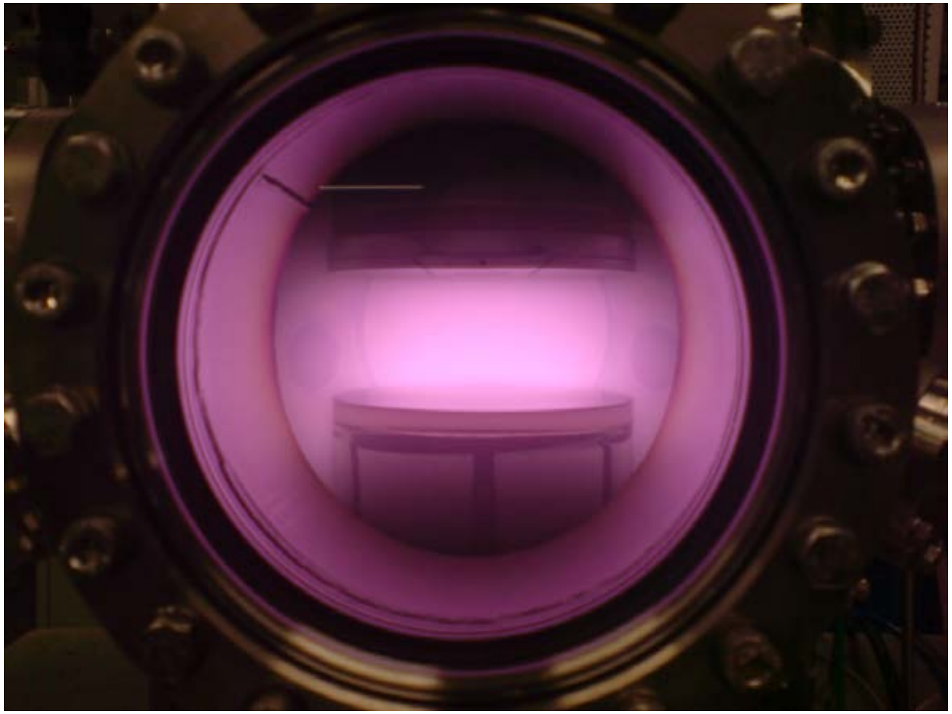
$$P_{abs} = P_{\text{Verlust}} = n_0 v_B A \left(E_{Ionisation} + E_{Randschicht}\right)$$

+ excitation,
+ electron loss to surfaces

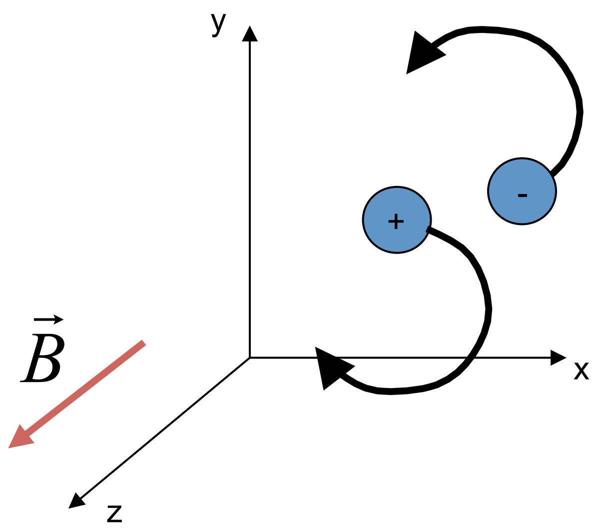
Power balance determines Electron density

More on this in the lecture by M. Turner and L. Alves

Transport in a plasma



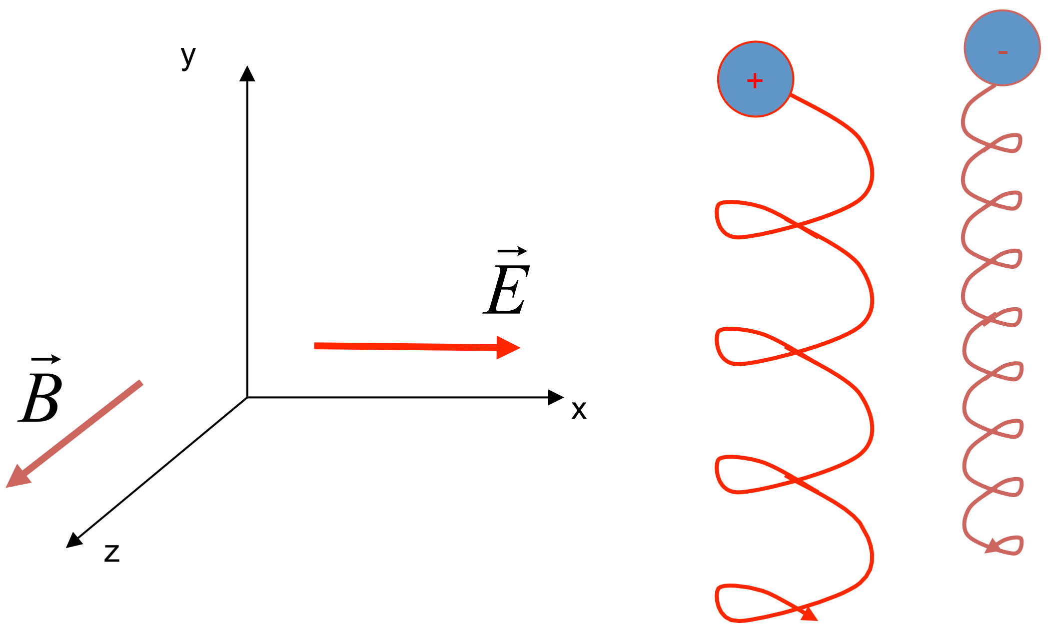
Transport in a plasma – single particle motion



$$m\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$\omega_c = \frac{|q|B}{m}$$

$$r_L = \frac{v_\perp}{\omega_c} = \frac{mv_\perp}{|q|B}$$



$$\vec{v}_{E\times B} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Transport in a plasma – single particle motion

electrons

$$\omega_{ce} = \frac{eB}{m_e} = 1.76 \times 10^{11} B[T]$$

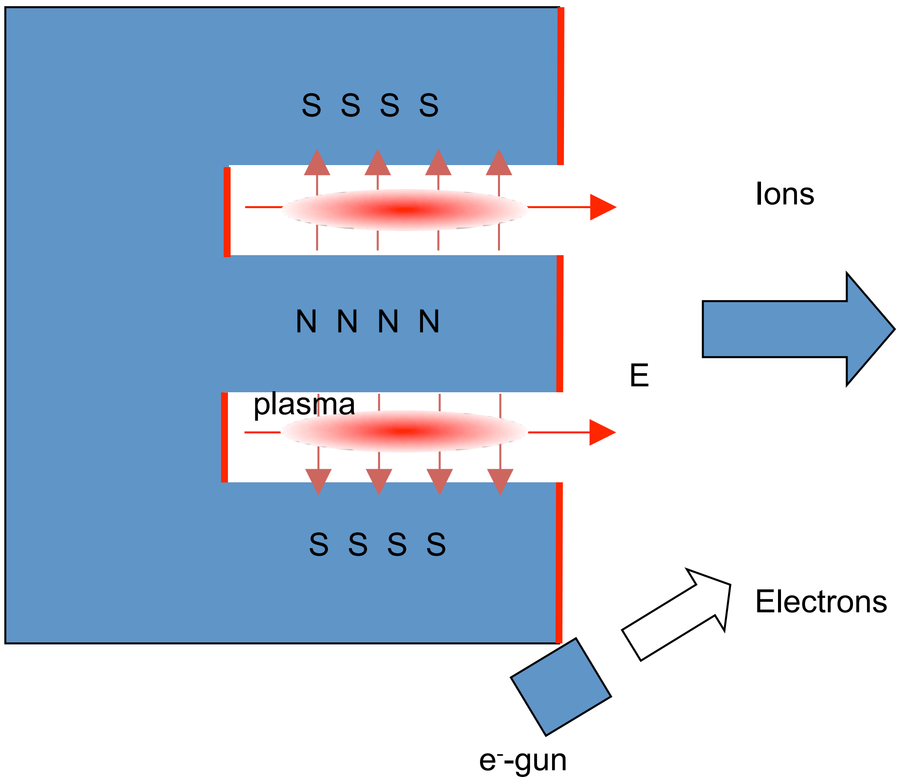
$$r_e = \frac{mv}{eB} = \frac{2.2 \times 10^{-6} \sqrt{T[eV]}}{B[T]}$$

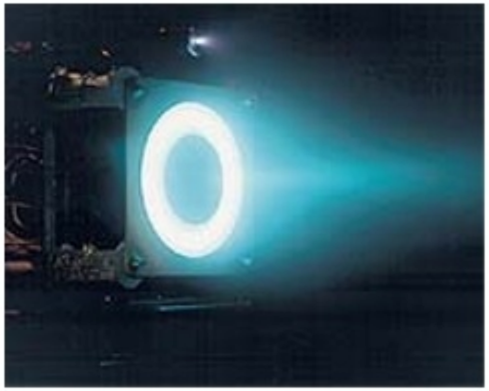
ions

$$\omega_{ci} = \frac{eB}{M_i} = \frac{0.96 \times 10^{8} B[T]}{A[amu]}$$

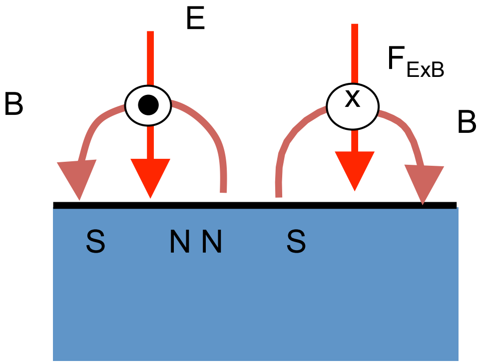
$$r_i = \frac{M_i v}{eB} = \frac{10^{-4} \sqrt{T[eV] A[amu]}}{B[T]}$$

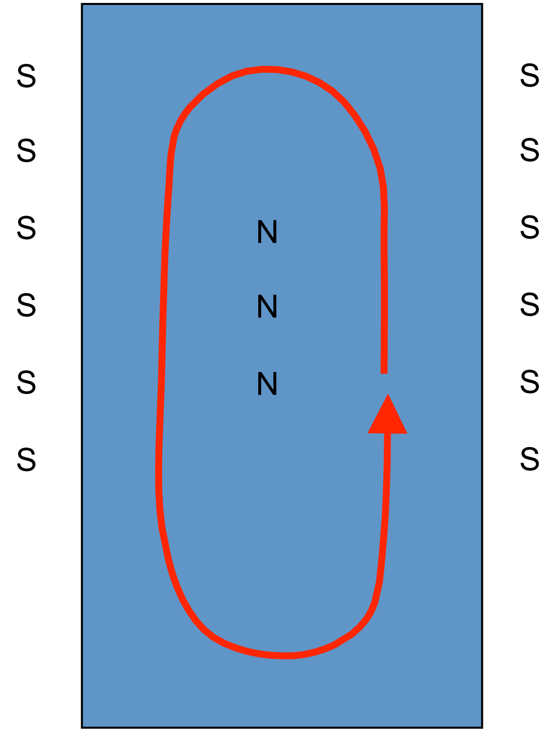
Transport in a plasma – single particle motion – example hall thrusters

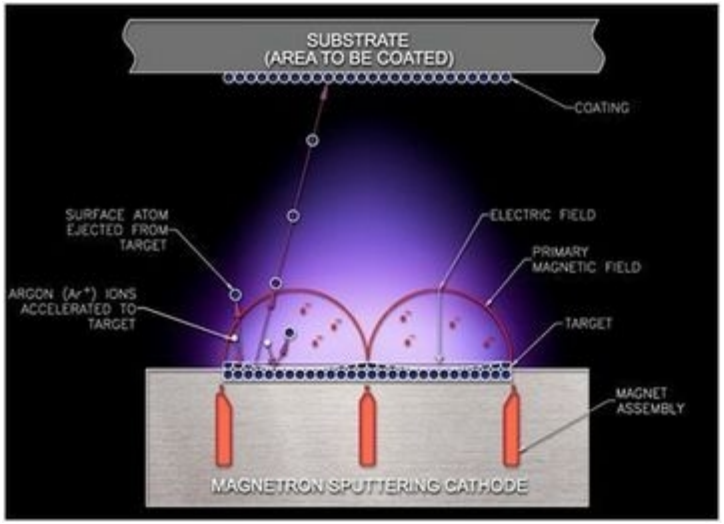


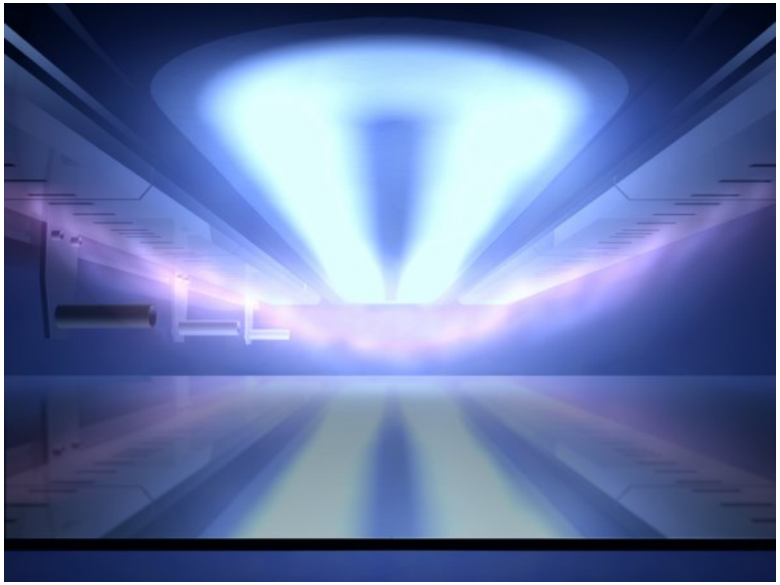


Transport in a plasma – single particle motion example magnetron

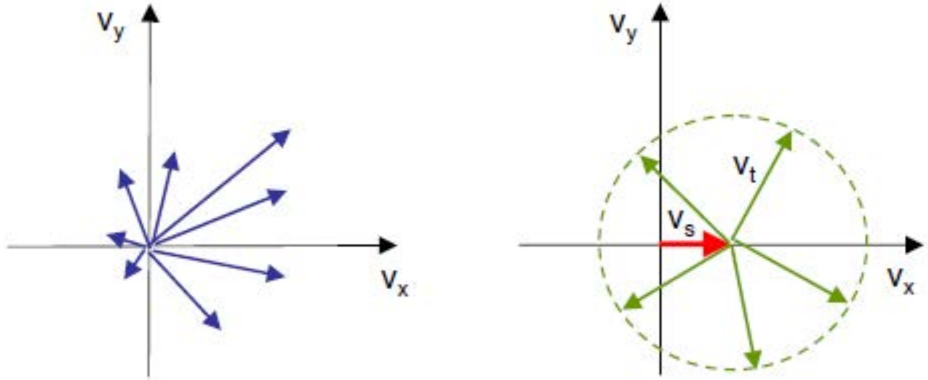








Transport in a plasma – motion as a fluid



Particle conservation
$$\frac{\partial n}{\partial t} + \nabla\left(n\vec{v}_s\right) = 0$$
RHS: plus source terms due to ionization or recombination

$$p = mn\langle v_t^2\rangle$$

Momentum conservation
$$mn\left[\frac{\partial \vec{v}_s}{\partial t} + \vec{v}_s\nabla\vec{v}_s\right] = n\vec{F} - \nabla p = nq(\vec{E} + \vec{v}_s \times \vec{B}) - \nabla p$$

$$mn\left[\frac{\partial}{\partial t}\vec{v} + (\vec{v}\nabla)\vec{v}\right] = qn\vec{E} - \nabla p - m\vec{v}n\nu_m$$

collisions

Energy conservation
$$\frac{\partial}{\partial t}n\langle\epsilon\rangle + \underbrace{\nabla n\langle\epsilon\rangle v_s}_{\text{convektion}} + \underbrace{p\nabla v_s}_{\text{Compression/expansion}} + \underbrace{\nabla q}_{\text{Heat conduction}} - \underbrace{nv_s\vec{F}}_{\text{Ohmic heating}} = 0$$

RUB

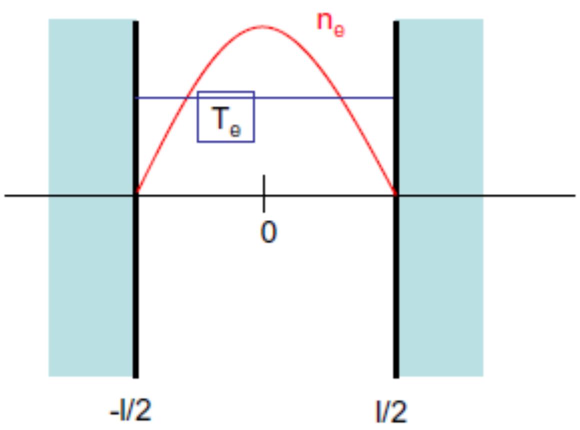
$$mn\left[\frac{\partial}{\partial t}\vec{v} + (\vec{v}\nabla)\vec{v}\right] = qn\vec{E} - \nabla p - m\vec{v}n\nu_m$$

$$\vec{v} = \frac{1}{mn\nu_m}\left(\pm en\vec{E} - \nabla p\right)$$

$$\frac{\nabla p}{p} = \gamma\frac{\nabla n}{n}$$

$$\vec{j} = n\vec{v} = n\frac{\pm e}{m\nu_m}\vec{E} - \frac{k_BT}{m\nu_m}\nabla n$$

a typical solution



$$\mu = \frac{|q|}{m\nu_m}$$

mobility

$$D = \frac{k_BT}{m\nu_m}$$

diffusion

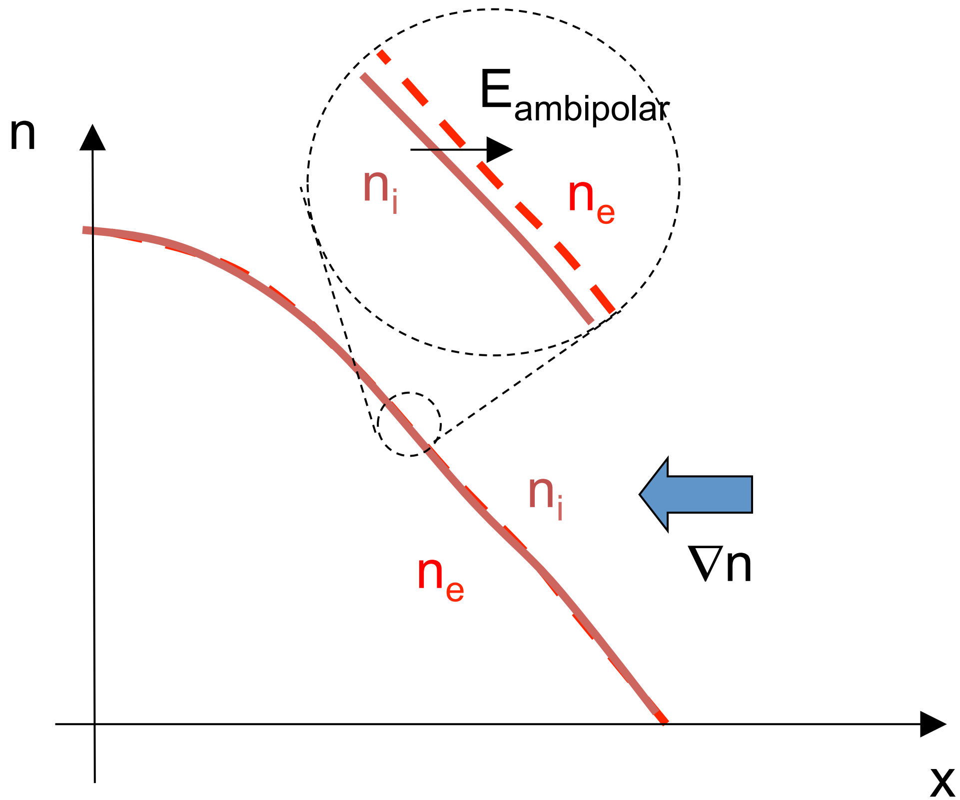
$$\vec{j} = \mu_i n_i\vec{E} - D_i\nabla n_i$$

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

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

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

$$\vec{j} = \mu_i n \frac{D_i - D_e}{\mu_i + \mu_e} \frac{\nabla n}{n} - D_i \nabla n = -\frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e} \nabla n$$



$$D_{amb} = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}$$

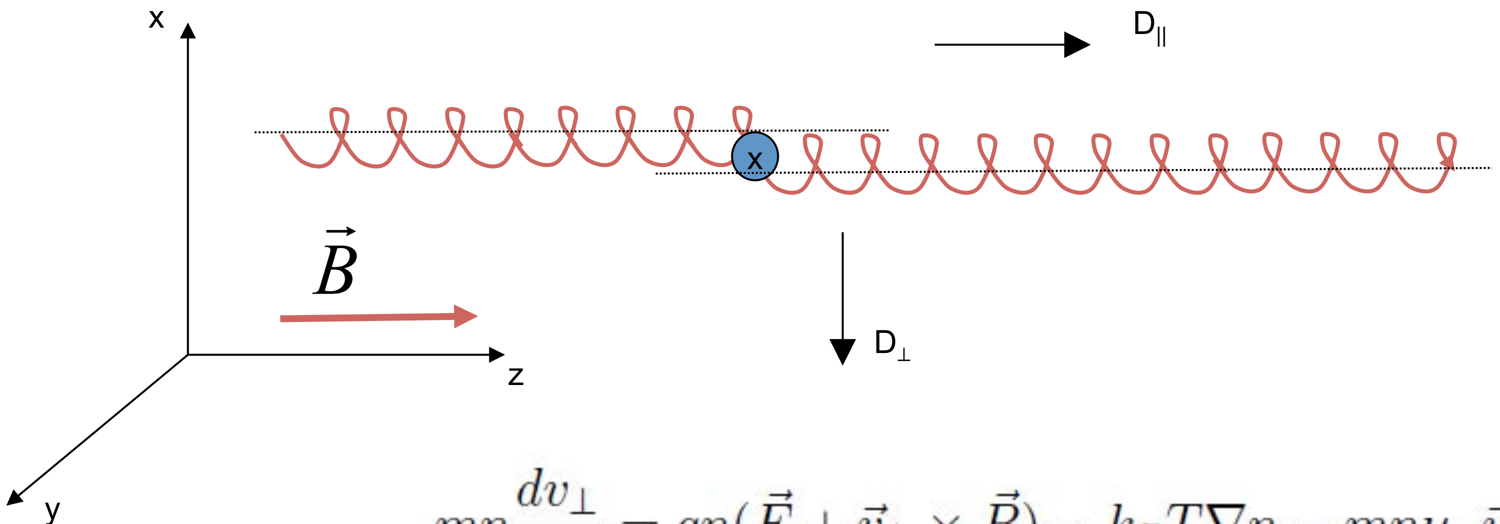
for $\mu_e \gg \mu_i.$ and Te>>Ti

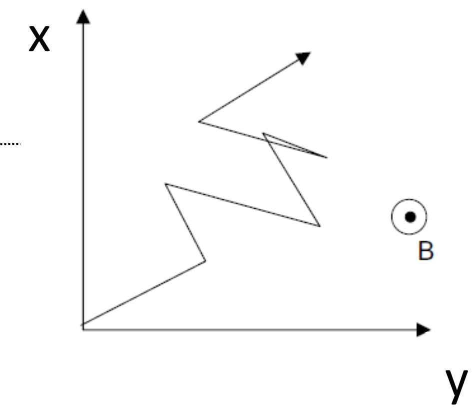
$$D_{amb} = D_i \frac{T_e}{T_i} = \frac{k_B T_e}{M \nu_{m,Ionen}}$$

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

Transport in a plasma – magnetic confinement

RUB





$$mn\frac{dv_\perp}{dt} = qn(\vec{E} + \vec{v}_\perp \times \vec{B}) - k_B T \nabla n - mn\nu_m \vec{v}$$

without inertia

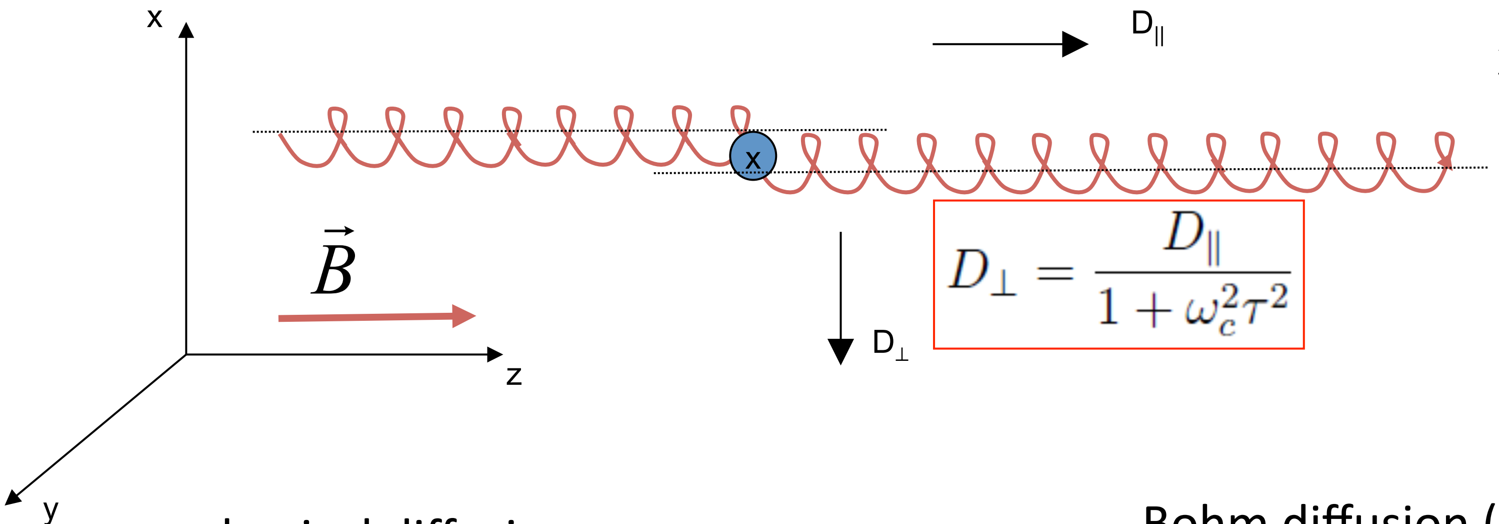
$$\begin{cases} mn\nu_m v_x = \pm enE_x - k_B T_e \frac{\partial n}{\partial x} \pm env_y B \\ mn\nu_m v_y = \pm enE_y - k_B T_e \frac{\partial n}{\partial y} \mp env_x B \end{cases}$$

$$v_x(1+\omega_c^2\tau^2) = \pm\mu E_x - \frac{D}{n}\frac{\partial n}{\partial x} + \omega_c^2\tau^2\frac{E_y}{B} \mp \omega_c^2\tau^2\frac{k_B T}{eB}\frac{1}{n}\frac{\partial n}{\partial y}$$

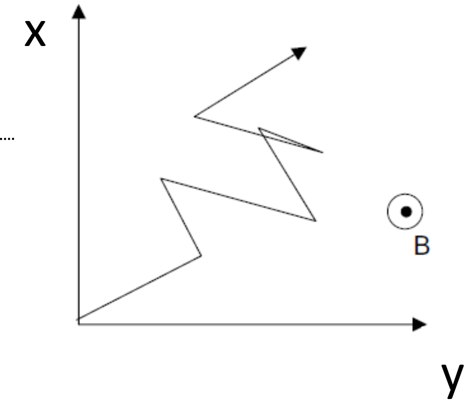
drift diffusion ExB-drift diamag. drift

$$D_\perp = \frac{D_{||}}{1+\omega_c^2\tau^2}$$

Transport in a plasma – classical vs. Bohm diffusion



$$D_\perp = \frac{D_\parallel}{1+\omega_c^2\tau^2}$$



classical diffusion

$$D_\perp = \frac{k_B T}{m\nu_m}\frac{\nu_m^2}{\omega_c^2} \propto \frac{\nu_m}{B^2} \propto \frac{r_L^2}{\tau_m}$$

for $\omega^2\tau^2 \gg 1$

Bohm diffusion (empirical)

$$D_\perp = \frac{1}{16}\frac{k_B T}{eB} = D_{\mathrm{Bohm}}$$

Idea: instabilities induce electric fields, which drive ExB drift

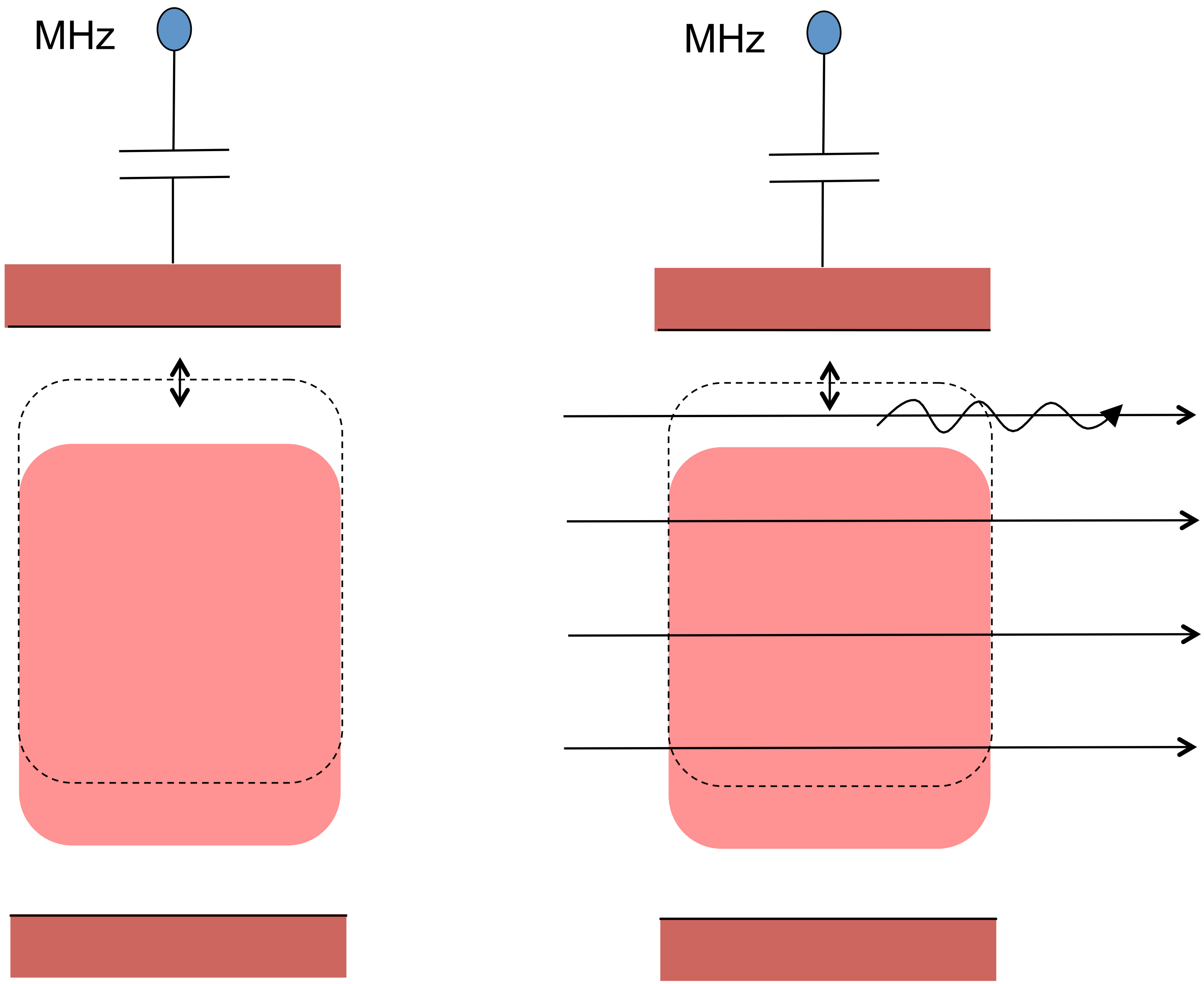
$$\vec{v}_\perp = \frac{\vec{E}\times\vec{B}}{B^2} \qquad \delta\Gamma_\perp = \delta n\frac{\vec{E}\times\vec{B}}{B^2} \propto \delta n\frac{E}{B}$$

$$E = \frac{\Phi}{R} \simeq \frac{k_B T_e}{eR}$$

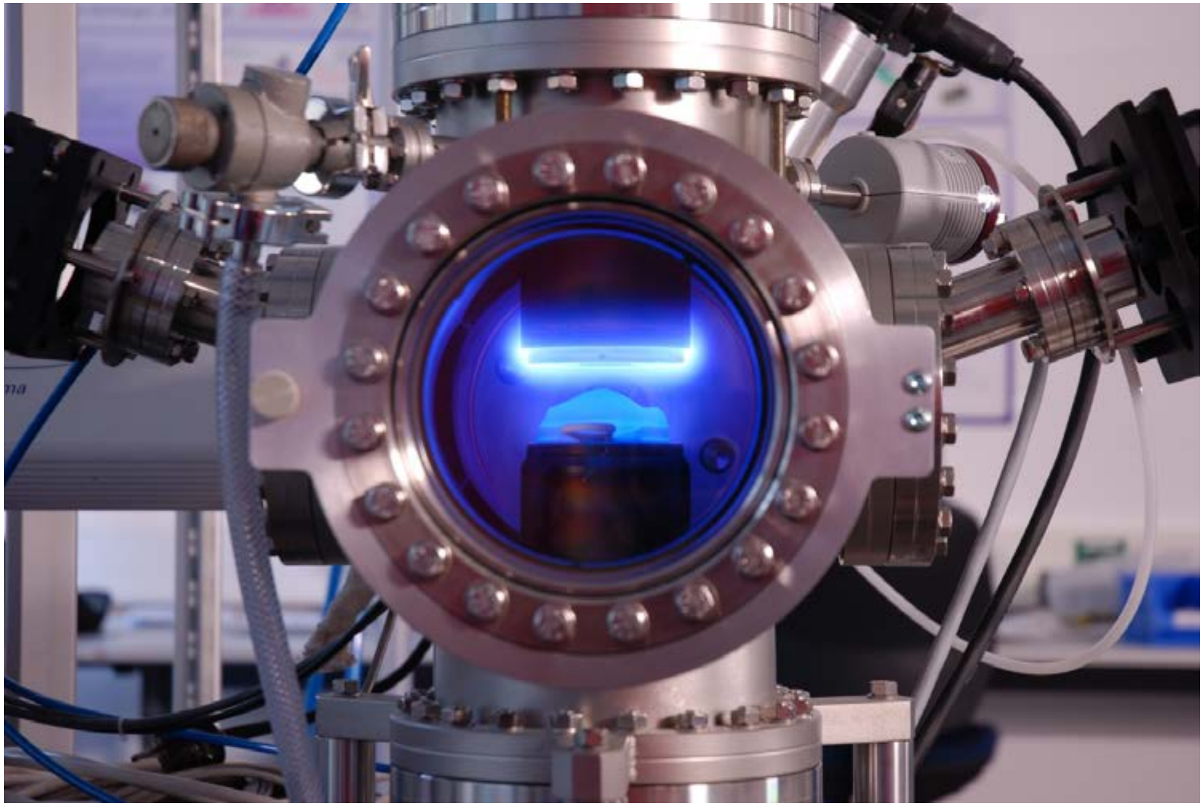
$$\Gamma_\perp = \frac{\delta n}{R}\frac{k_B T_e}{eB} \simeq \frac{k_B T}{eB}\nabla n$$

Transport in a plasma – magnetic confinement

RUB



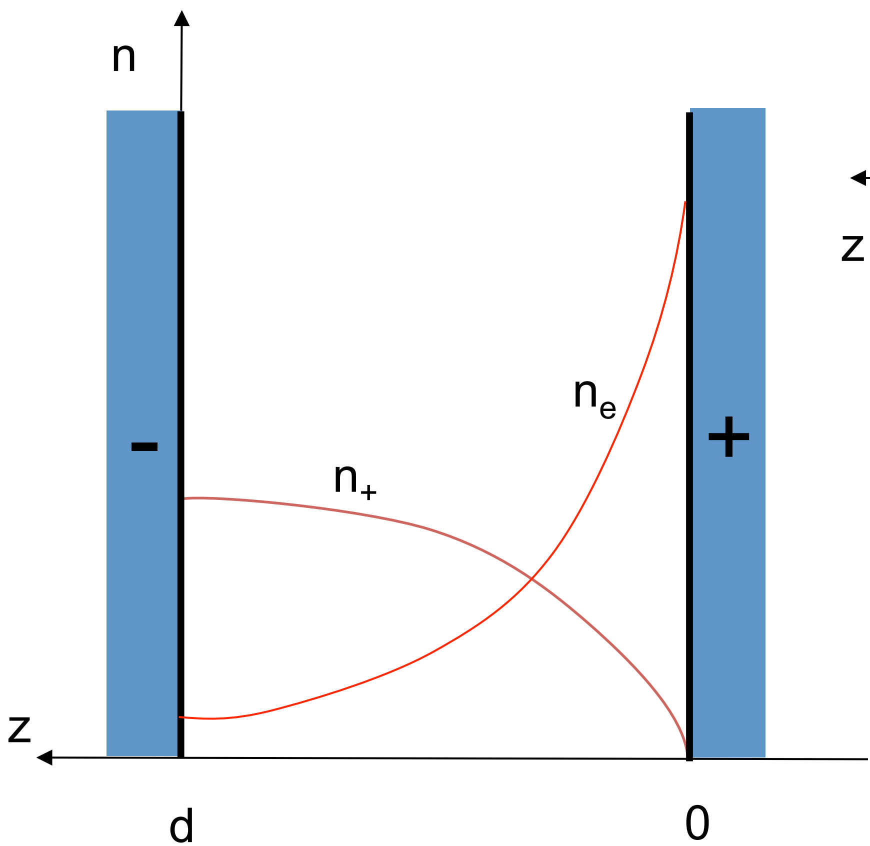
Ignition of a plasma

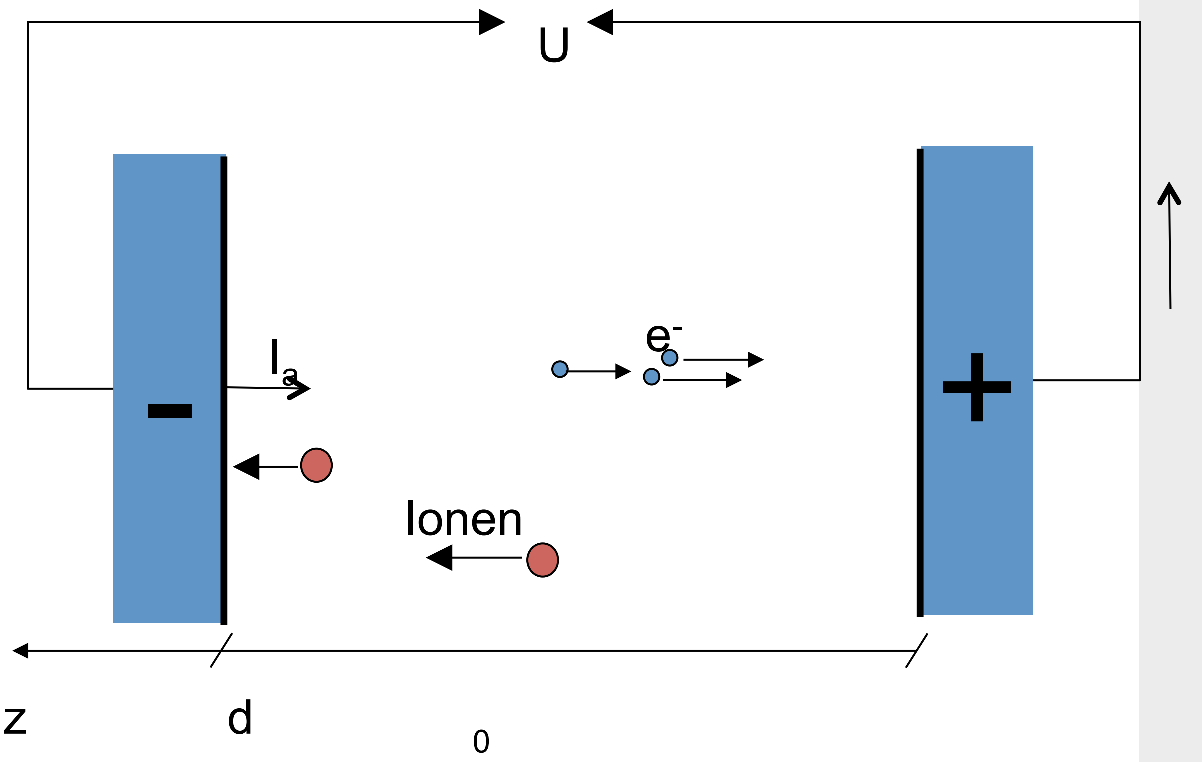


Ignition of a plasma – Townsend regime

1. Townsend coefficient
gas amplification

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





$$n_e = \frac{I_a}{eAv_{d,-}}e^{\alpha(d-z)}$$

$$n_+ = \frac{I_a}{eAv_{d,+}}e^{-\alpha d}\left(1 - e^{-\alpha z}\right)$$

$$I = I_e + I_+ = I_a e^{\alpha d}$$

Ignition of a plasma – Townsend regime – Secondary effects

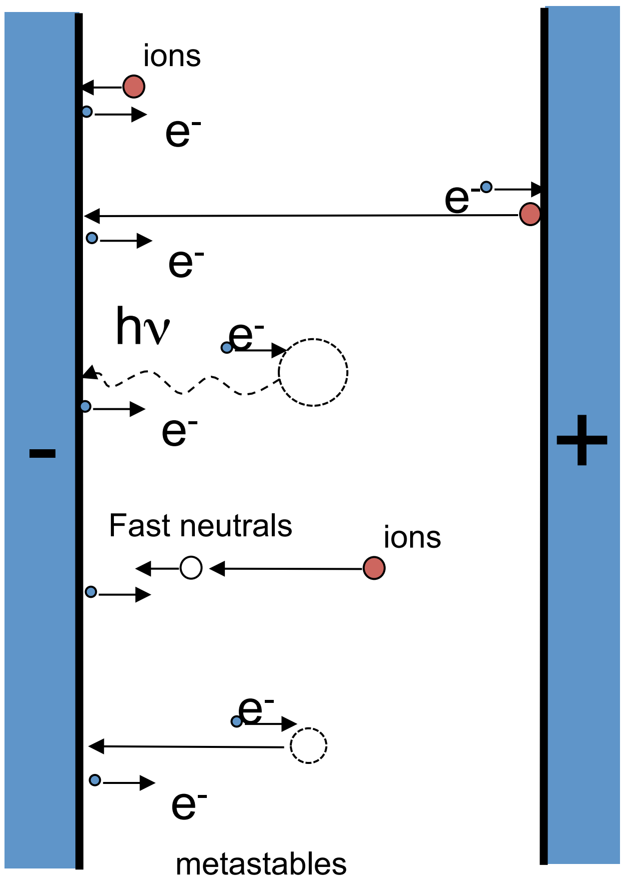
Ionbombardment at the cathode

Secondary ion emission at the anode

photoeffect

fast neutrals

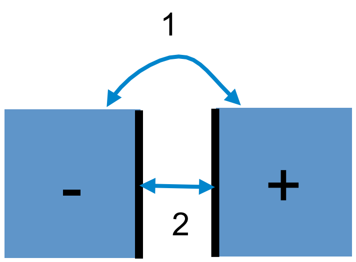
metastables



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

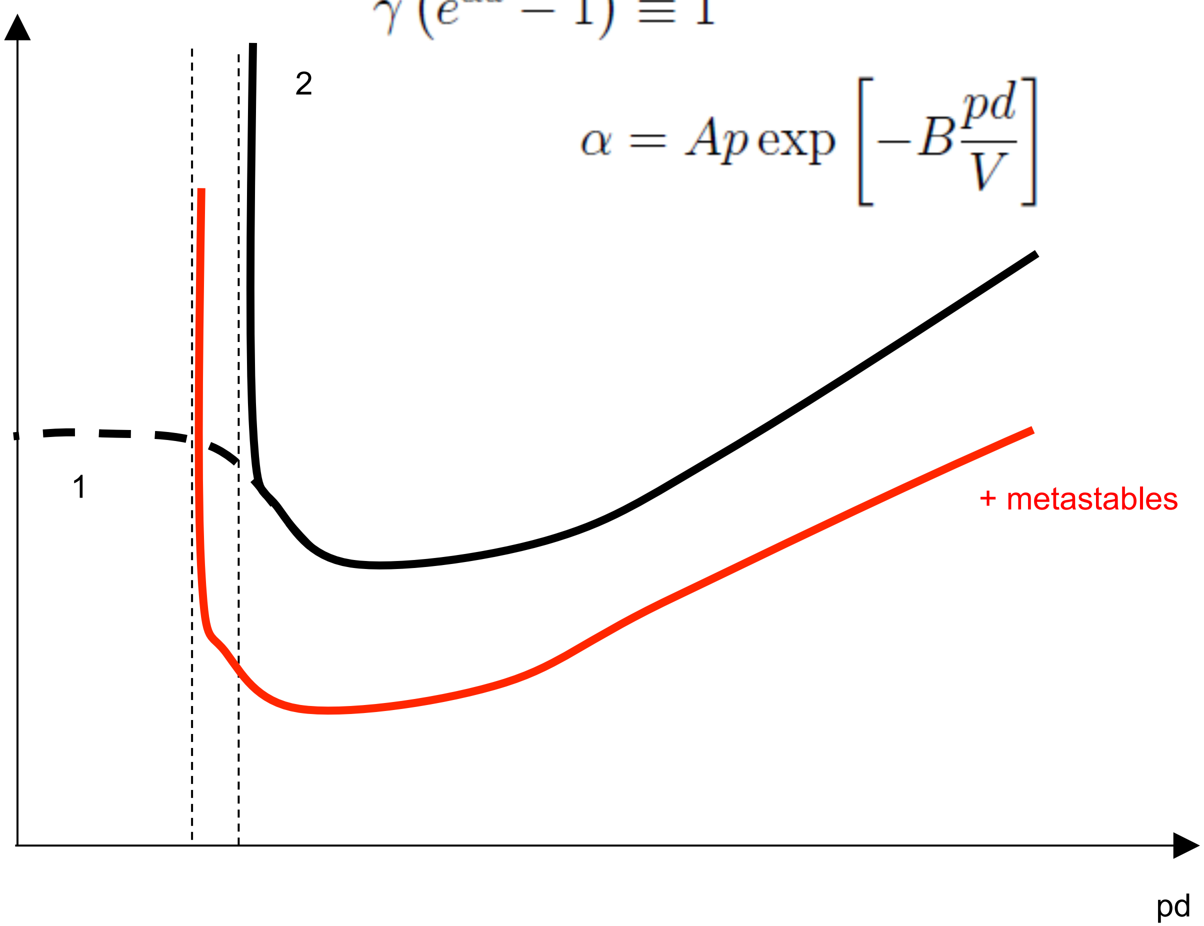
$$\gamma\left(e^{\alpha d}-1\right) \equiv 1$$

Ignition of a plasma – the Paschen curve



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

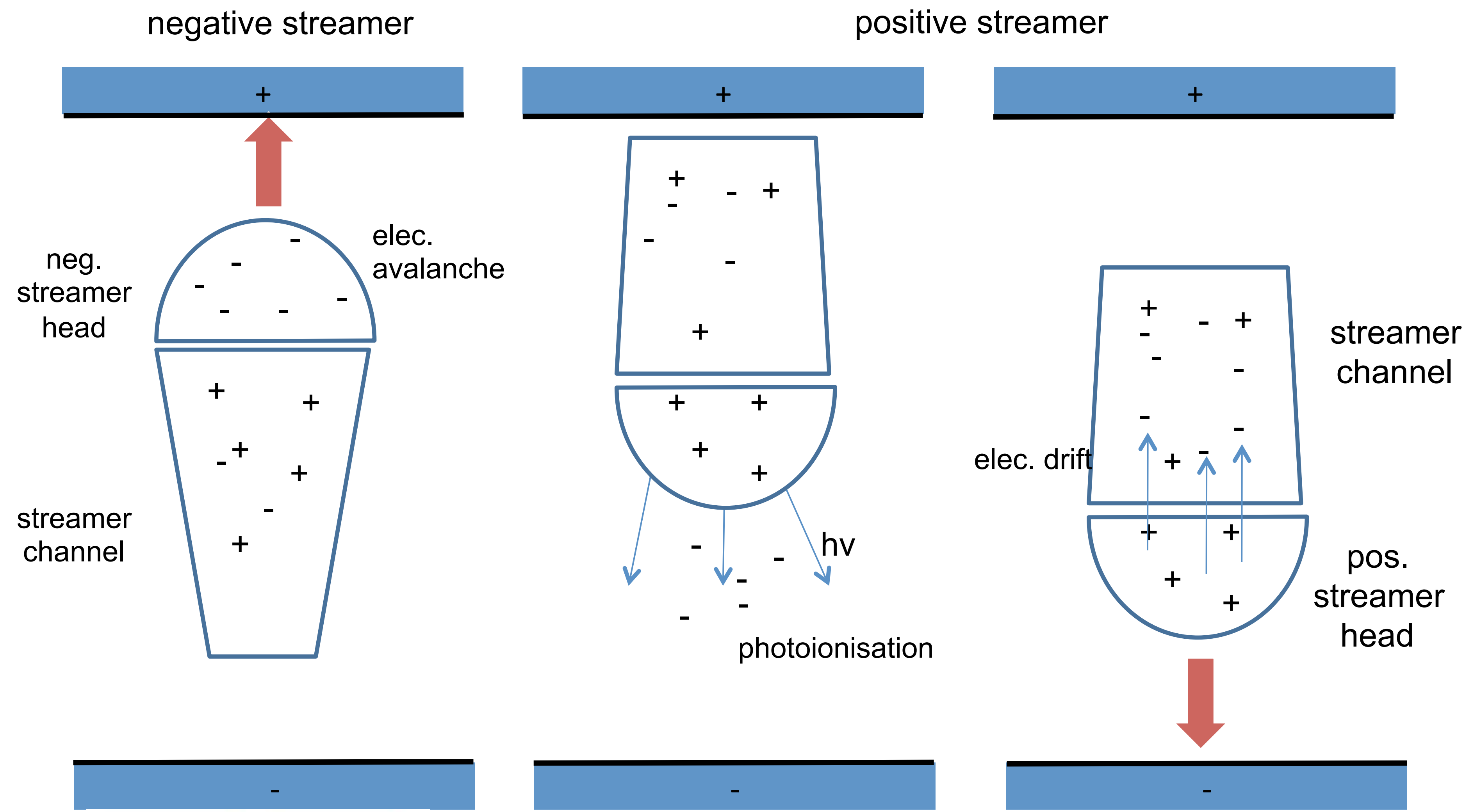
$$\alpha = Ap\exp\left[-B\frac{pd}{V}\right]$$

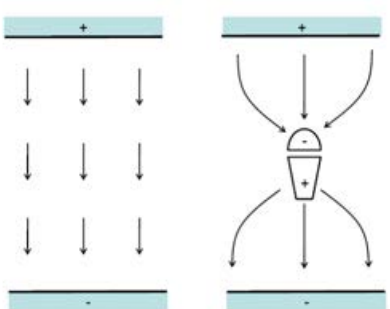


	A[cm^{-1}Torr^{-1}]	B[V cm^{-1}Torr^{-1}]	$e\frac{B}{A}$ [eV]
He	1.8	50	27.5
Ar	12	200	16.7
H_2	10.6	350	33
CO_2	20	466	23.3

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

Ignition of a plasma – High presssure - streamers





$$E_a = \frac{e}{4\pi\epsilon_0 R^2} e^{\alpha d} \qquad R = \frac{1}{\alpha}.$$

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

Meek criterion

Ignition of a plasma – High presssure - streamers

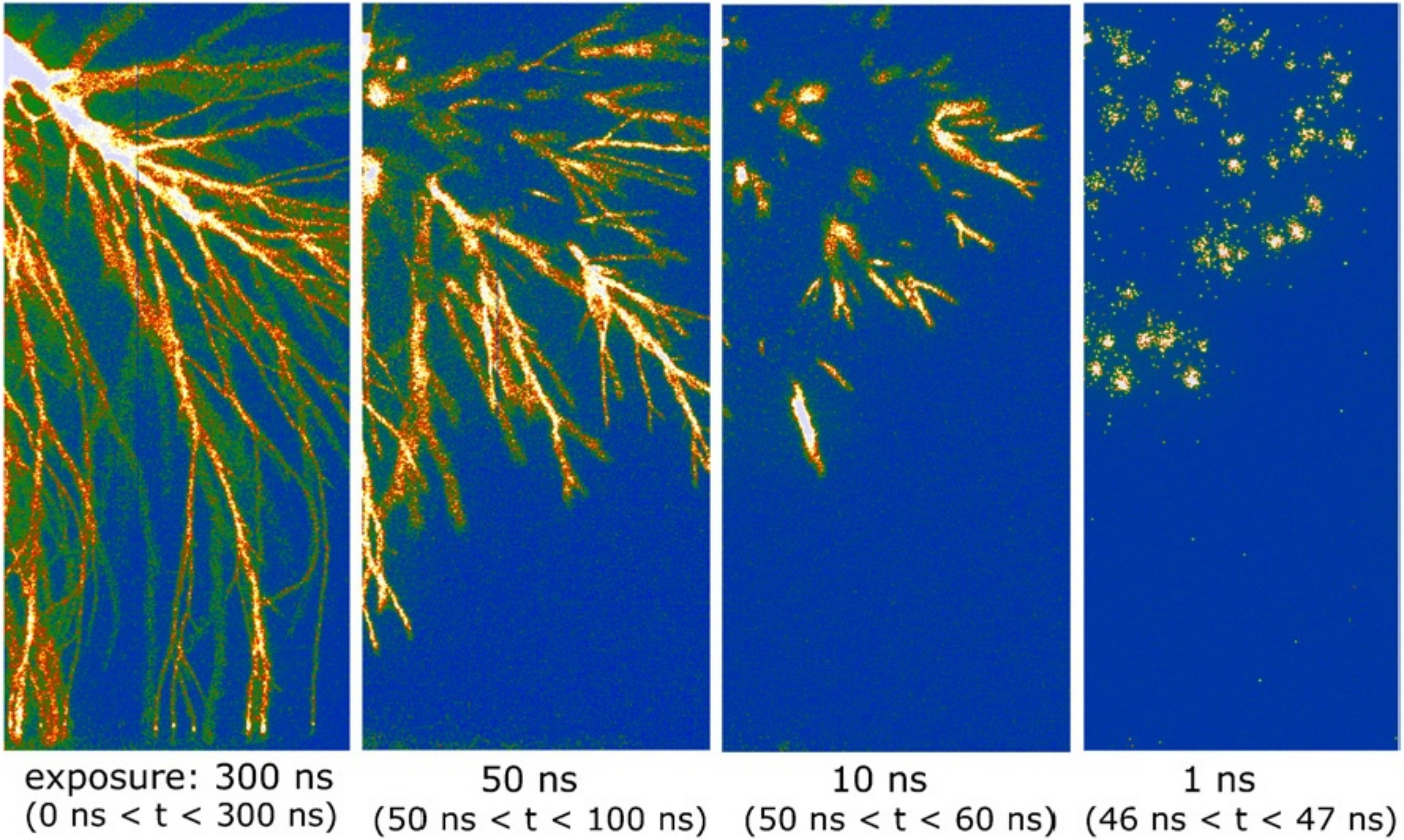
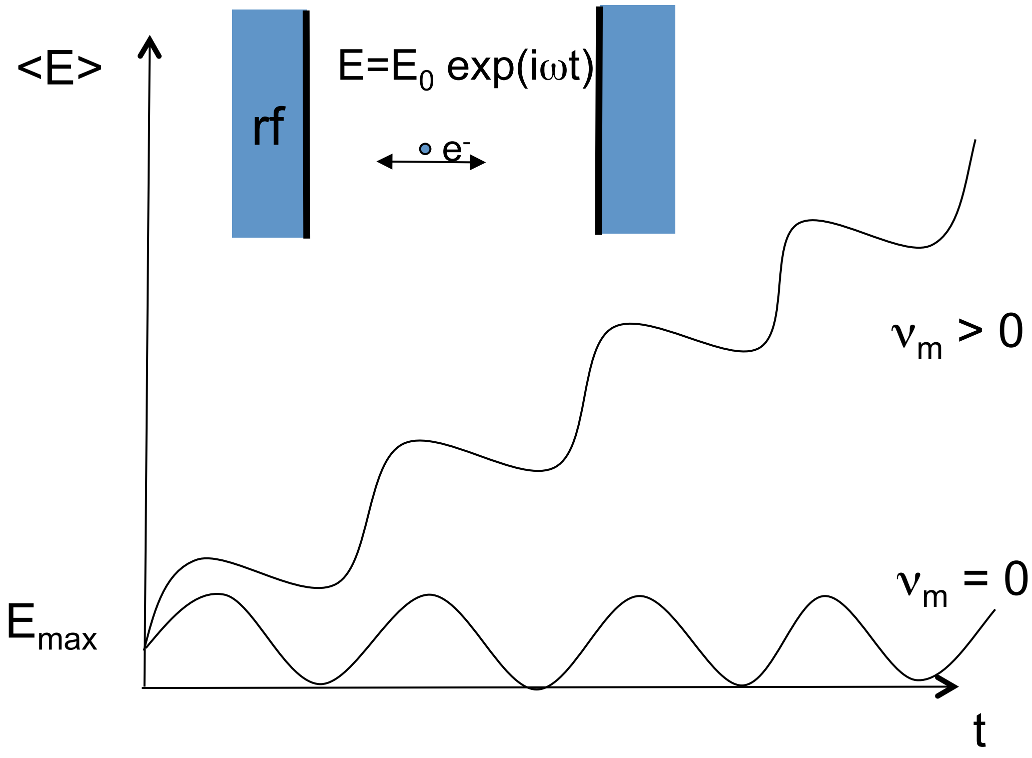


Abbildung 2.14: Photographie einer Streamerentladung bei unterschiedlichen Belichtungszeiten. [U. Ebert et al. *The multiscale nature of streamers*, Plasma Sources Science and Technol. 15, S118 (2006)]

Ignition of a plasma – rf-voltages

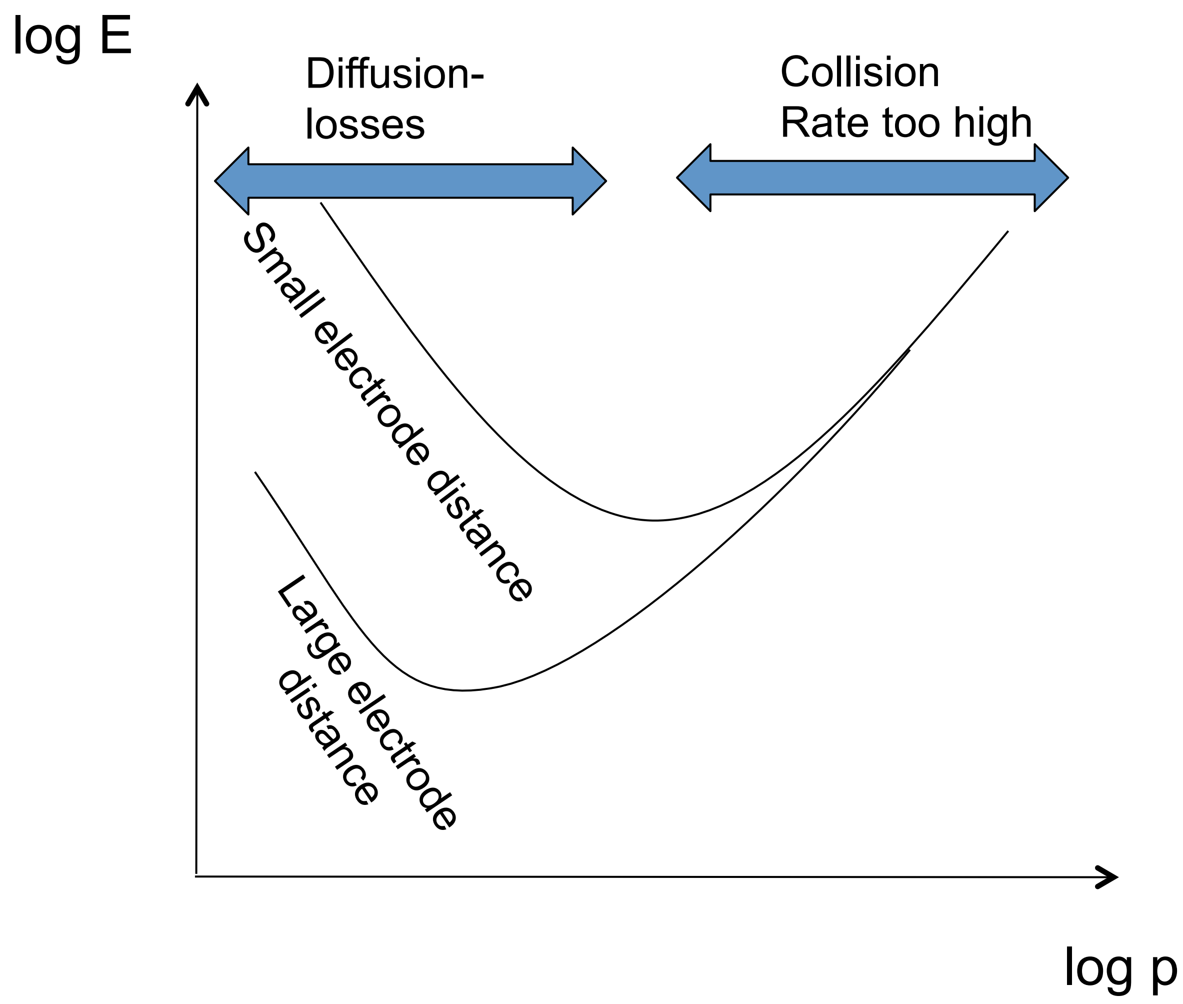


$$E_{max} = \frac{1}{2} m v_{max}^2 = \frac{1}{2} \frac{q^2 E_0^2}{m\omega^2}$$

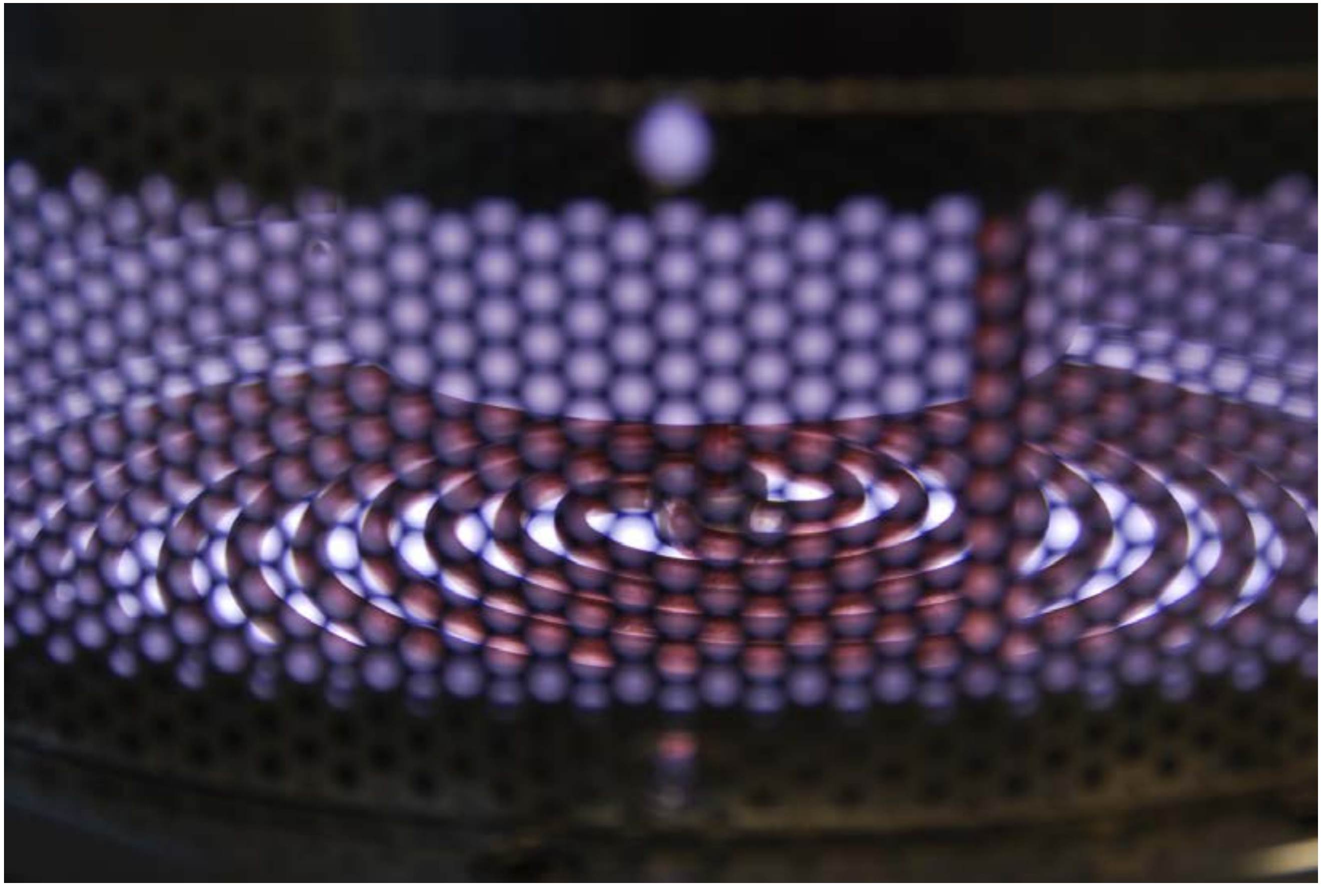
$$\langle E \rangle = \frac{m_g e^2 E_0^2}{2 m_e^2 (\omega^2 + \nu_m^2)} = E_{max} \frac{m_g}{m_e} \frac{\omega^2}{\omega^2 + \nu_m^2}$$

$$E_{eff}^2 = \frac{\nu_m^2}{\nu_m^2 + \omega^2} E_0^2$$

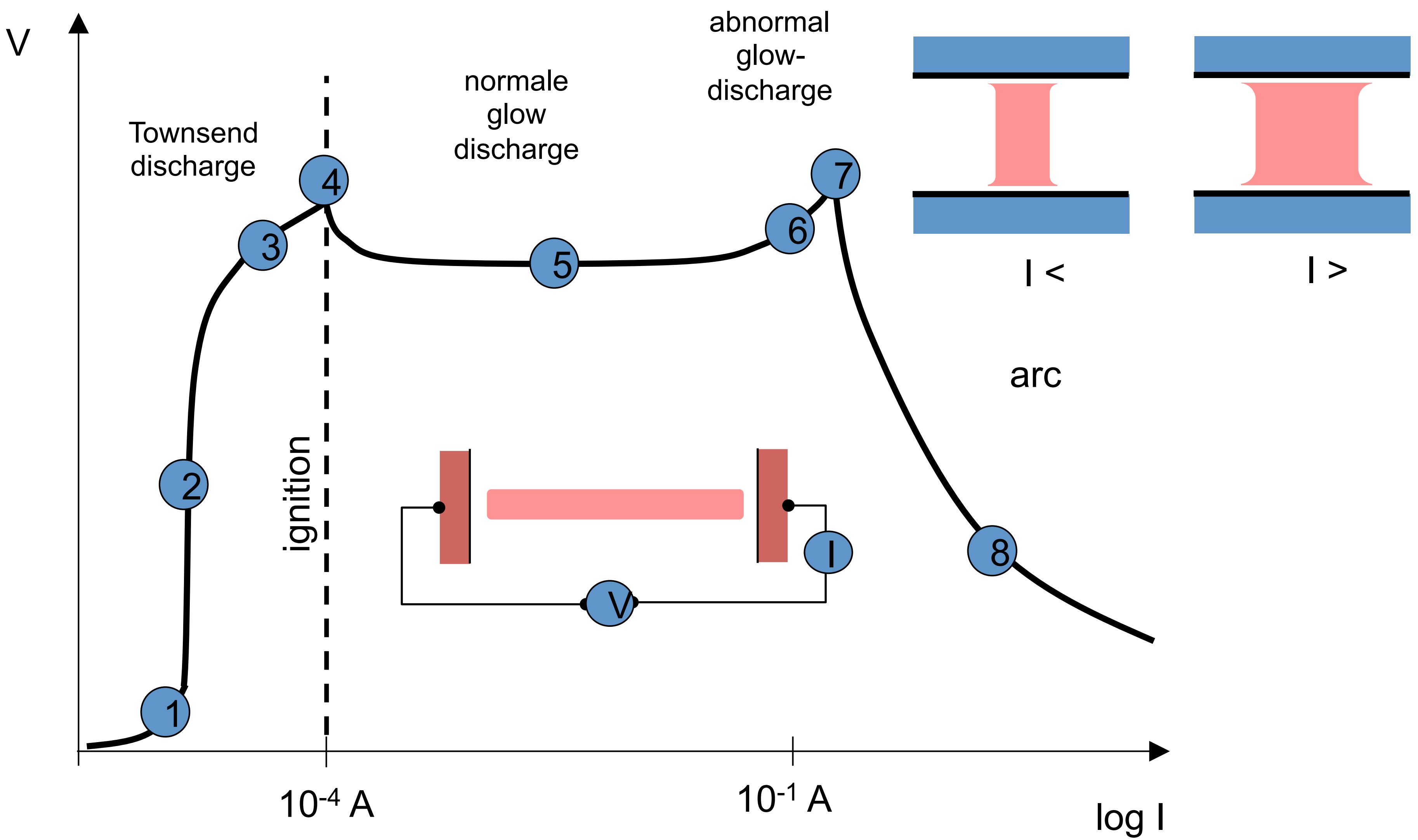
Ignition of a plasma – Paschen curve for rf-voltages



Sustaining a plasma

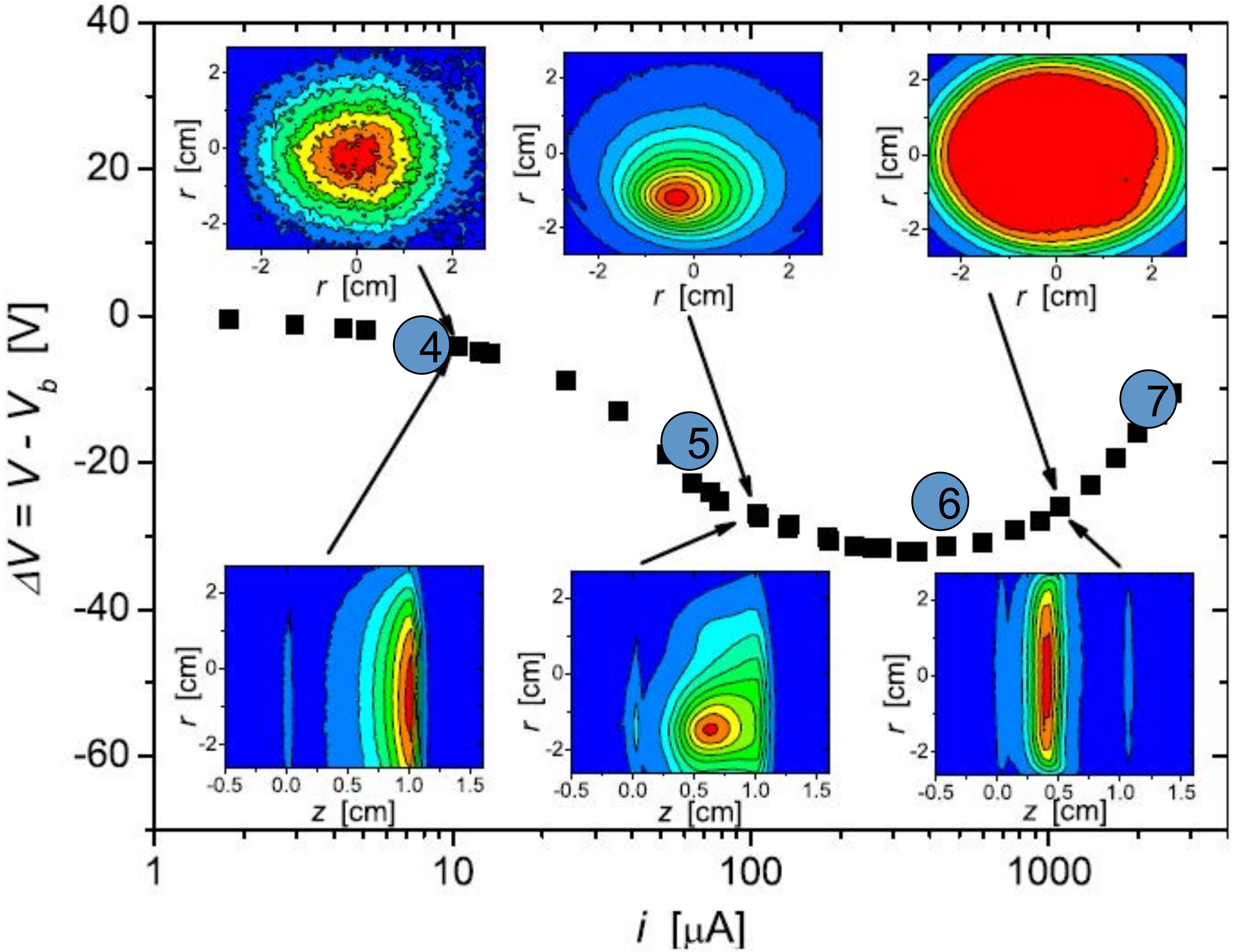


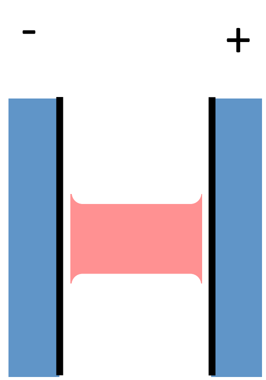
Sustaining a plasma – current voltage characteristics of a DC plasma



6 $$j_0 = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{V^{3/2}}{s^2}$$

Sustaining a plasma – instabilities at breakdown



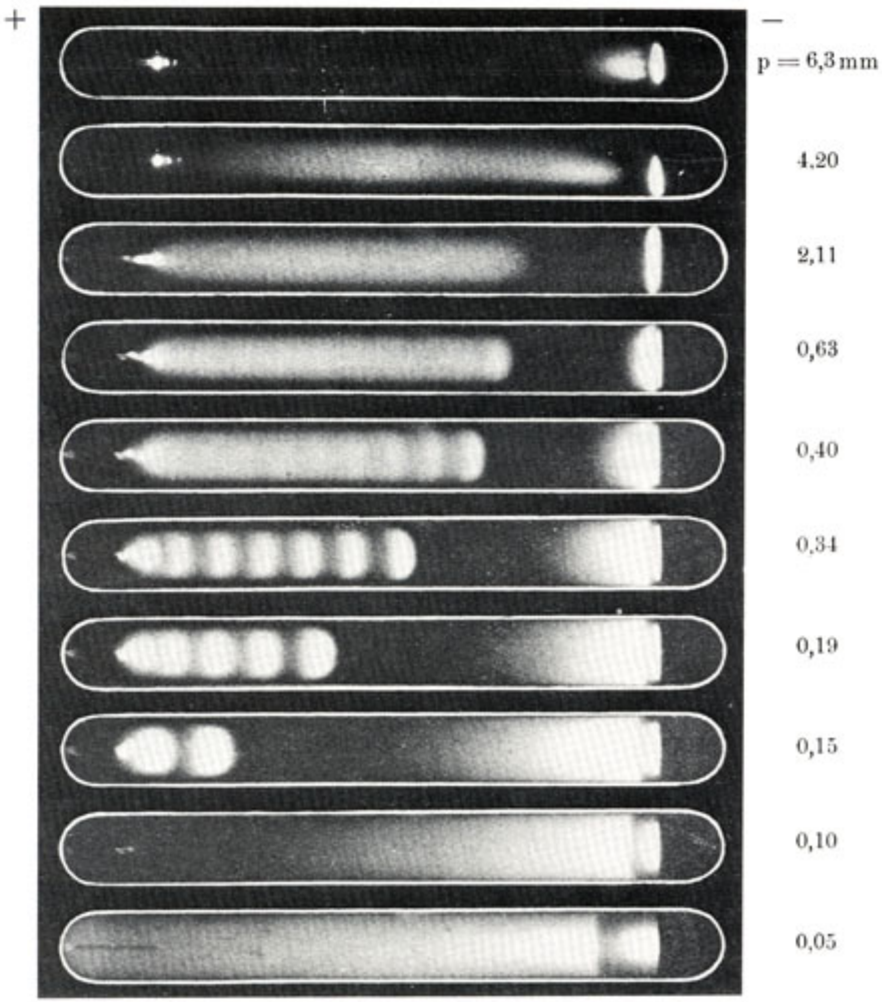


I. Stefanovic et al.

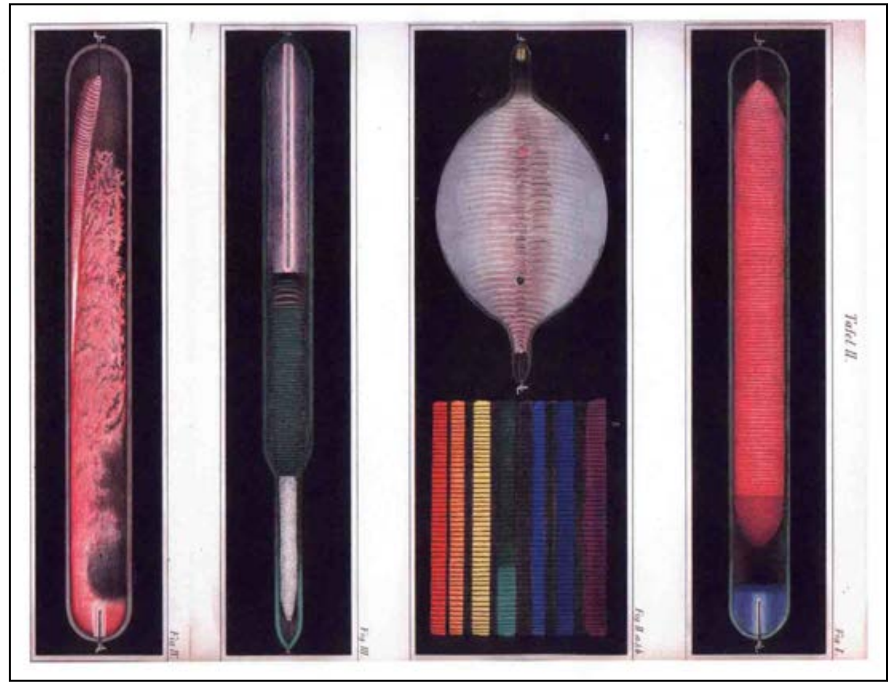
Sustaining a plasma – striations

RUB

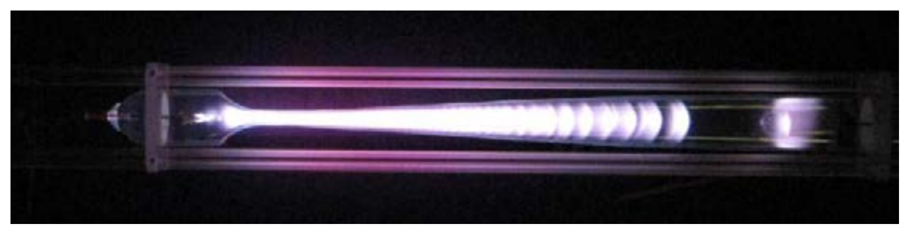
Kaufmann, Handbuch der Experimentalphysik, 1929



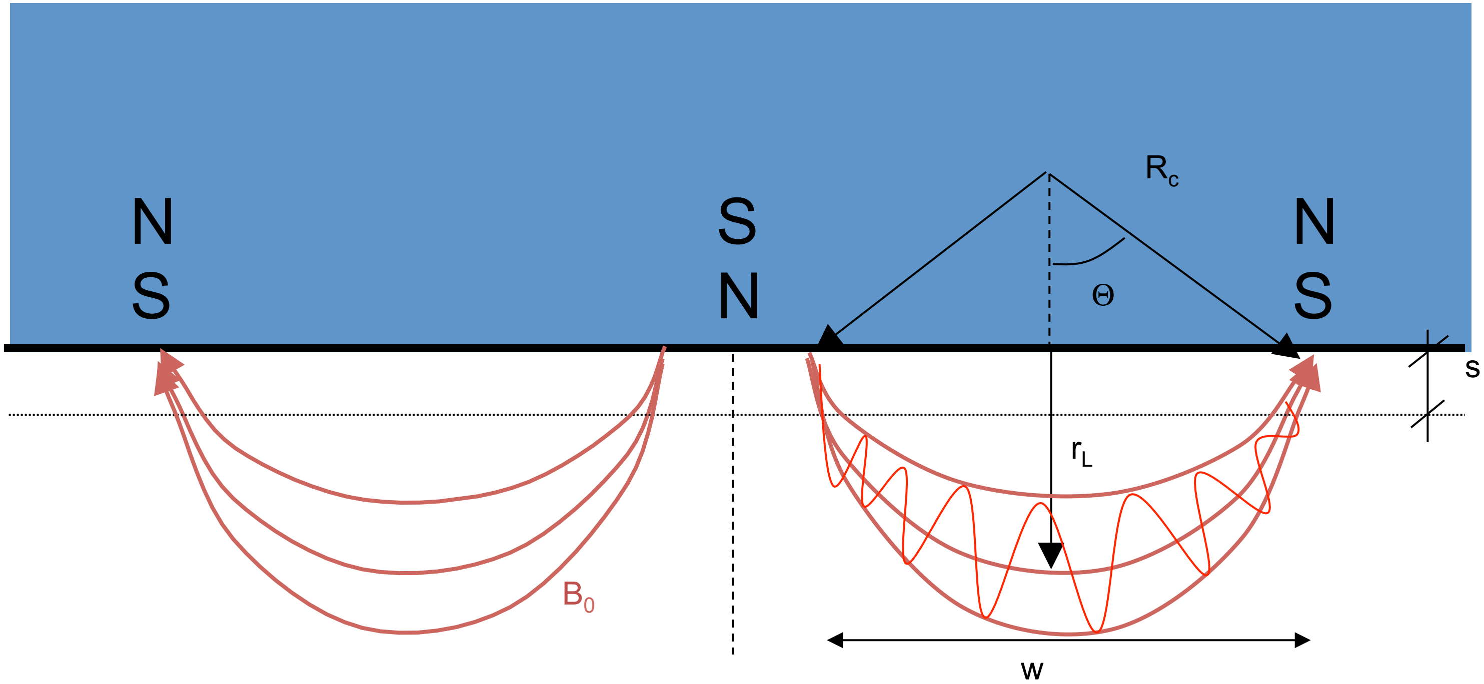
Meyer, Berlin 1858

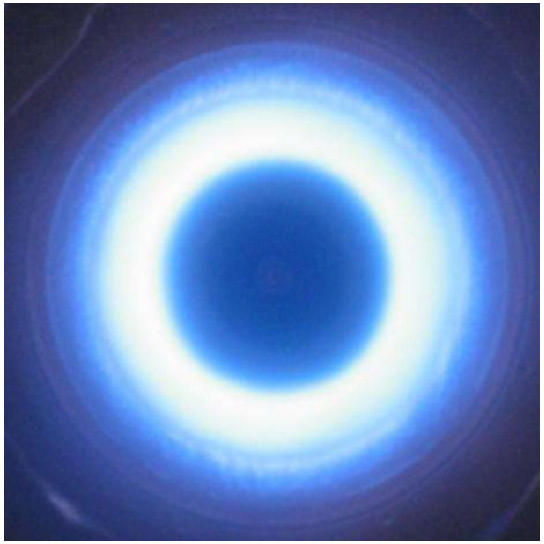


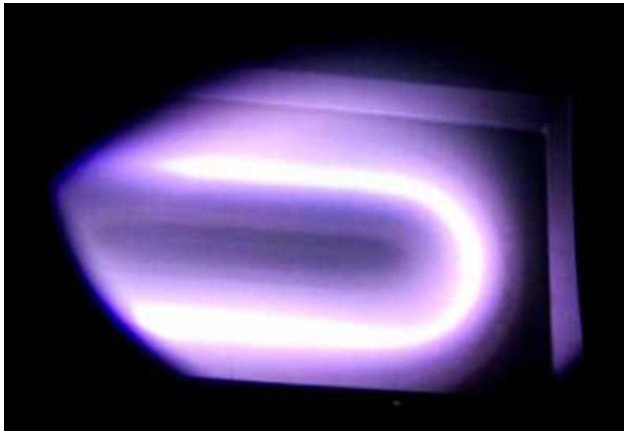
RUB



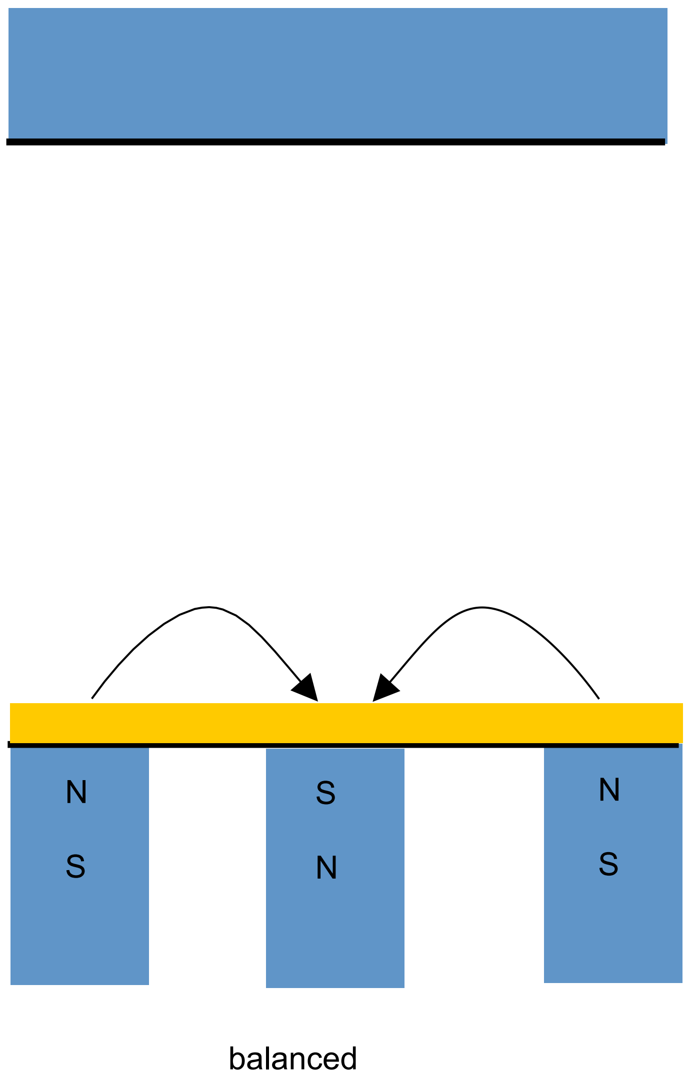
Sustaining a plasma – magnetron discharges

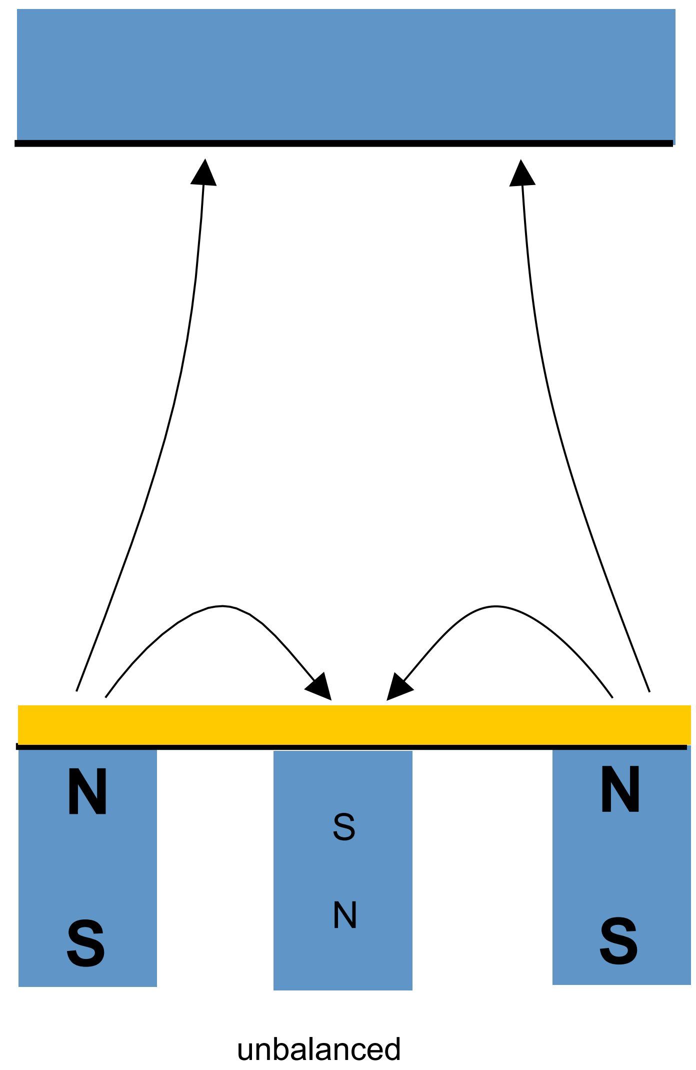




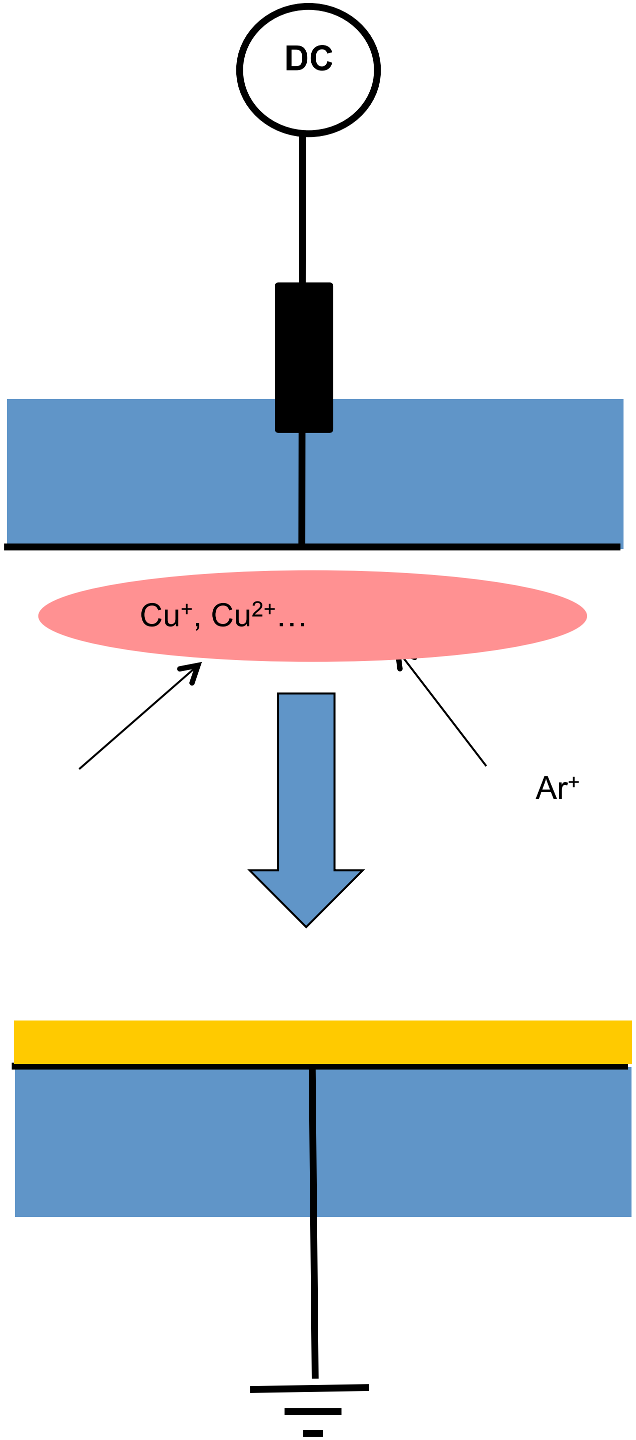


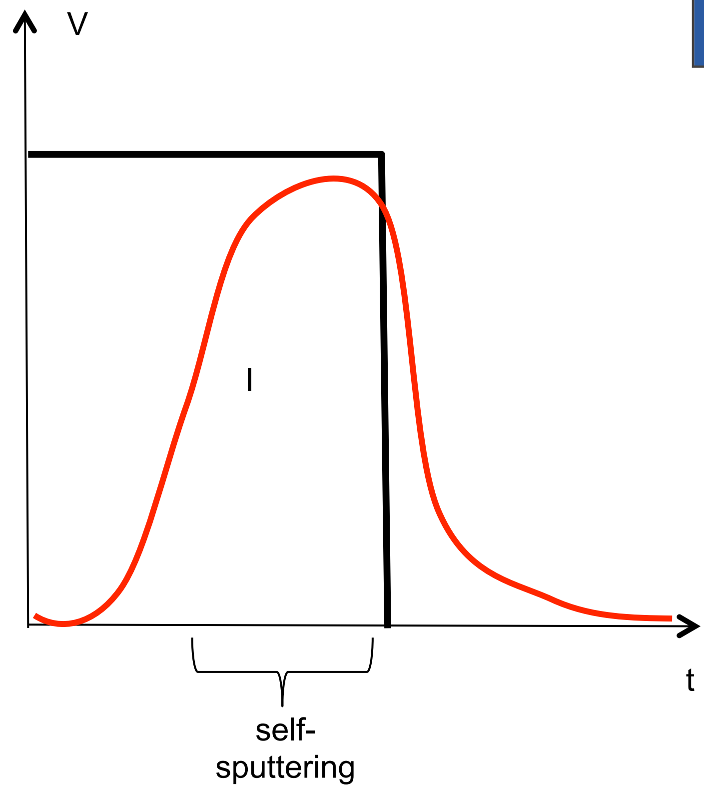
Sustaining a plasma – balanced / unbalanced magnetrons

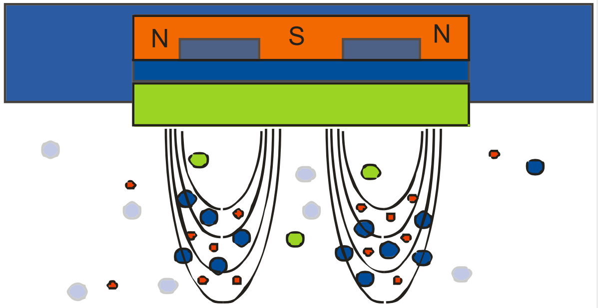


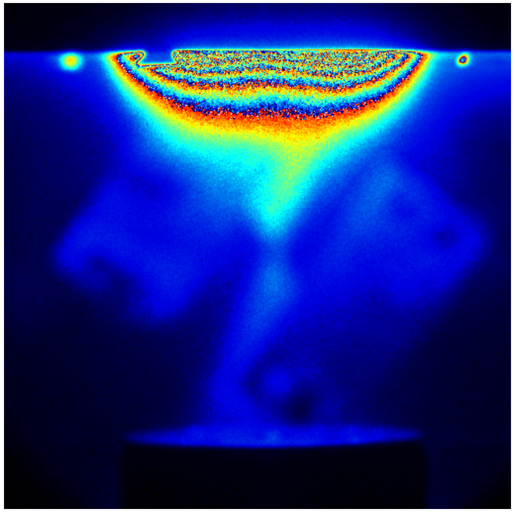


Sustaining a plasma – High Power Pulses Magnetron Sputtering (HPPMS)

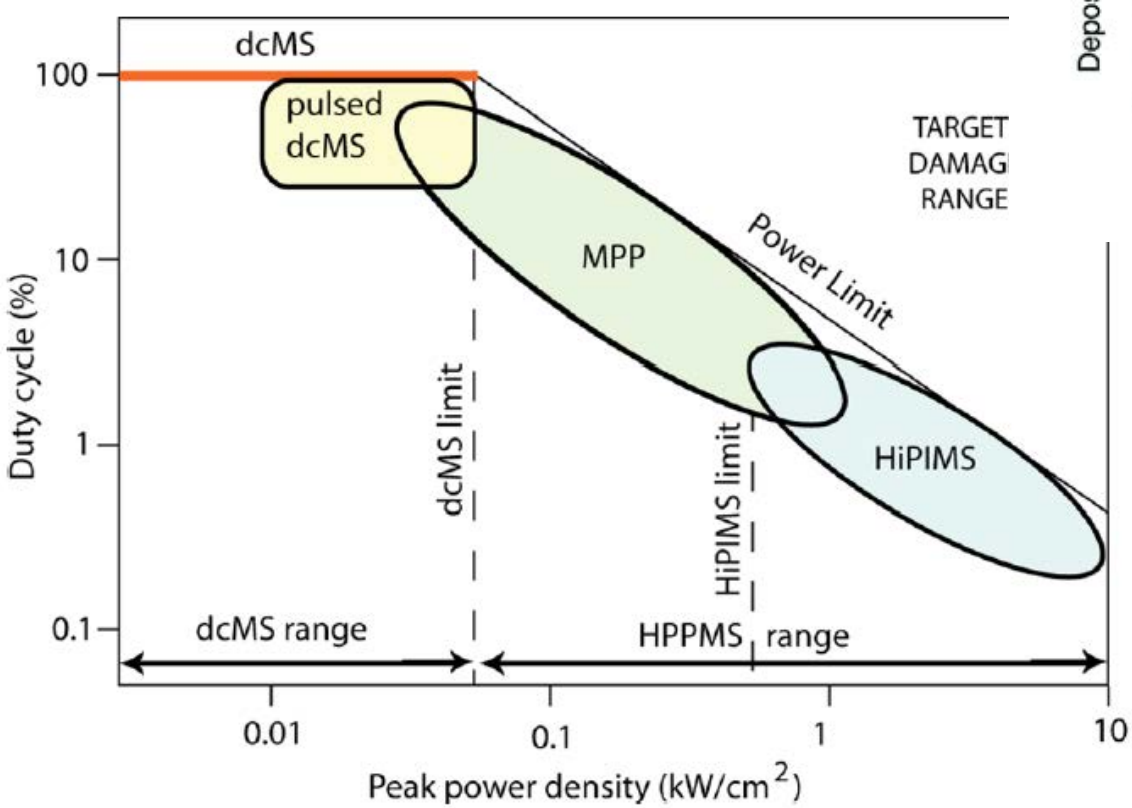


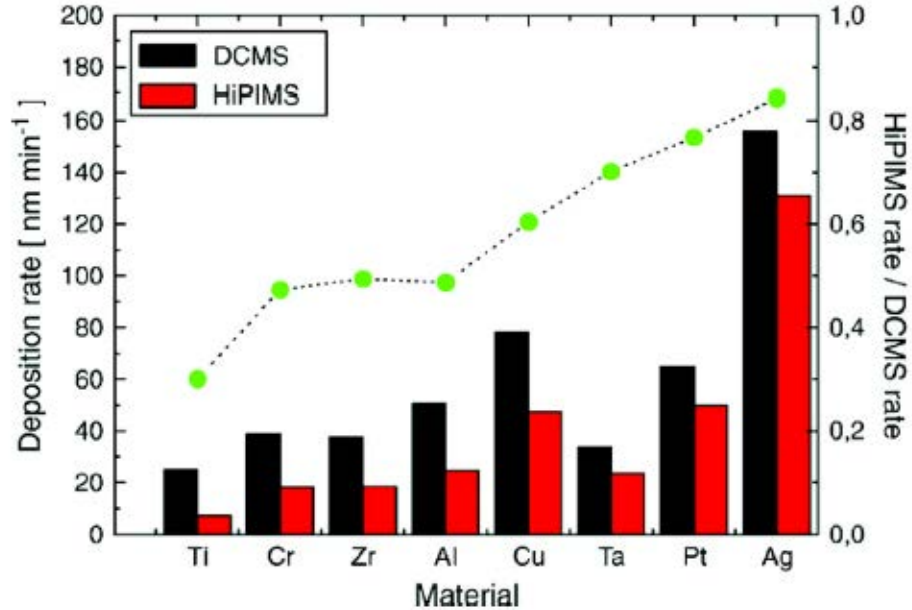






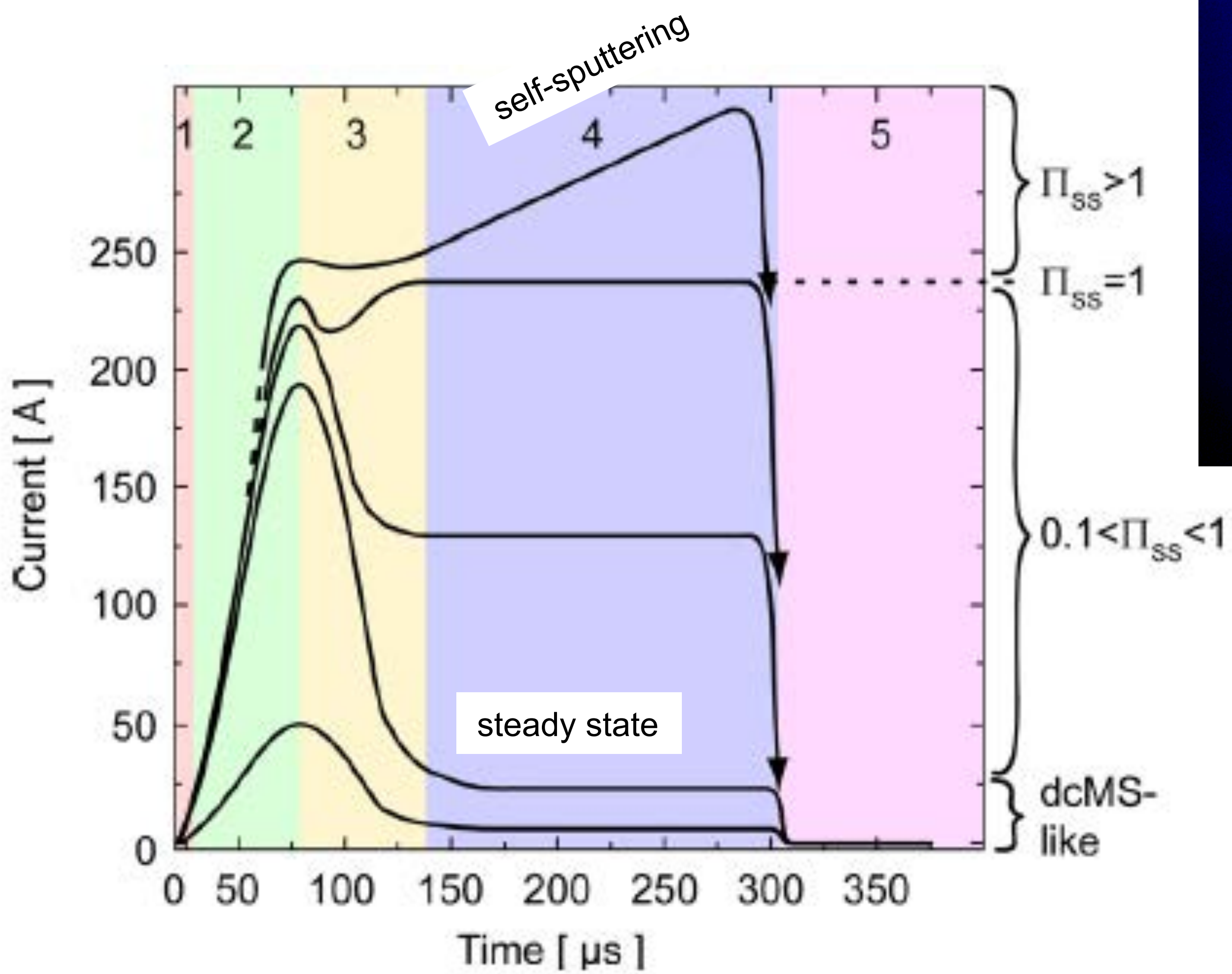
Sustaining a plasma – High Power Pulses Magnetron Sputtering (HPPMS)

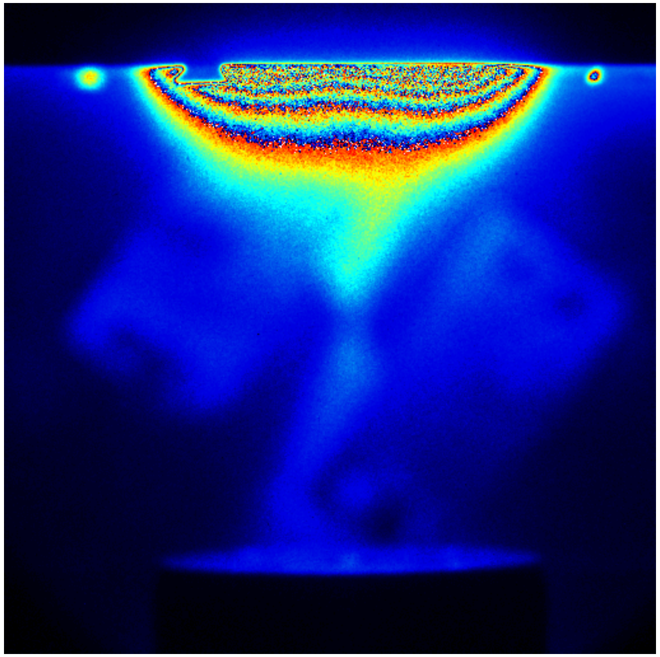




J. Gudmundsson, N. Brenning,
D. Lundin, U. Helmersson, JVSTA 30, 030801
(2012)

Sustaining a plasma – High Power Pulses Magnetron Sputtering (HPPMS)

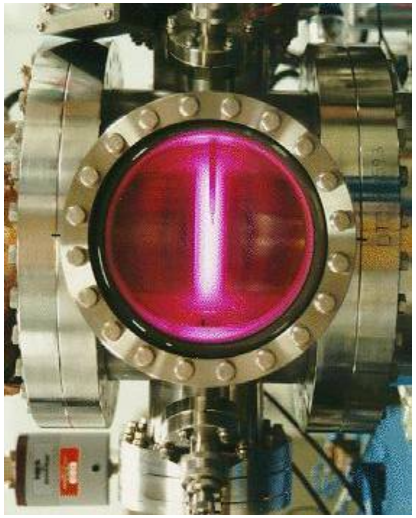


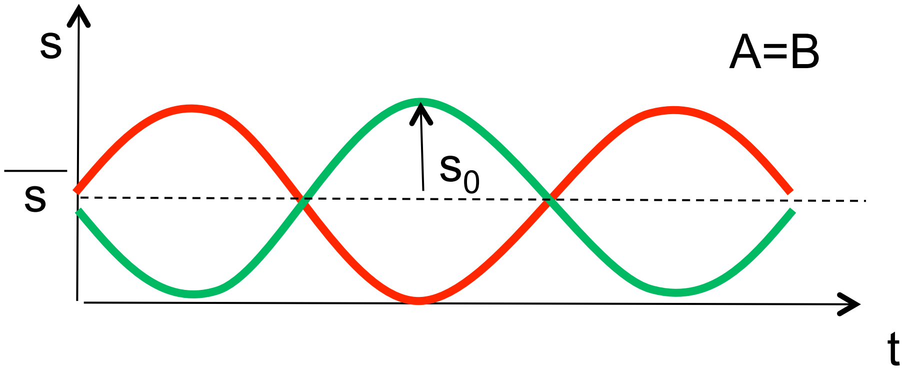


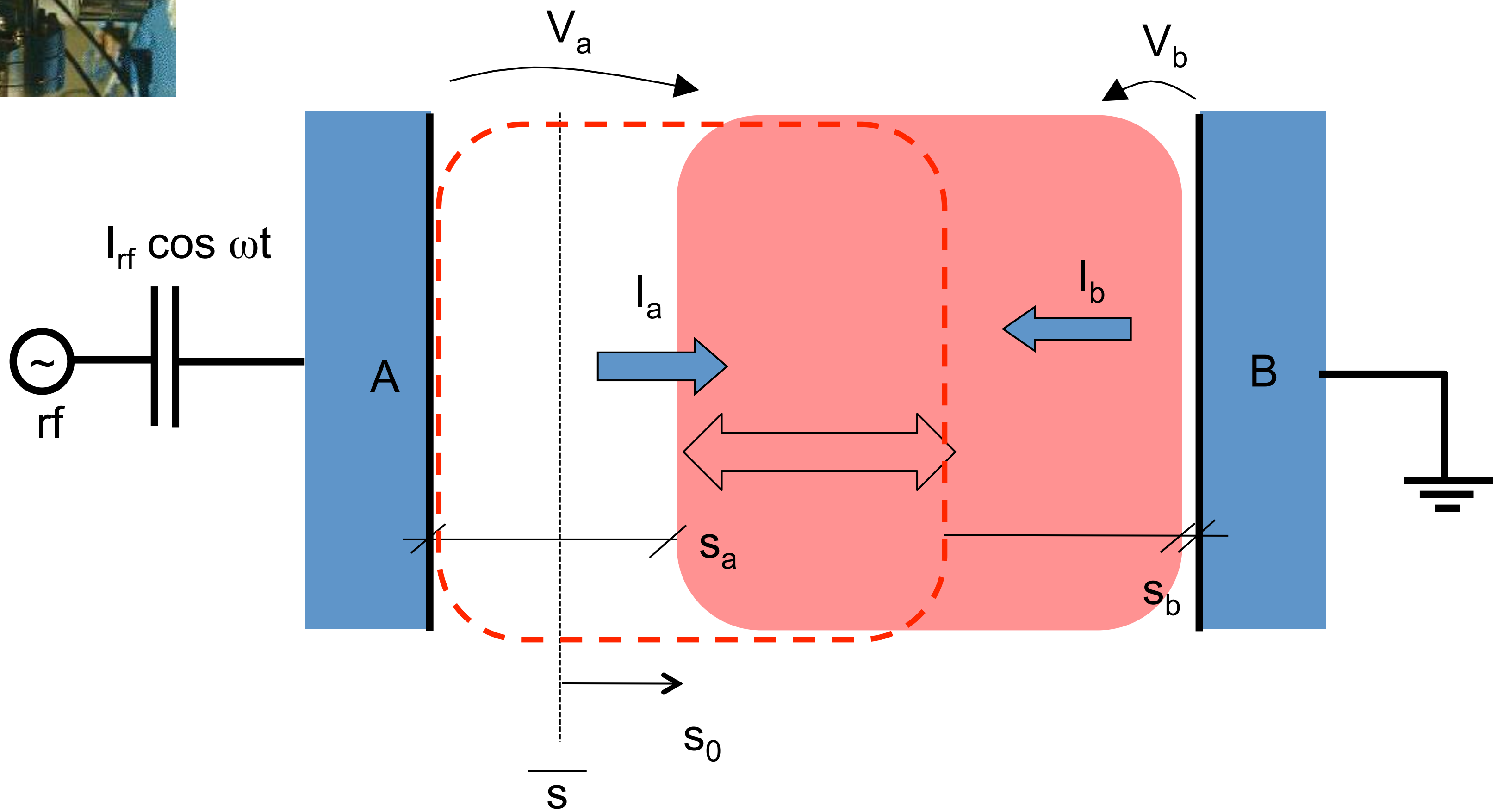
1: ignition
2: plasma build-up
3: gas depletion
4: steady state or
runaway self sputtering

J. Gudmundsson, N. Brenning, D. Lundin, U. Helmersson, JVSTA 30, 030801 (2012)

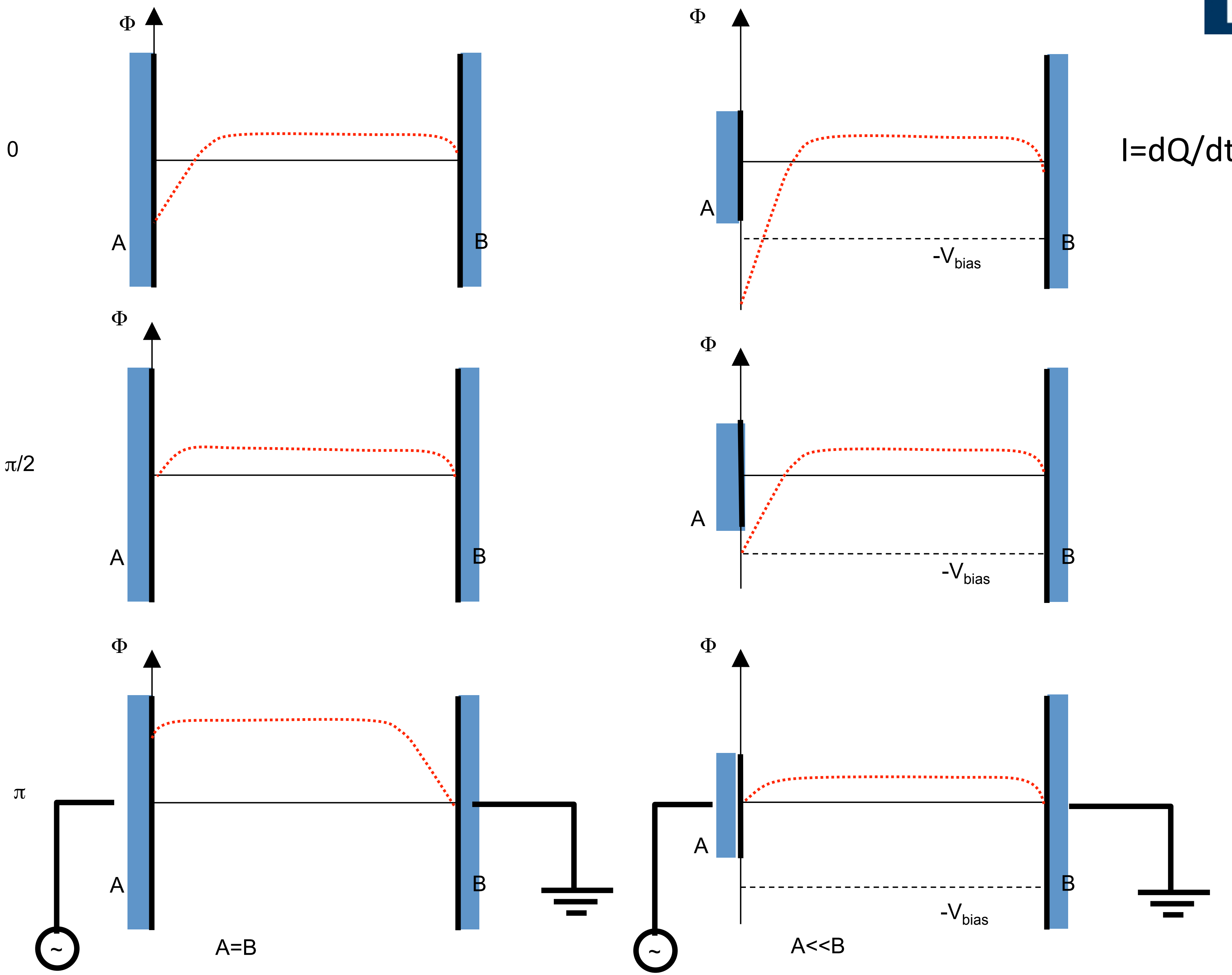
Sustaining a plasma – rf discharges – capacitive coupling



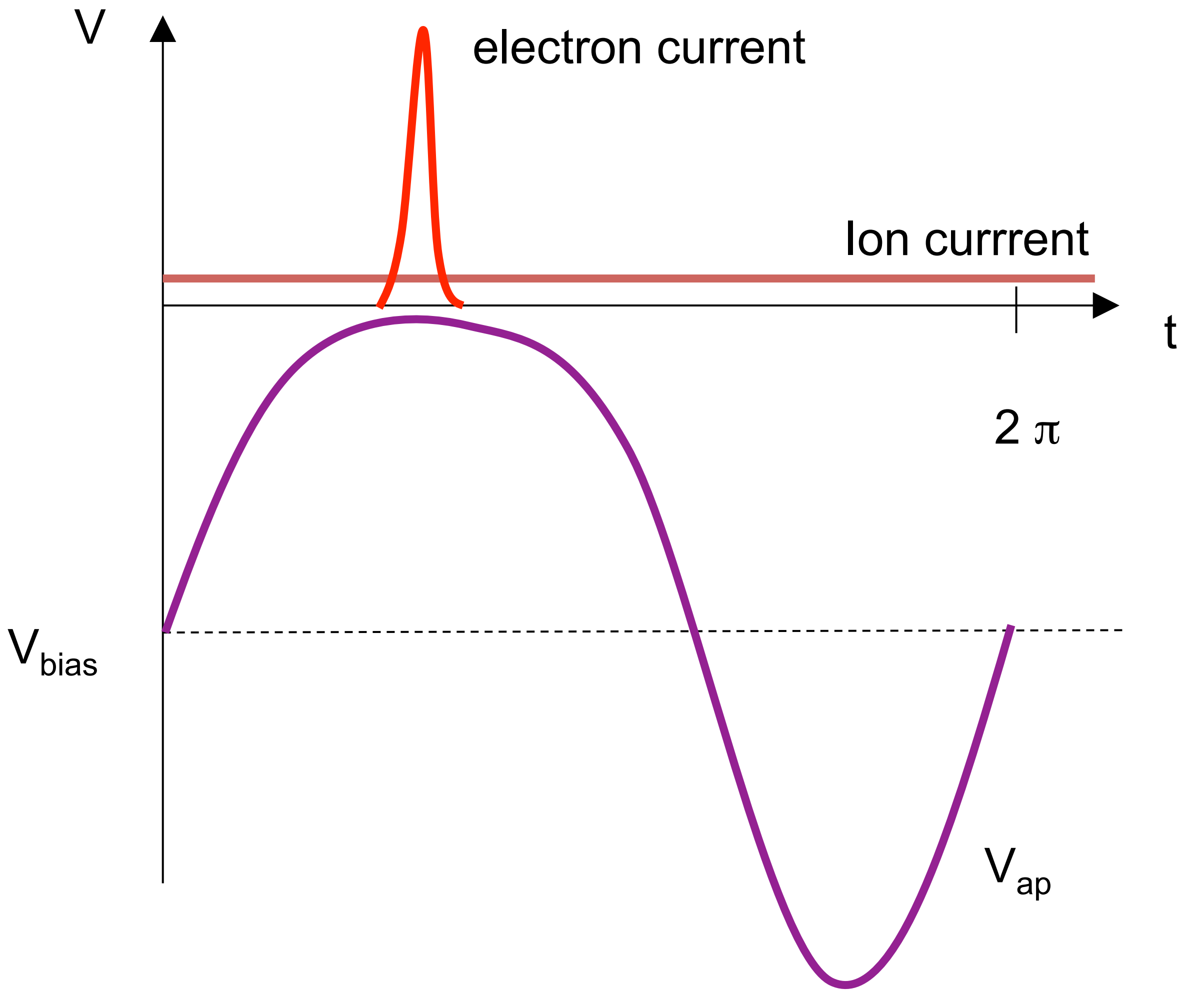


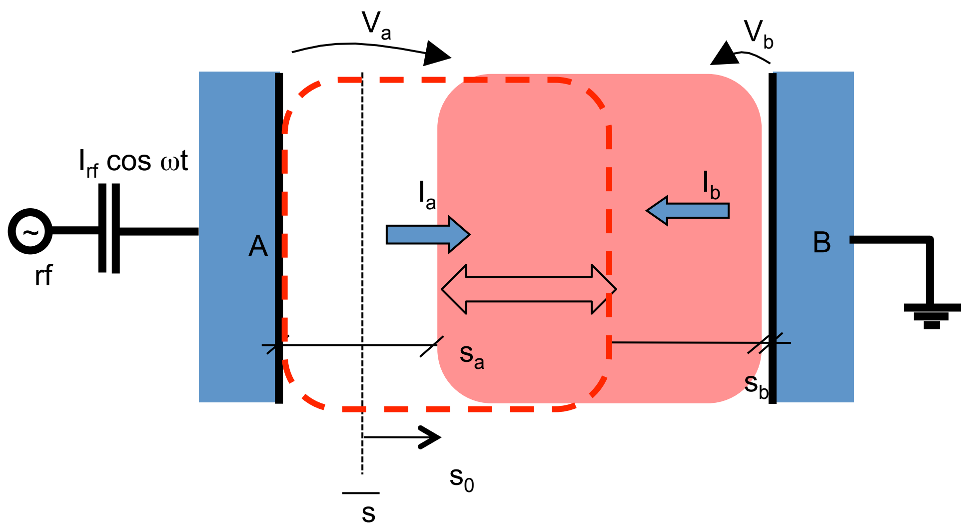


Sustaining a plasma – rf discharges – capacitive coupling/self bias

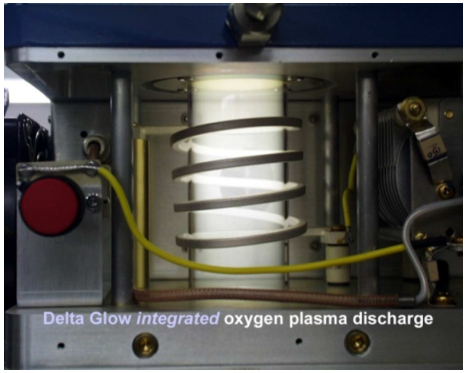


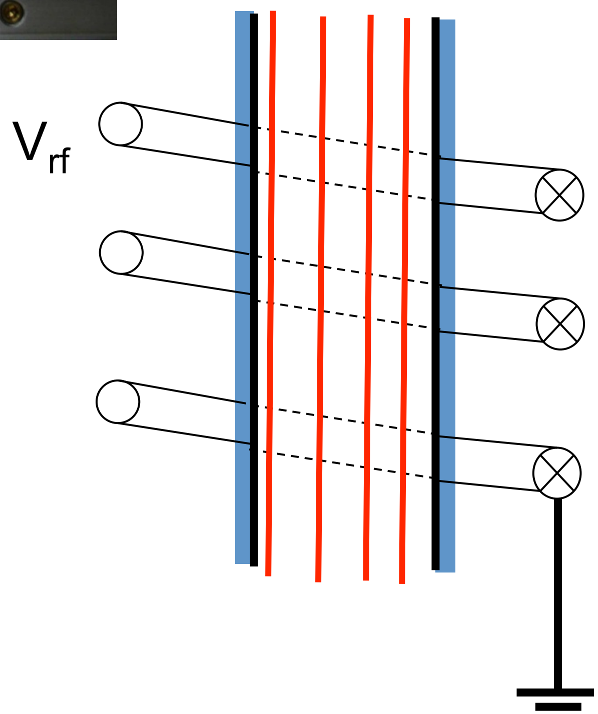
Sustaining a plasma – rf discharges



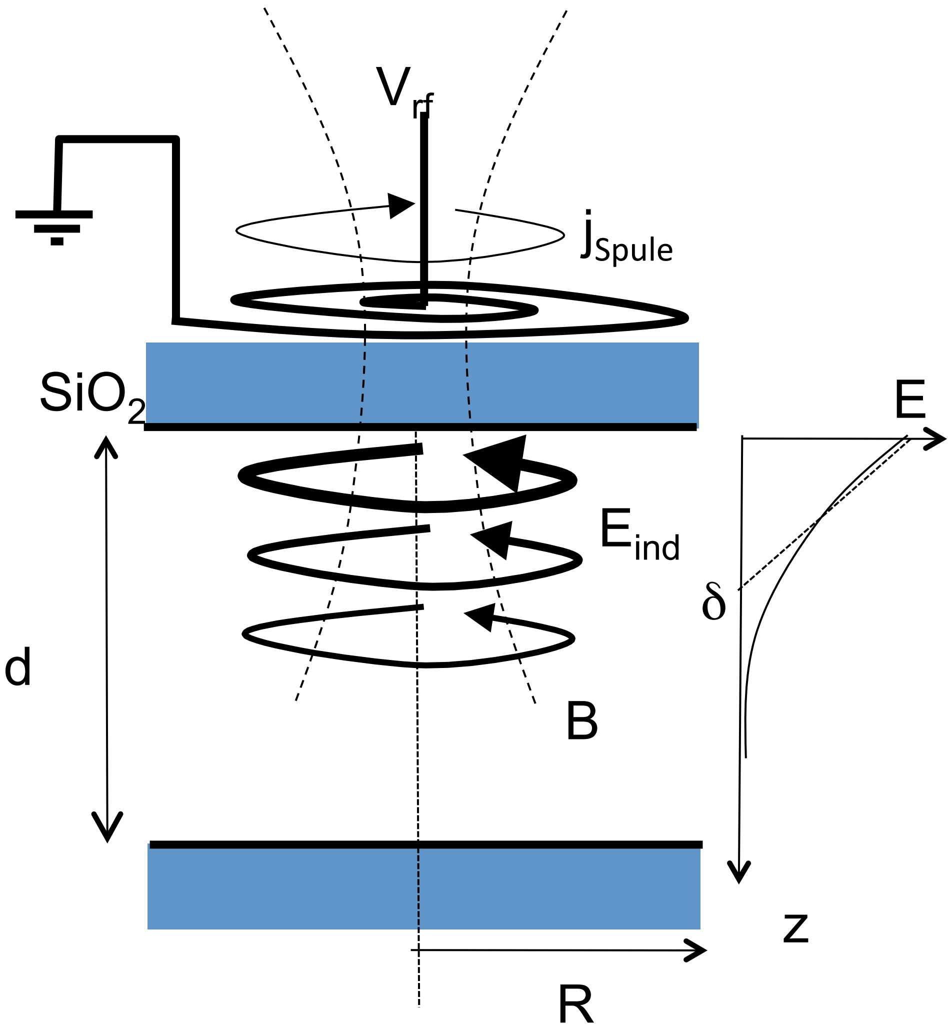


Sustaining a plasma – rf discharges - inductive coupling ICP





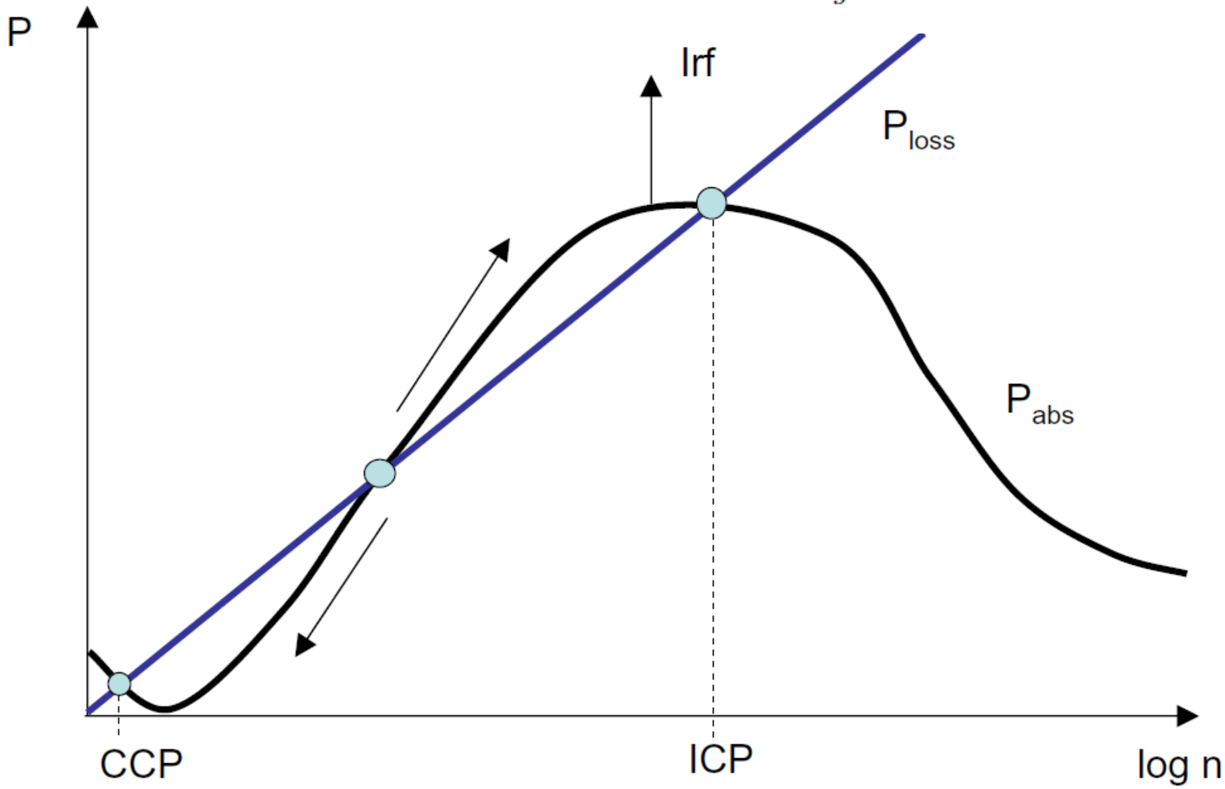
Cylindrical configuration

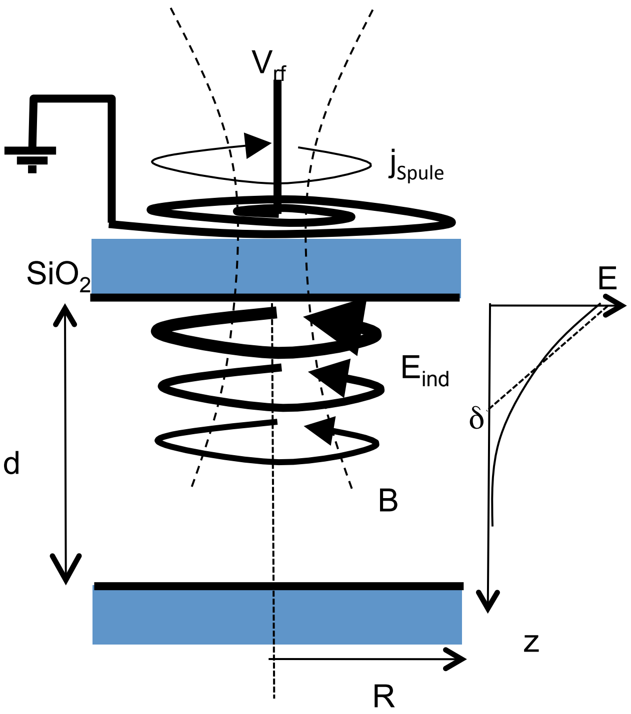


Planar configuration

Sustaining a plasma – ICP discharges – non linear power coupling

$$P_{loss} \propto n_g n \nu_{Ionisation} \epsilon_{Ionisation}$$





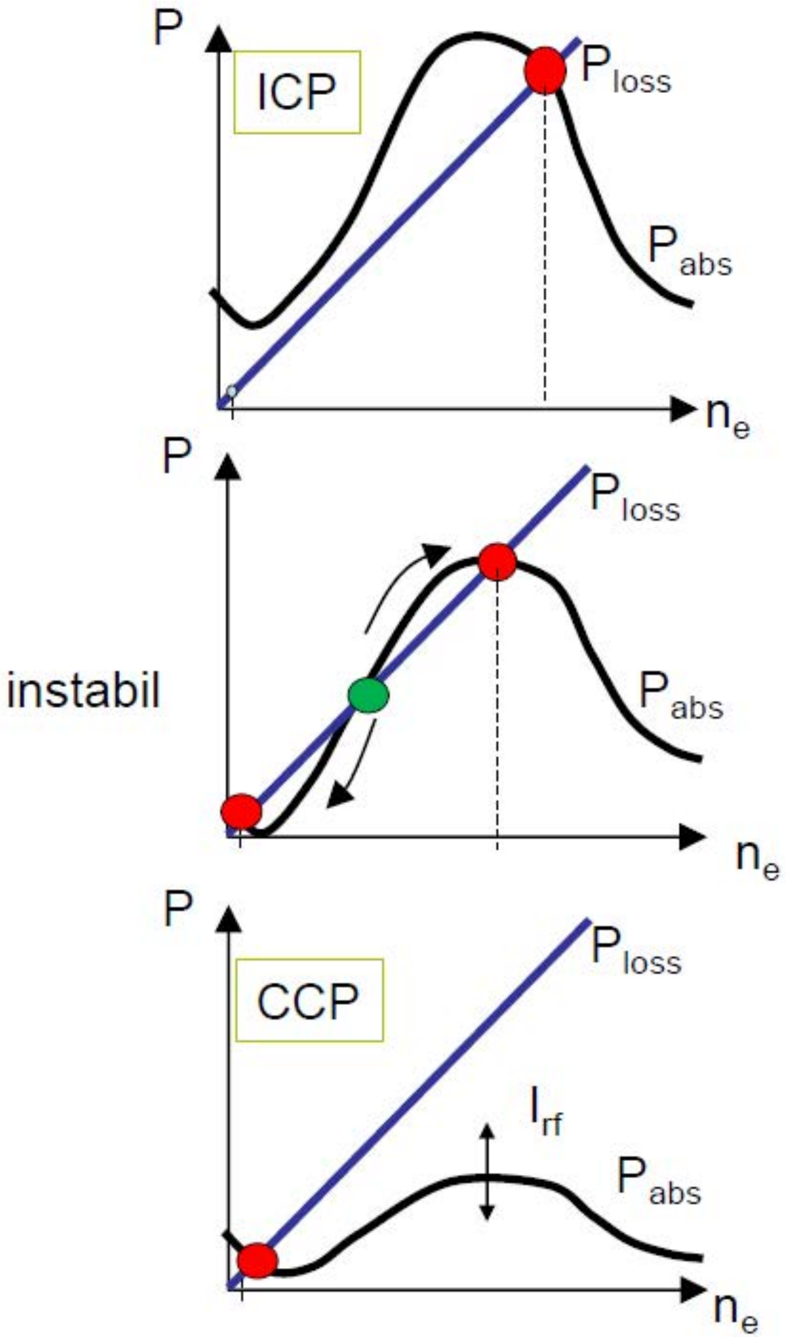
$$j_\Theta \propto I_{rf} n$$

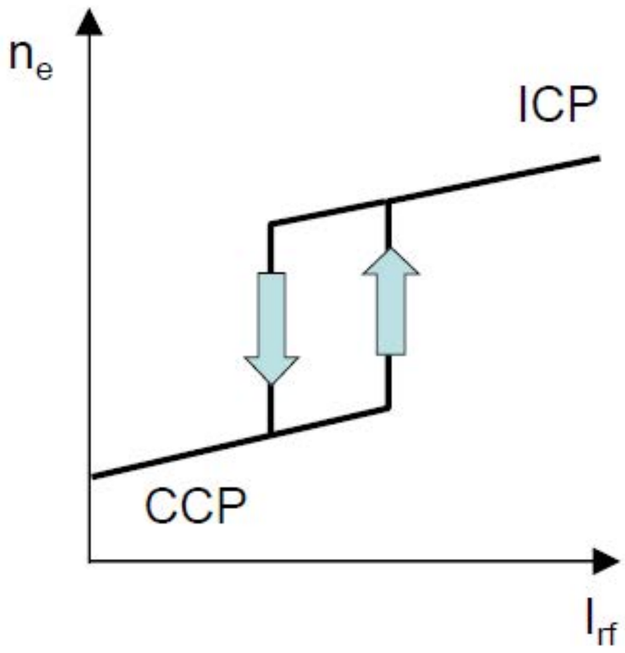
$$j_\Theta \propto \frac{I_{rf}}{\delta r}$$

$$P_{abs} = \frac{1}{2} I_{rf}^2 n^2 \frac{1}{\sigma} A d \propto I_{rf}^2 n$$

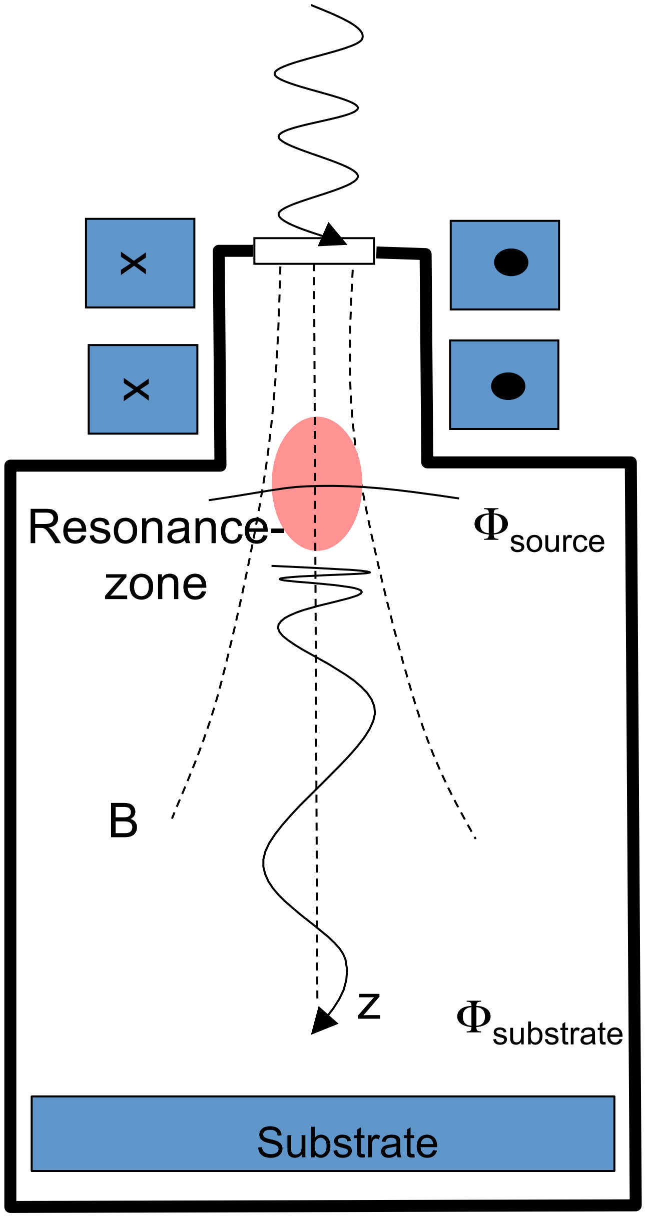
$$P_{abs} = \frac{1}{2} I_{rf}^2 \frac{1}{\delta^2} \frac{1}{\sigma} A \delta \propto I_{rf}^2 n^{-1/2}$$

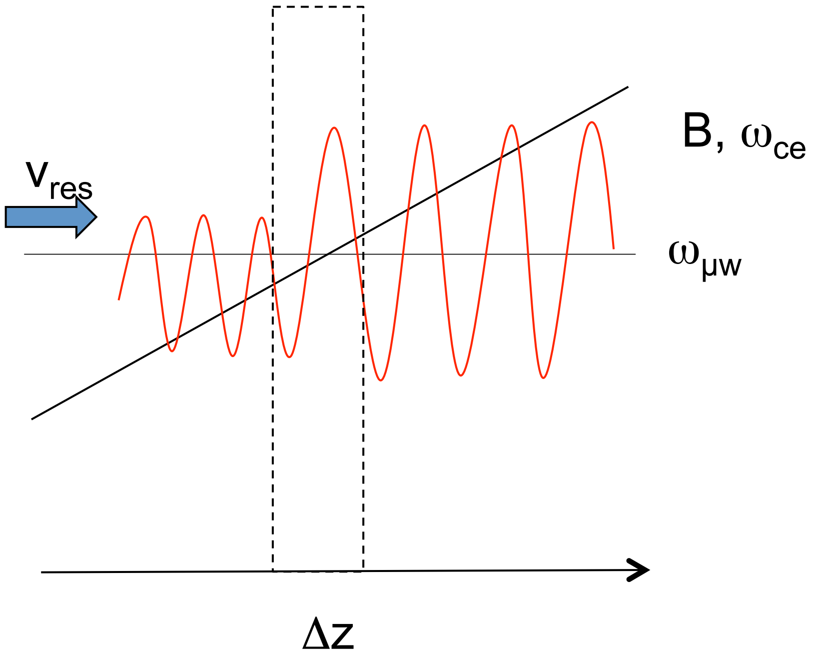
Sustaining a plasma – ICP discharges - hyteresis

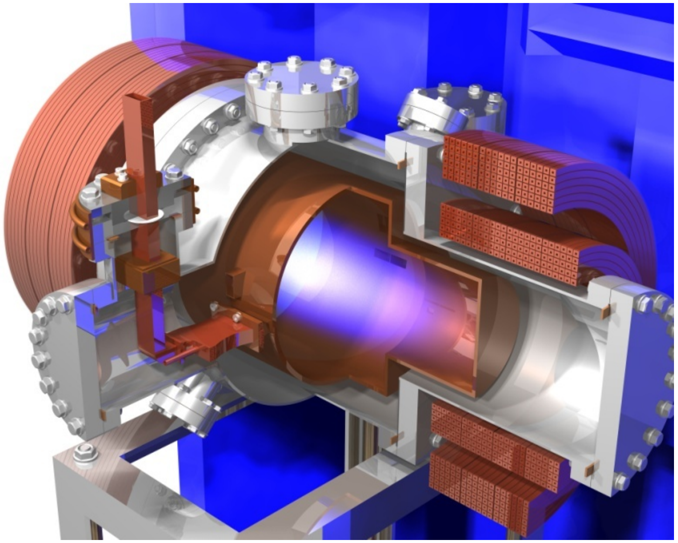




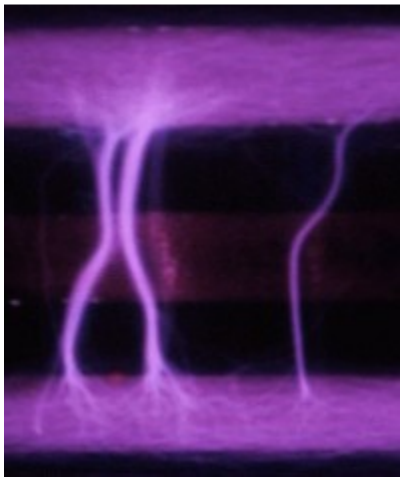
Sustaining a plasma – electron cyclotron discharges

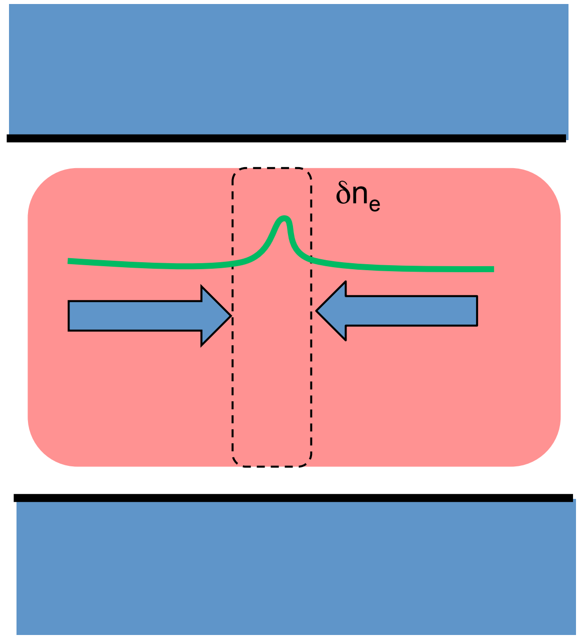


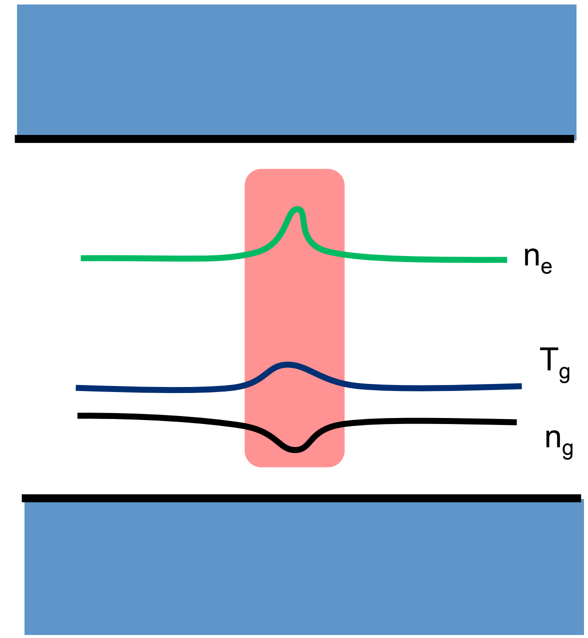




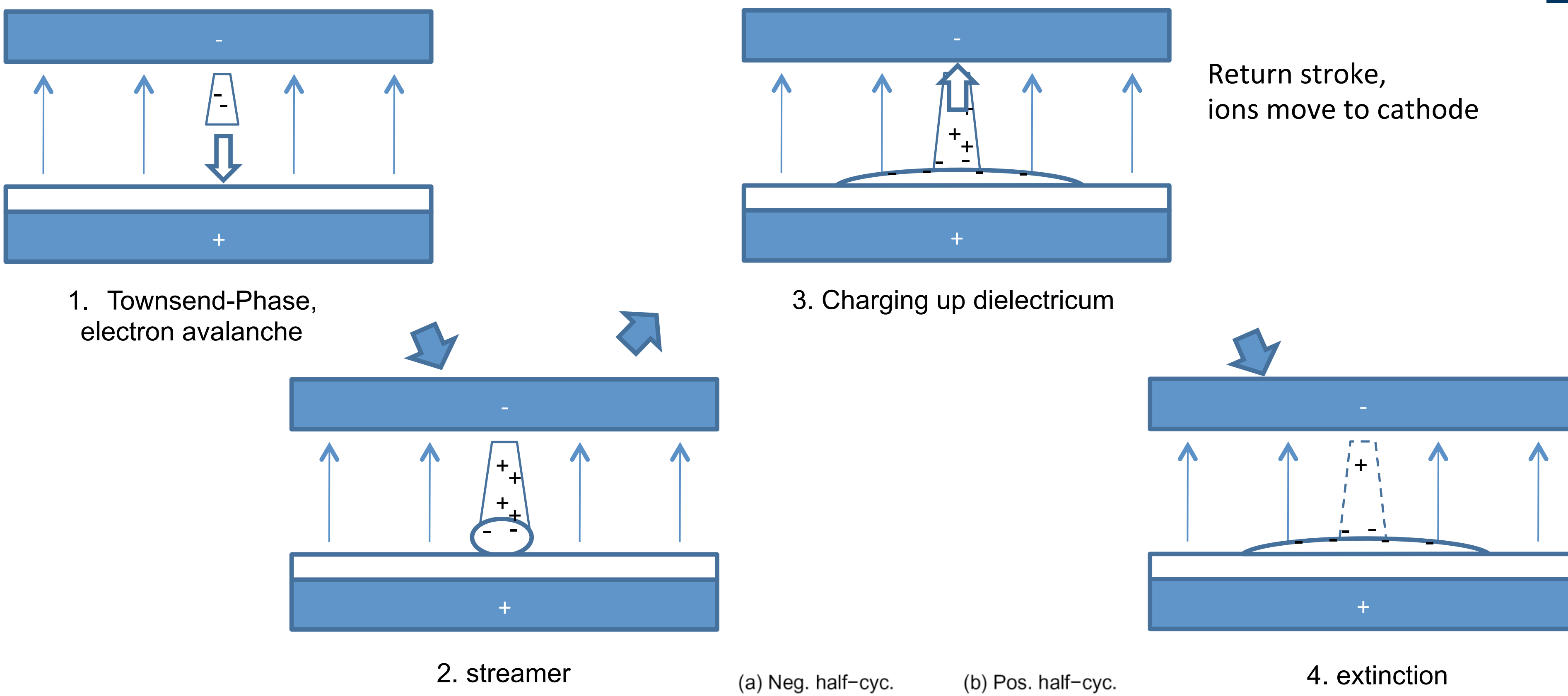
Sustaining a plasma – high pressure discharges - filamentation

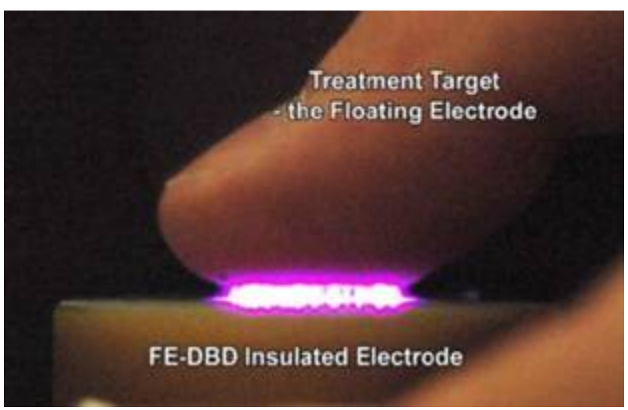


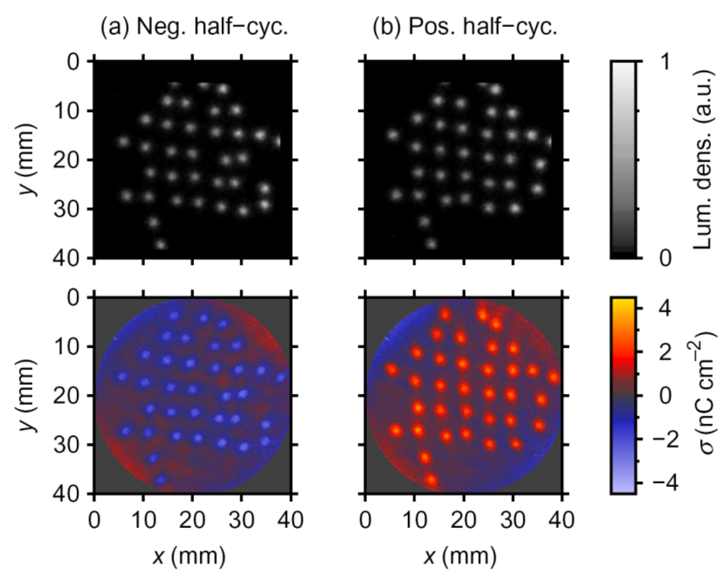




Sustaining a plasma – barrier discharges







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

Summary

RUB

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

Further reading:

Books:

- Lieberman Lichtenberg,
  Principles of Plasma Discharges and Materials Processing

- Alexander Piel
  An Introduction to Laboratory, Space, and Fusion Plasmas

- F. Chen
  Plasma Physics and Controlled Fusion

- Pascal Chabert und Nicholas Braithwaite
  Physics of Radio-Frequency Plasmas

Scripts: (in German)

http://reaktiveplasmen.rub.de/index.php?option=com_content&view=category&layout=blog&id=47&Itemid=112

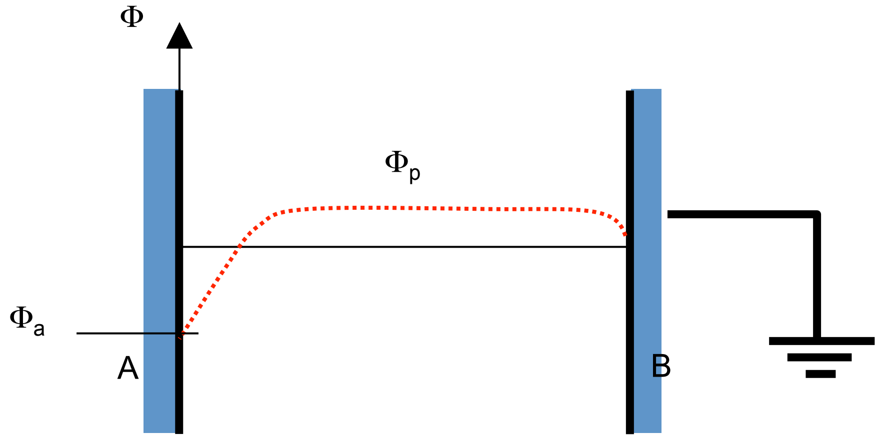
- Introduction to Plasmaphysics I: Fundamentals

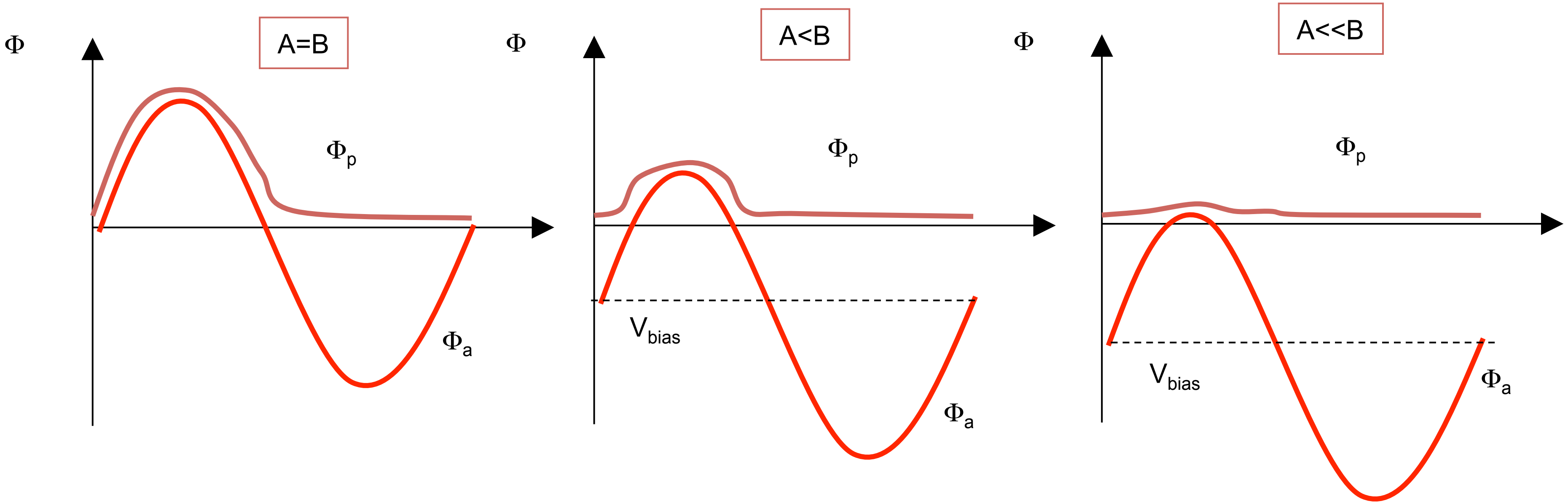
- Introduction to Plasmaphysics II: Low temperature plasmas

- Plasma Surface Interactions

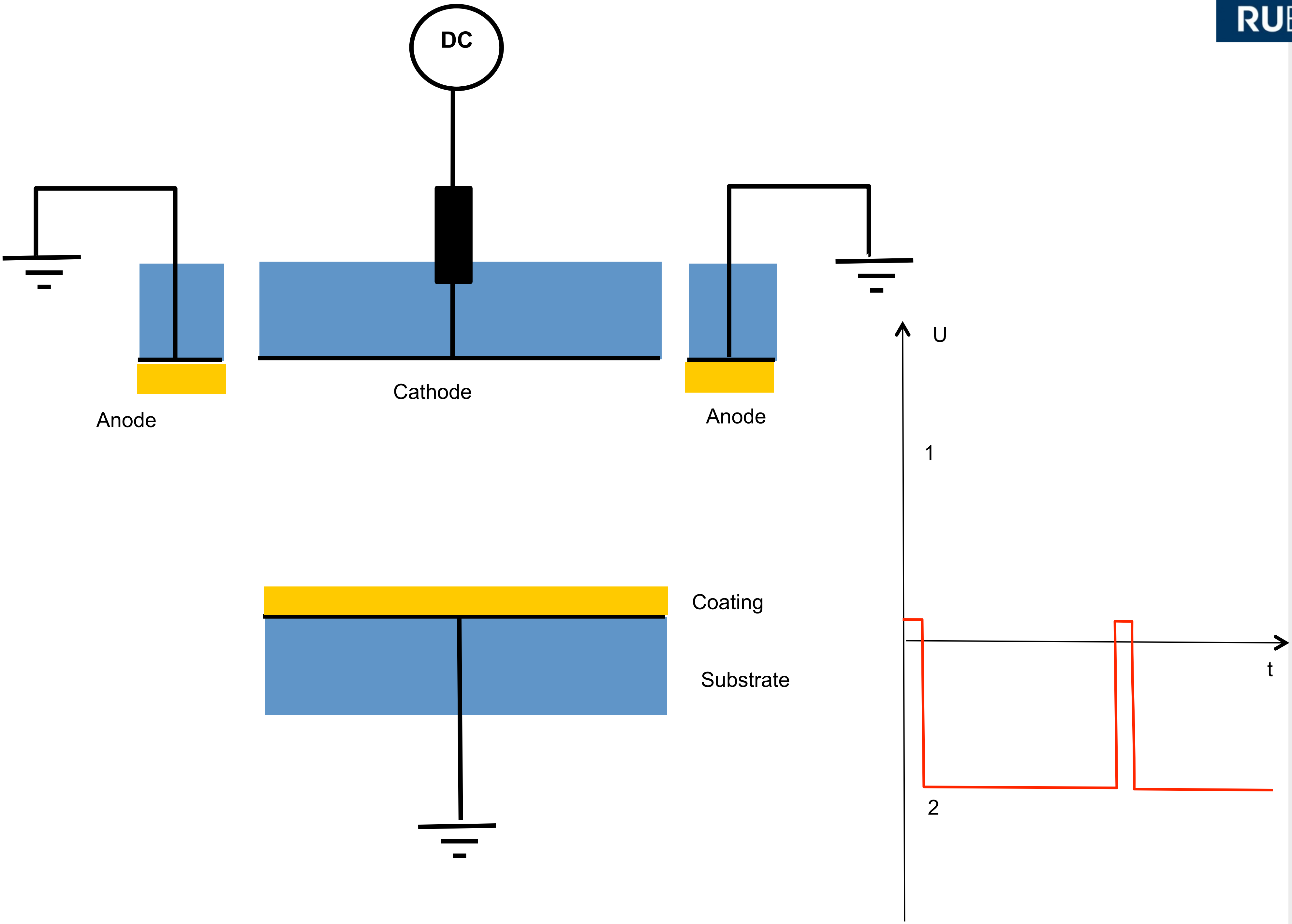
Backup

Sustaining a plasma – rf discharges – capacitive coupling/self bias

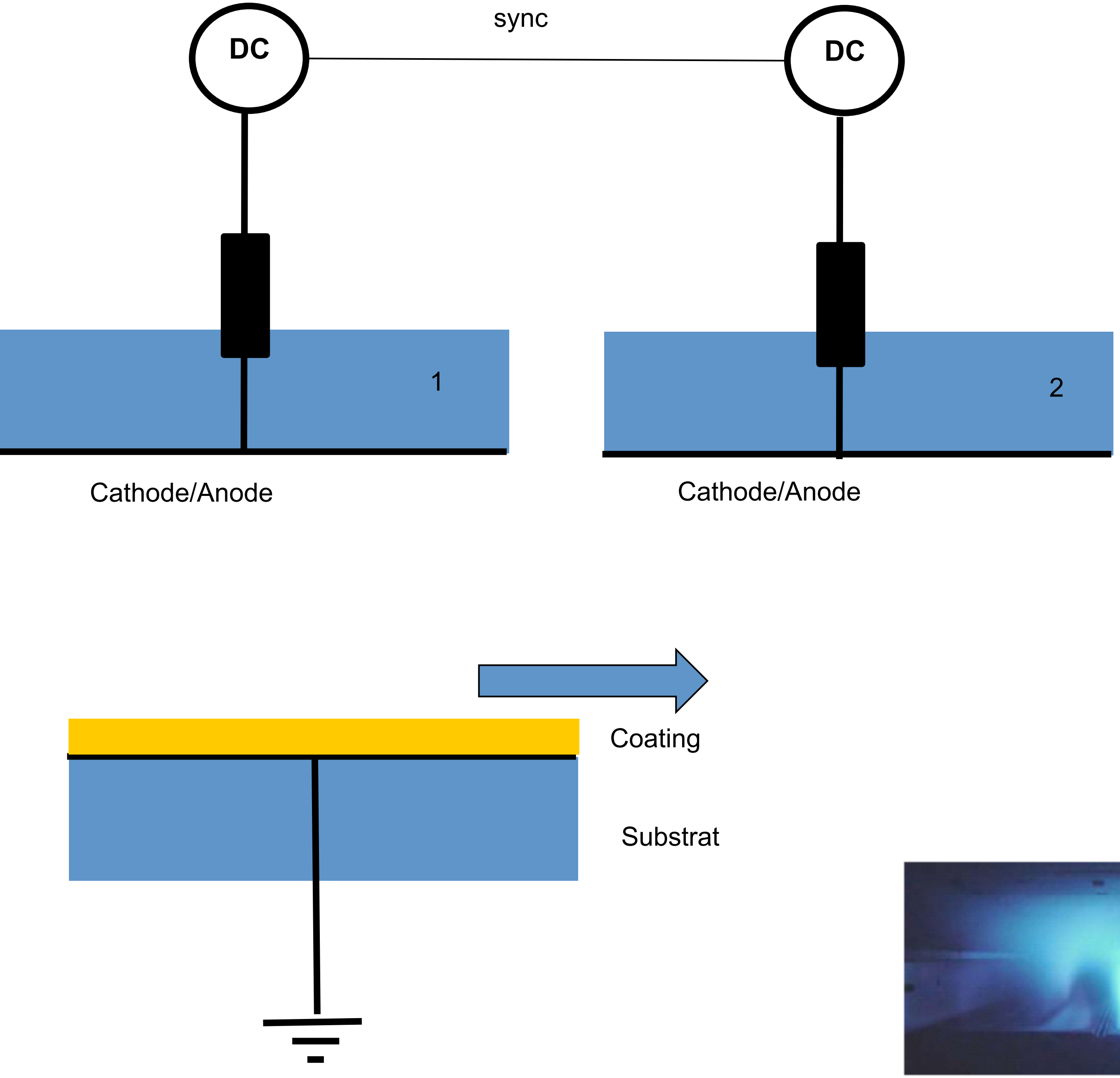


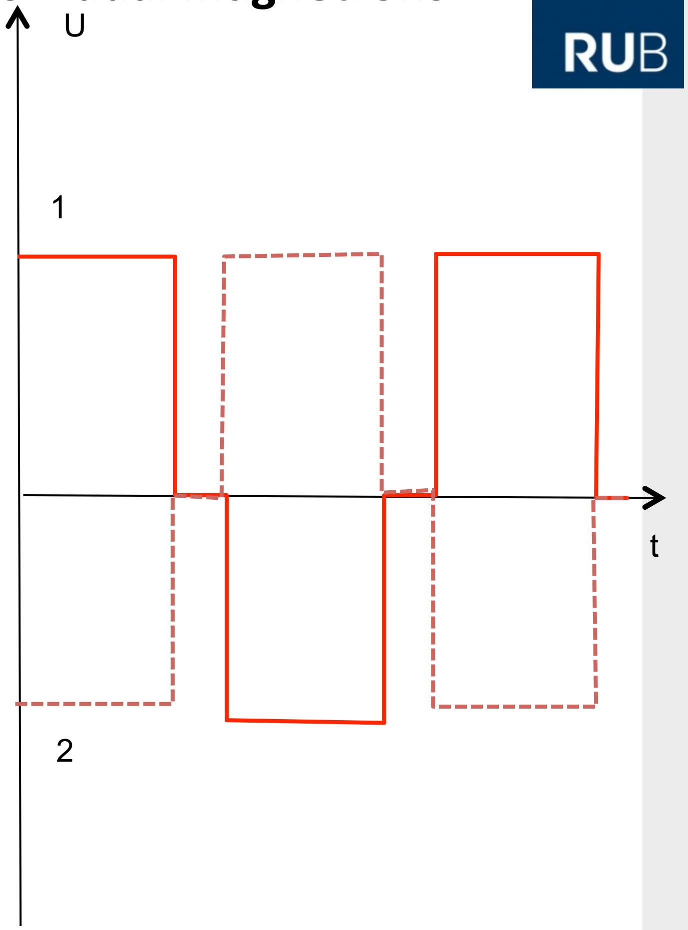


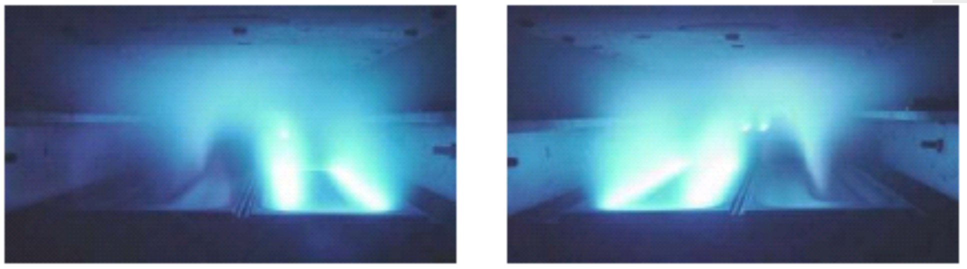
Sustaining a plasma – bipolar sputtering for insulating coatings



Sustaining a plasma – bipolar sputtering for insulating coatings – dual magnetrons







Sustaining a plasma – rf discharges – stochastic heating

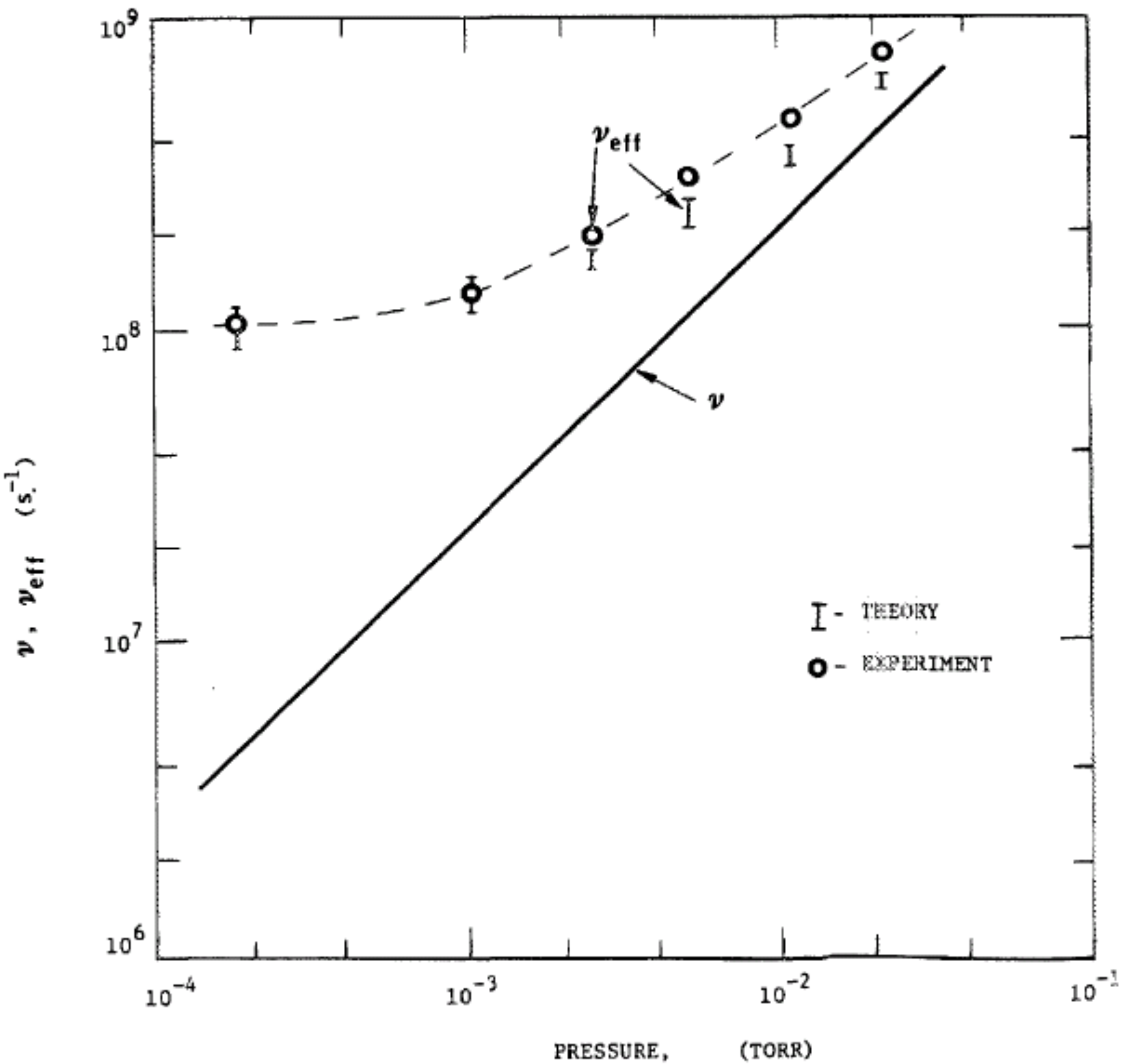


Abbildung 3.16: Effektive Stoßrate in einem rf-Plasma in Abhängigkeit vom Druck [O. Popov, V. Godyak, *Power dissipated in low-pressure rf discharge plasmas*, J. Appl. Phys. 57, 53 (1985)]

Sustaining a plasma – rf discharges – stochastic heating – Fermi acceleration

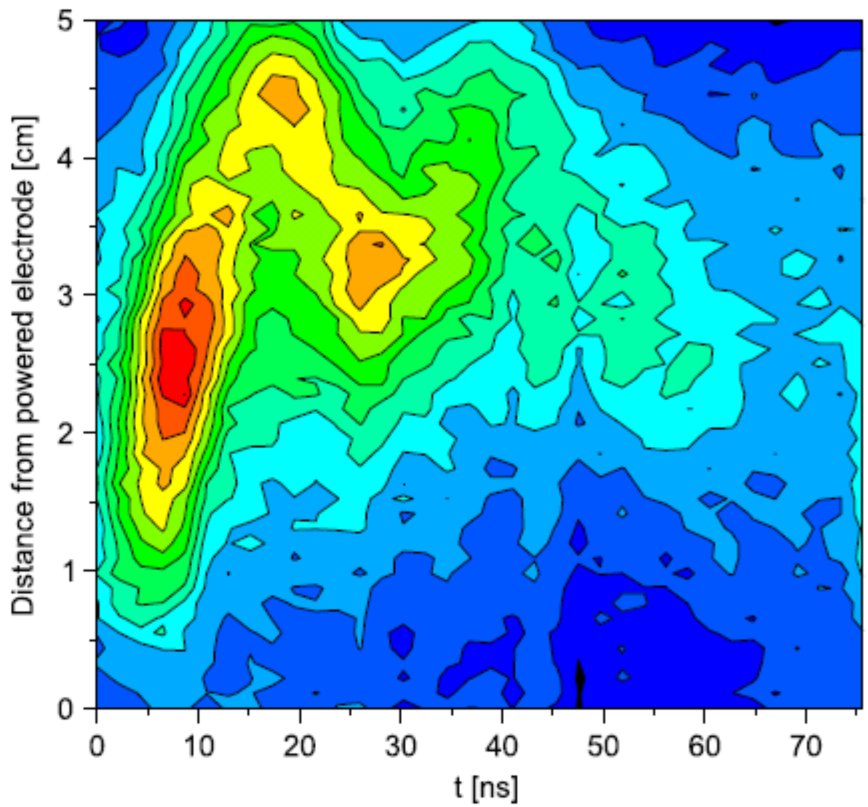
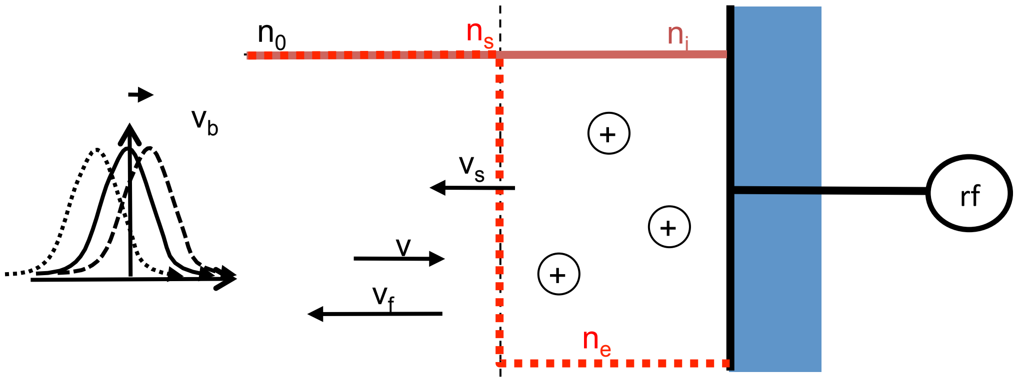


Abbildung 3.17: PROES Daten einer rf-Entladung [J. Schulze, B. Heil, D. Luggenhölscher, T. Mussenbrock, R.P. Brinkmann, U. Czarnetzki, *Electron beams in asymmetric capacitively coupled rf discharges at low pressure*, J. Phys. D 41, 42003 (2008)]



Moving frame Rest frame

$$v' = -v - v_s$$

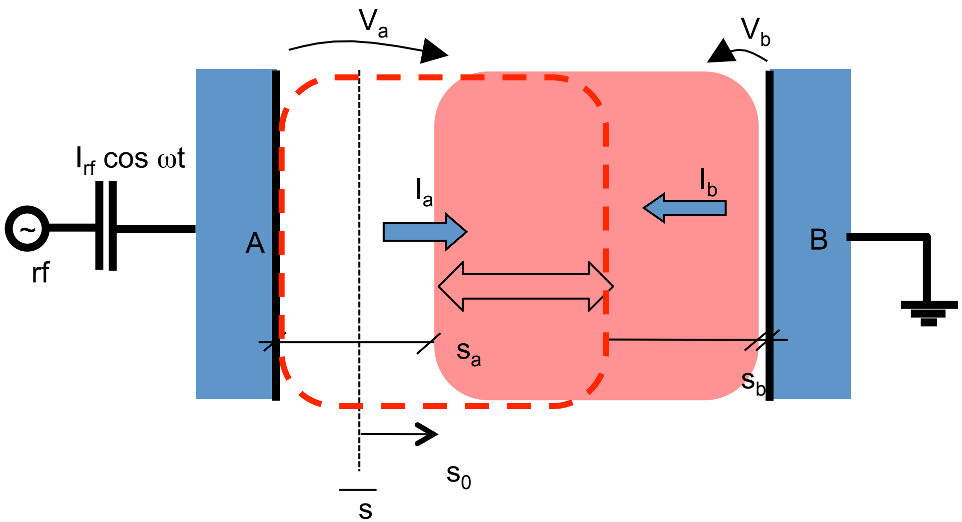
$$v'_f = v_f - v_s$$

hard wall collision: $v' = -v'_f$

$$v_f = v + 2v_s$$

$$\bar{P} = \frac{1}{2} m \frac{j_{rf}^2}{e^2 n} v_{th} \qquad \Delta E = \frac{1}{2} m_e \left(v_f^2 - v^2\right)$$

Sustaining a plasma – rf discharges – stochastic heating?
Non-linear electron resonance heating



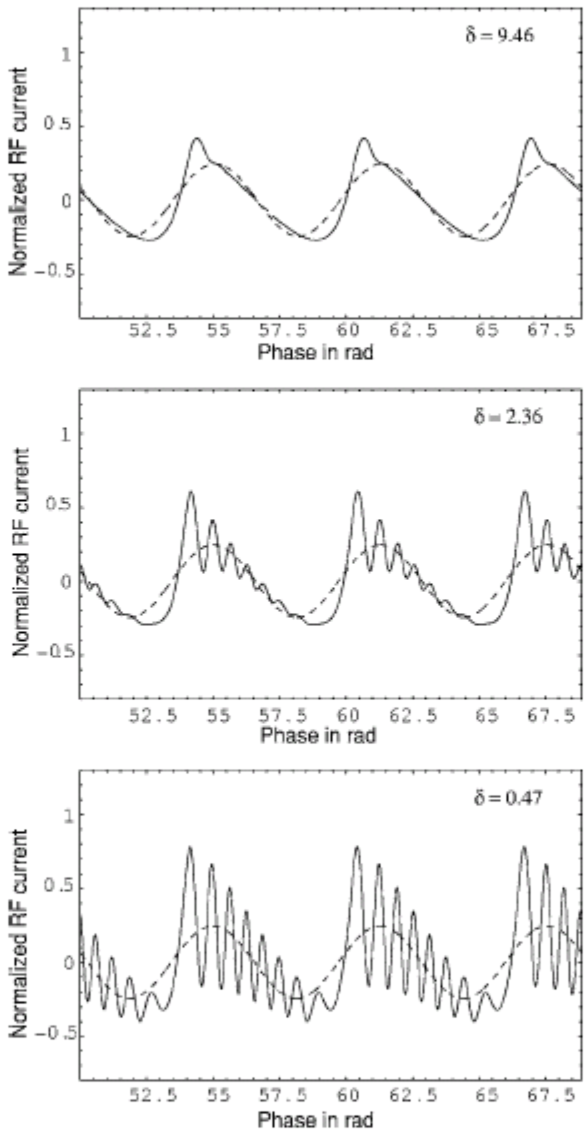


Abbildung 3.23: Modell der Zeitabhängigkeit des Stromes in einer asymmetrischen rf Entladung für 20 Pa, 5 Pa und 1 Pa (von oben nach unten) [T. Mussenbrock, R.P. Brinkmann *Nonlinear electron resonance heating in capacitive rf discharges*, Appl. Phys. Lett. 88, 151503 (2006)]

Sustaining a plasma – rf discharges – multi frequency discharges

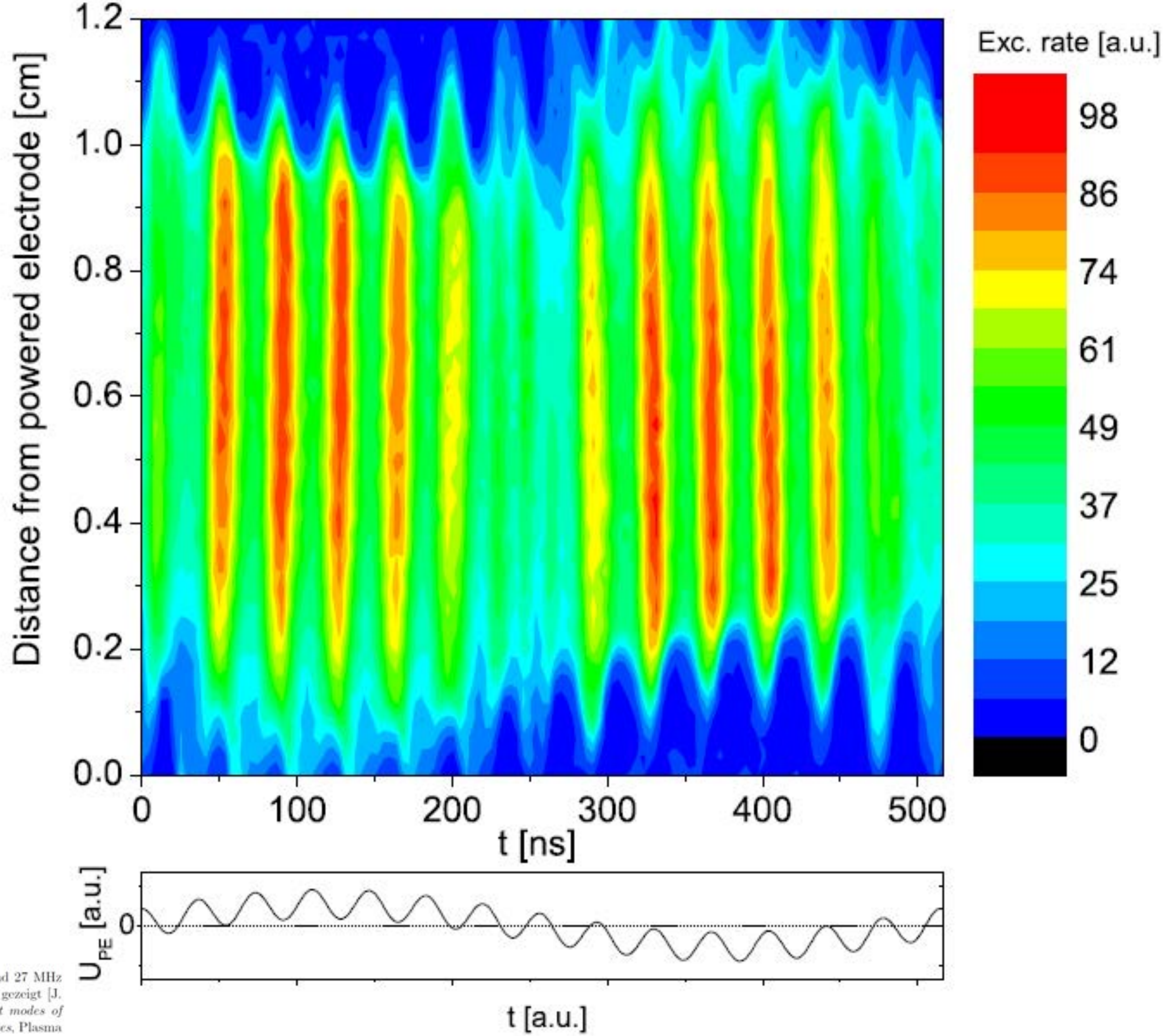
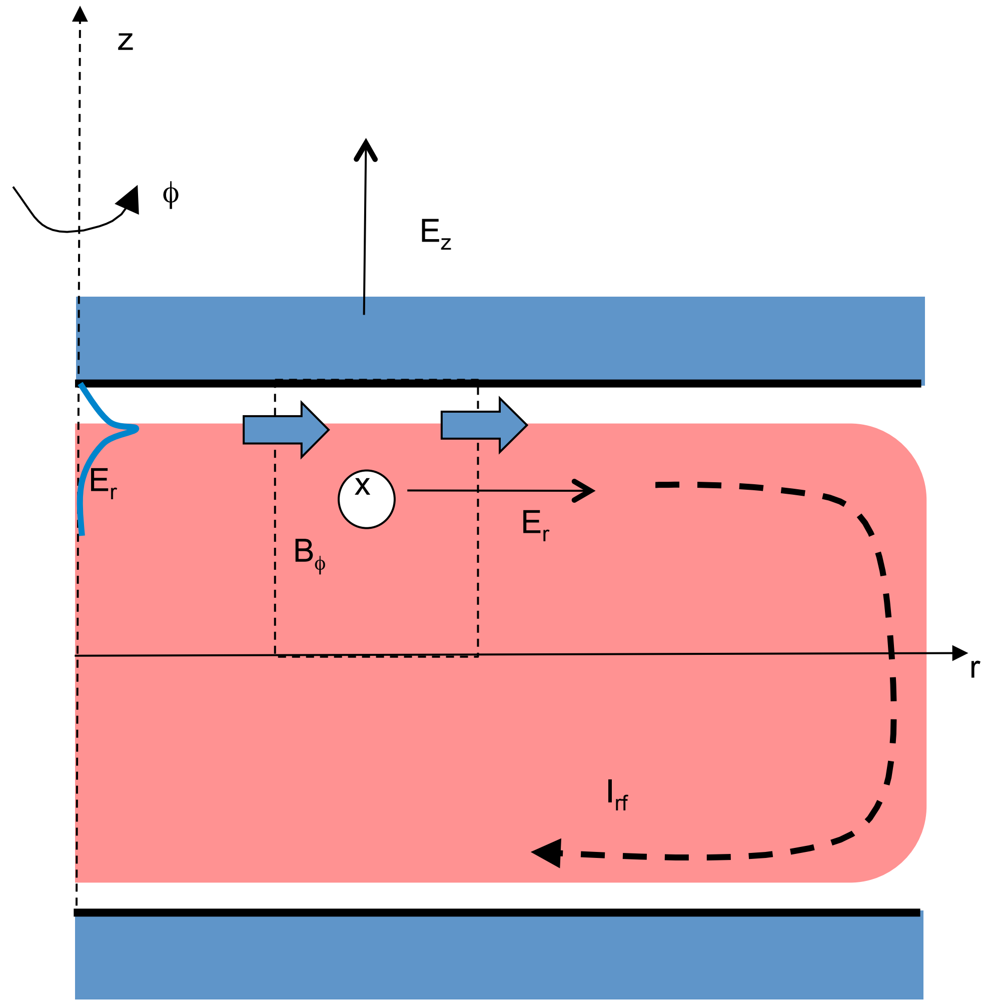


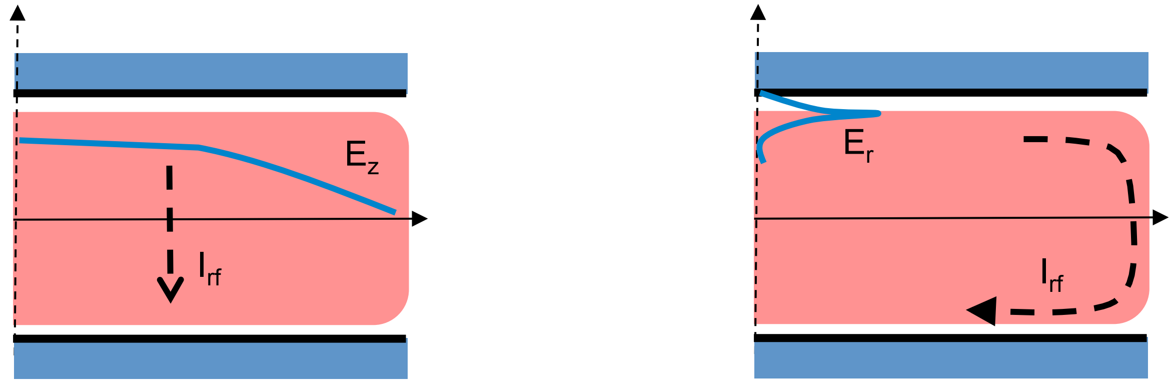
Abbildung 4.25: PROES-Bilder einer Entladung die mit 2 und 27 MHz getrieben wird. Der Spannungsverlauf ist in dem unteren Panel gezeigt [J. Schulze, Z. Donko, D. Luggenhölscher, U. Czarnetzki, *Different modes of electron heating in dual-frequency capacitively coupled rf discharges*, Plasma Sources Sci. Technol. 18, 34011 (2009)].

Sustaining a plasma – rf discharges –large area reactors/high frequency discharges



Oerlikon

Sustaining a plasma – rf discharges –high frequency discharges (60 MHz)



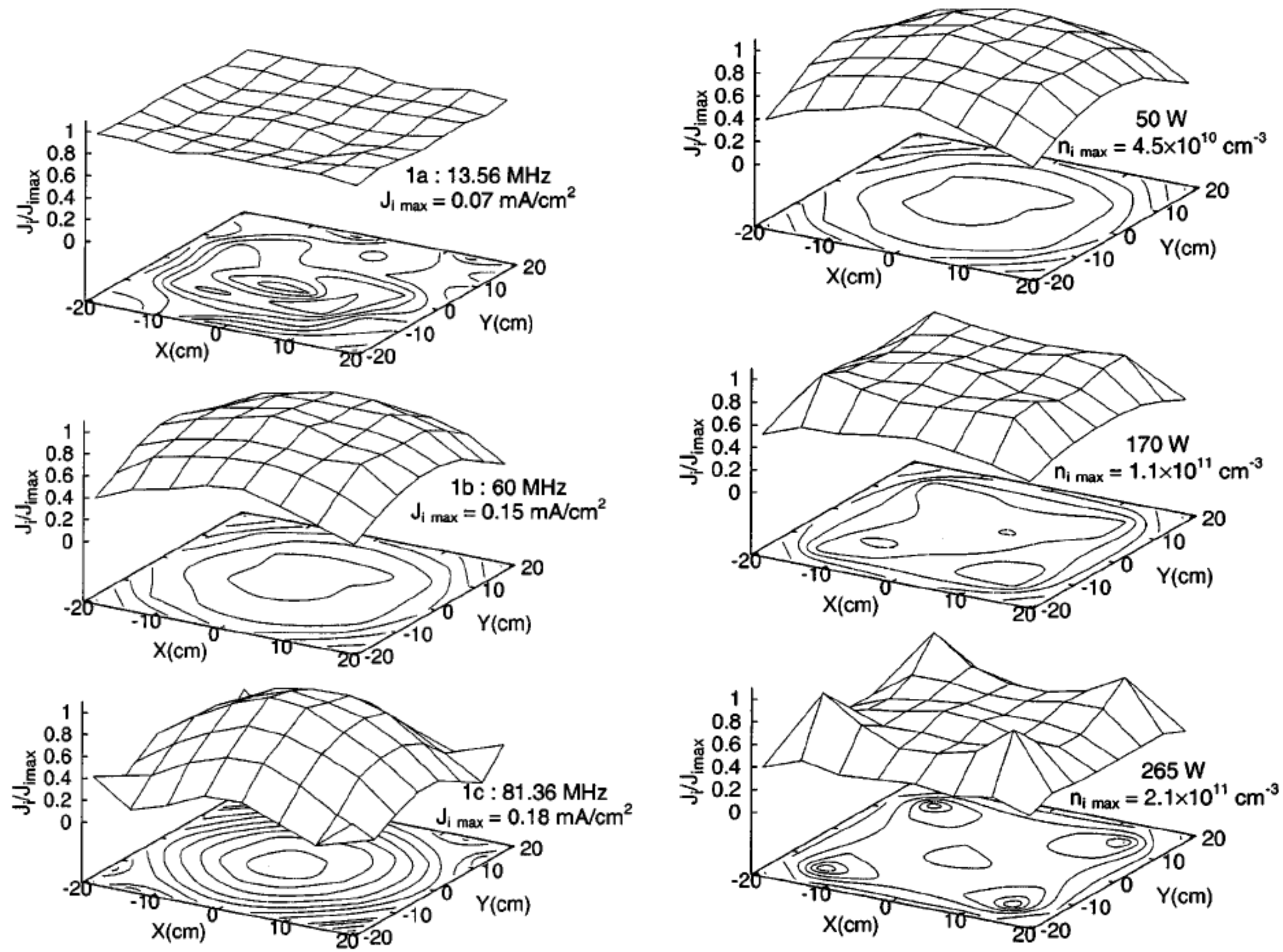


Abbildung 4.27: Verteilung des Ionenflusses auf eine Elektrode in Abhängigkeit von der anregenden Frequenz (linke Seite) und bei 60 MHz aber zunehmender Leistung [A. Perret, P. Chabert, J.-P. Booth, J. Jolly, J. Guillon, P. Auvray *Ion flux non uniformities in large-area high-frequency capacitive discharges*, Appl. Phys. Lett. 83, 243 (2003)].

Sustaining a plasma – rf discharges – large area reactors

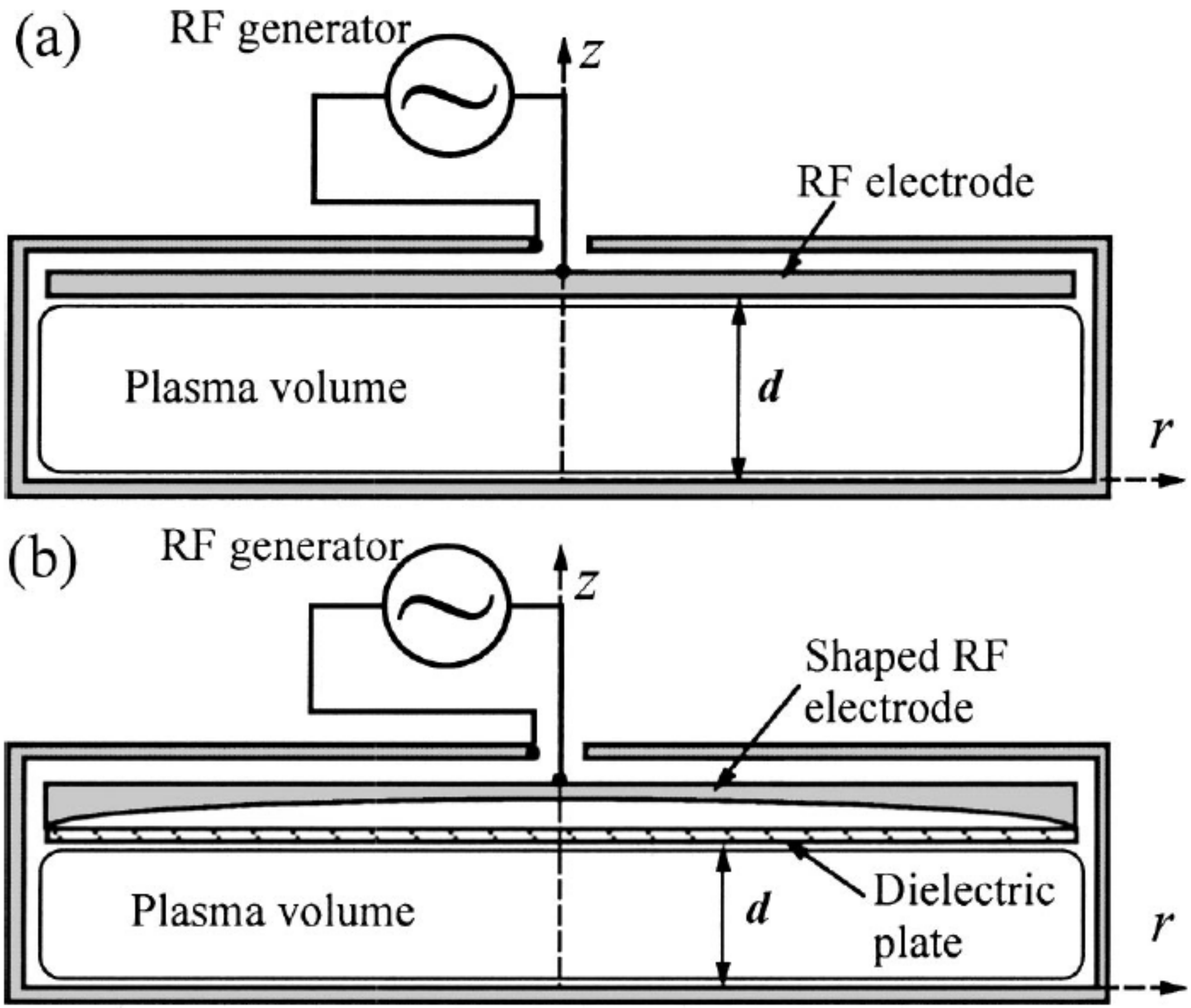


Abbildung 4.28: Modell einer dielektrischen Linse zur Kompensation von Inhomogenitäten im Plasma, die durch stehende Wellen entstehen [L. Sansonnens, J. Schmitt *Shaped electrode and lens for a uniform radio-frequency capacitive plasma*, Appl. Phys. Lett. 82, 182 (2003)].