

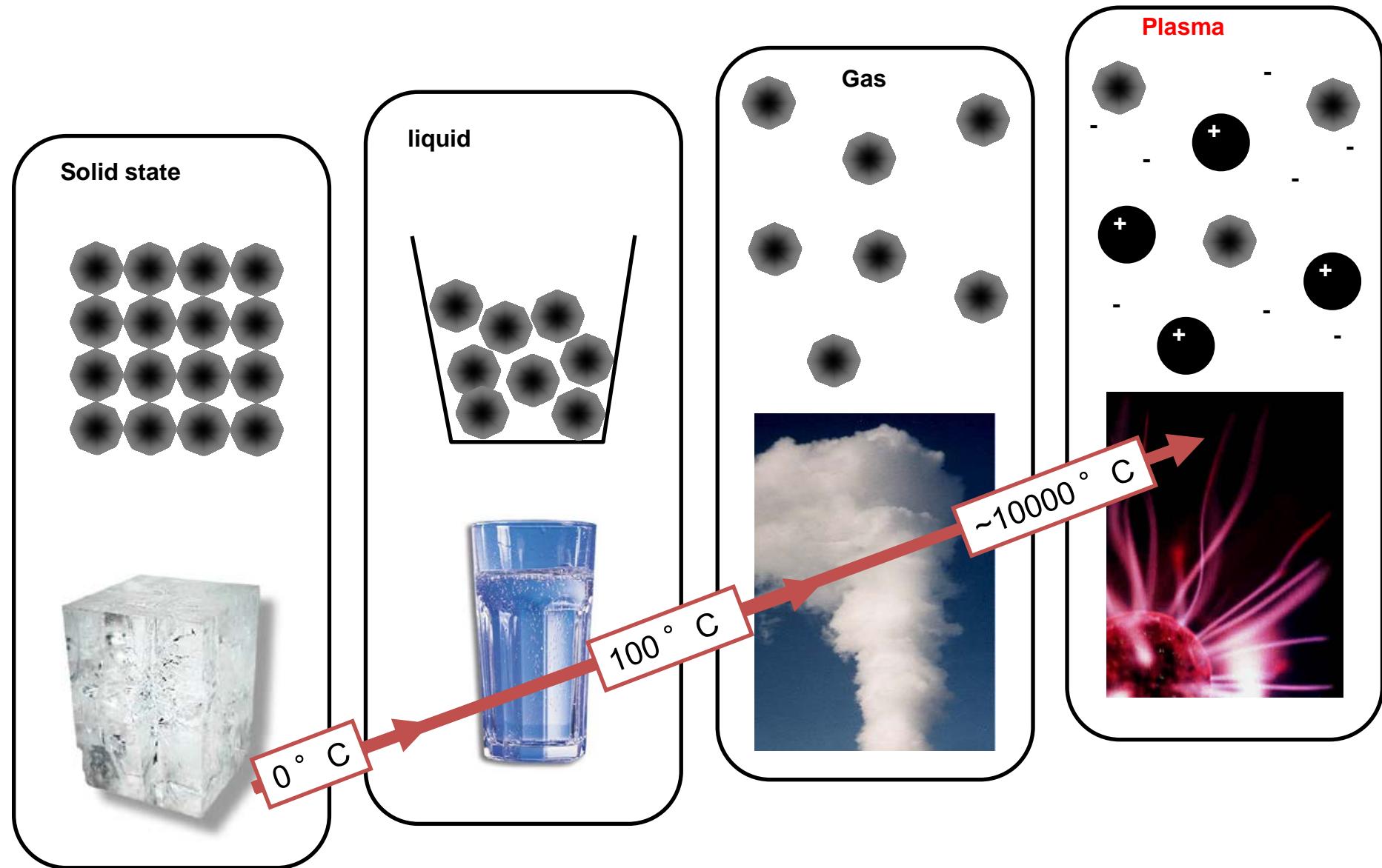
# Fundamentals of Plasmas

Achim von Keudell

Research Department Plasmas with Complex Interactions  
Ruhr-Universität Bochum

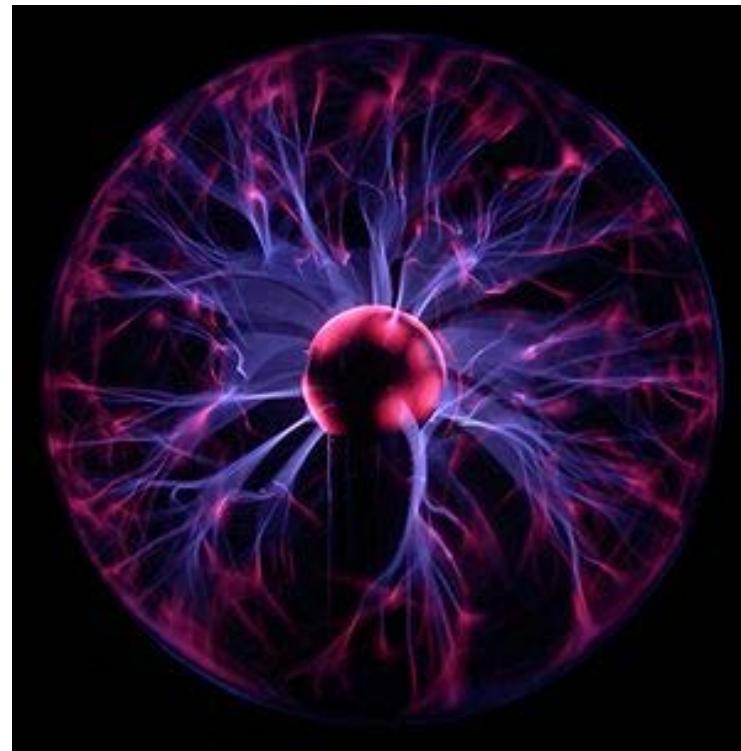
- RESEARCH DEPARTMENT  
Plasmas with Complex Interactions
- DFG FORSCHERGRUPPE 1123  
Physics of Microplasmas

# Plasma as the fourth state of matter

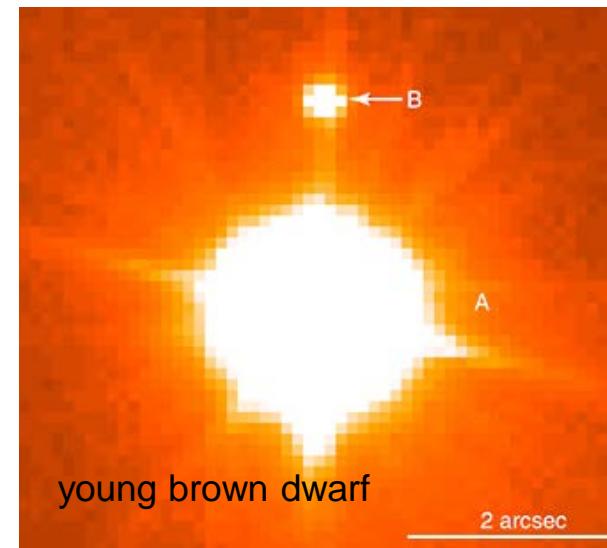
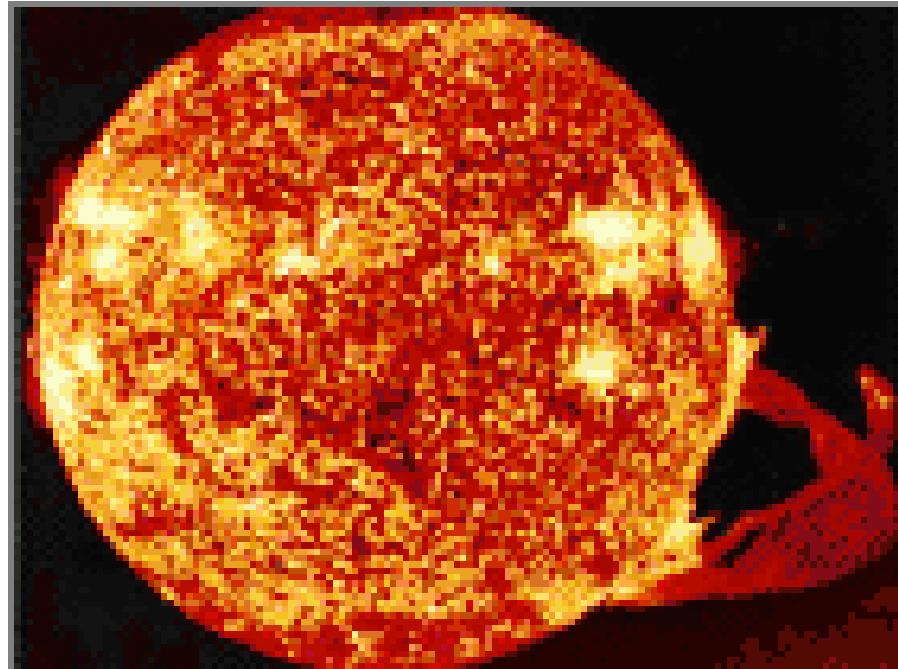
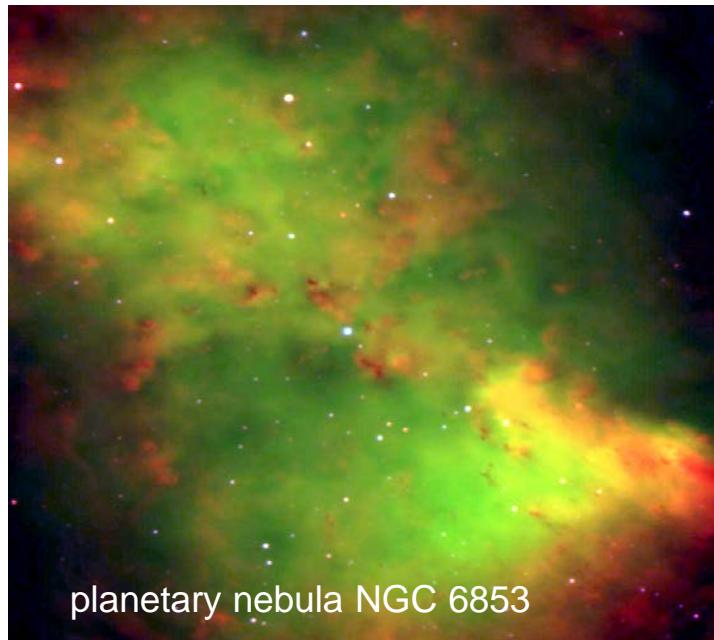


## Definition

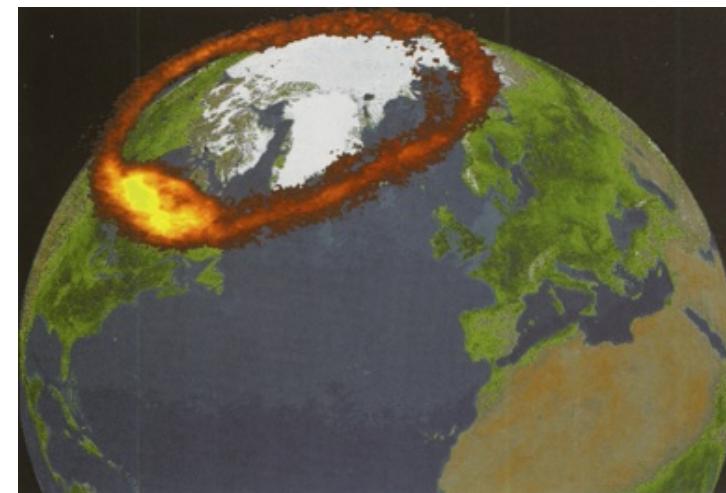
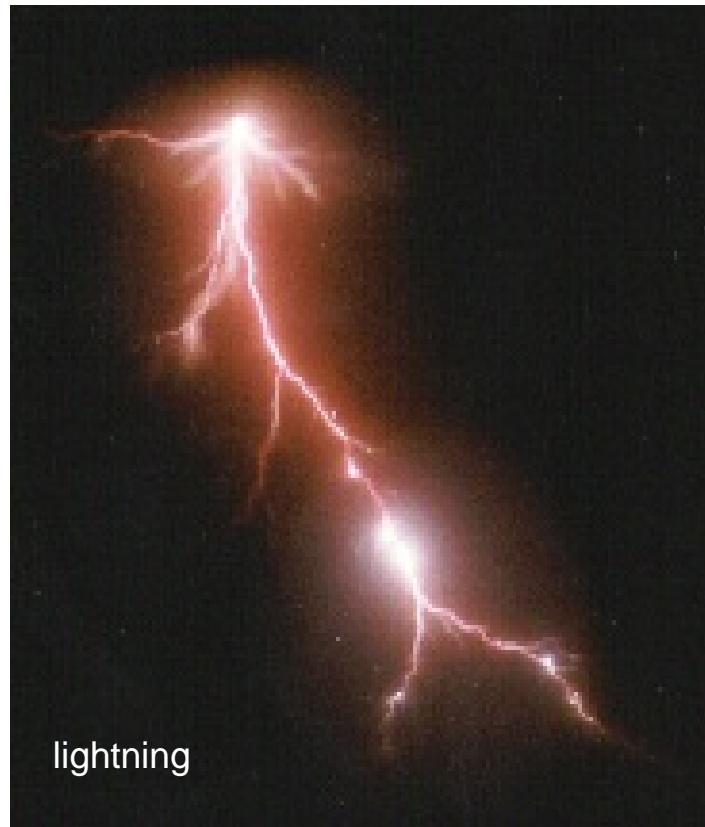
Plasma is a (hot) ionized gas with reactive particles like electrons, ions, and radicals.



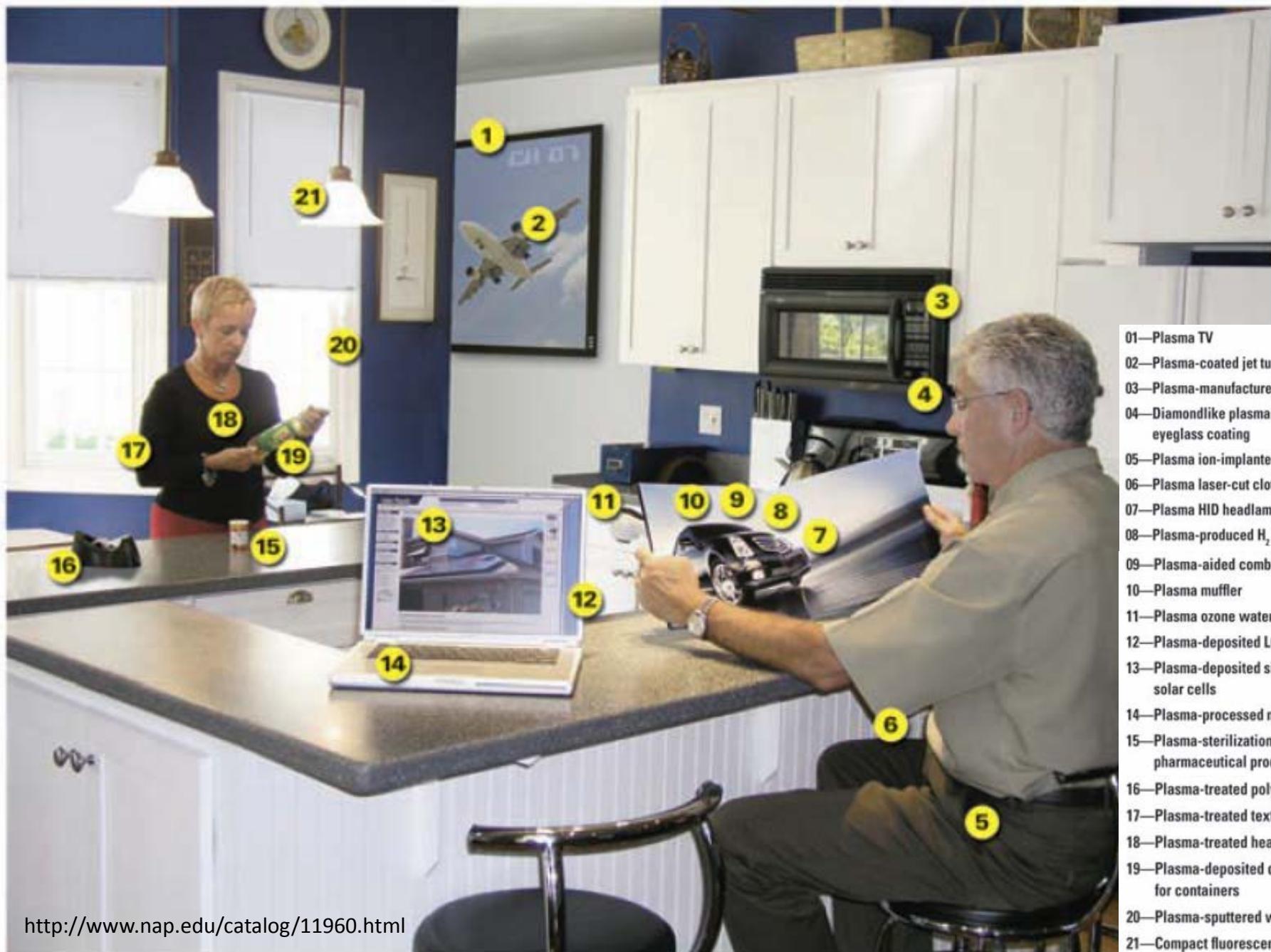
More than 99% of visible matter is plasma.



# Natural plasmas on earth



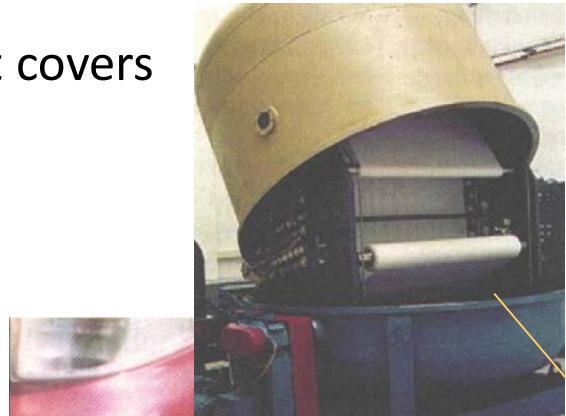
# Low temperature plasmas for our daily lives



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

- 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<sub>2</sub> 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

seat covers

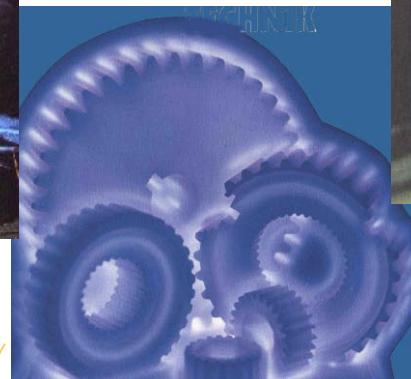


welding

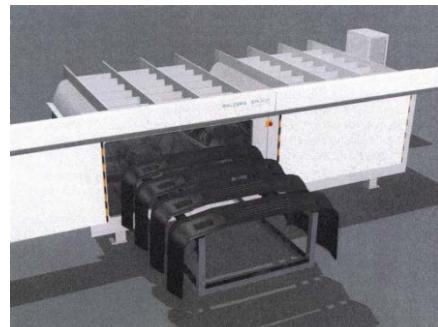
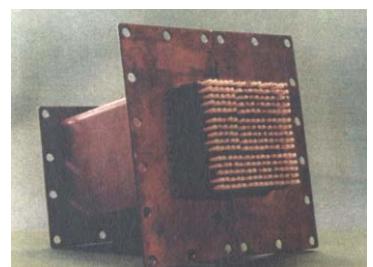
surface hardening



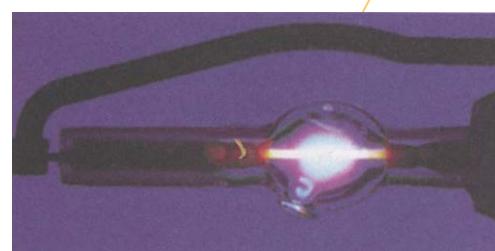
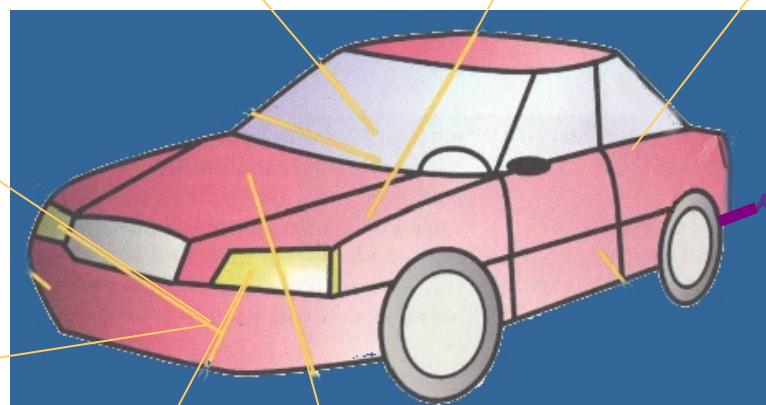
# automotive



soot removal



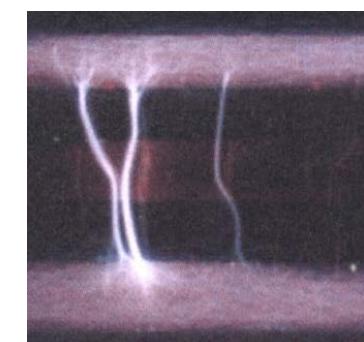
colored plastic parts  
pasting



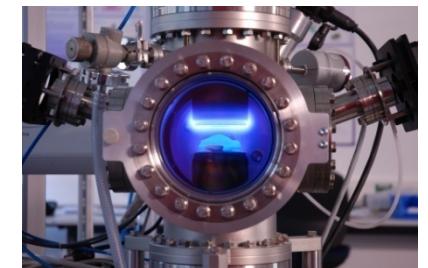
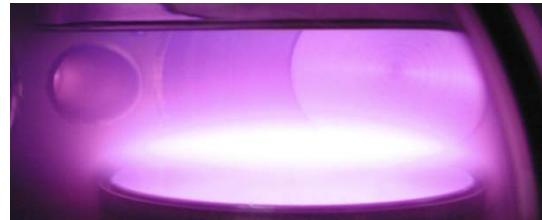
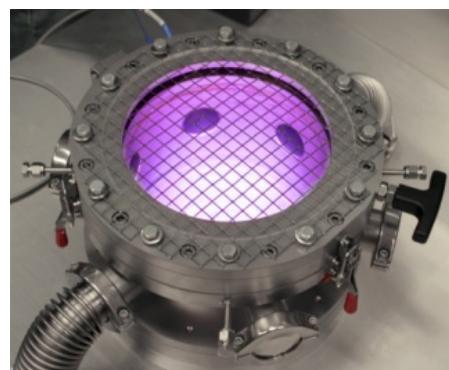
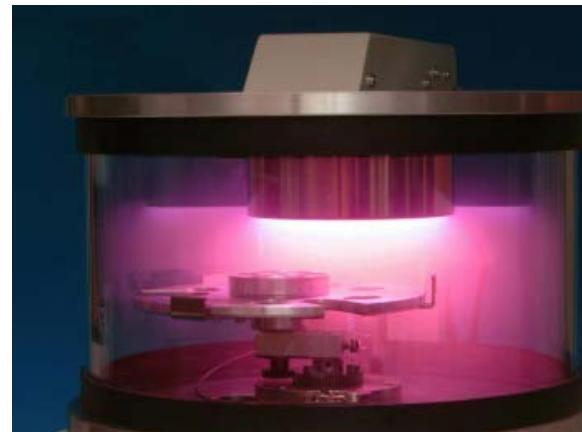
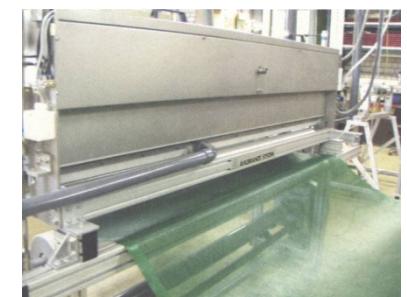
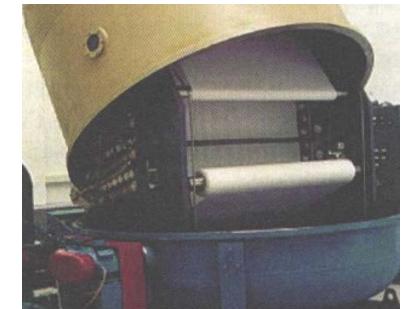
lamps



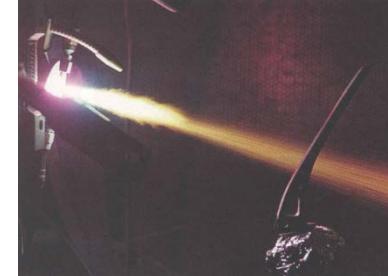
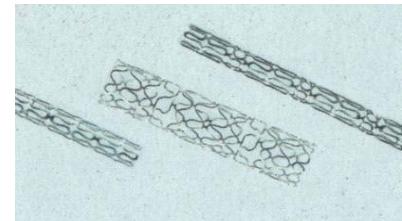
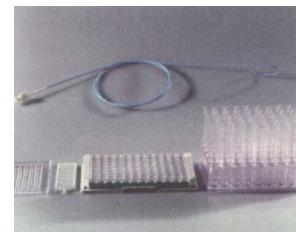
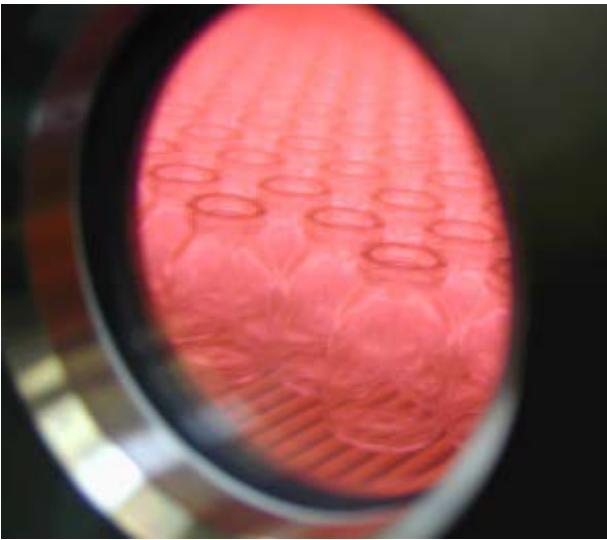
ignition



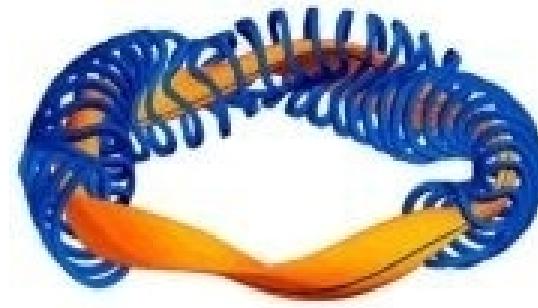
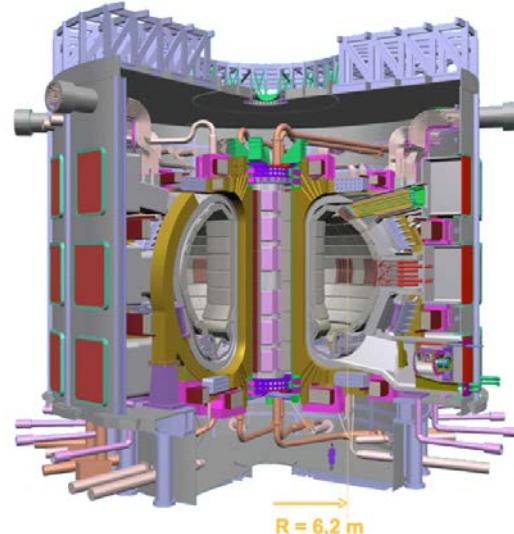
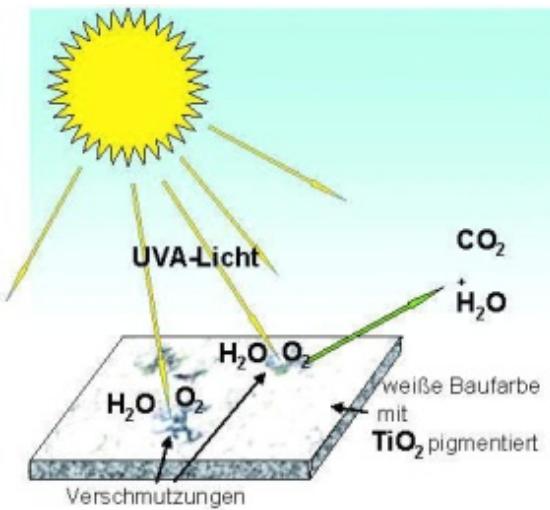
- Light generation (Plasmalamps)
- Plasmaetching in Microelectronics (Computerchips)
- Plasma based deposition (PECVD)
- Plasma spraying
- Surface modification (z.B. Hardening of metals, textiles and polymers)
- Surface sterilisation (z.B. inactivation of germs)



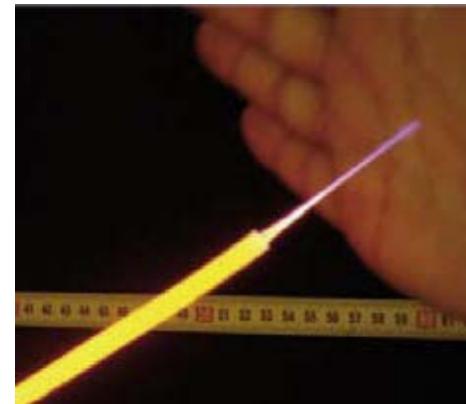
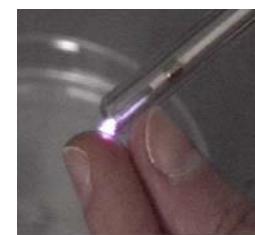
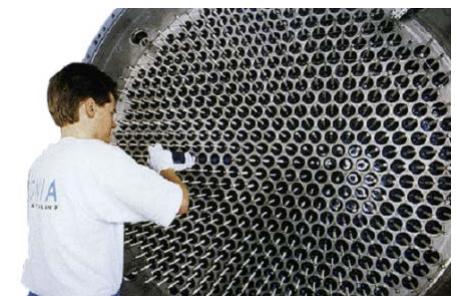
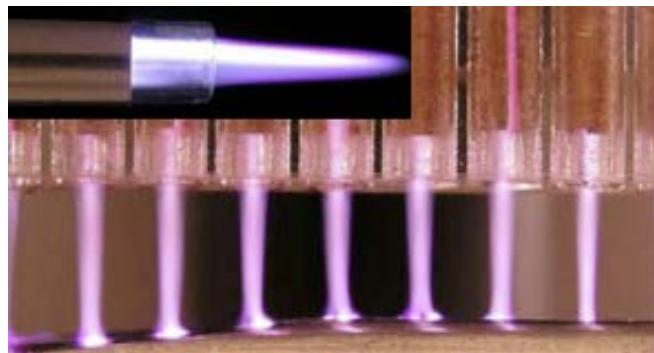
- Artificial knee – plasma coated
- Catheters – plasma coated
- Stents – plasma coated
- Artificial hips – plasmaspraying
- Sterilisation in Hospitals
- Drugs – plasma treated
- Sterilisation of vials

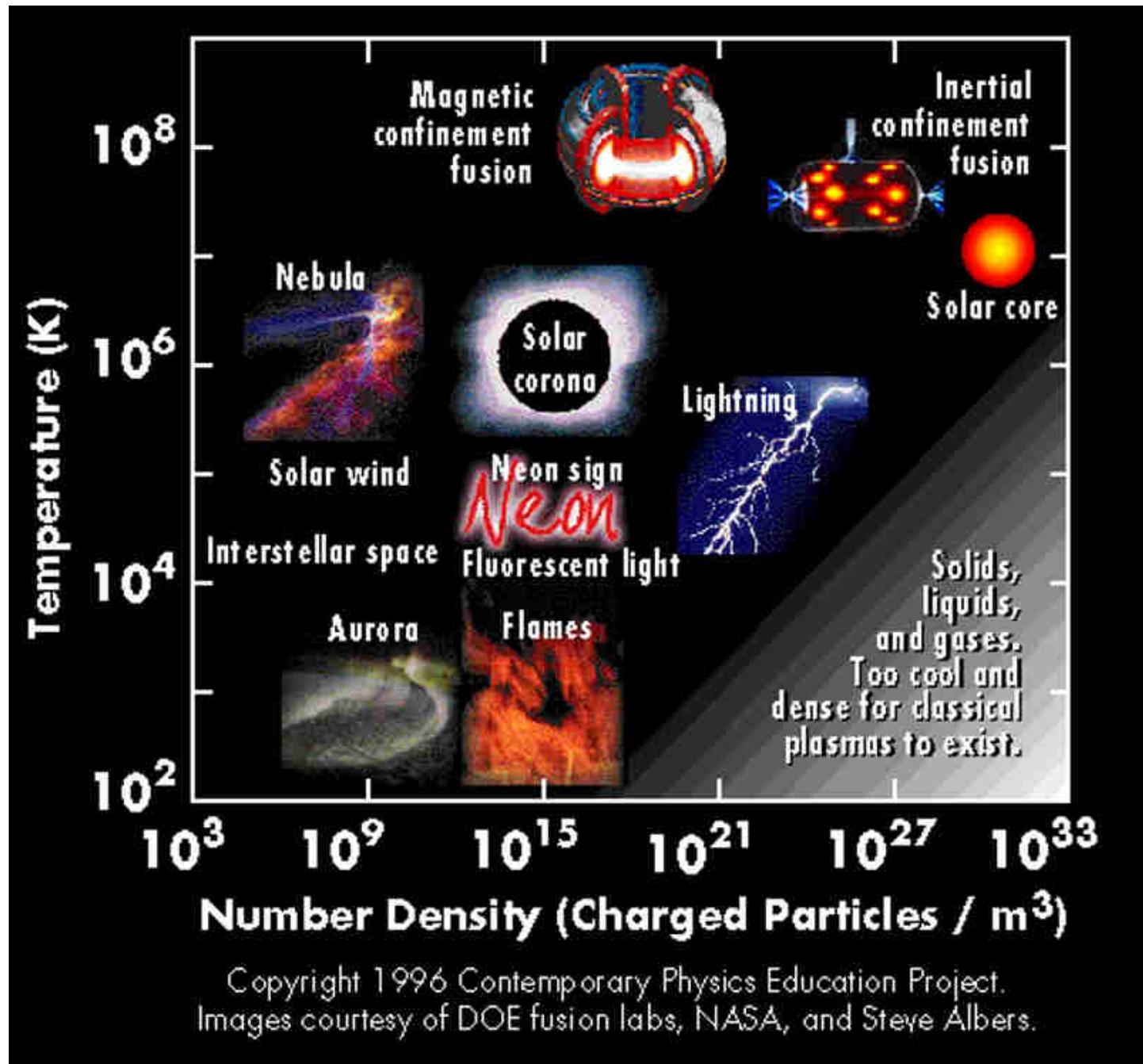


- Energy Storage (photocatalytic processes)
- Plasma switches (power plants)
- Solar panels
- Nuclear fusion
  - W 7-X, IPP Greifswald
  - ITER, Cadarache (Frankreich)



- Waste treatment
- Water and air cleaning
- Plasma medicine





## 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

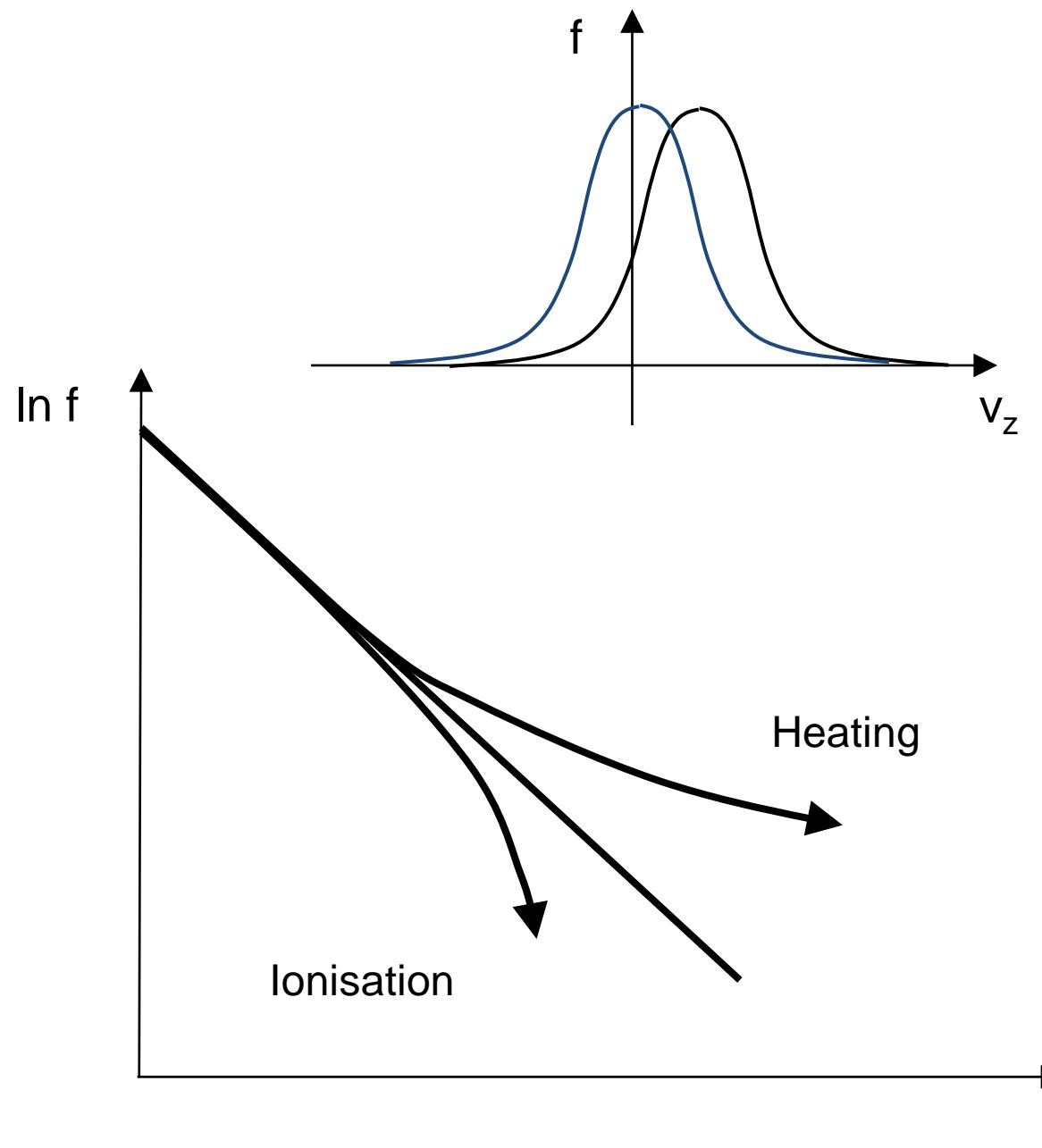
## 4. Transport in a plasma

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

## 5. How to sustain a plasma

- DC plasma
- Rf-plasmas
- Plasma heating

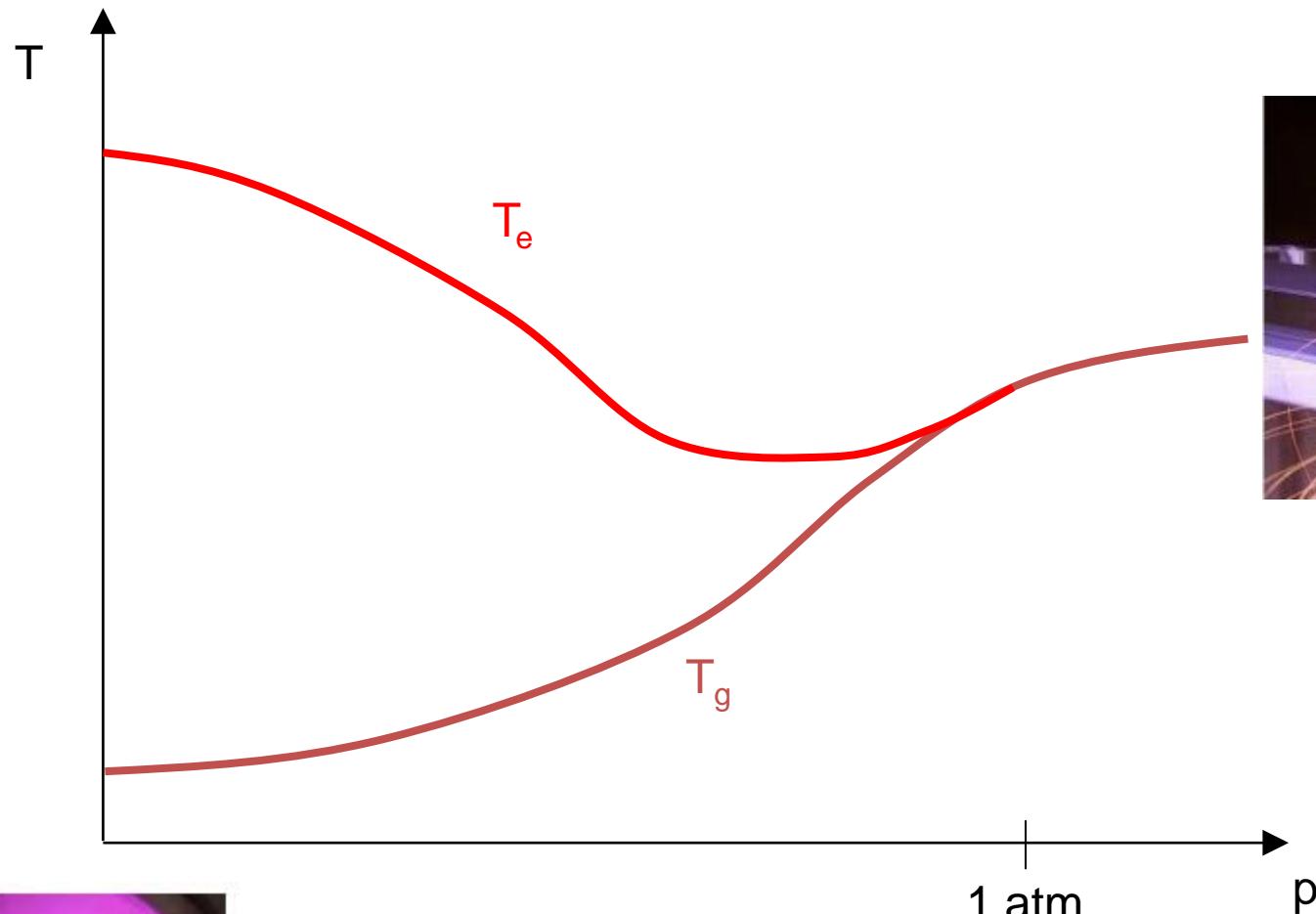
# What is a plasma ? Concept 1 - temperature



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

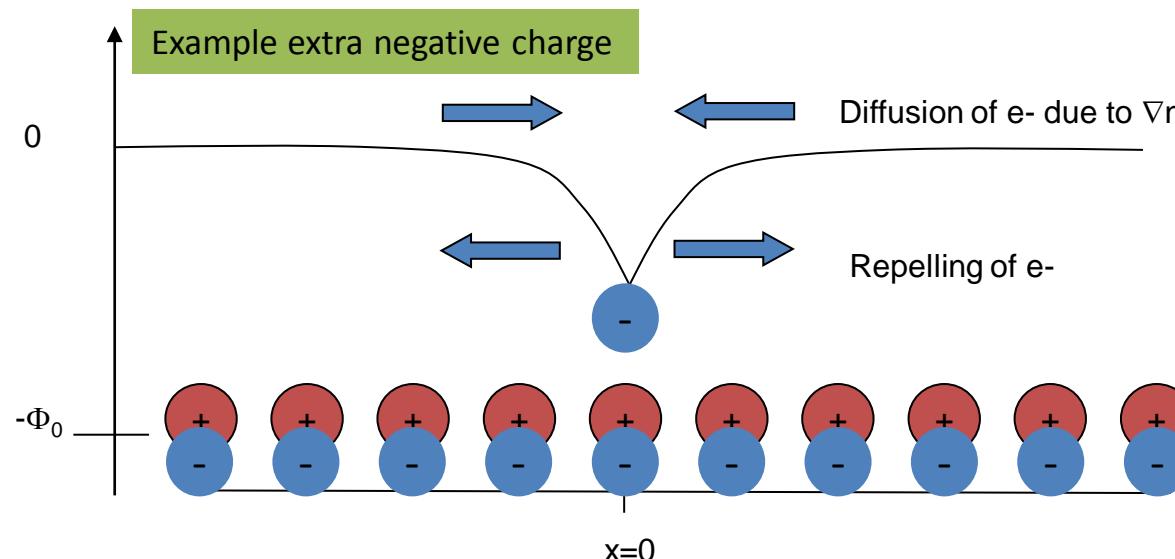
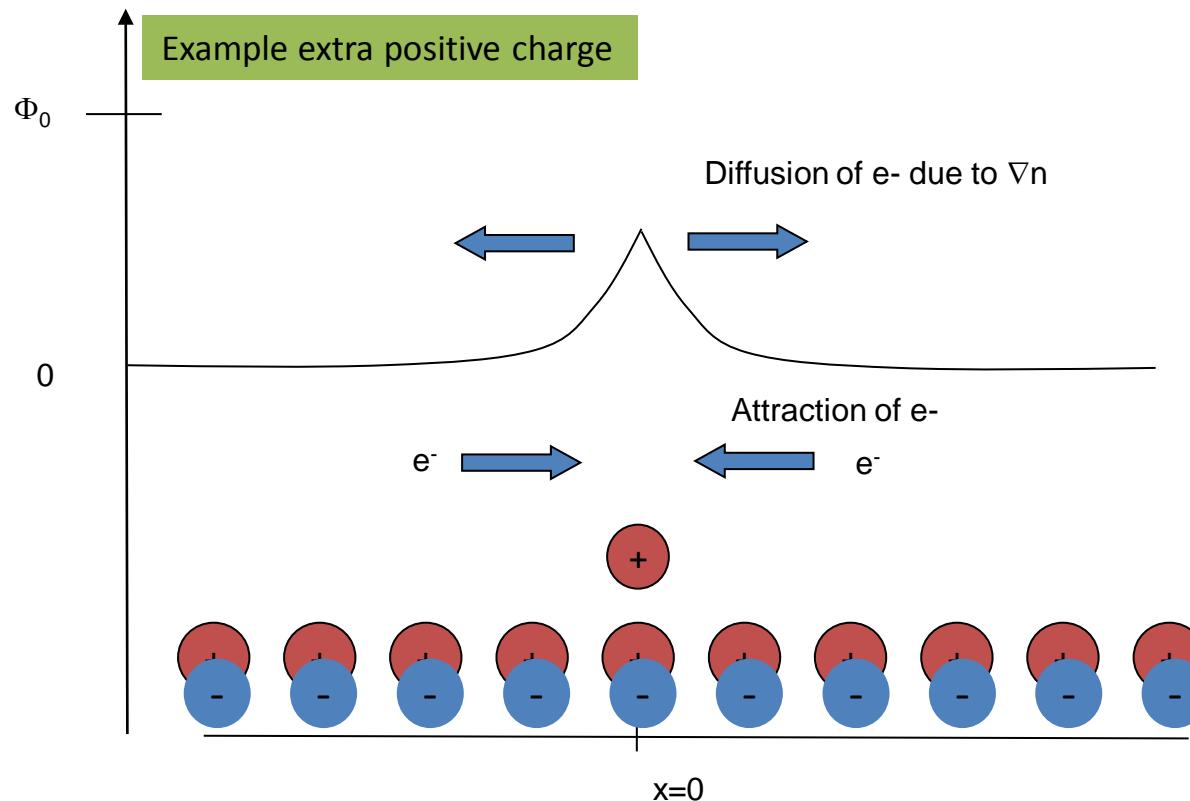
More details in the lecture  
on kinetics, see also master class

# What is a plasma ? Concept 1 - temperature



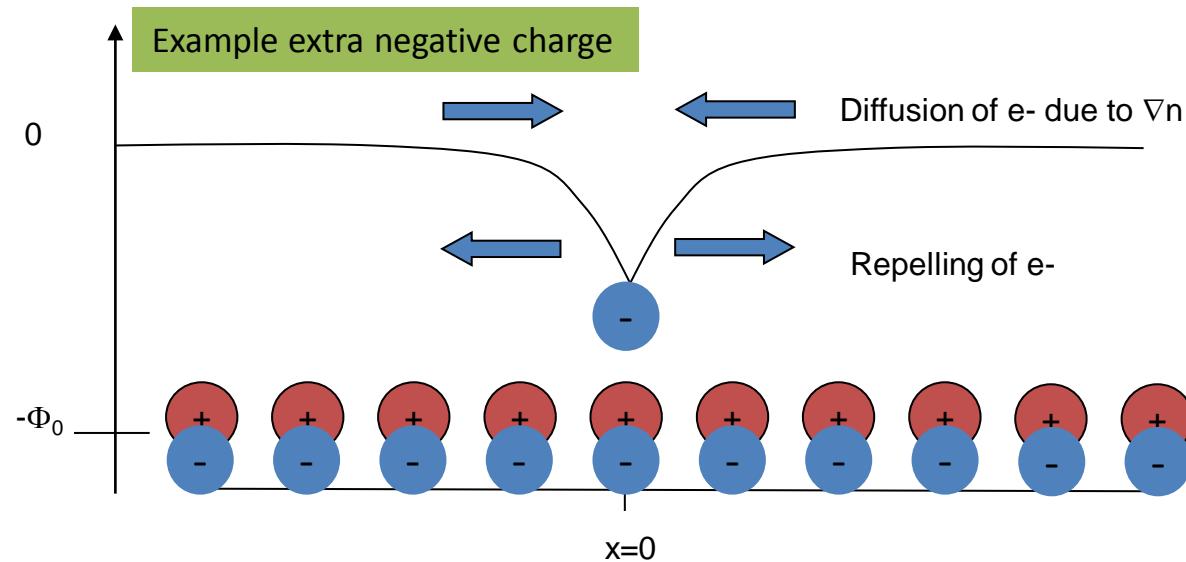
However, the concept of temperature is only an approximation.  
Most plasmas are dominated by non-equilibrium.  
Distribution function are needed rather than temperatures.  
See also lectures on kinetics

# 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)



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

$$\epsilon_0 \frac{d^2\Phi}{dx^2} = en_0 \left( e^{\frac{e\Phi(x)}{k_B T}} - 1 \right)$$

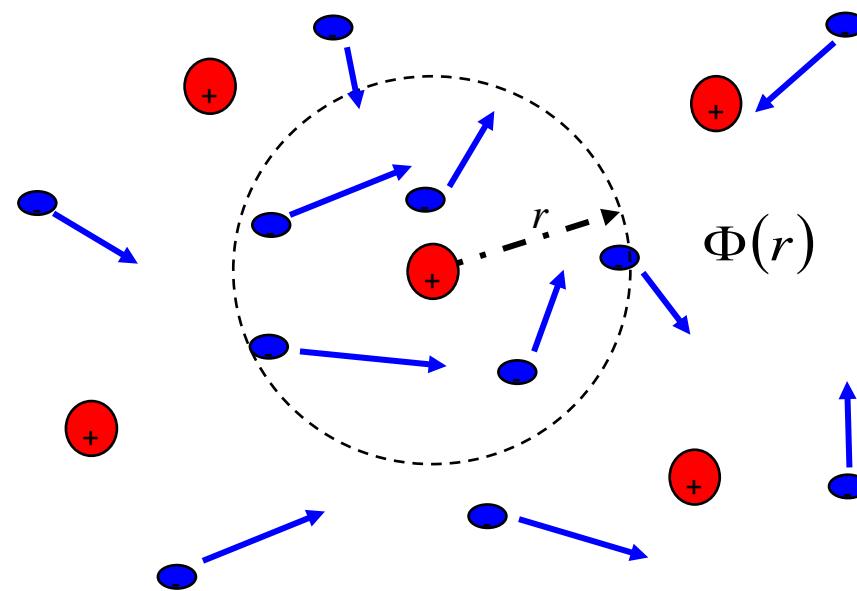
with  $\frac{e\Phi}{k_B T} \ll 1$

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

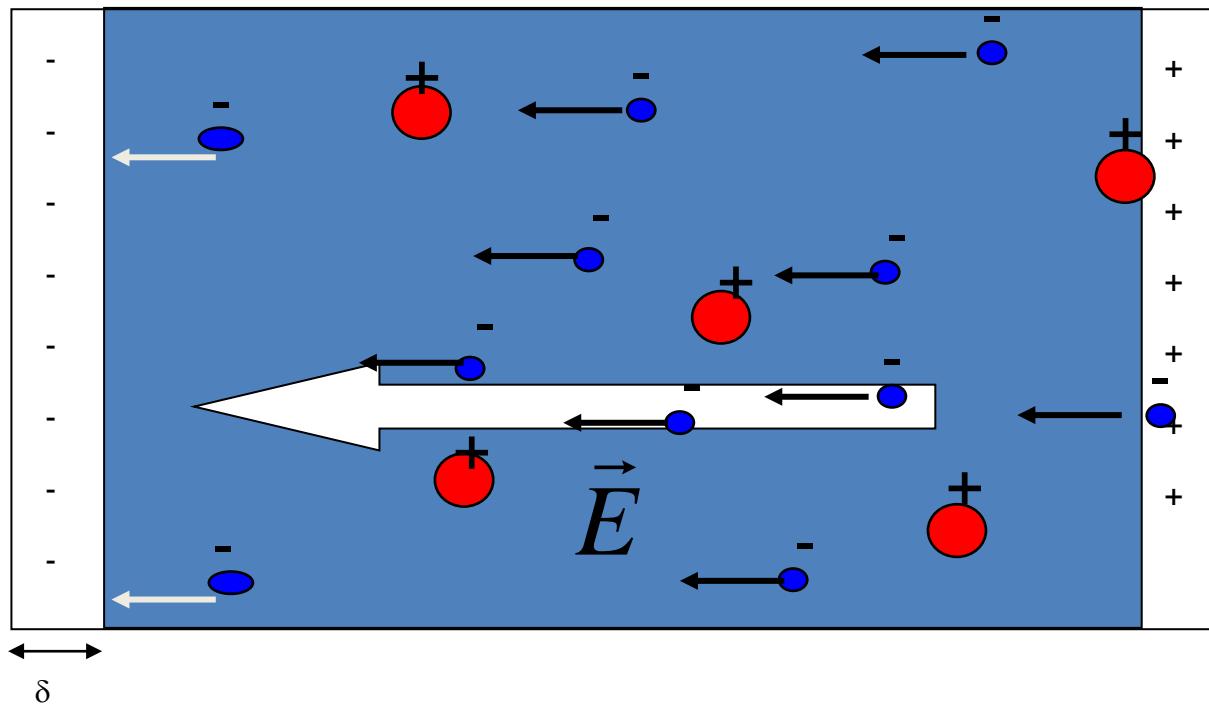
$$\epsilon_0 \frac{d^2\Phi}{dx^2} = en_0 \left( 1 + \frac{e\Phi(x)}{k_B T} + \dots - 1 \right) \simeq en_0 \frac{e\Phi}{k_B T}$$

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

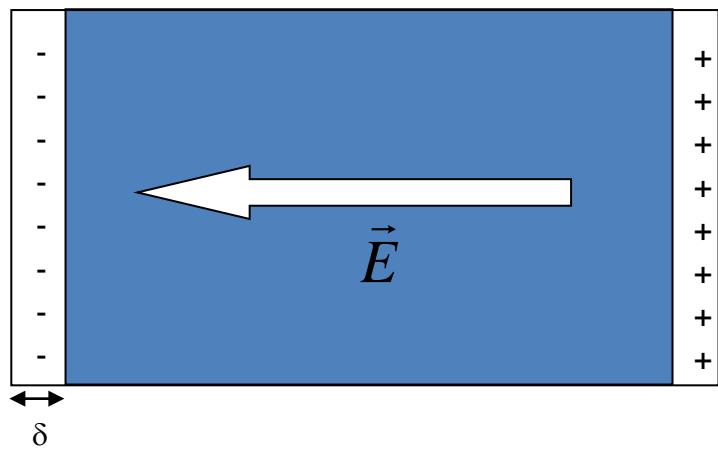
$$N_D = \frac{4\pi}{3} \lambda_D^3 n \gg 1$$



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



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



$$E = \frac{1}{\epsilon_0} end\delta$$

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

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

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

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

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

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

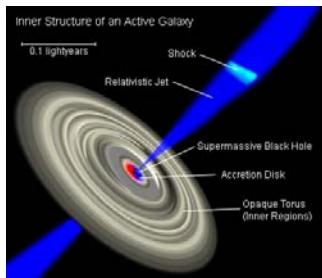
Assume:  
100 MHz RF plasma in Ar  
 $n_e = 10^{16} \text{ m}^{-3}$

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

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

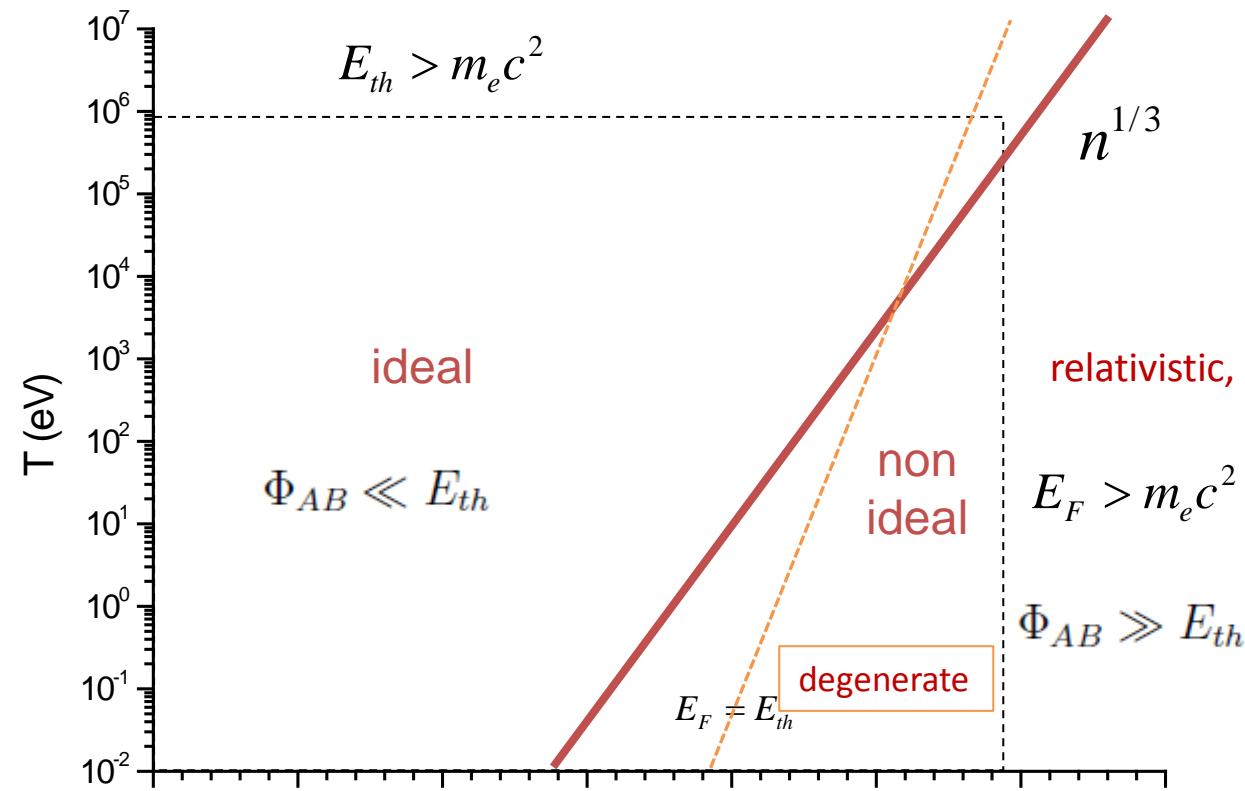
Electrons can easily follow the RF cycle,  
ions can NOT !!

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

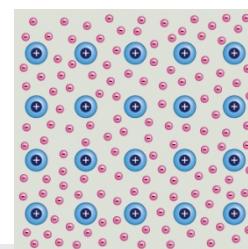


relativistic

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

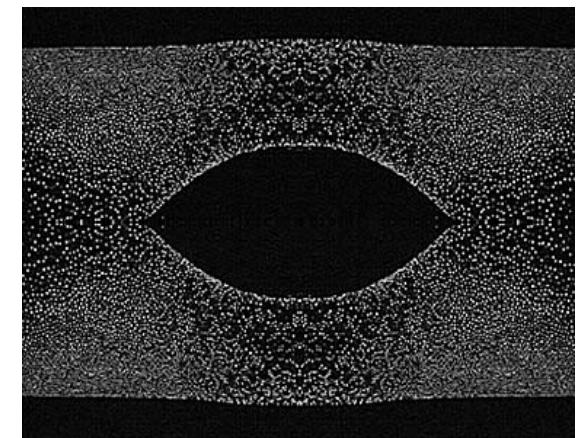


degenerate plasma:  
electrons in a metal



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

Non-ideal plasma:  
Plasma crystal



Ideal plasma – plasma larger than the Debye length:

$$L \gg \lambda_d$$

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

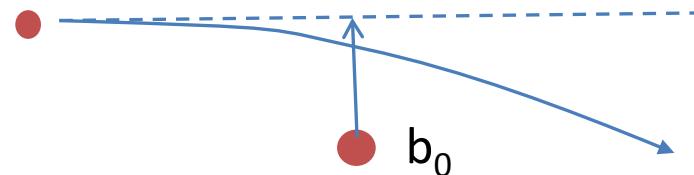
$$N_D = \frac{4\pi}{3} \lambda_D^3 n \gg 1$$

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

Ideal plasma – thermal energy must be larger than the Coulomb 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

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

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

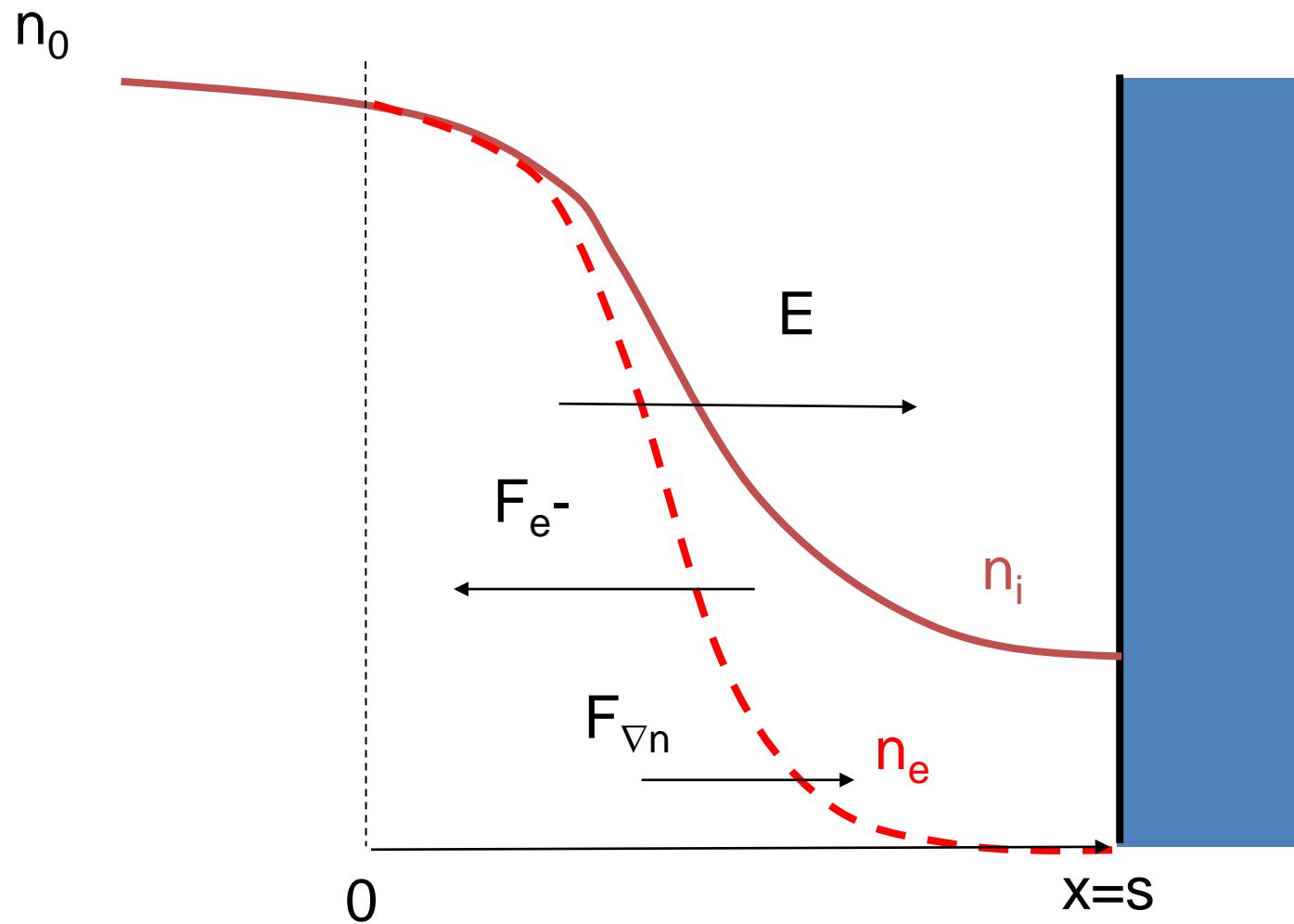
# Parameter of a plasma – Nick Braithwaite's Plasma Calculator

PLASMA CALCULATOR						
(N St J Braithwaite, European Summer School)						
<b>Physical Constants</b>						
e/C 1.60E-19	kJ_K^1 1.38E-23	me/kg 9.00E-31	Mp/kg 1.67E-27	eps0/F_m^1 8.85E-12	mu0/H_m^-1 1.26E-06	c0/m_s^1 3.00E+08
<b>Gas data</b>						
p/Pa 6.00E+00	Tg/K 3.00E+02	Mq/amu 4.00E+01	X-Sectn/m^2 1.00E-19			
<b>Plasma data</b>				Instructions		
				Adjust gas, plasma and system data		
kTe/eV 2.00E+00	ne/m^3 1.00E+16	(data boxes in this band are not protected)				
Plasma parameters are immediately updated						
<b>System data</b>						
L/m 1.00E-01	RF/MHz 1.36E+01	B/T 1.00E-01	muwave/MHz 2.45E+03	rho_Cu/ohm_m 2.00E-08		
<b>Plasma</b>				<b>System</b>		
<b>Lengths/m</b>						
inter-neutral 8.84E-08	inter-ch 4.64E-06	mfp 6.90E-03	Debye 1.05E-04	dskin 2.48E-01	dskin_Cu 1.93E-05	L 1.00E-01
<b>Frequencies/rad_s^-1</b>						
wpe 5.67E+09	wpi 2.08E+07	wce 1.78E+10				
				wRF 8.52E+07	wm 1.54E+10	
<b>Frequencies/MHz</b>						
fpe 9.03E+02	fpi 3.31E+00	fce 2.83E+03	nu 8.64E+01	RF 1.36E+01 muwave 2.45E+03		
<b>Speeds/m_s^-1</b>						
ce 9.52E+05	ve 5.96E+05	cs 2.19E+03	cg 3.97E+02			
<b>Fluxes/m^-2_s^-1</b>						
Gi 2.19E+19	Gg 1.44E+23					
<b>Conductivity/ohm^-1_m^-1</b>						
sigDC 3.29E+00	Re[sigRF] 1.67E+00	Im[sigRF] -1.65E+00				
<b>Densities/m^-3</b>						
ng 1.45E+21	ne 1E+16	% ionisation 0.00069				
Comments to n.s.braithwaite@open.ac.uk						

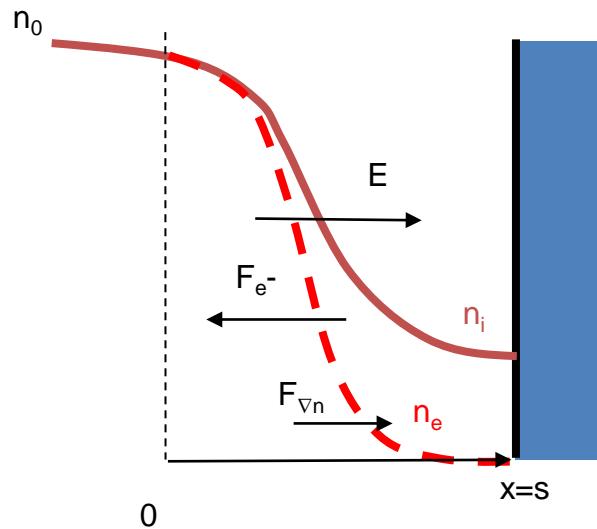
# The edge of a plasma



# A plasma in front of a wall – sheath physics



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



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

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

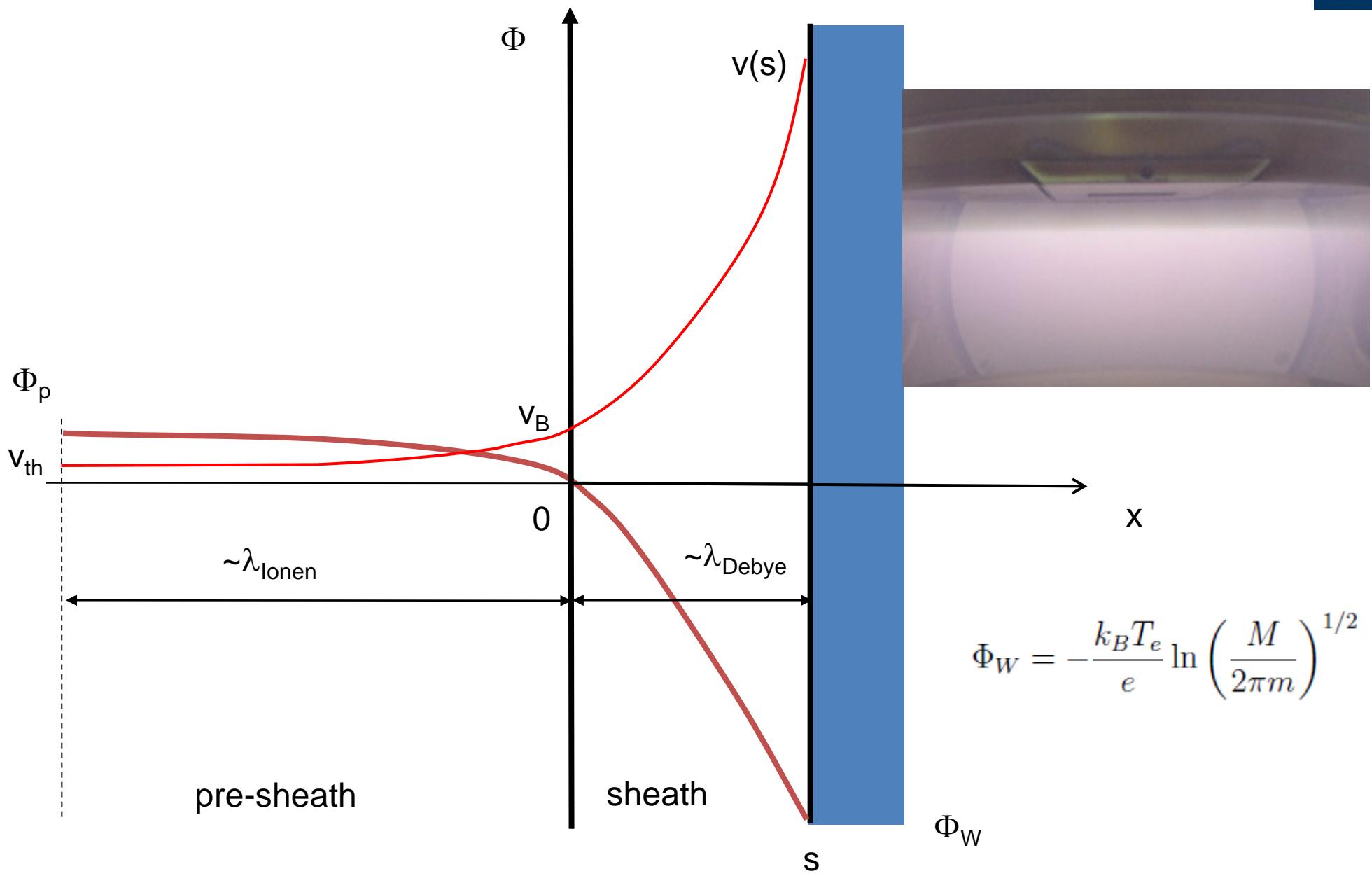
$$n_e(x) = n_0 e^{\frac{e\Phi(x)}{k_B T_e}}$$

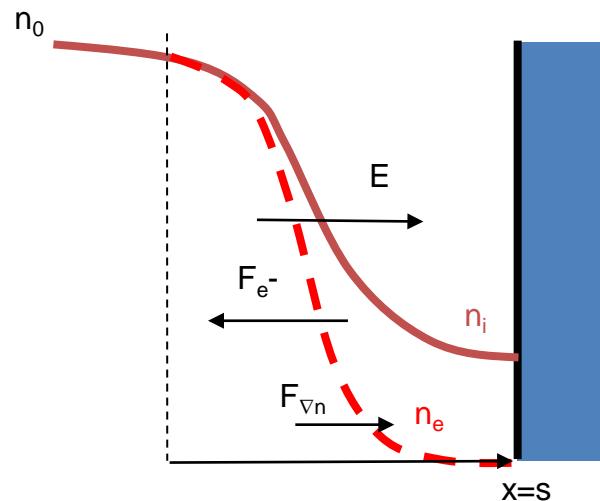
$$n_i(x) = n_0 \left(1 - \frac{2e\Phi(x)}{Mv_0^2}\right)^{-1/2} = n_0 \left(1 - \frac{e\Phi(x)}{E_0}\right)^{-1/2}$$

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

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

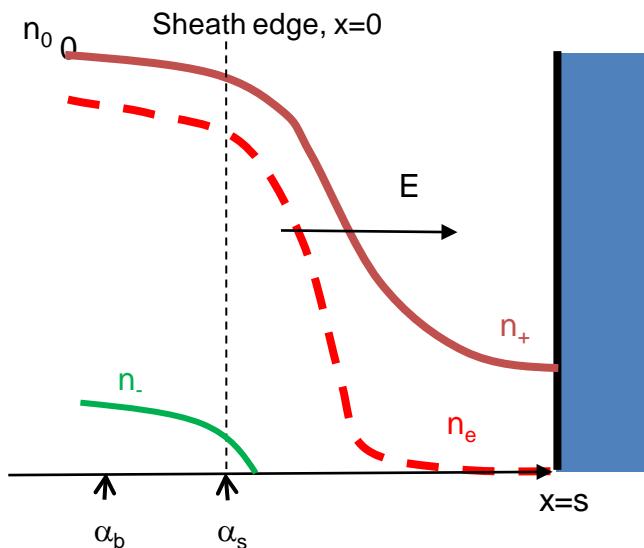
# A plasma in front of a wall – sheath physics – potential, ion velocity





Multiple ions

$$\sum_j \frac{en_j}{m_j v_j^2} \leq \frac{en_e}{k_B T_e}$$

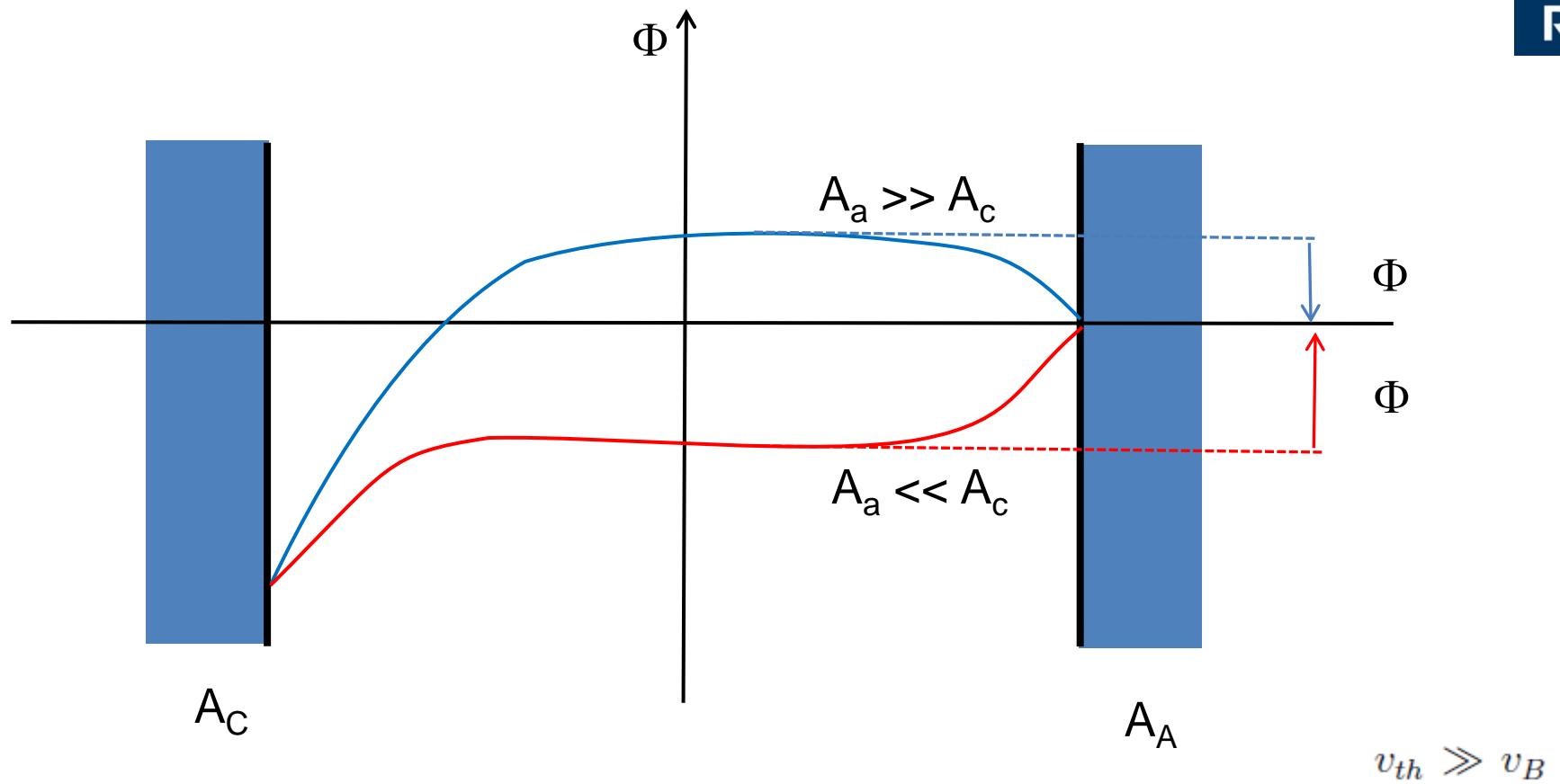


Electronegative plasmas

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

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

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



Flux balance ions and electrons

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

$$\begin{array}{l} \rightarrow \\ \rightarrow \end{array}$$

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

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

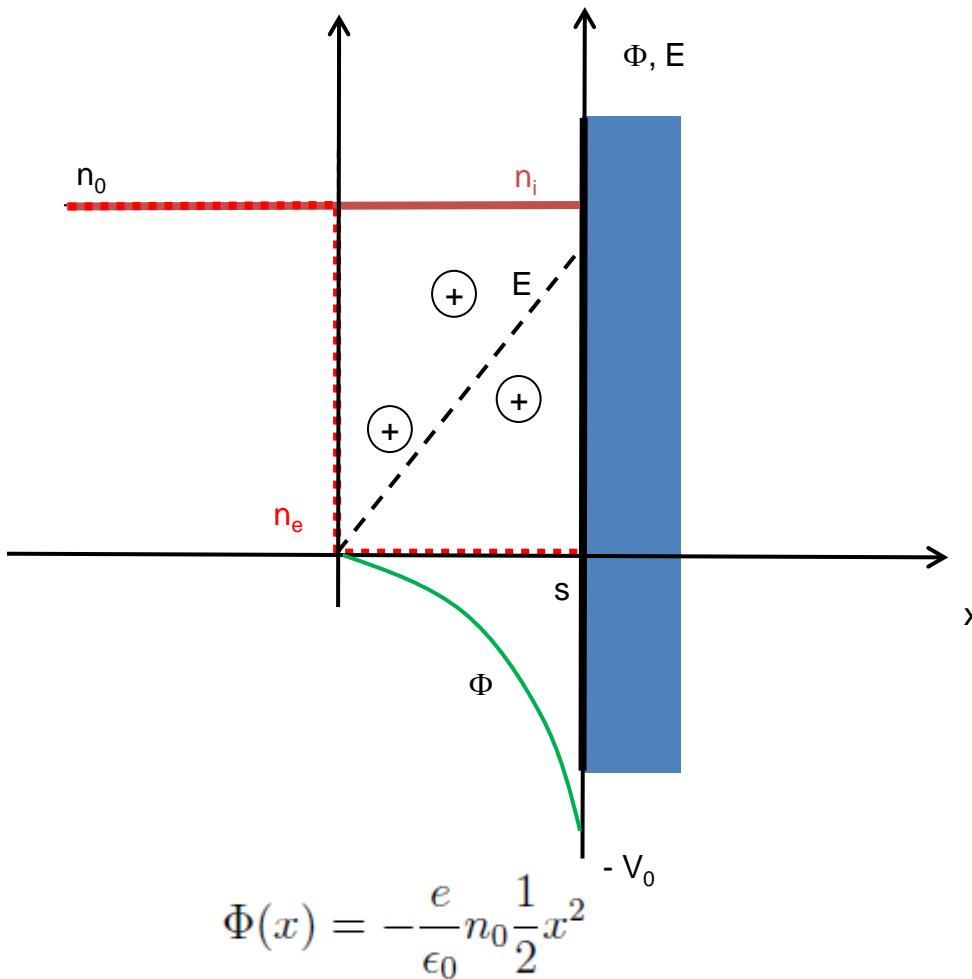
Plasma potential

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

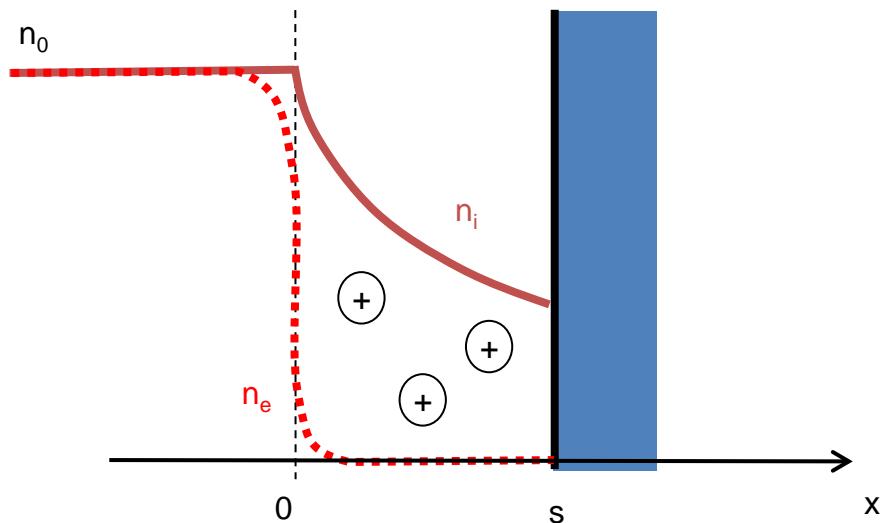
$$A_a \ll A_c \quad \Phi \simeq \frac{k_B T_e}{e} \ln \left[ \frac{4v_B}{v_{th}} \frac{A_c}{A_a} \right] > 0$$

Potential difference going from plasma to wall

## Matrix sheath



## Child Langmuir sheath



$$en(x)v(x) = j_0$$

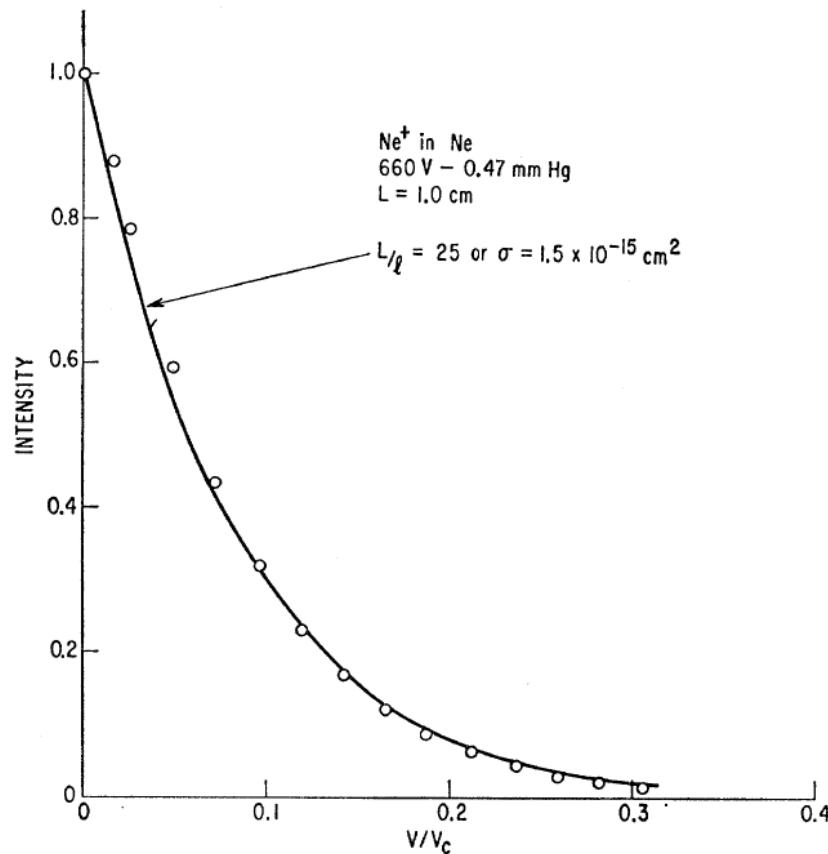
$$\frac{1}{2} M v^2(x) = -e\Phi(x) + \underbrace{\frac{1}{2} M v_0^2}_{\ll}$$

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

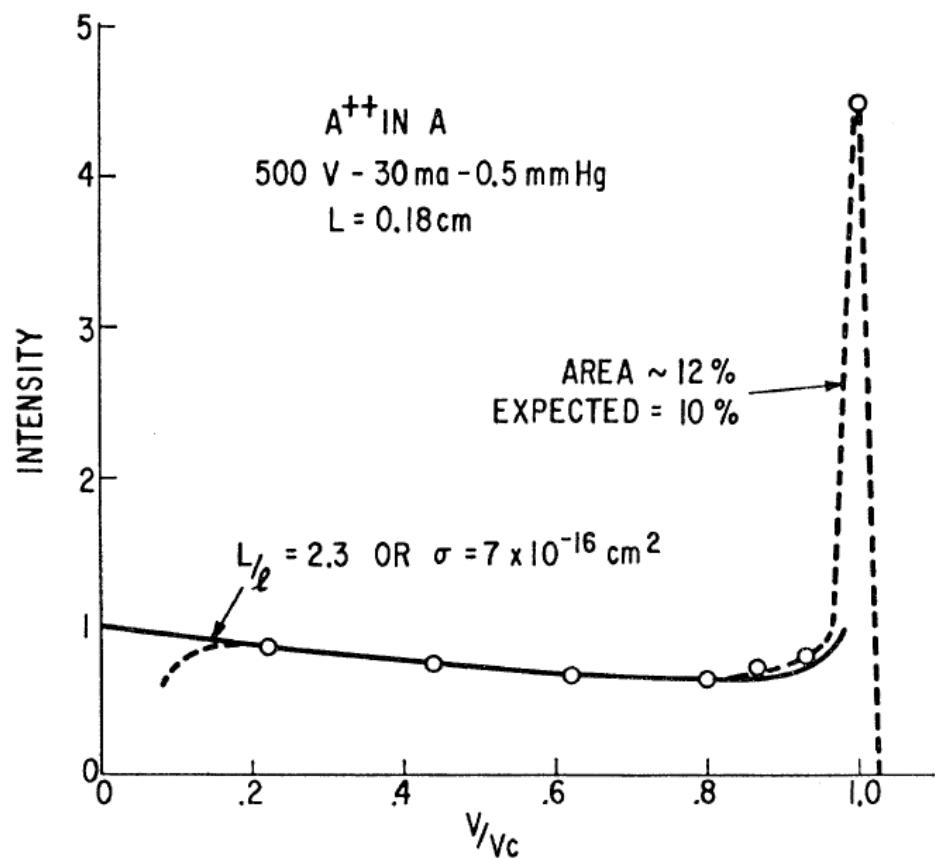
$$s = \left( \frac{2\epsilon_0 V}{en_0} \right)^{1/2} = \lambda_D \left( \frac{2eV}{k_B T_e} \right)^{1/2}$$

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

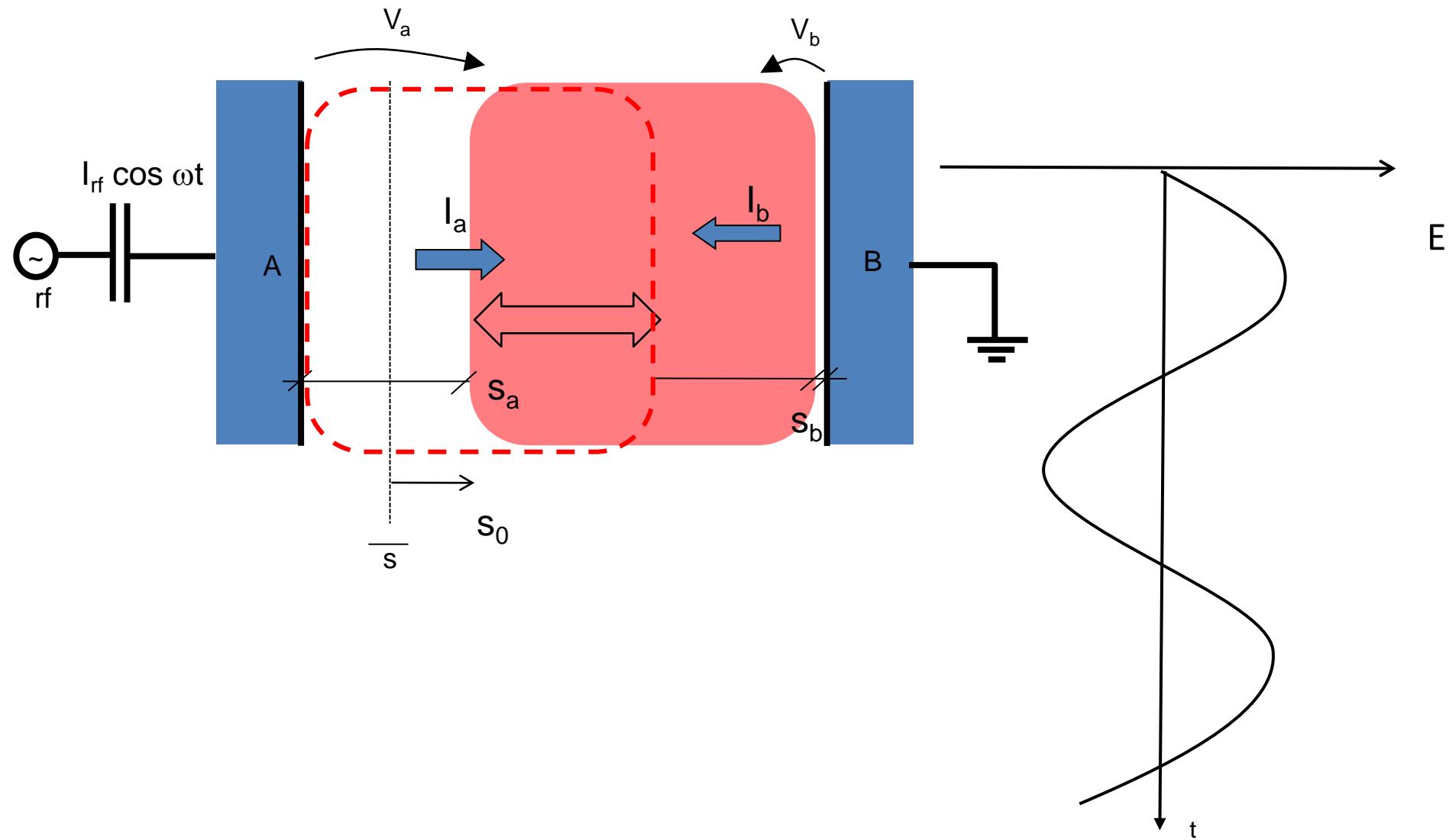
many collisions in the sheath



Few collisions in the sheath



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



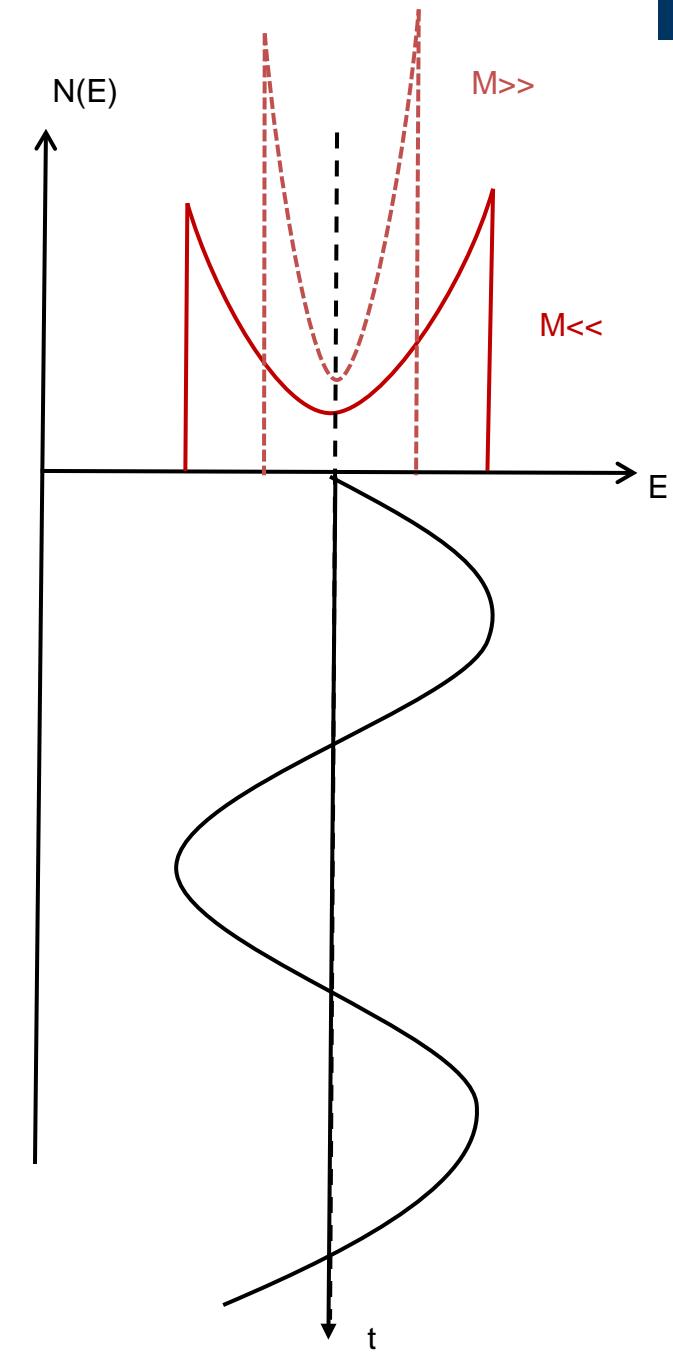
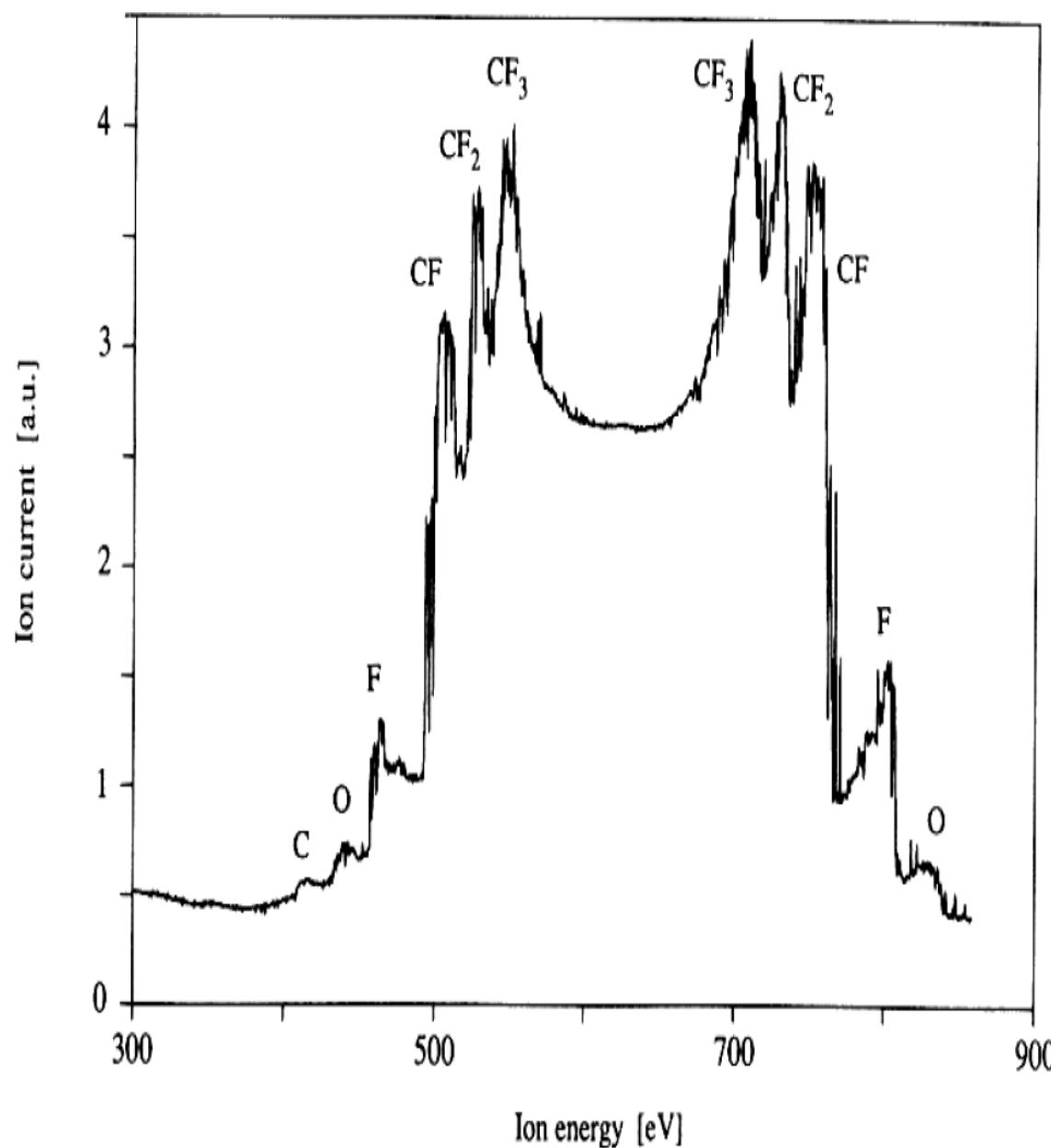


Abbildung 3.13: Messung der Ionenenergieverteilung in einem CF-rf-Plasma [A. Kuypers, H. Hopman *Measurement of ion energy distributions an the powered rf electrode in a variable magnetic field*, J. Appl. Phys. 67, 1229 (1990)]

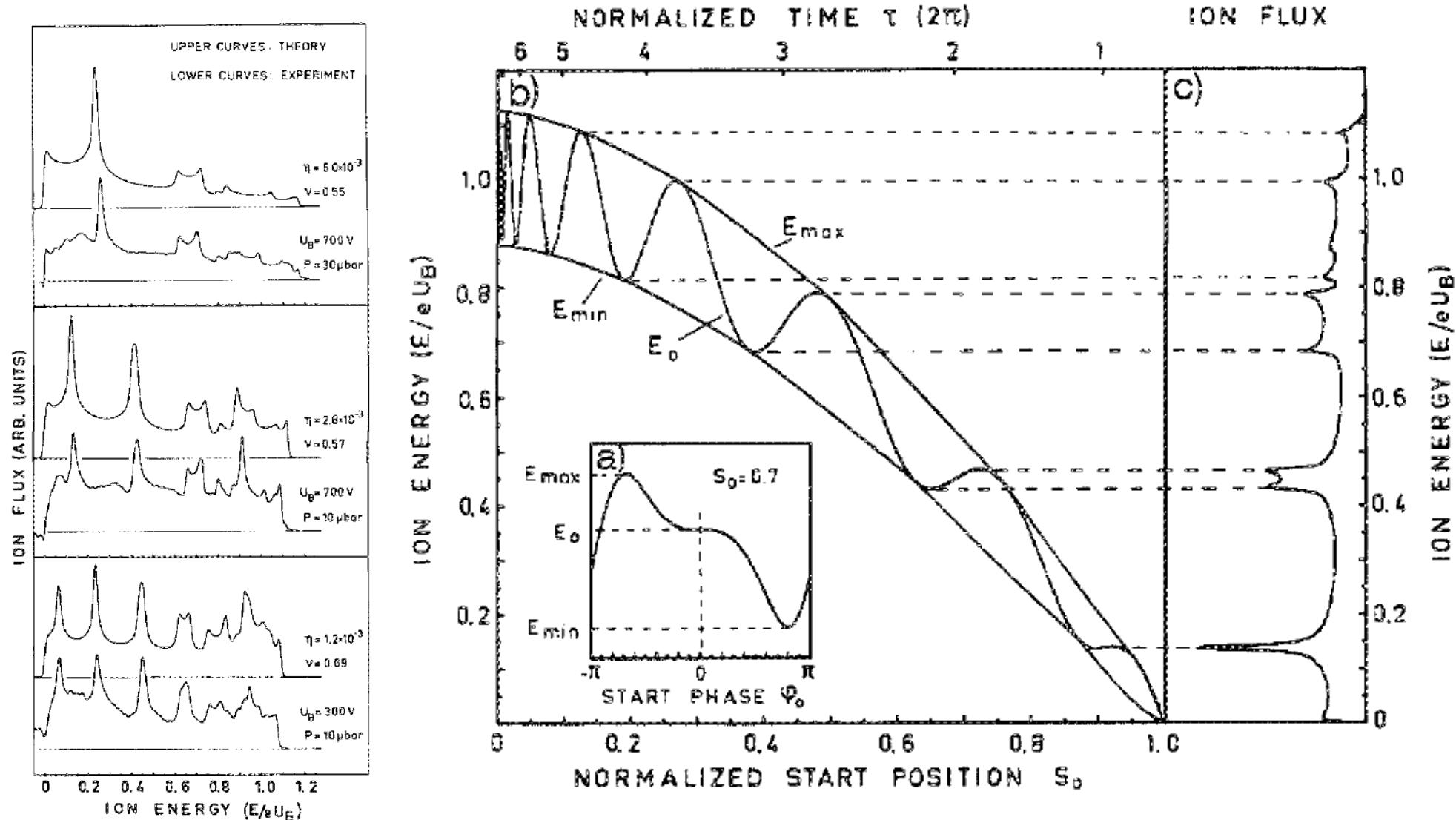
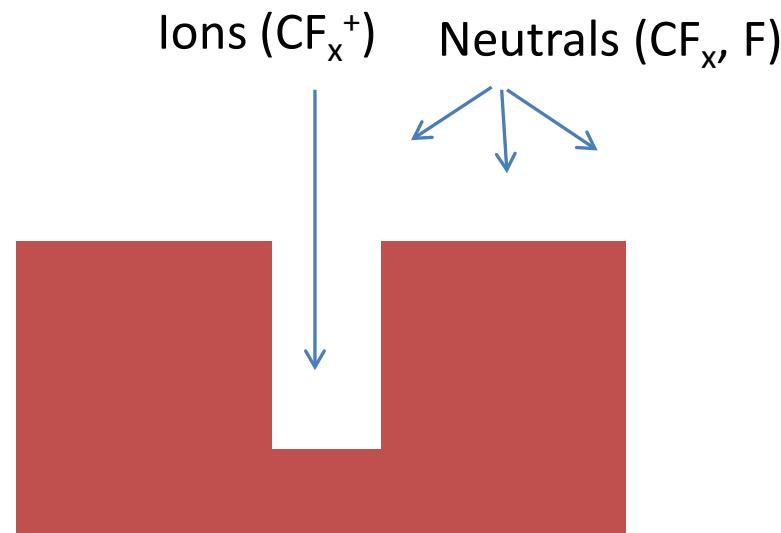
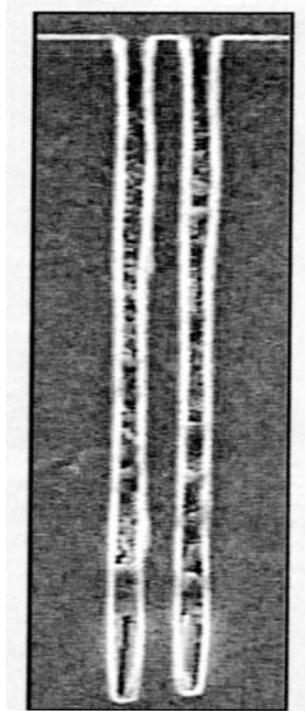
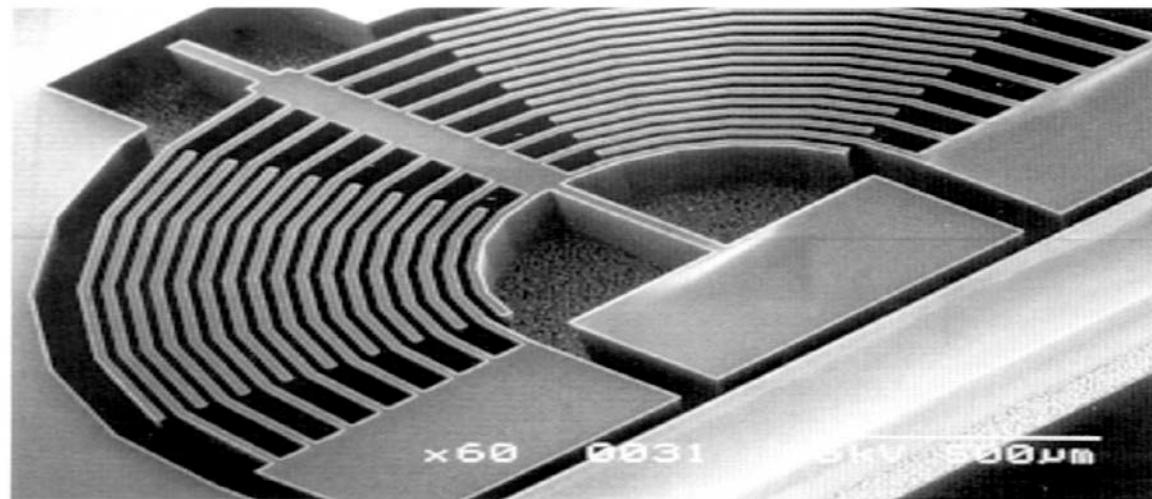
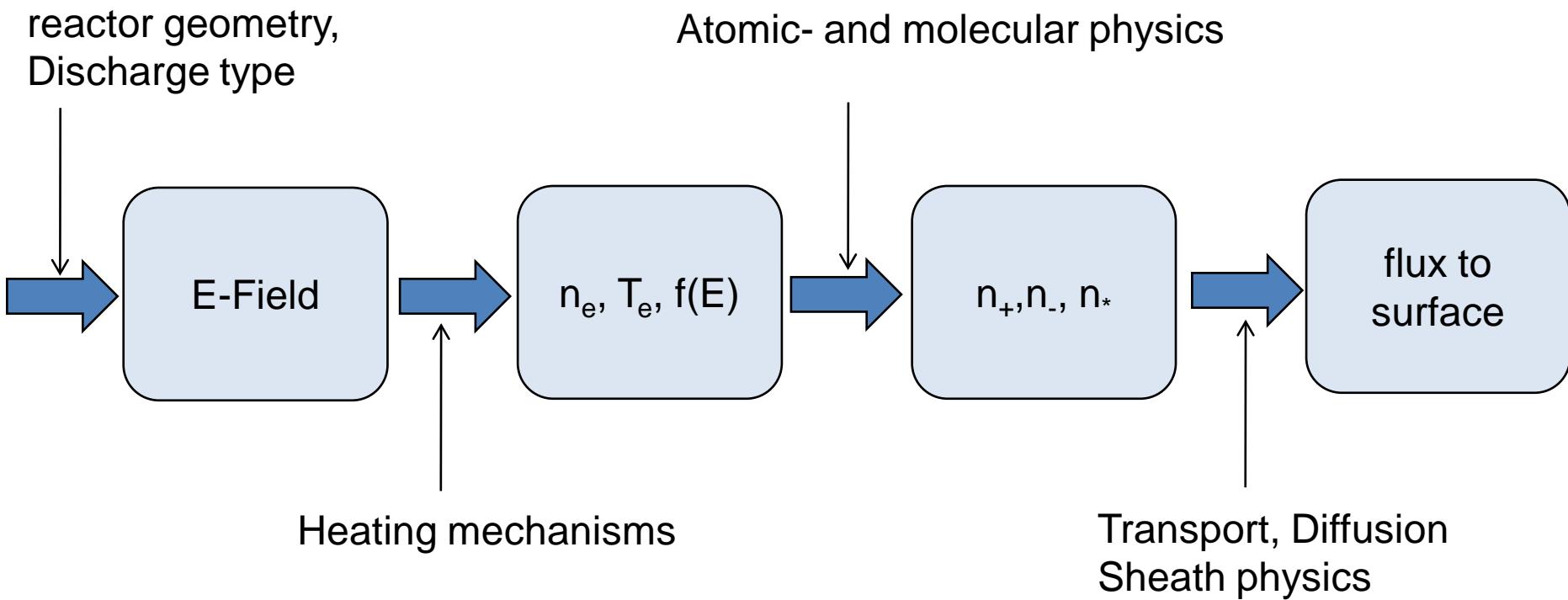


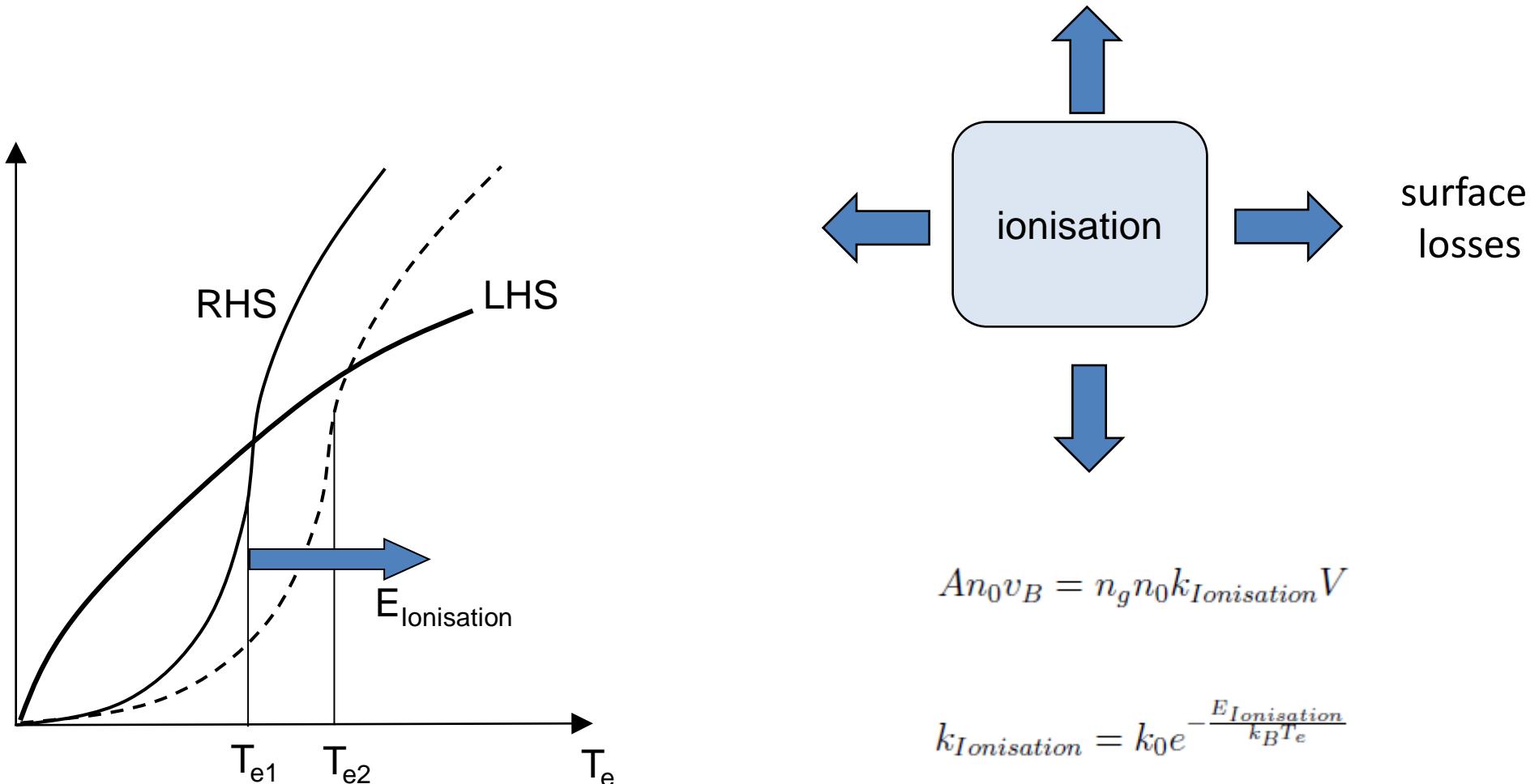
Abbildung 3.14: Stoßbestimmte Ionenergieverteilungen in einer rf-Randschicht, [C. Wild, P. Koidl *Structured ion energy distribution in radio frequency glow-discharge systems* Appl. Phys. Lett. 54, 505 (1989)]



# Working point of a Plasma – global model



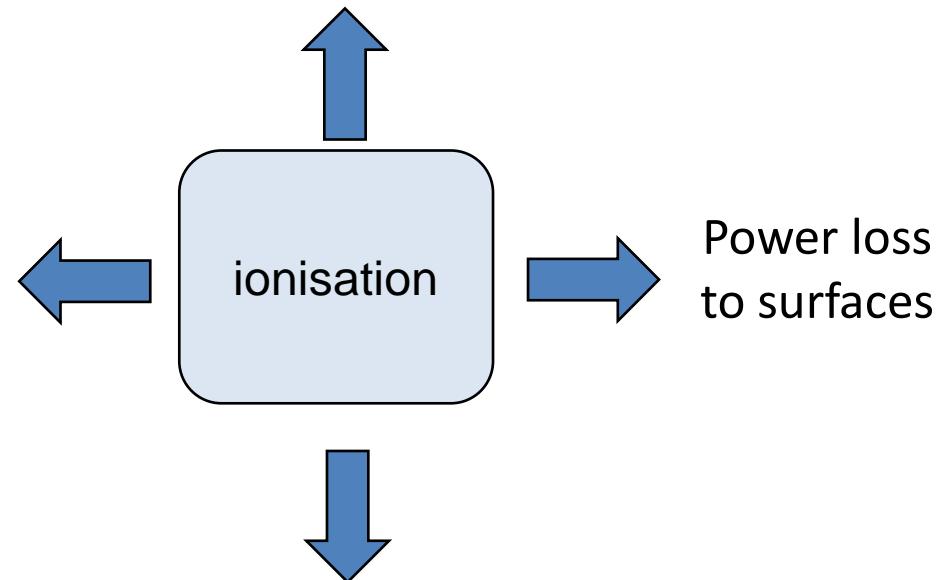
# Working point of a Plasma – global model



Particle balance determines  
Electron temperature

$$An_0 \sqrt{\frac{k_B T_e}{M}} = n_g n_0 k_0 e^{-\frac{E_{Ionisation}}{k_B T_e}} V$$

Absorbed power is a complicated function of electron density



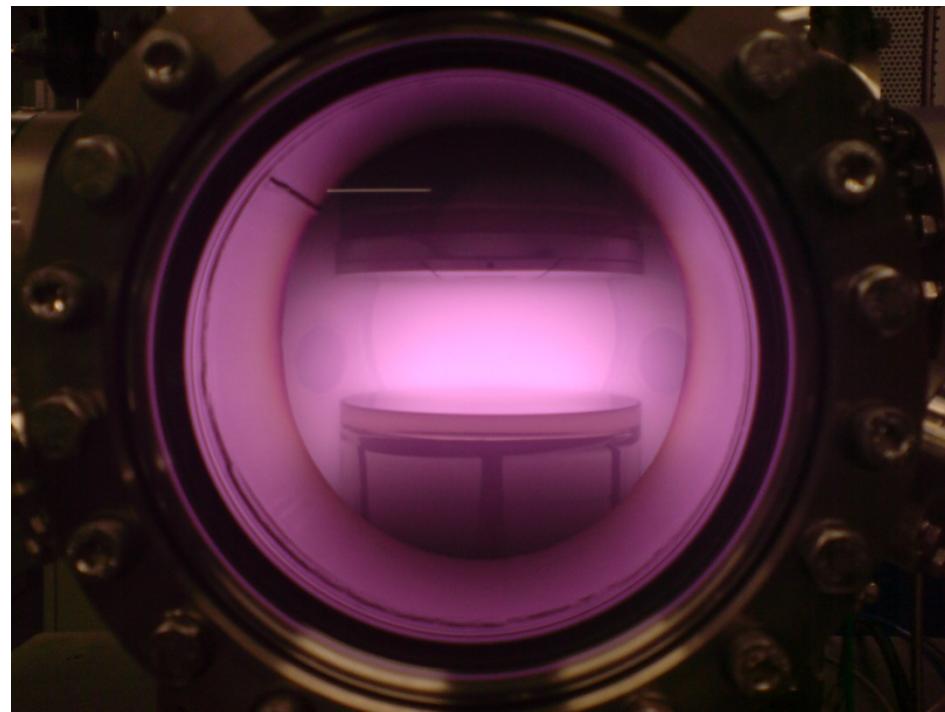
$$P_{abs} = P_{Verlust} = n_0 v_B A (E_{Ionisation} + E_{Randschicht})$$

+ excitation,  
+ electron loss to surfaces

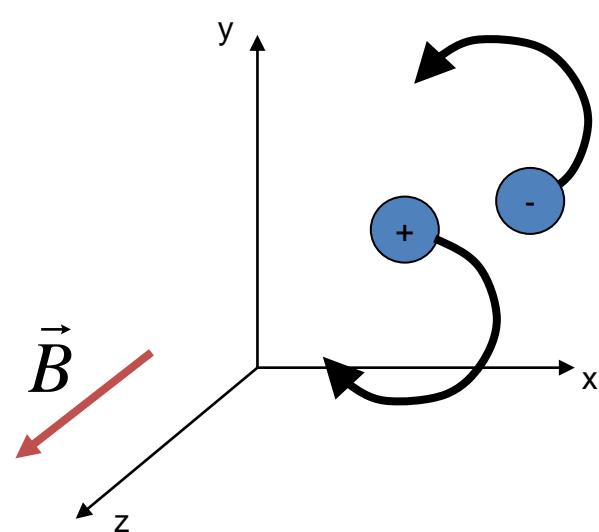
Power balance determines  
Electron density

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

# Transport in a plasma



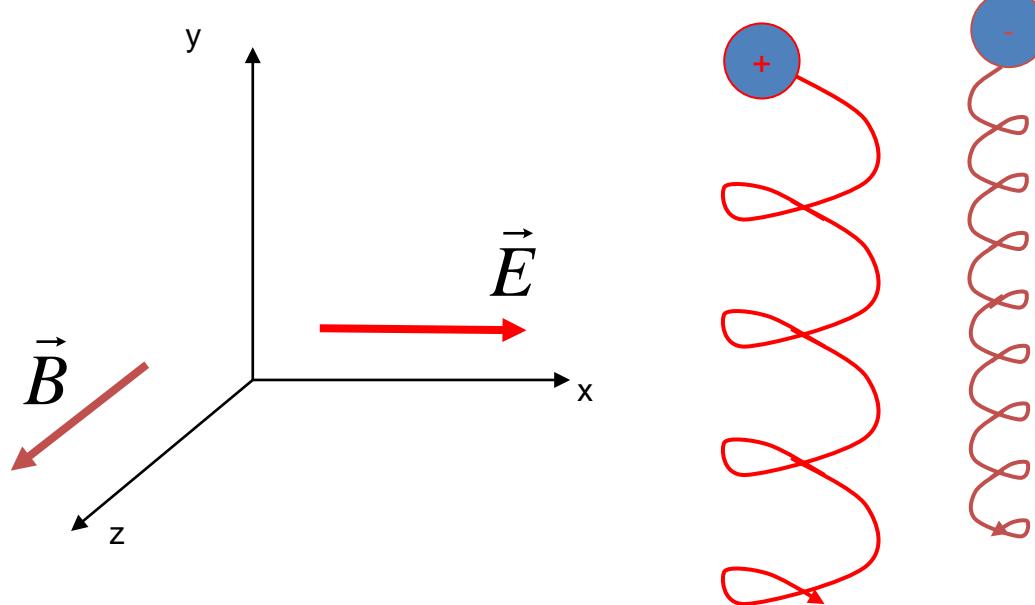
# Transport in a plasma – single particle motion



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

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

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



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

electrons

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

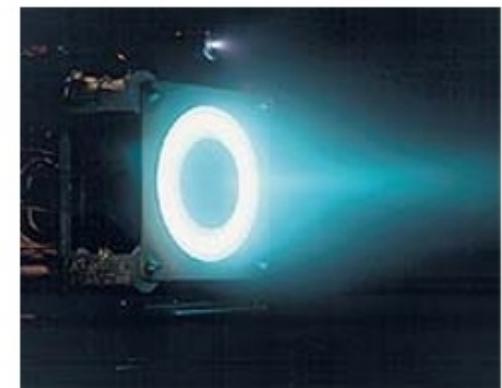
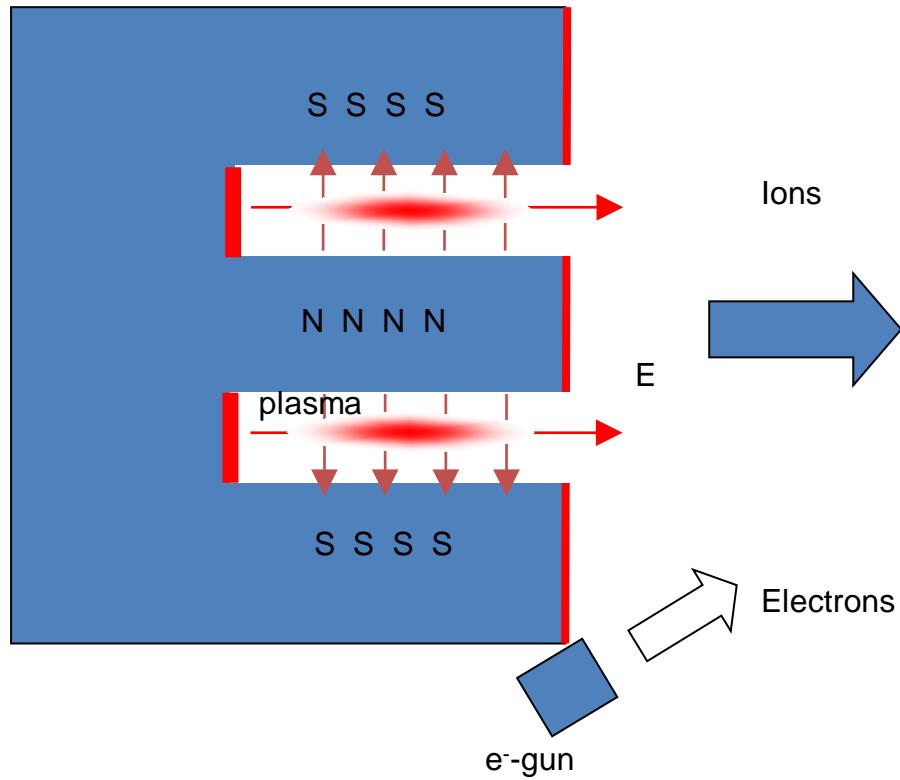
$$r_e = \frac{mv}{eB} = \frac{2.2 \times 10^{-6} \sqrt{T[eV]}}{B[T]}$$

ions

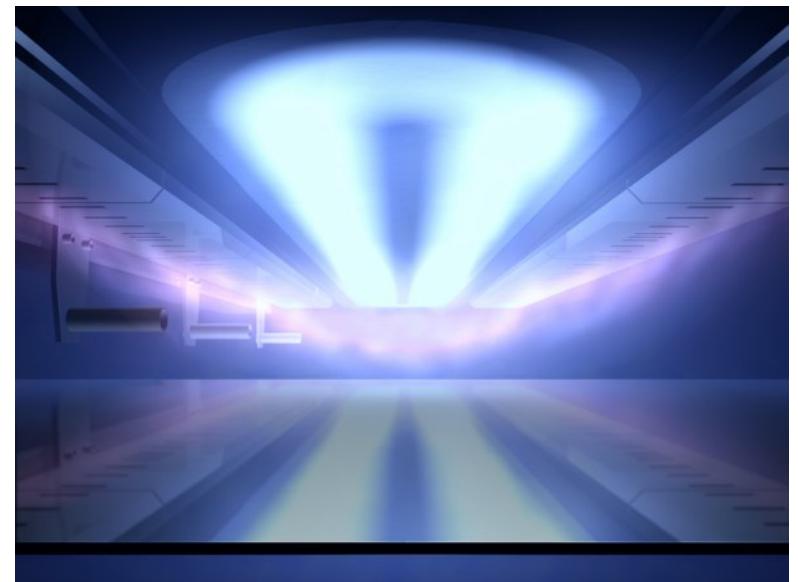
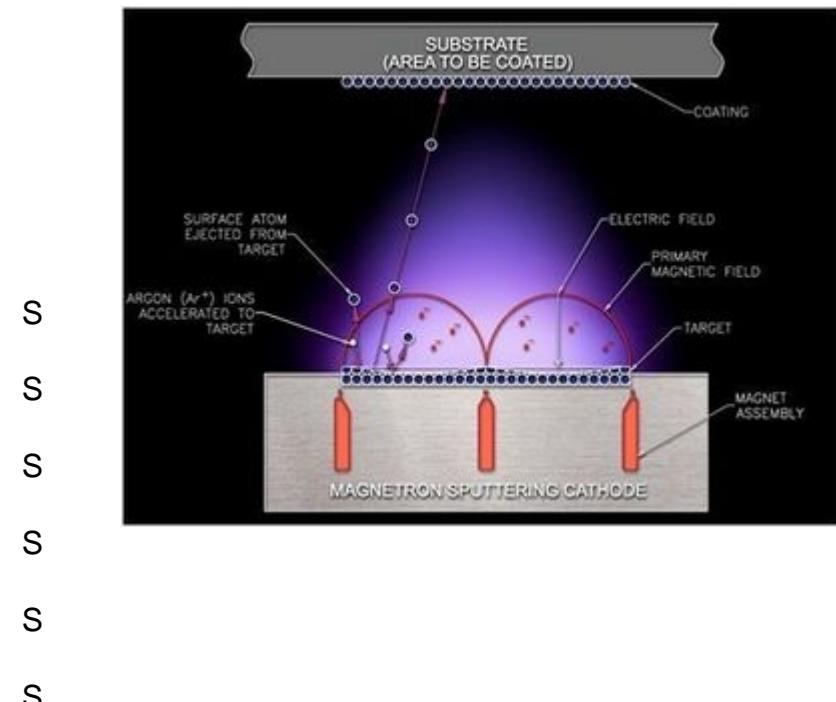
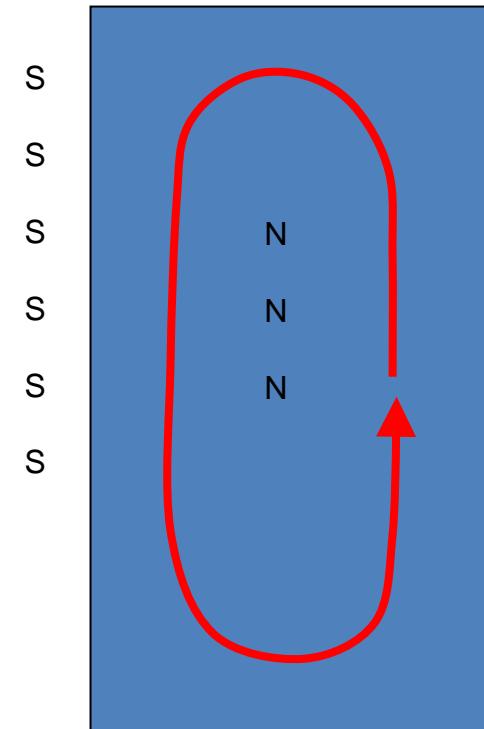
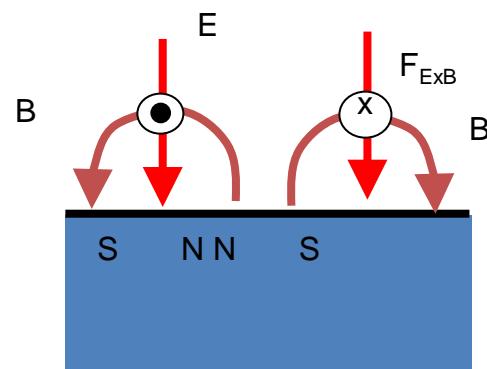
$$\omega_{ci} = \frac{eB}{M_i} = \frac{0.96 \times 10^8 B[T]}{A[amu]}$$

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

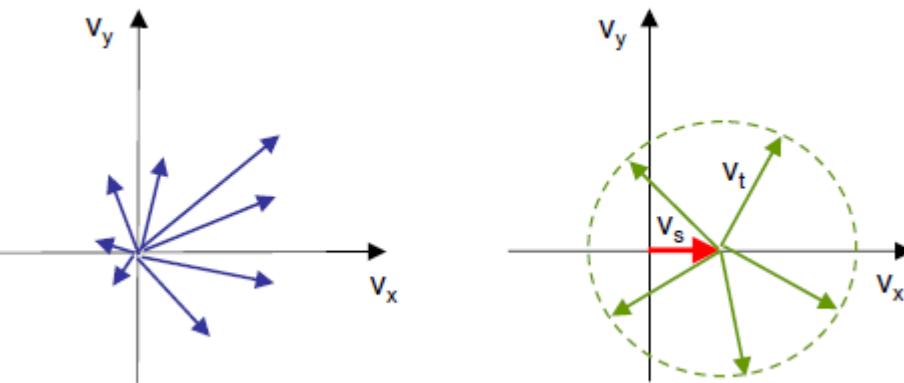
# Transport in a plasma – single particle motion – example hall thrusters



# Transport in a plasma – single particle motion example magnetron



More on this in the lecture of A. Hecimovic



Particle conservation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \vec{v}_s) = 0$$

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

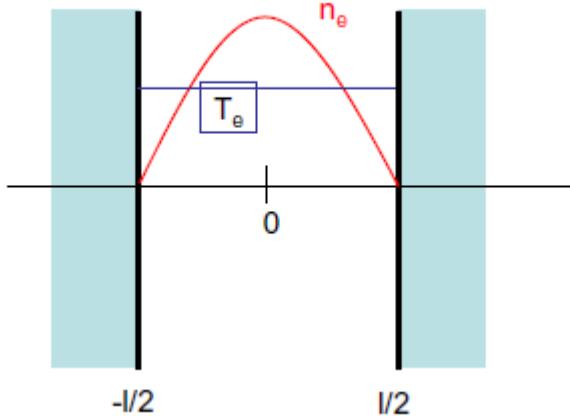
$$\frac{\partial}{\partial t} n\langle \epsilon \rangle + \underbrace{\nabla n \langle \epsilon \rangle v_s}_{\text{convektion}} + \underbrace{p \nabla v_s}_{\text{Compression/expansion}} + \underbrace{\nabla q}_{\text{Heat conduction}} - \underbrace{n v_s \vec{F}}_{\text{Ohmic heating}} = 0$$

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

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

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

a typical solution



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

mobility

$$D = \frac{k_B T}{m \nu_m}$$

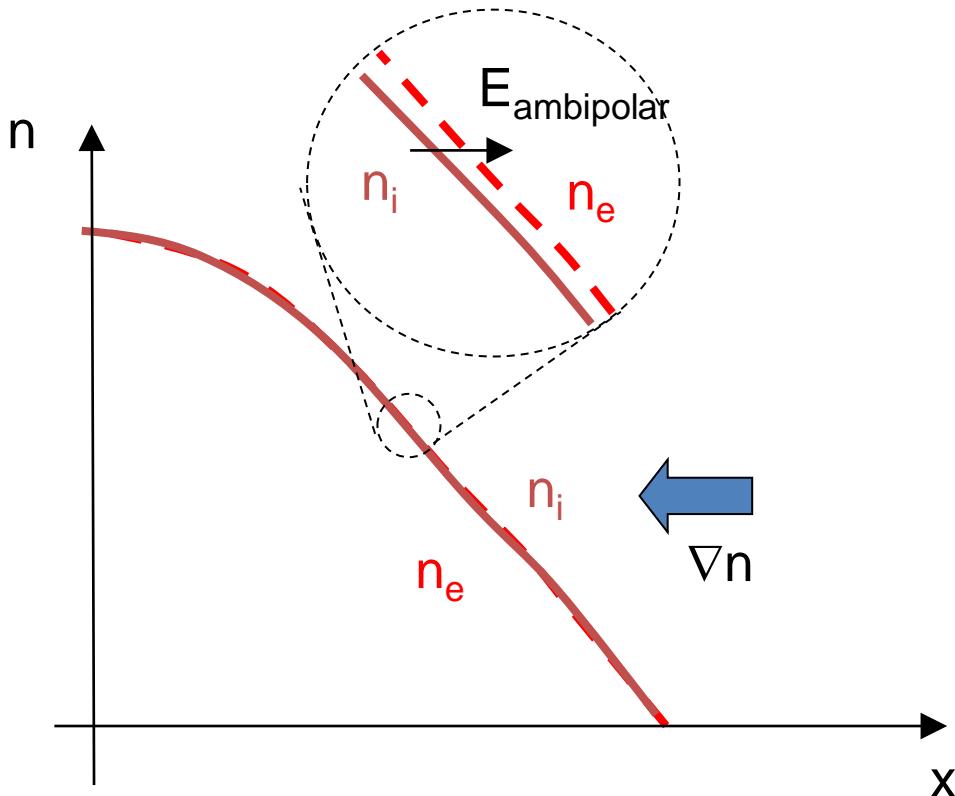
diffusion

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

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

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

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

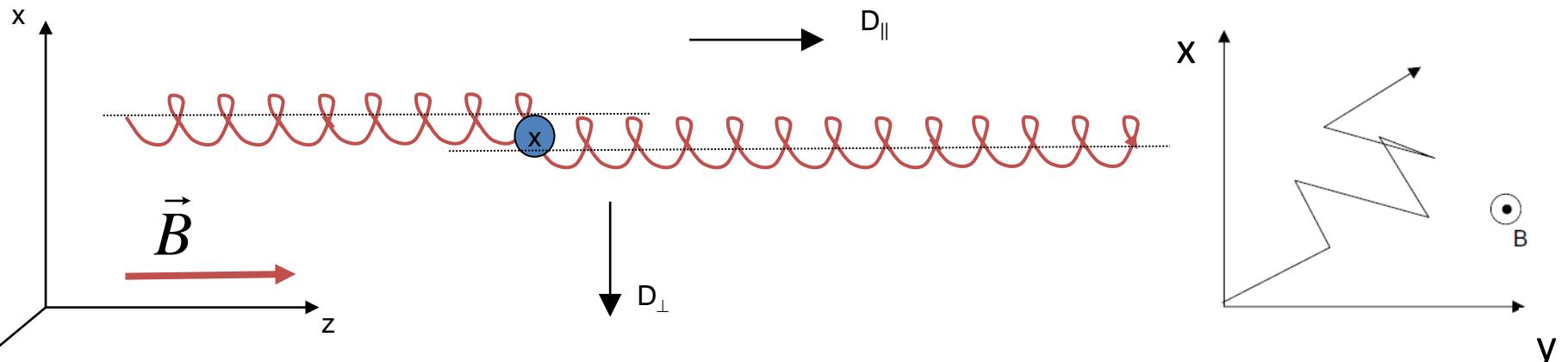


$$D_{amb} = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}$$

for  $\mu_e \gg \mu_i$ . and  $T_e \gg T_i$

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

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



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

without inertia

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

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

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

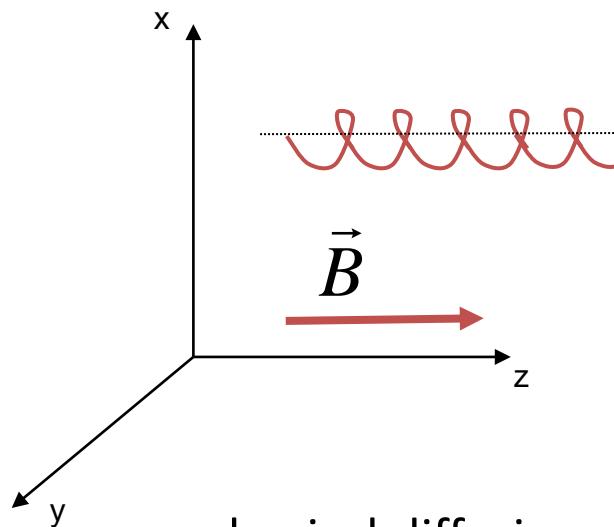
drift

diffusion

ExB-drift

diamag. drift

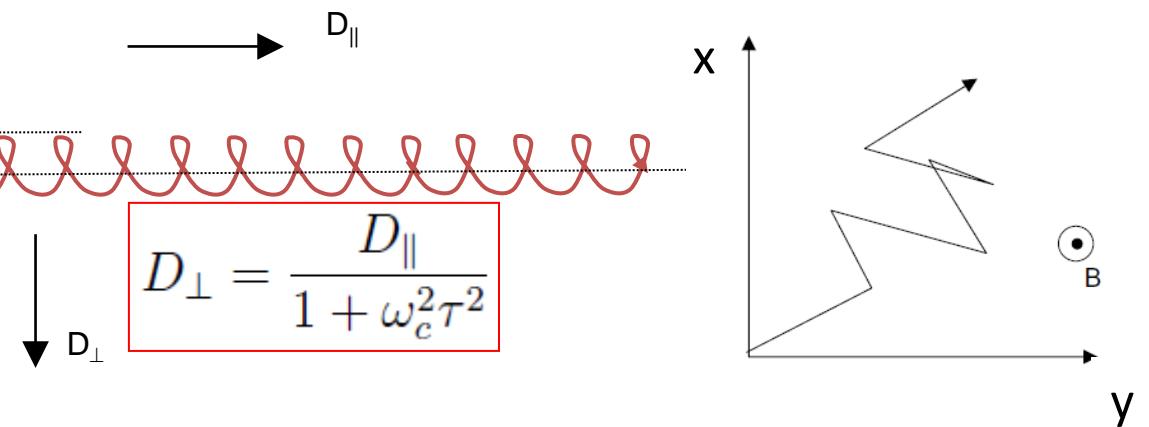
# Transport in a plasma – classical vs. Bohm diffusion



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)

$$D_{\perp} = \frac{1}{16} \frac{k_B T}{e B} = D_{\text{Bohm}}$$

Idea: instabilities induce electric fields, which drive ExB drift

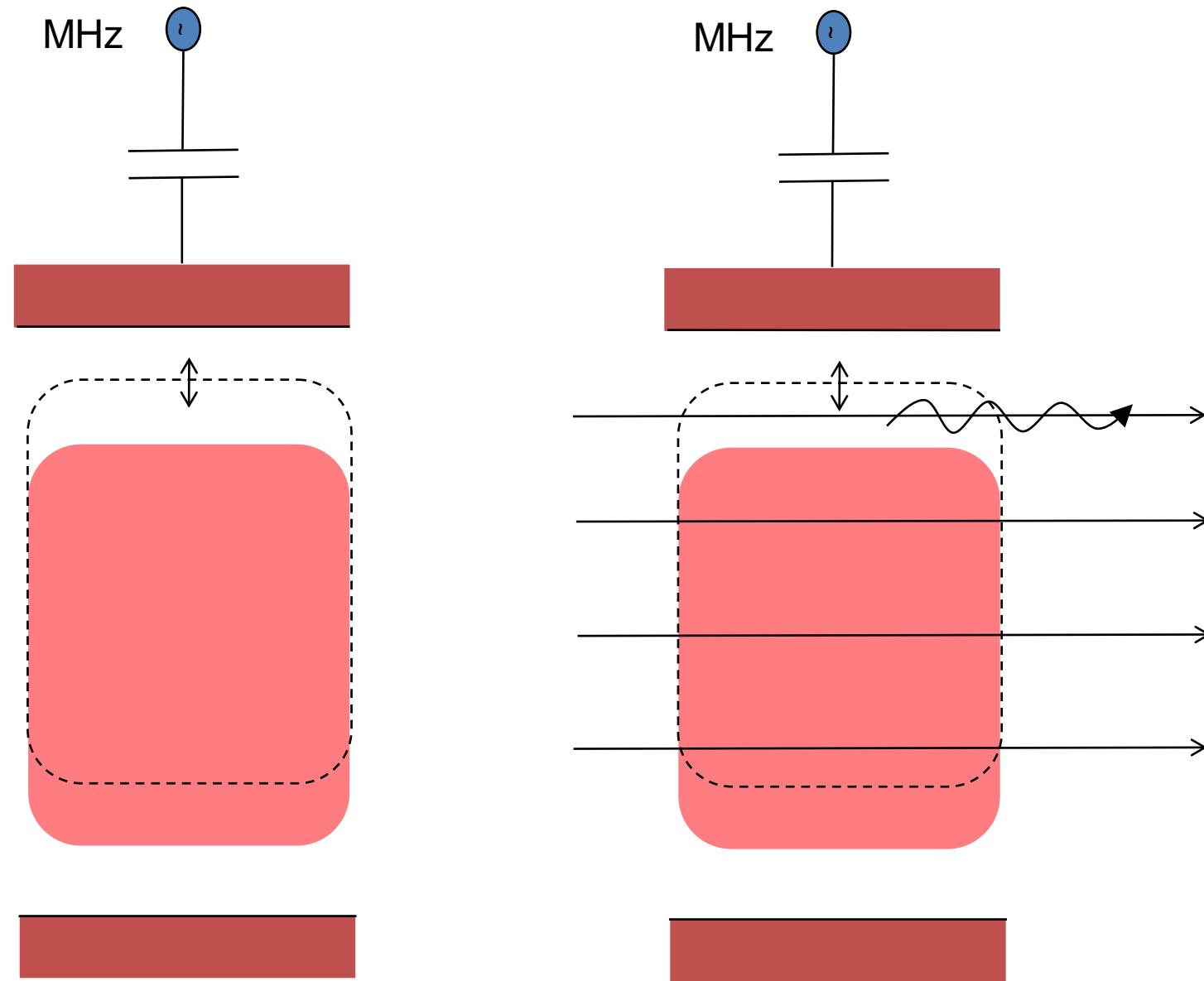
$$\vec{v}_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2}$$

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

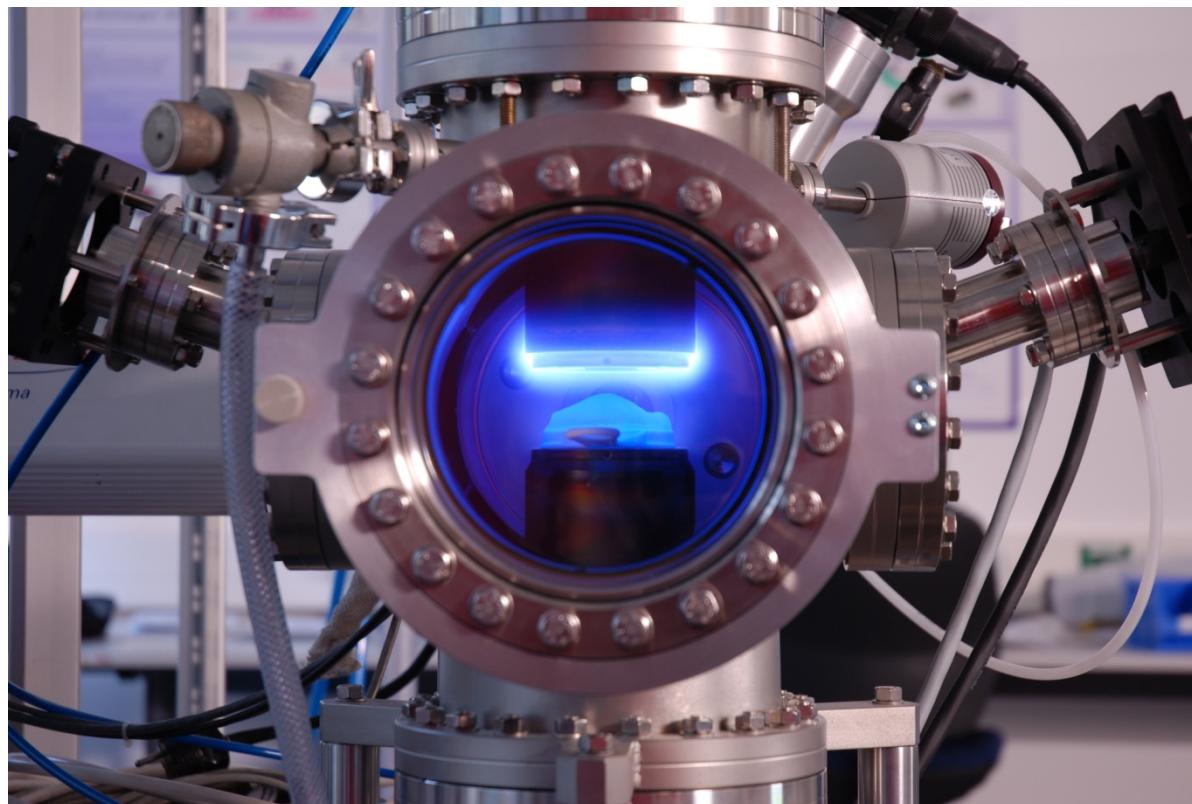
$$E = \frac{\Phi}{R} \simeq \frac{k_B T_e}{e R}$$

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

# Transport in a plasma – magnetic confinement

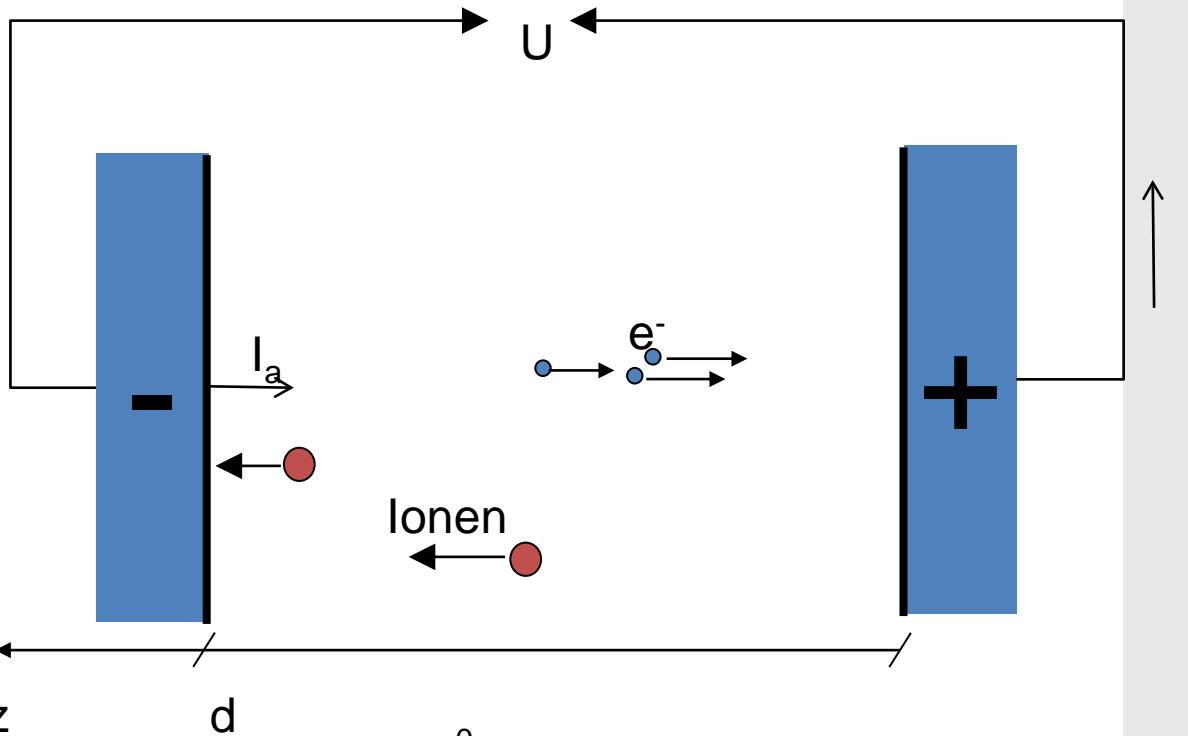
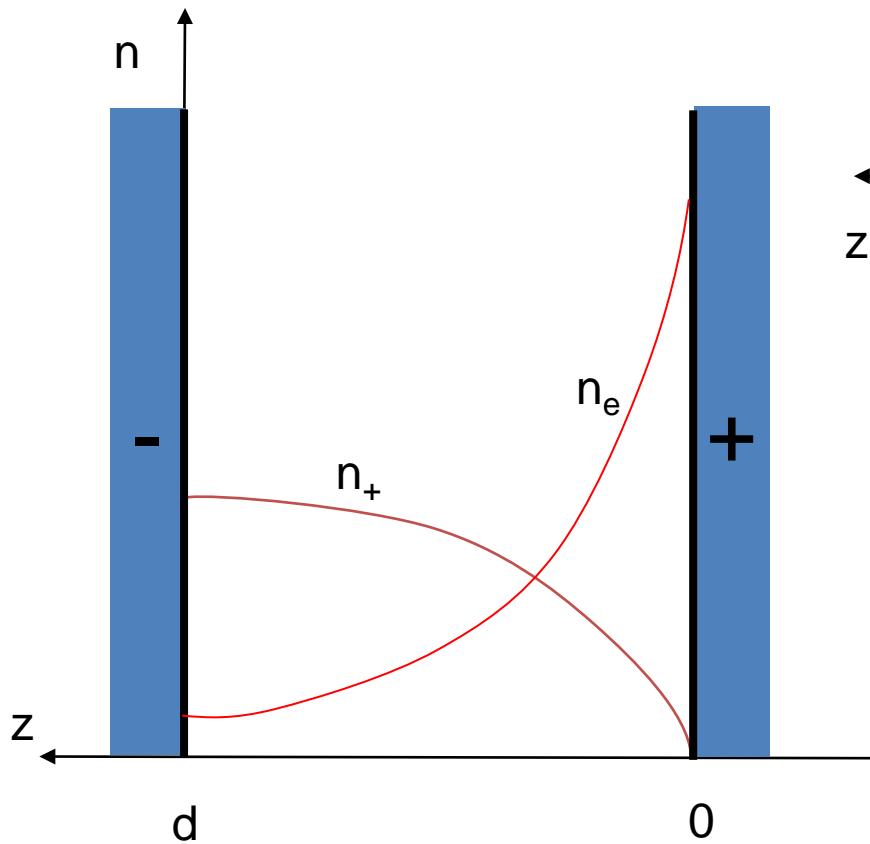


# Ignition of a plasma



## 1. Townsend coefficient gas amplification

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



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

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

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

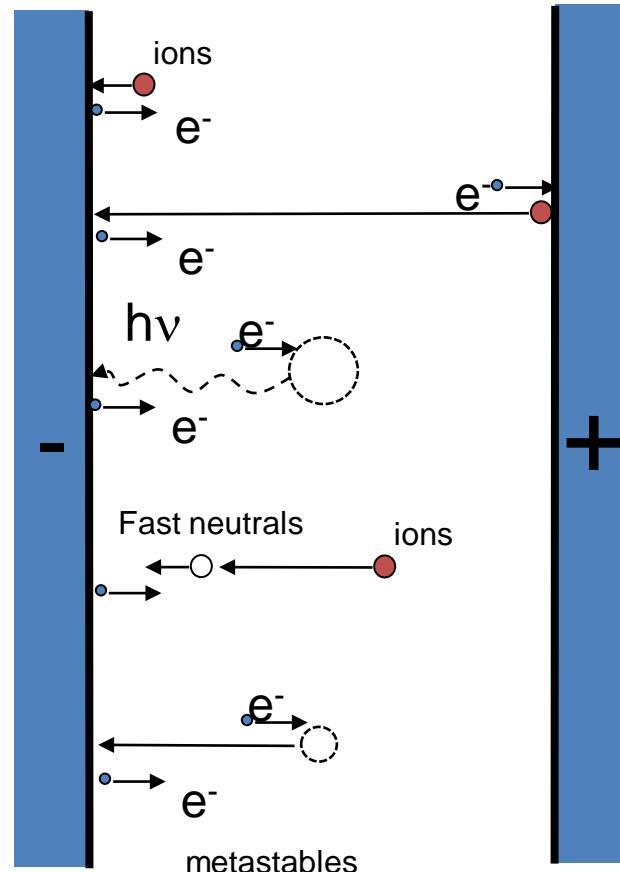
Ionbombardment  
at the cathode

Secondary ion  
emission  
at the anode

photoeffect

fast  
neutrals

metastables



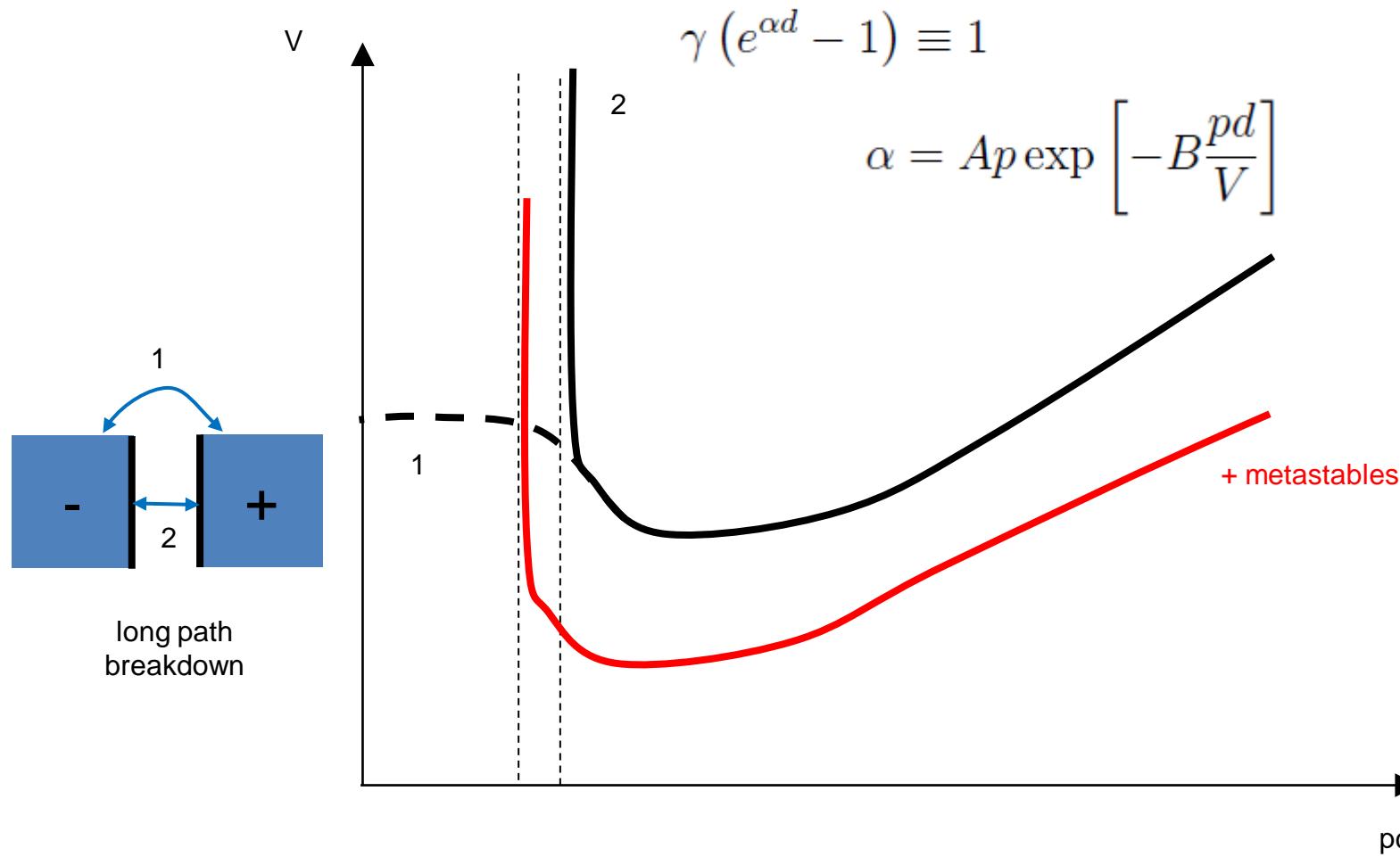
$$I = \underbrace{I_a e^{\alpha d}}_{\text{primary amplification}}$$

$$\frac{1}{1 - \gamma_i (e^{\alpha d} - 1)}$$

secondary amplification

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

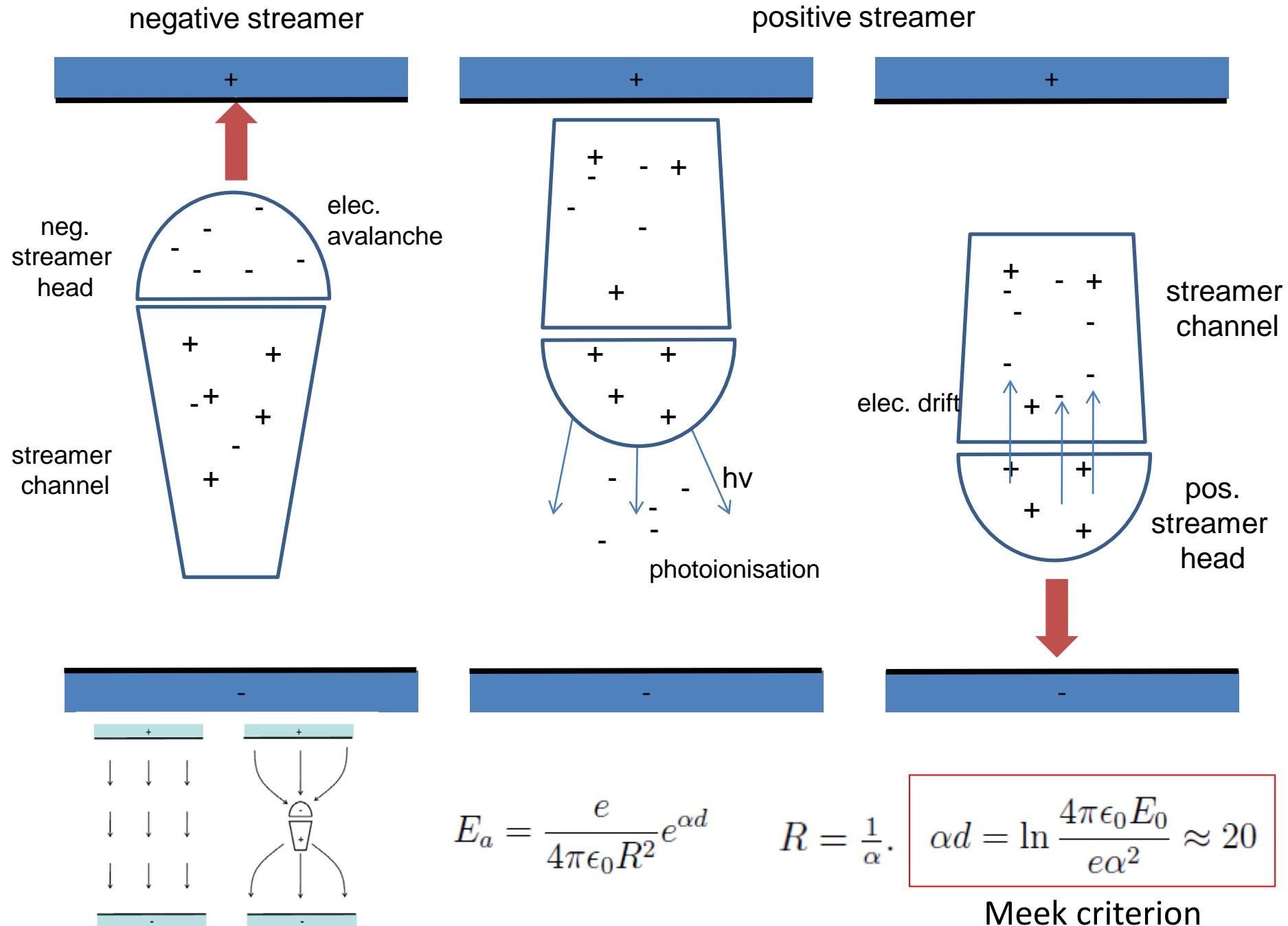
# Ignition of a plasma – the Paschen curve

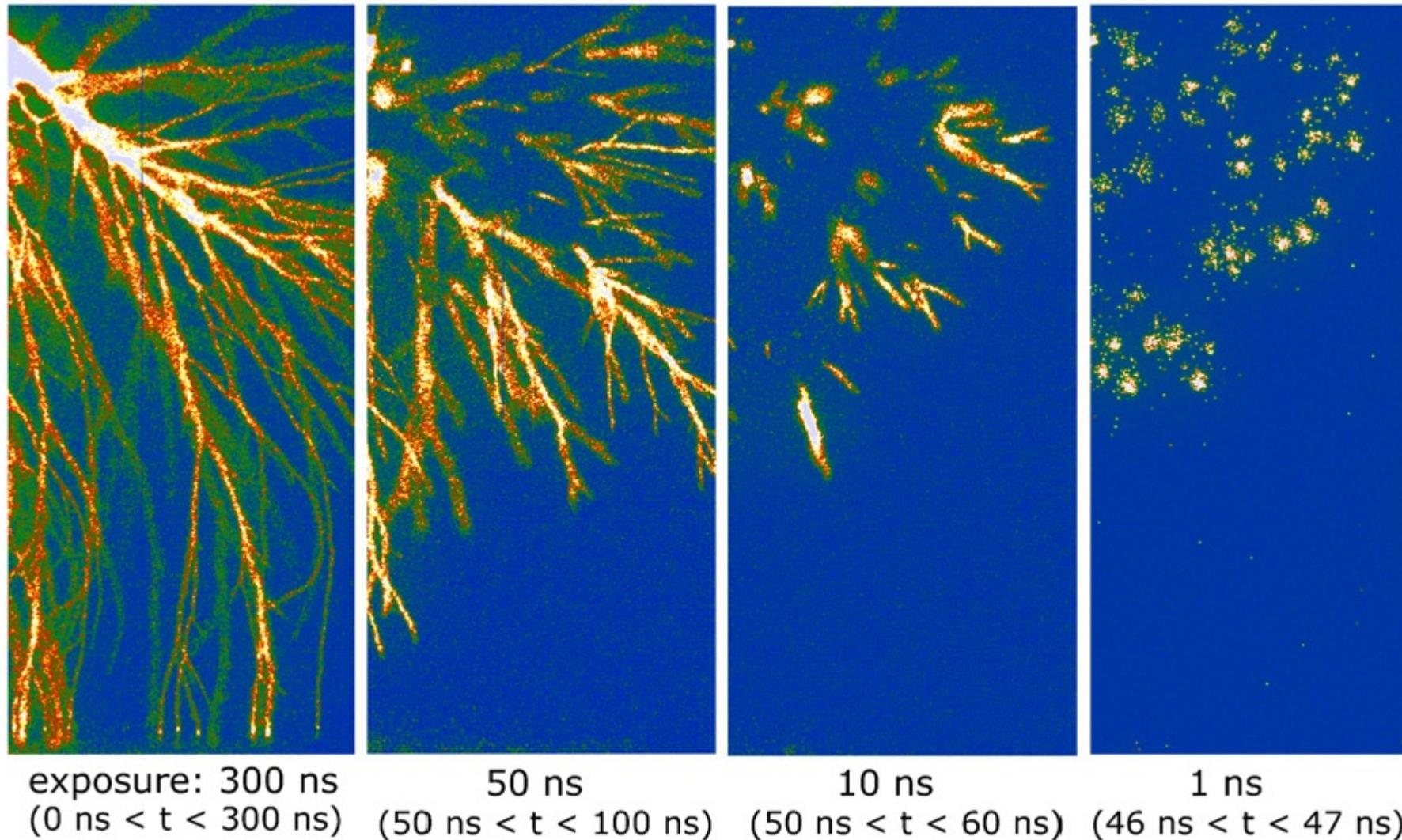


	$A [\text{cm}^{-1}\text{Torr}^{-1}]$	$B [\text{V cm}^{-1}\text{Torr}^{-1}]$	$e \frac{B}{A} [\text{eV}]$
He	1.8	50	27.5
Ar	12	200	16.7
H <sub>2</sub>	10.6	350	33
CO <sub>2</sub>	20	466	23.3

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

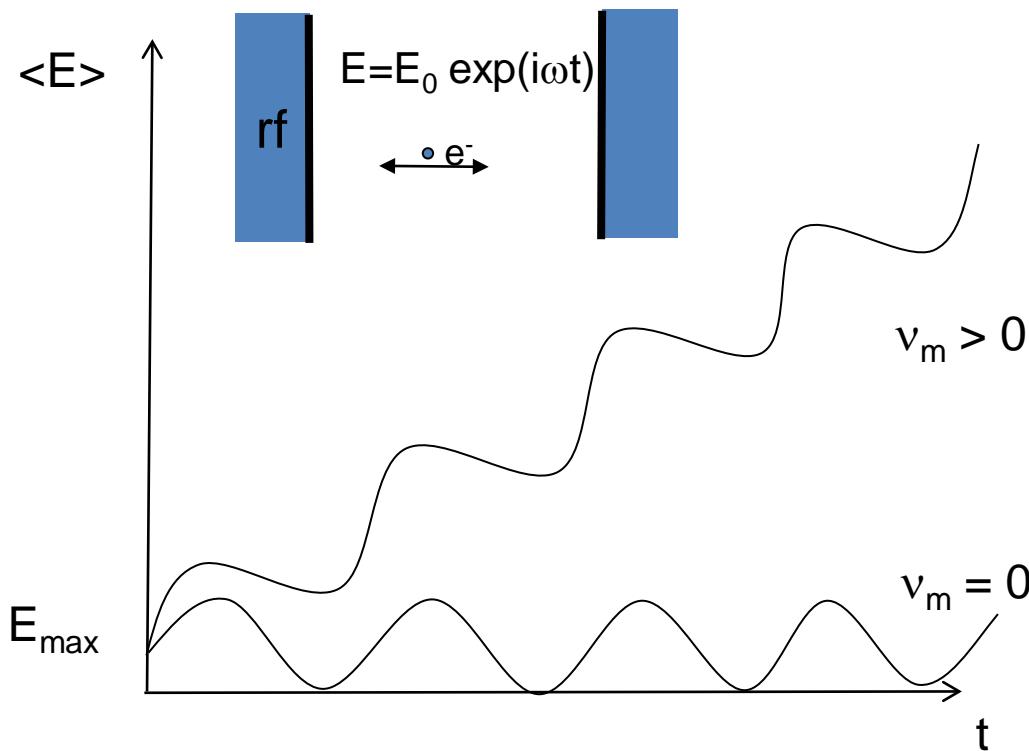
# Ignition of a plasma – High pressure - streamers





**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

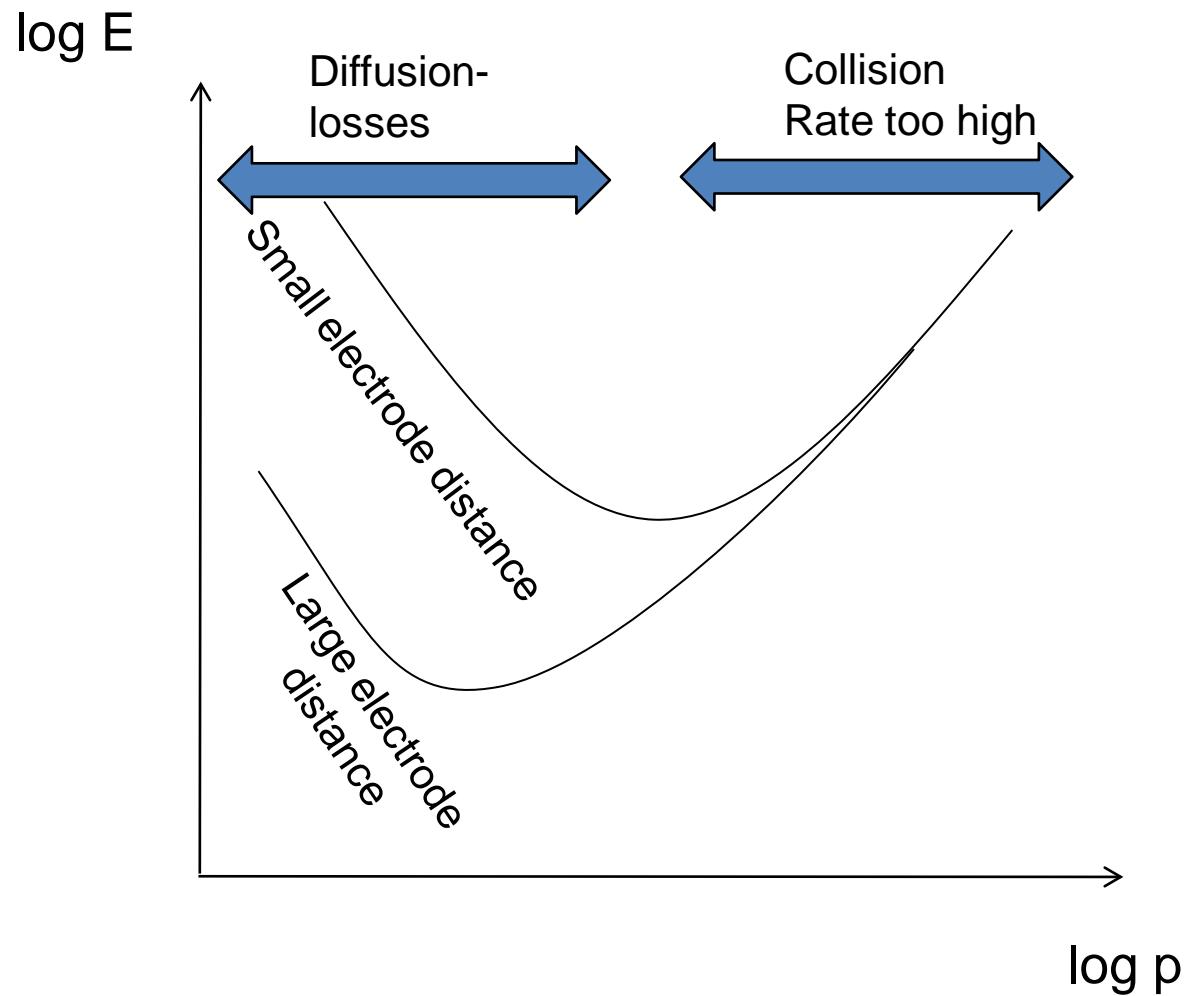


$$E_{max} = \frac{1}{2}mv_{max}^2 = \frac{1}{2}\frac{q^2E_0^2}{m\omega^2}$$

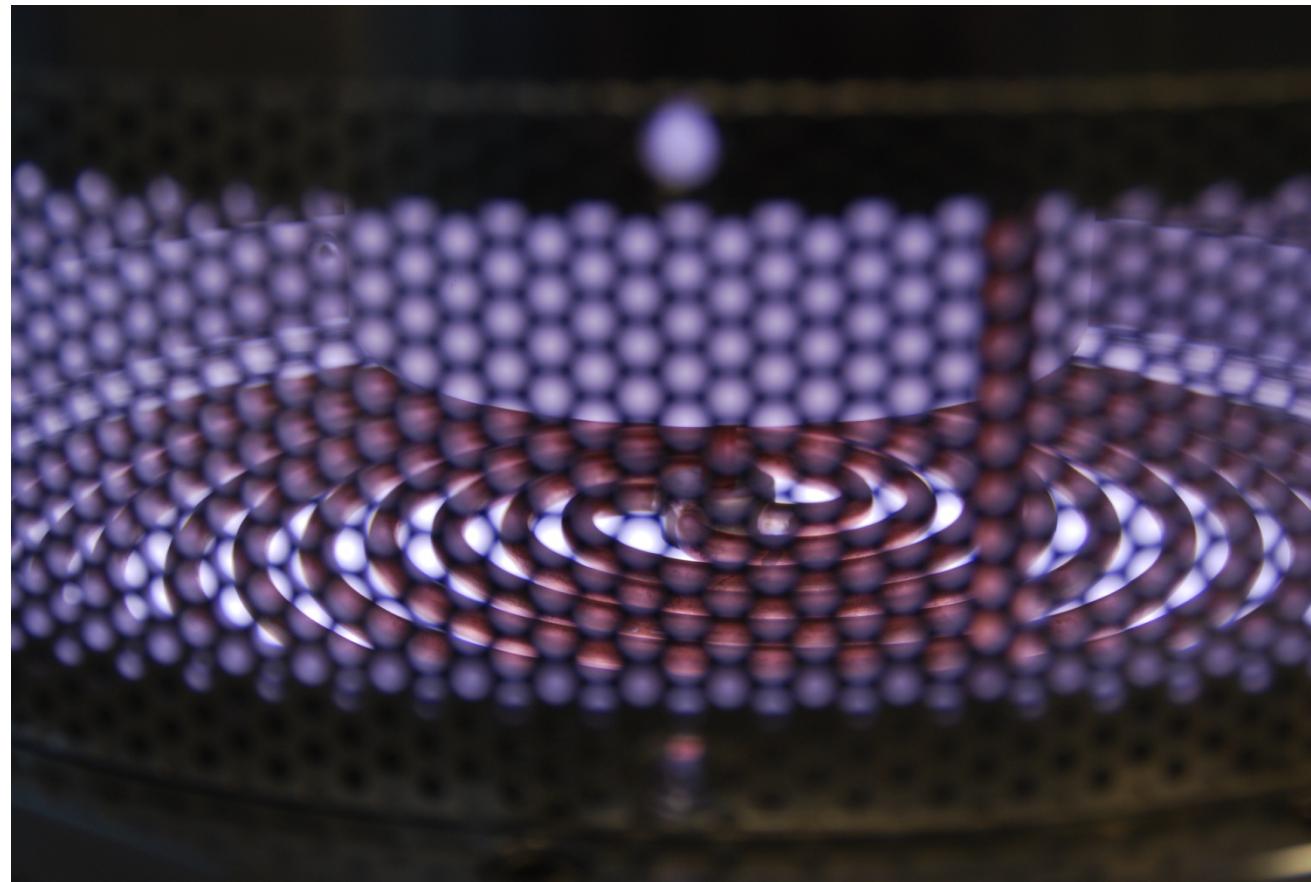
$$\langle E \rangle = \frac{m_g e^2 E_0^2}{2m_e^2(\omega^2 + \nu_m^2)} = E_{max} \frac{m_g}{m_e} \frac{\omega^2}{\omega^2 + \nu_m^2}$$

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

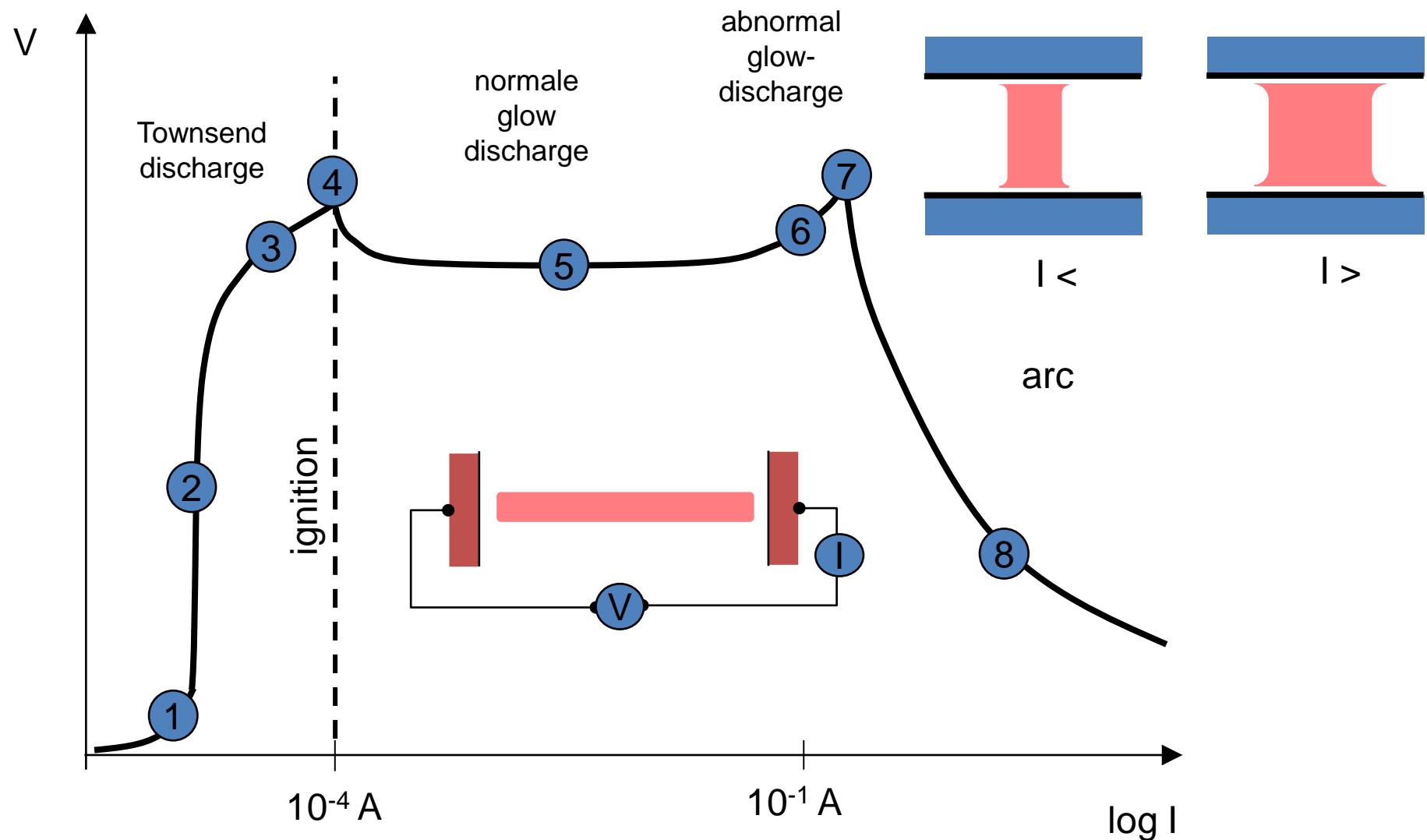
# Ignition of a plasma – Paschen curve for rf-voltages



# Sustaining a plasma

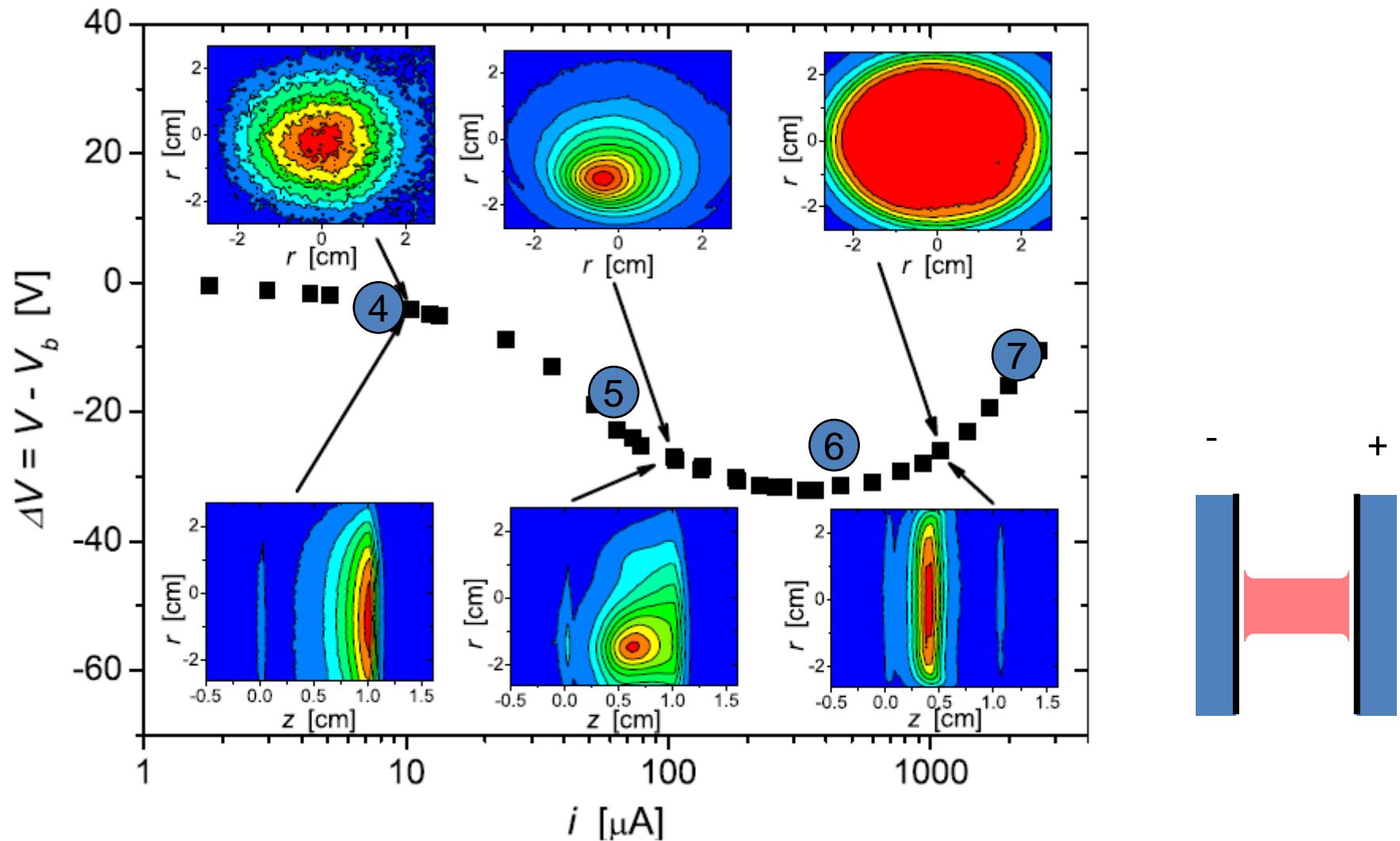


# Sustaining a plasma – current voltage characteristics of a DC plasma



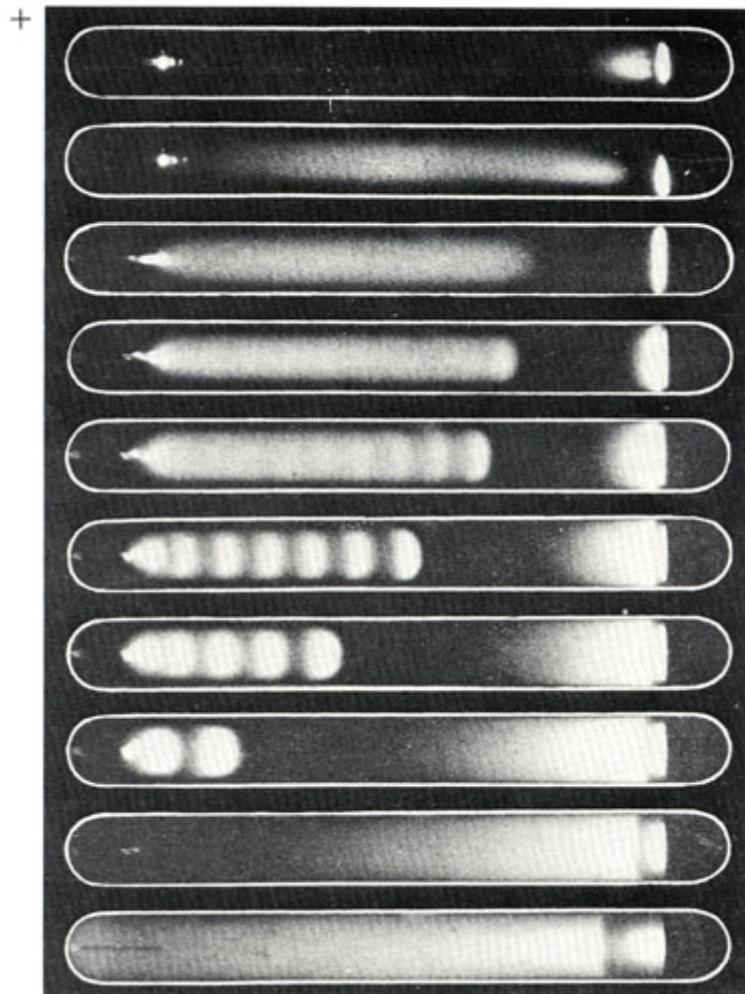
⑥  $j_0 = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{V^{3/2}}{s^2}$

# Sustaining a plasma – instabilities at breakdown

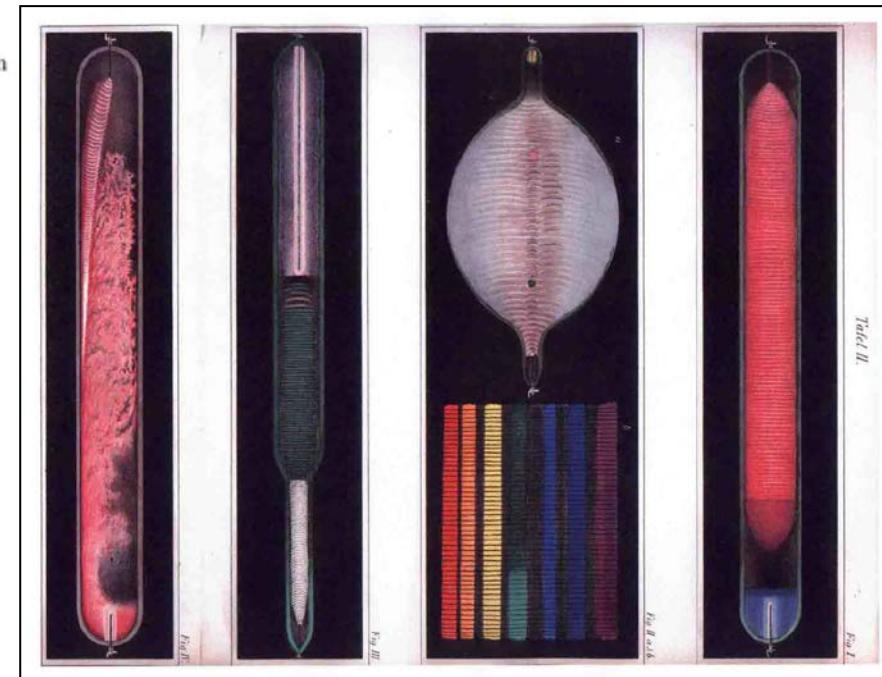


# Sustaining a plasma – striations

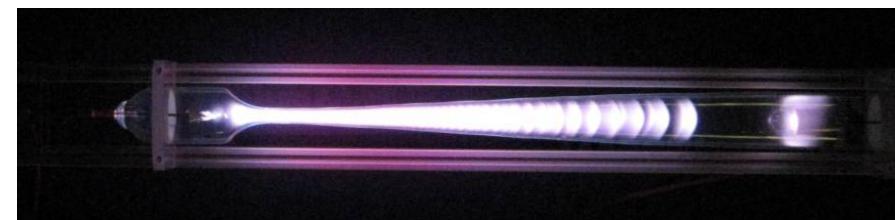
Kaufmann, Handbuch der Experimentalphysik, 1929



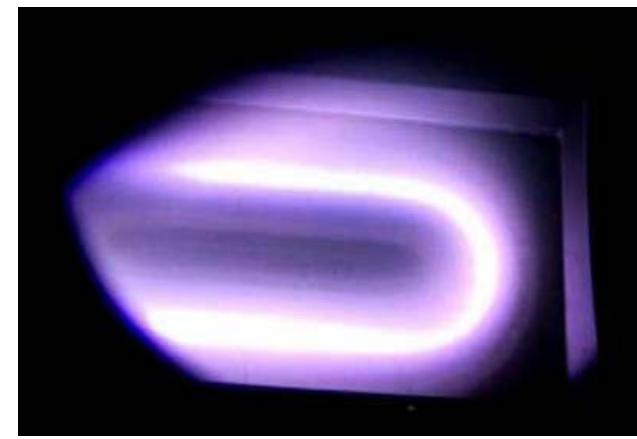
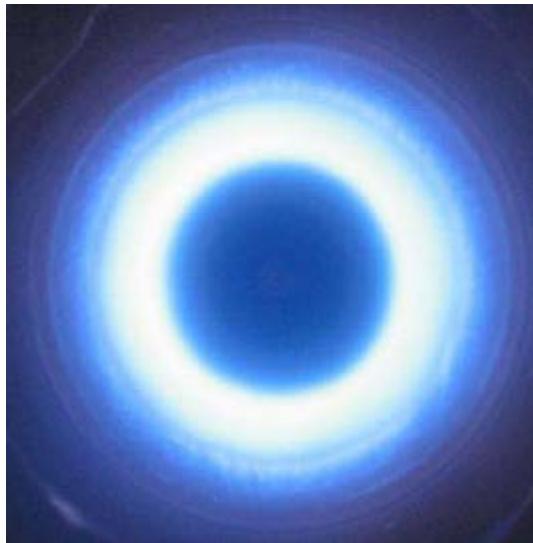
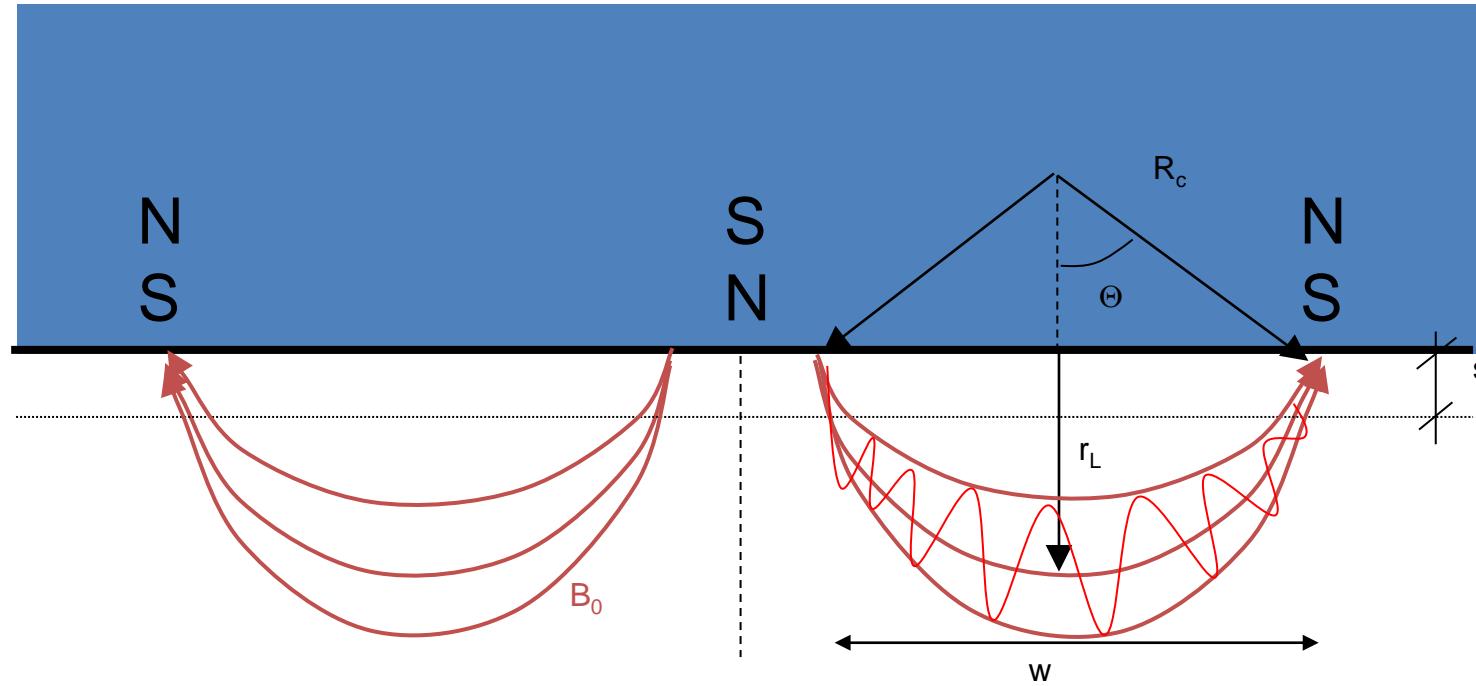
Meyer, Berlin 1858



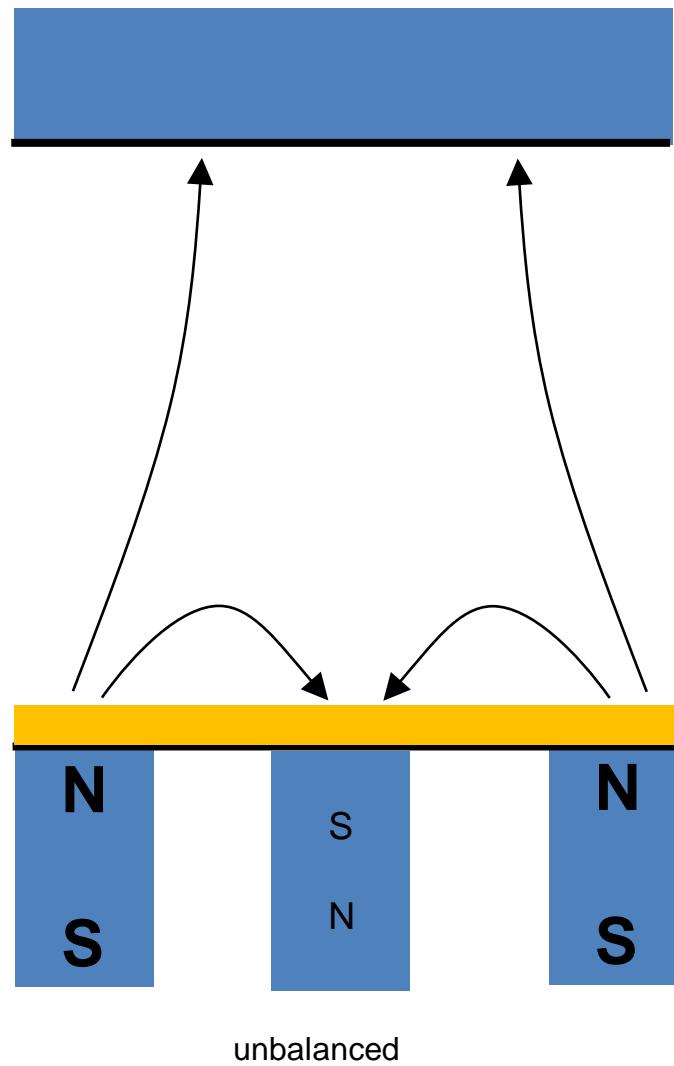
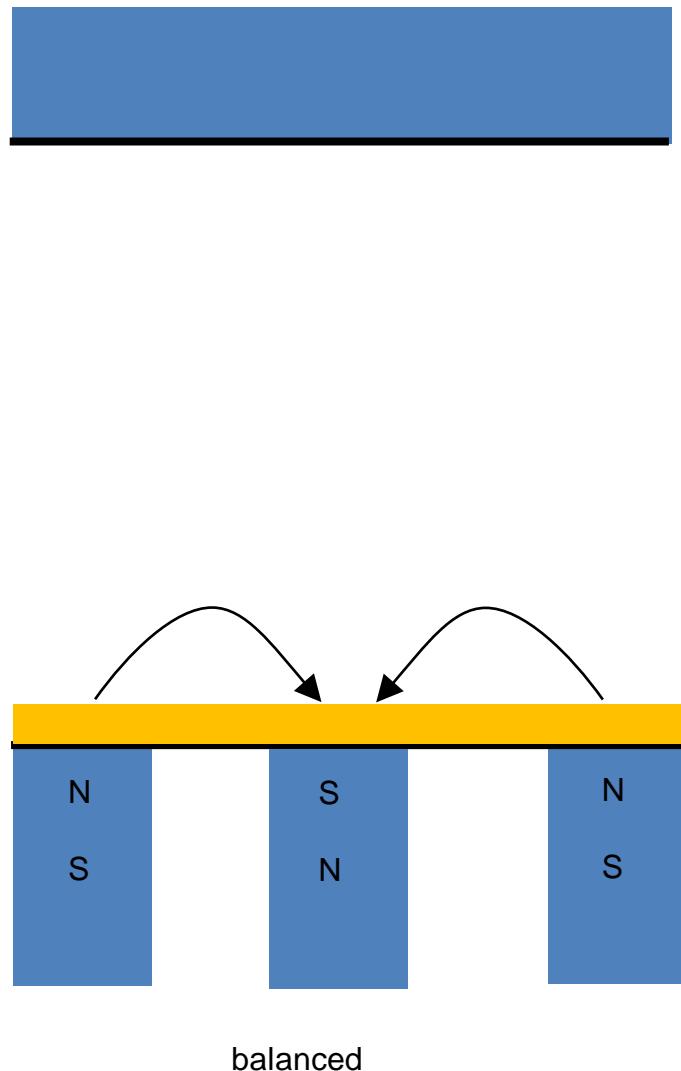
RUB



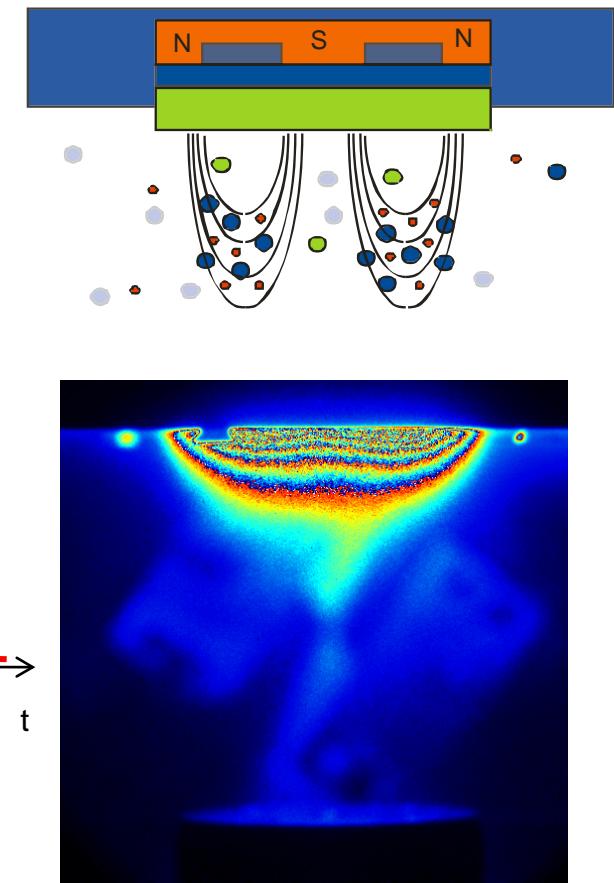
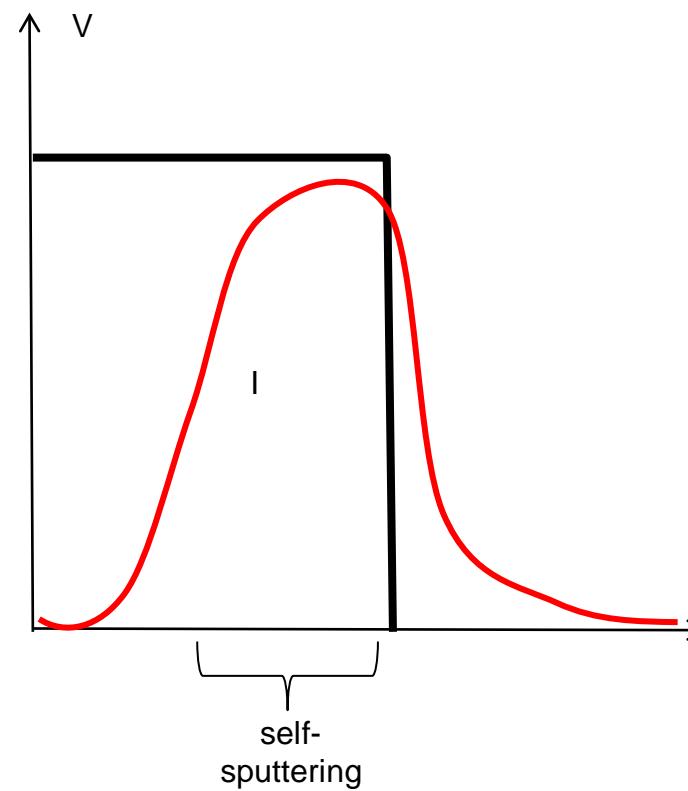
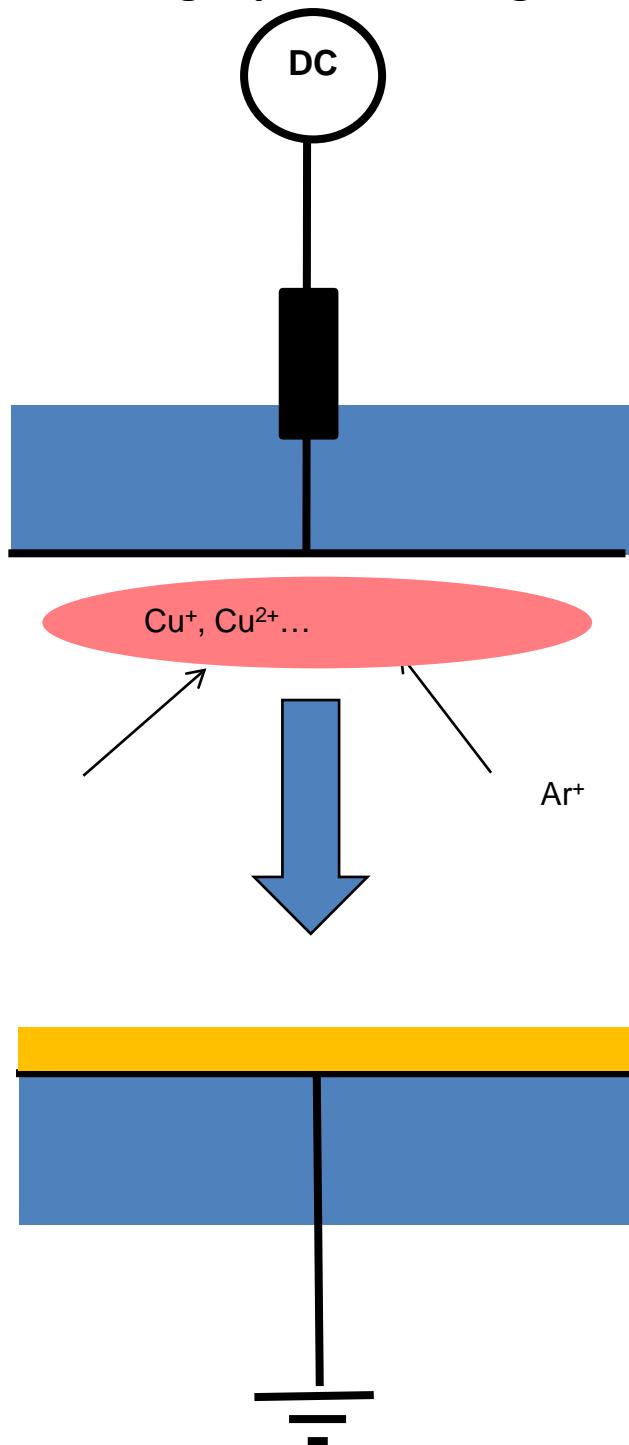
# Sustaining a plasma – magnetron discharges



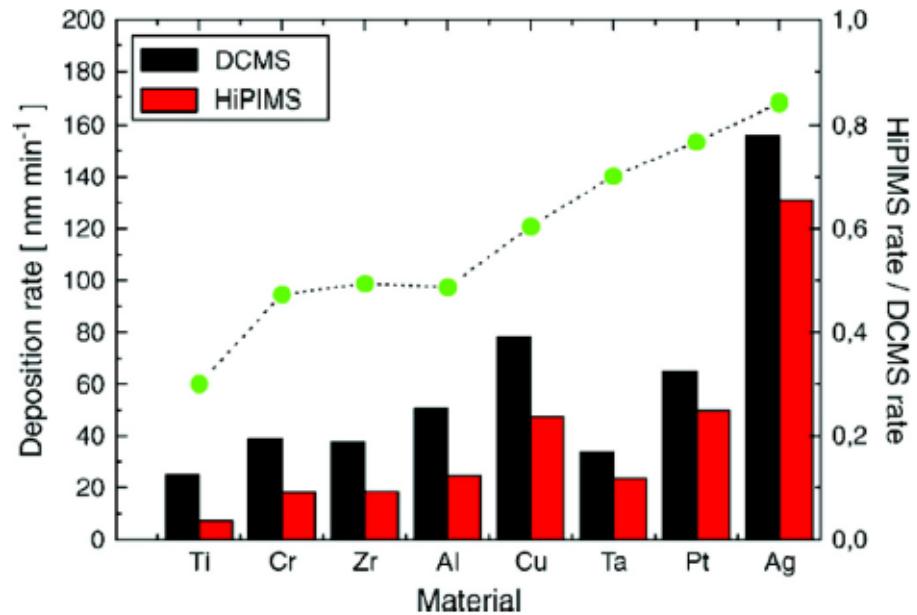
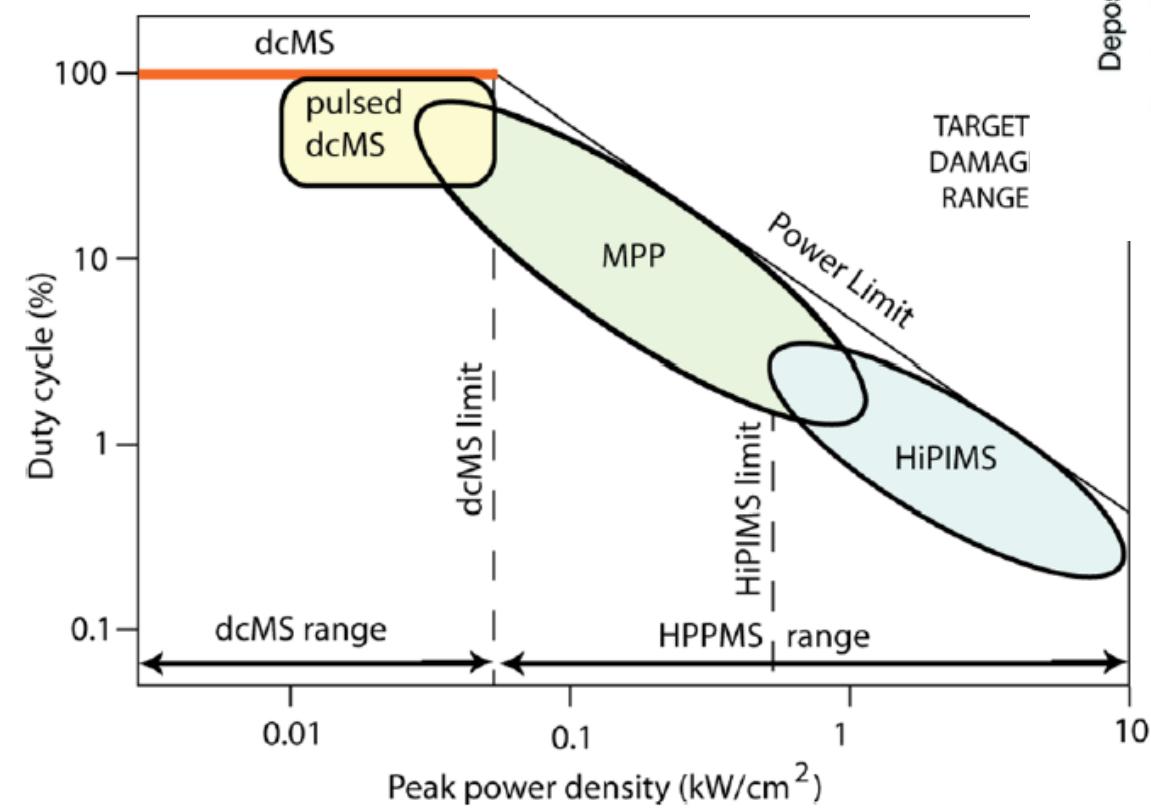
# Sustaining a plasma – balanced / unbalanced magnetrons



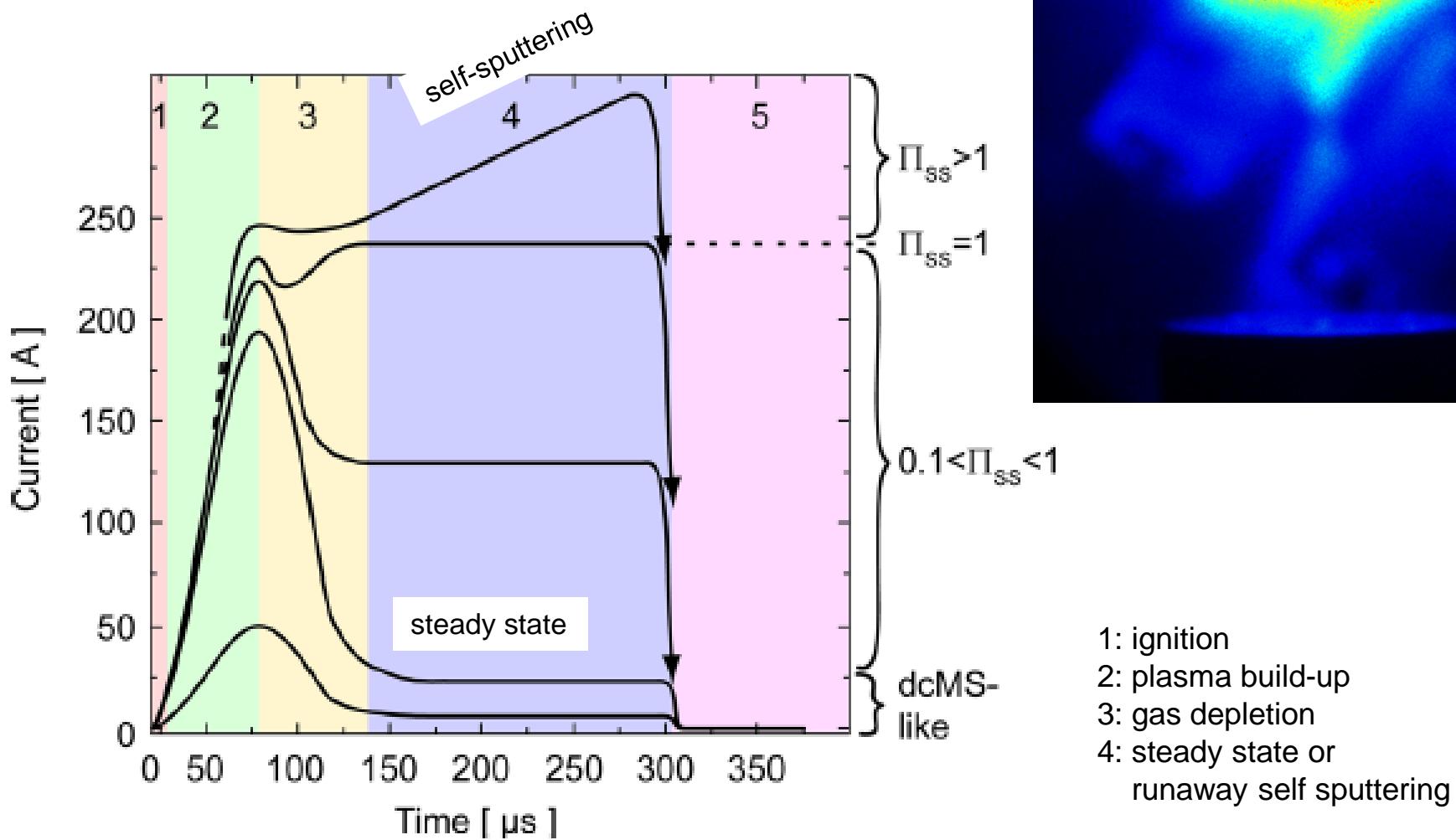
# Sustaining a plasma – High Power Pulsed Magnetron Sputtering (HPPMS)



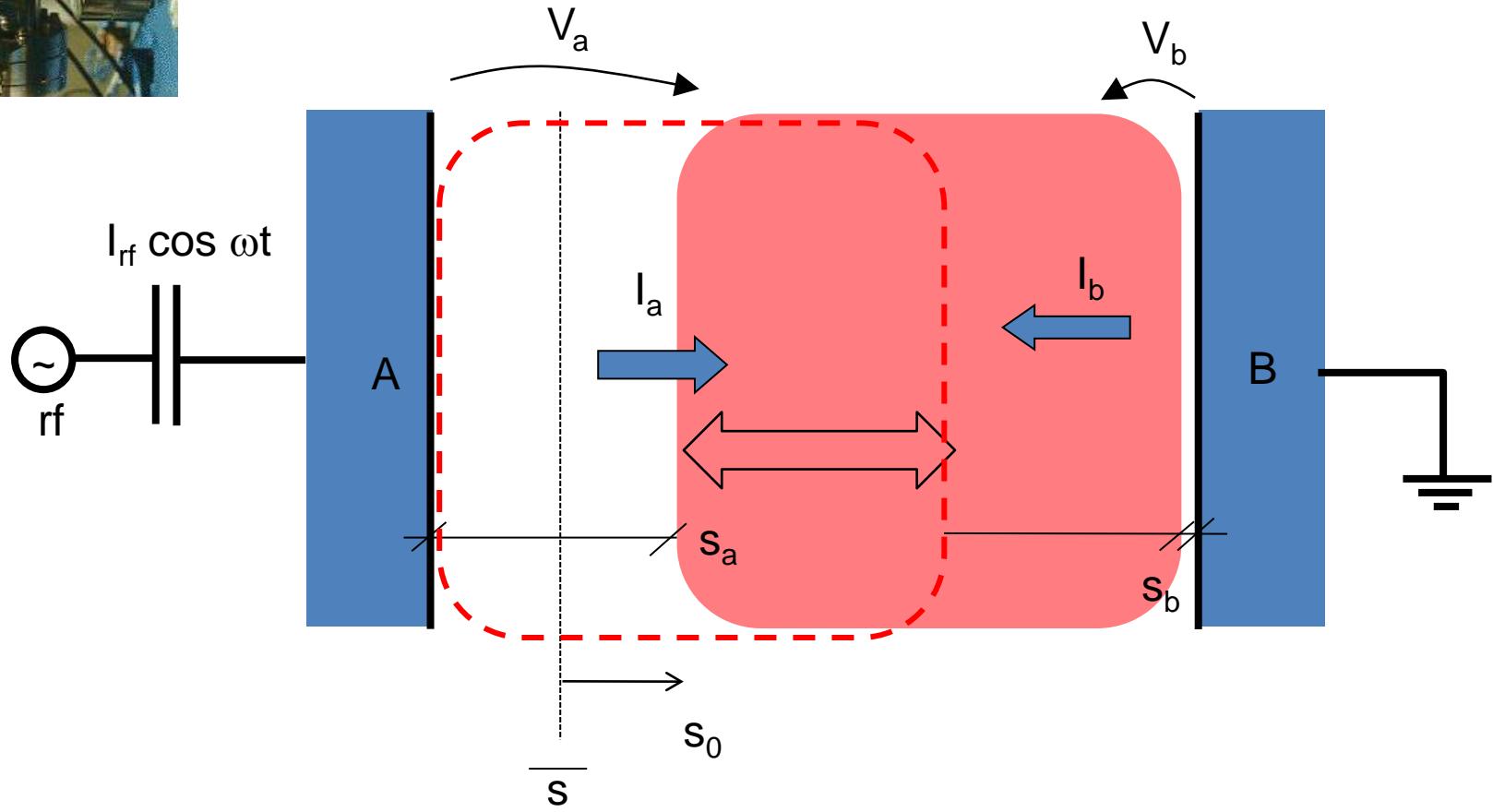
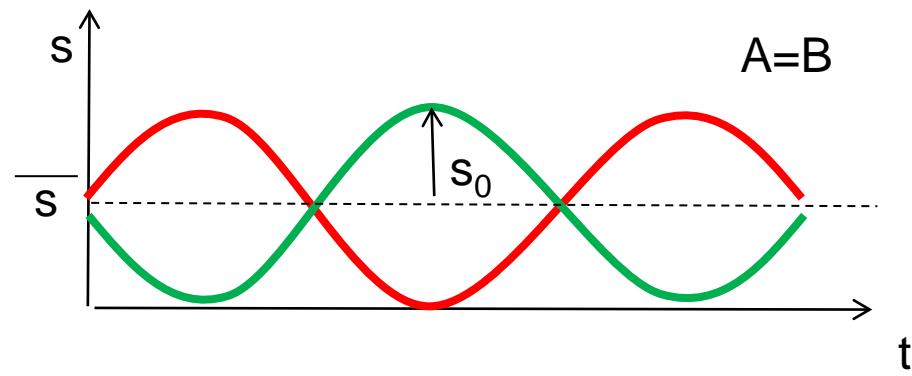
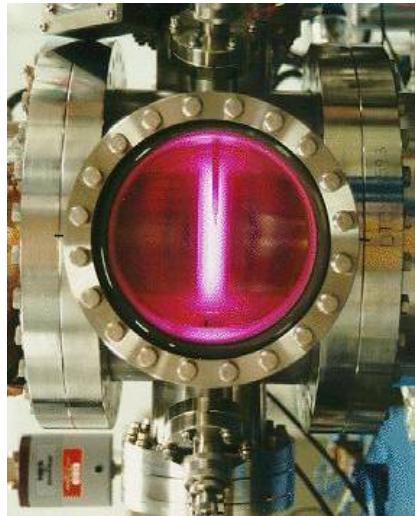
# Sustaining a plasma – High Power Pulses Magnetron Sputtering (HPPMS)



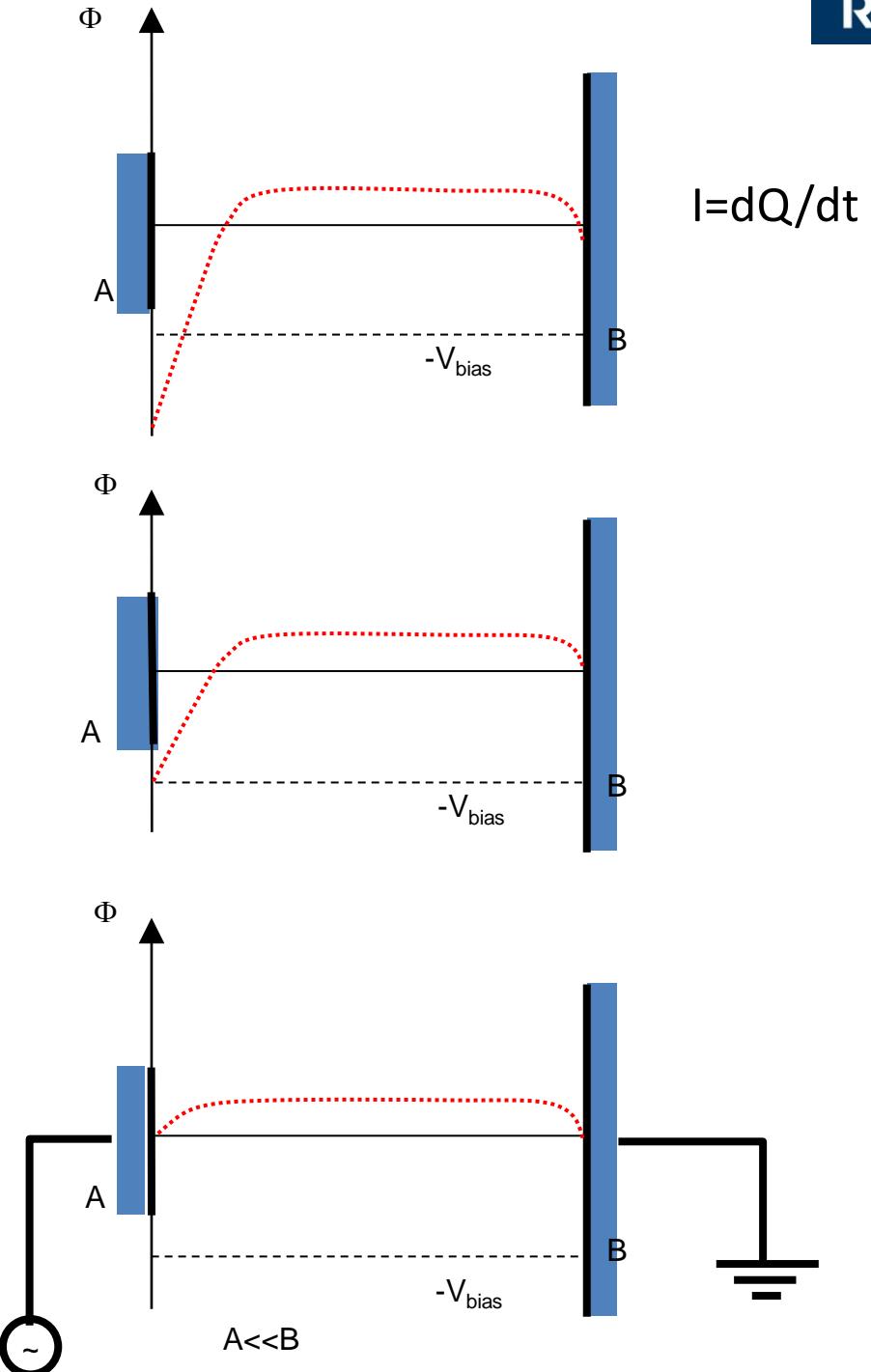
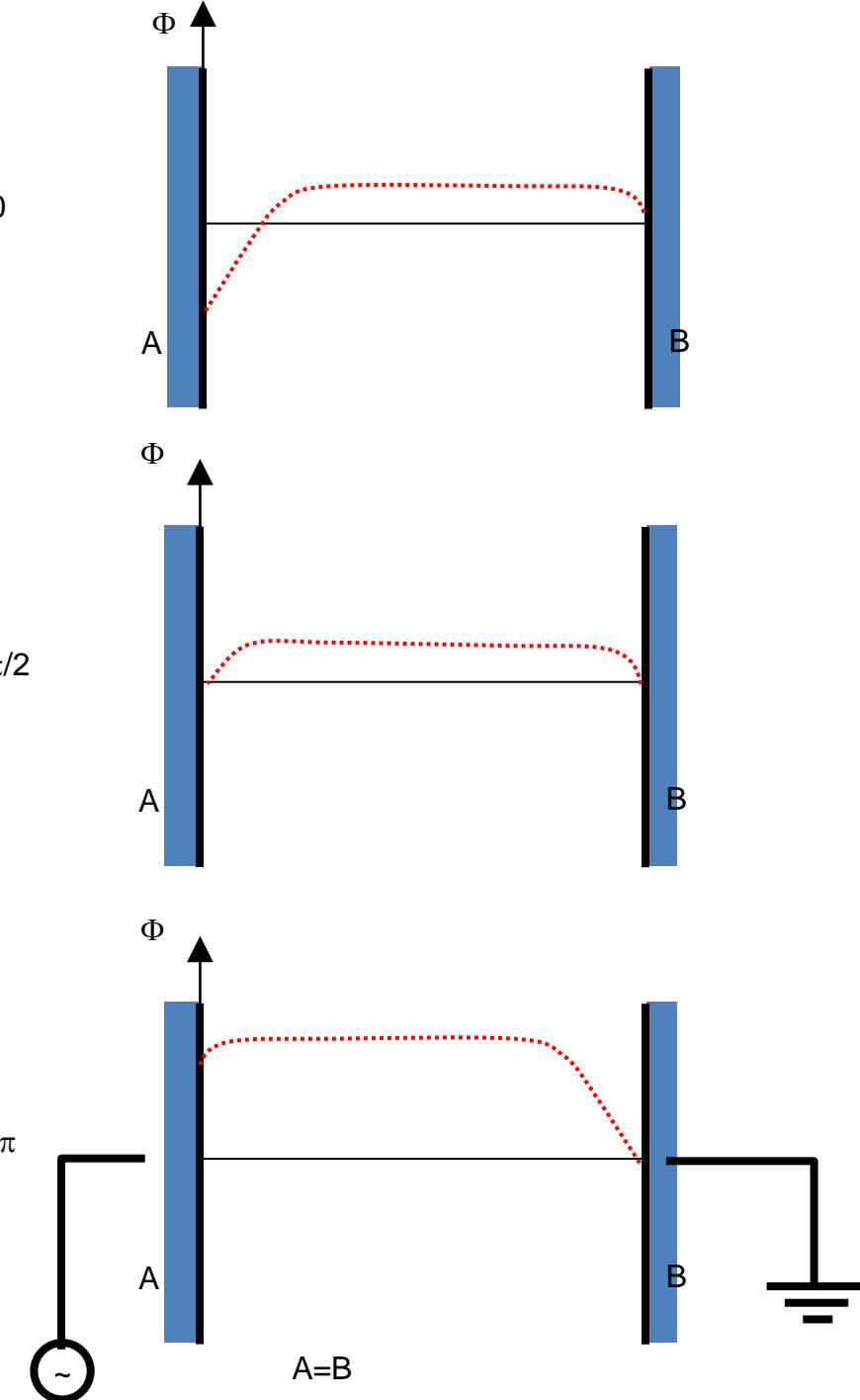
J. Gudmundsson, N. Brenning,  
D. Lundin, U. Helmersson, JVSTA 30, 030801  
(2012)



# Sustaining a plasma – rf discharges – capacitive coupling

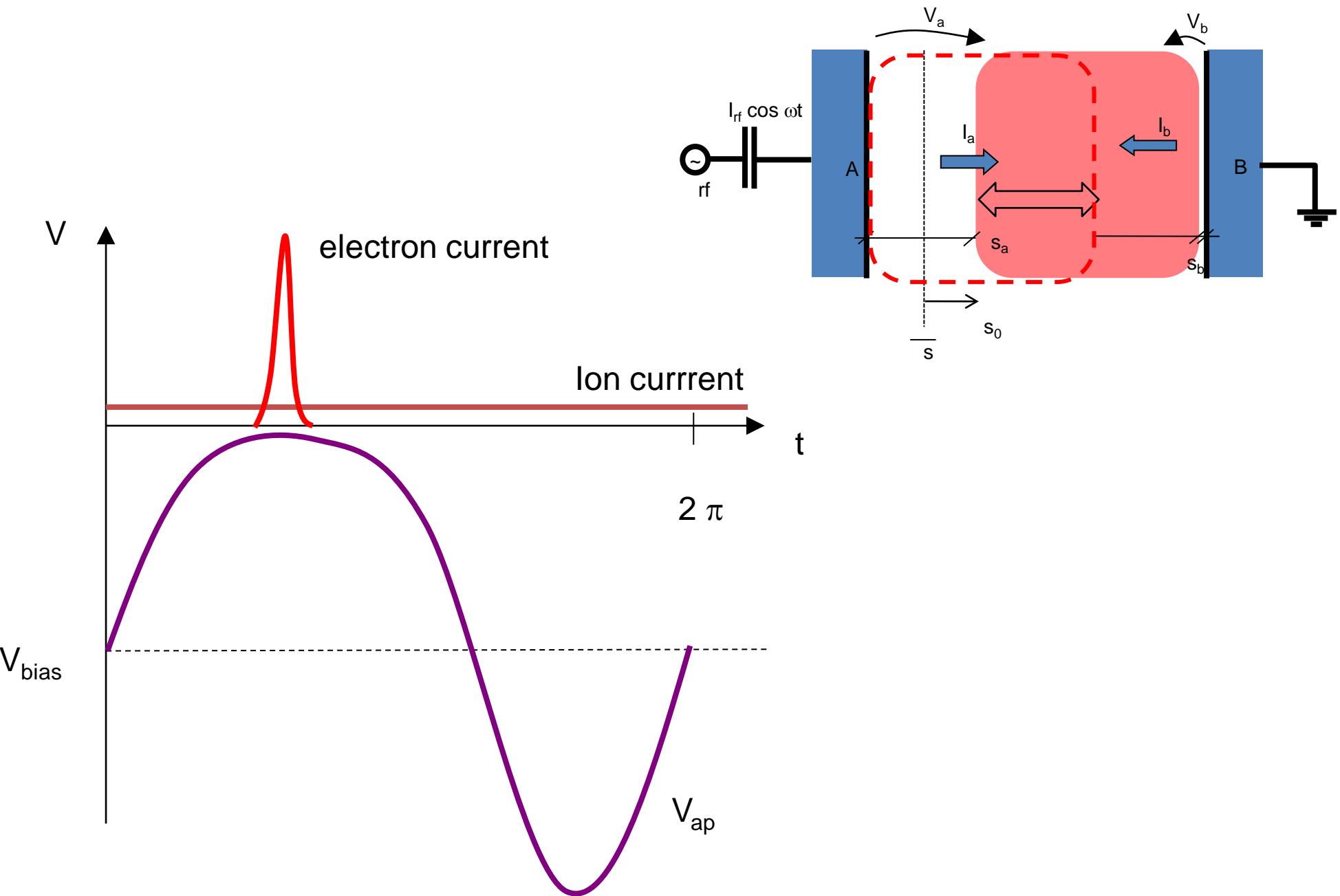


# Sustaining a plasma – rf discharges – capacitive coupling/self bias

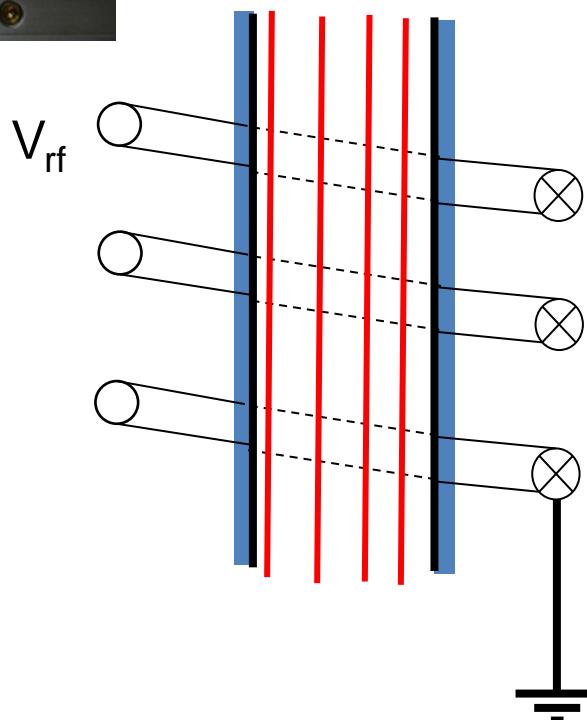
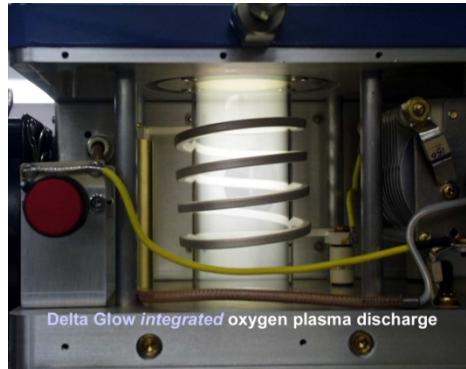


$$I = dQ/dt$$

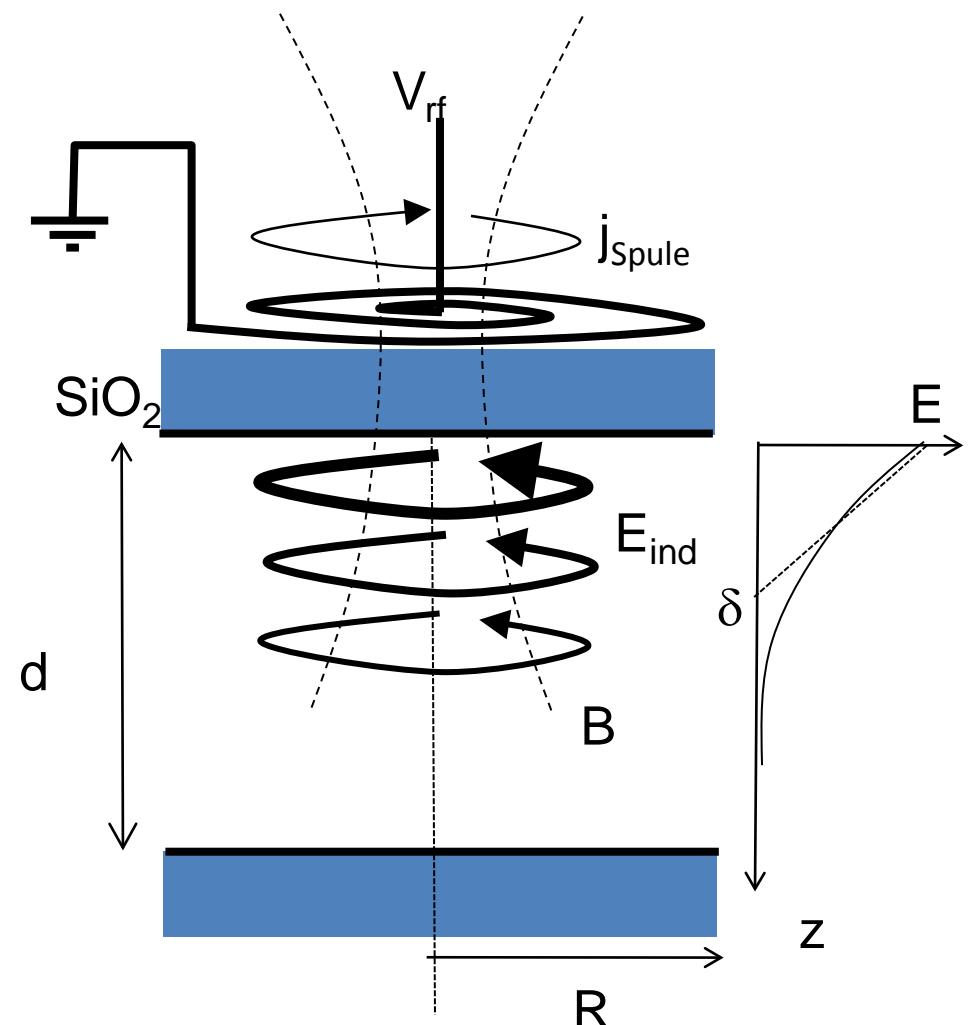
# Sustaining a plasma – rf discharges



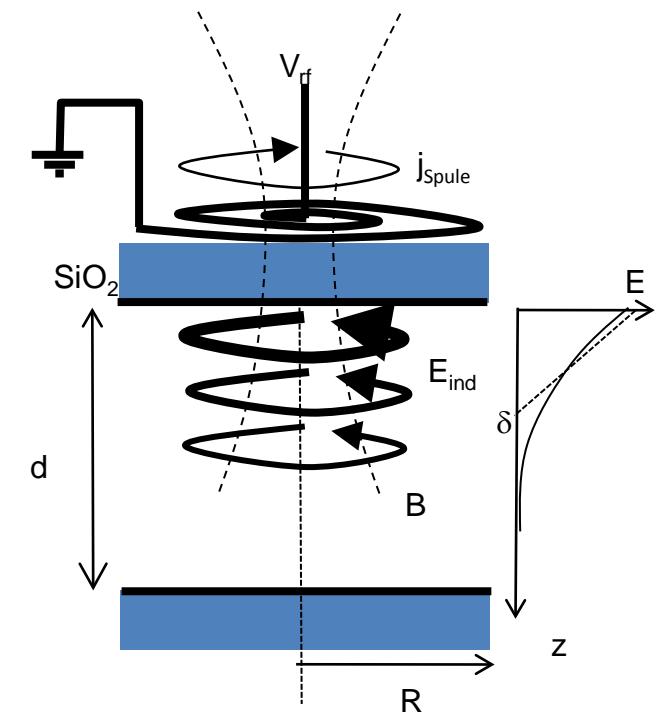
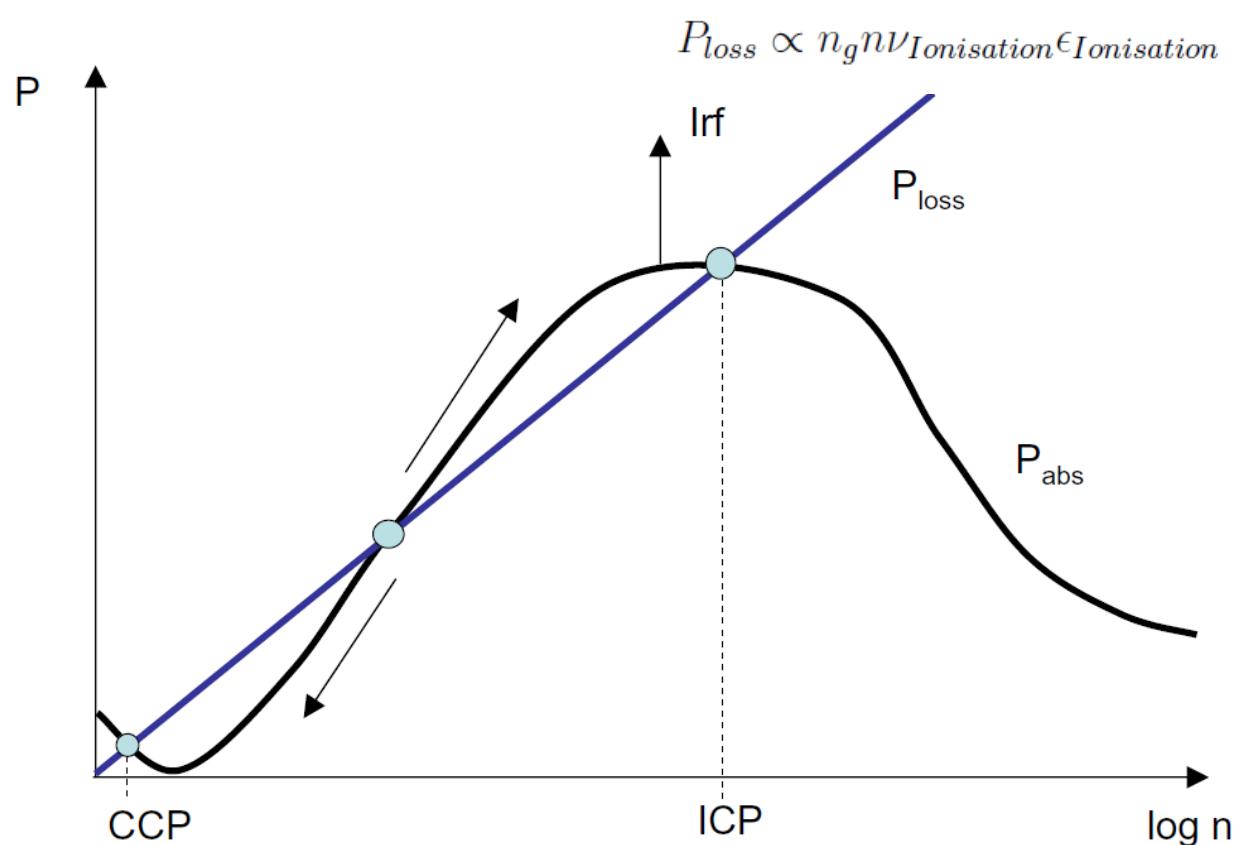
# Sustaining a plasma – rf discharges - inductive coupling ICP



Cylindrical configuration



Planar configuration



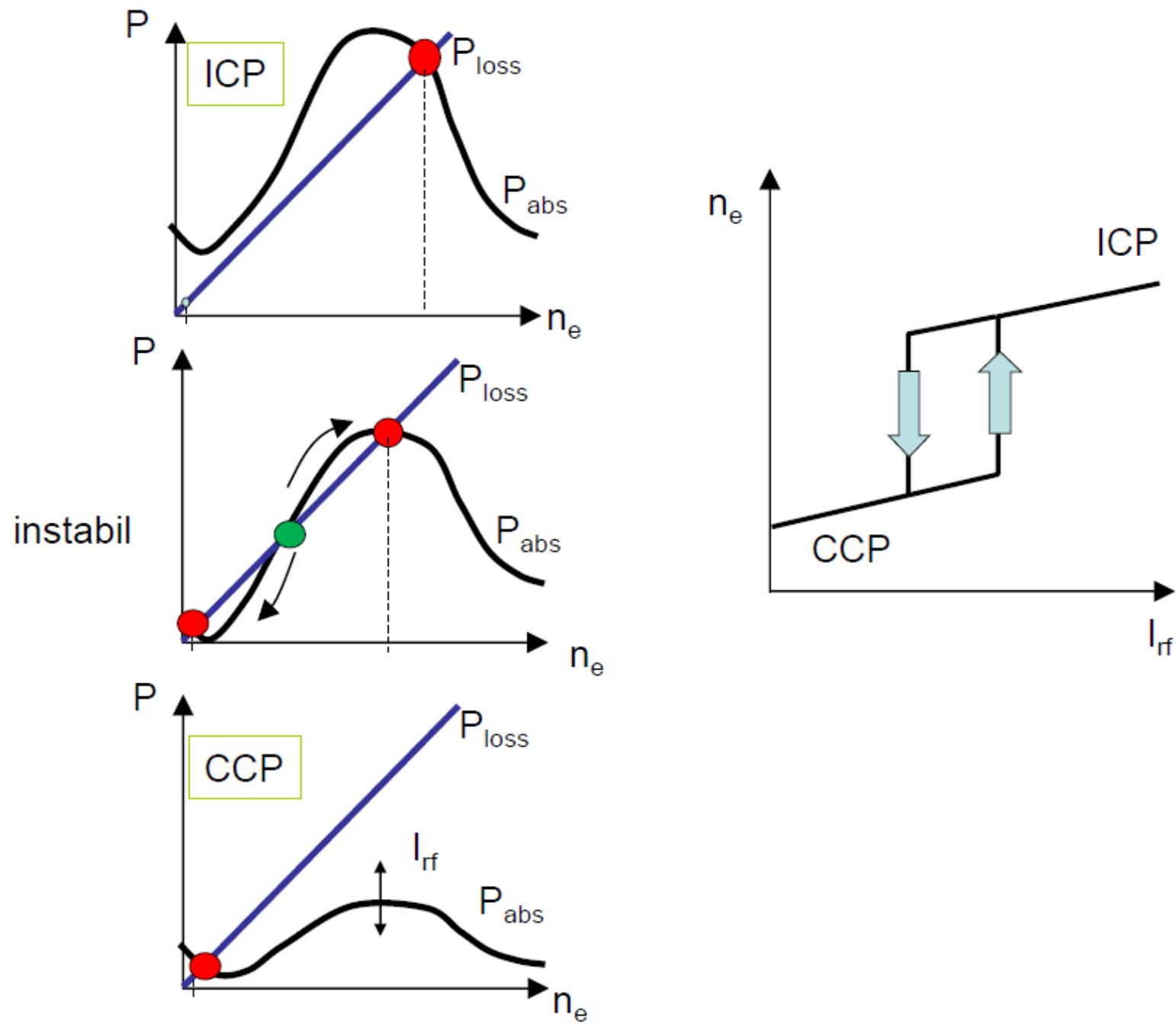
$$j_\Theta \propto I_{rf} n$$

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

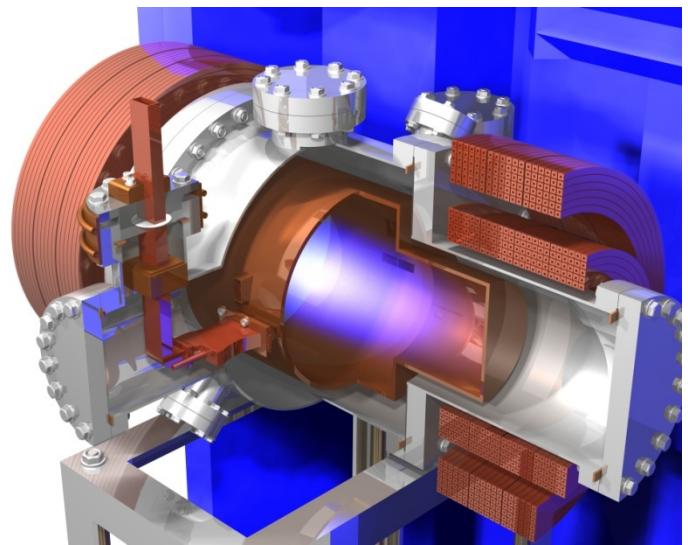
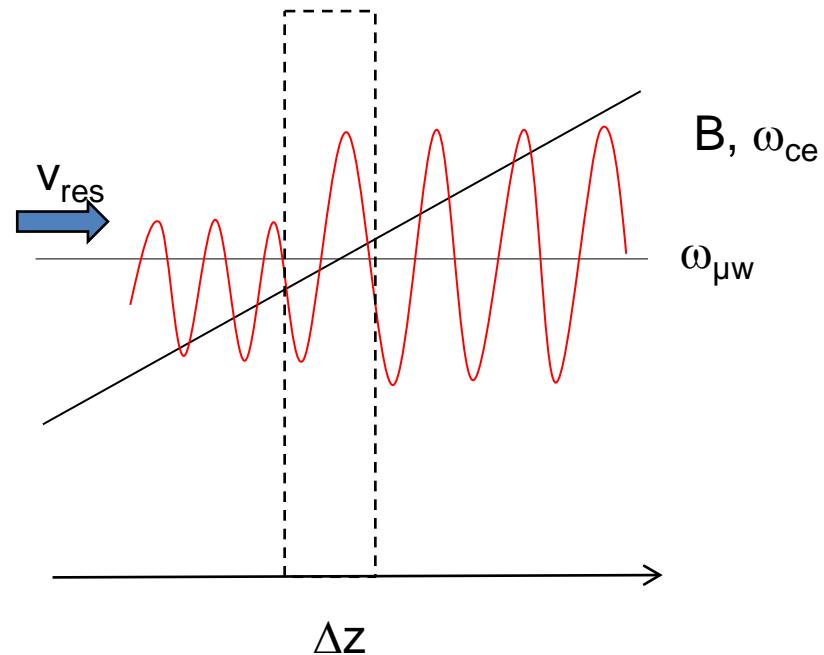
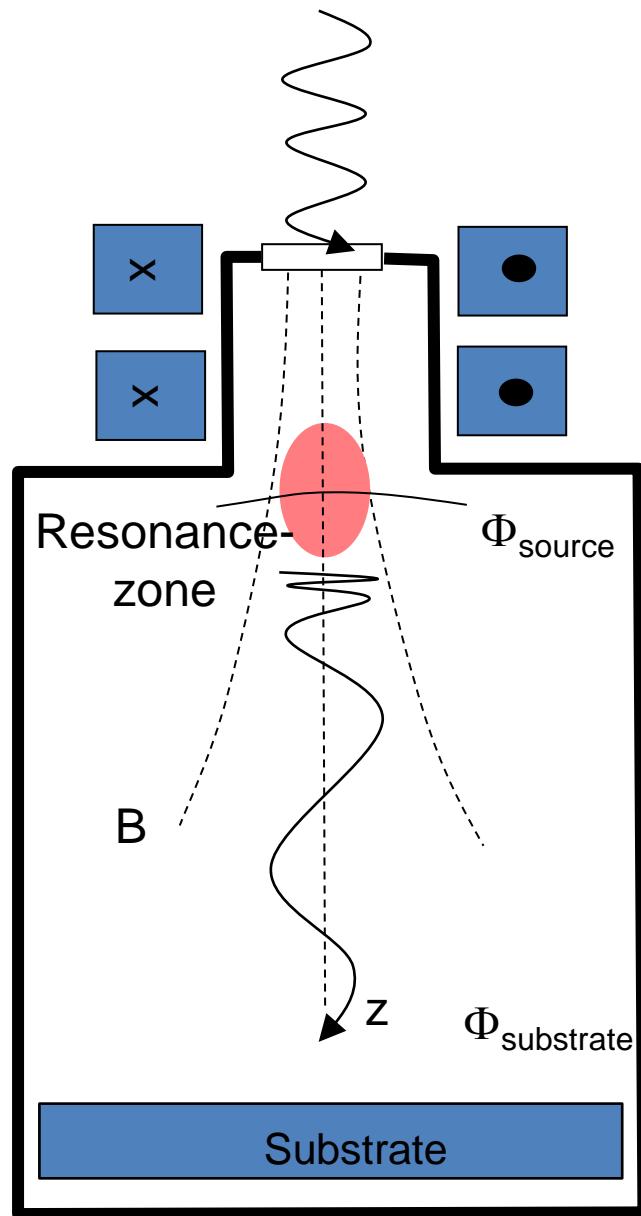
$$P_{abs} = \frac{1}{2} I_{rf}^2 n^2 \frac{1}{\sigma} A d \propto I_{rf}^2 n$$

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

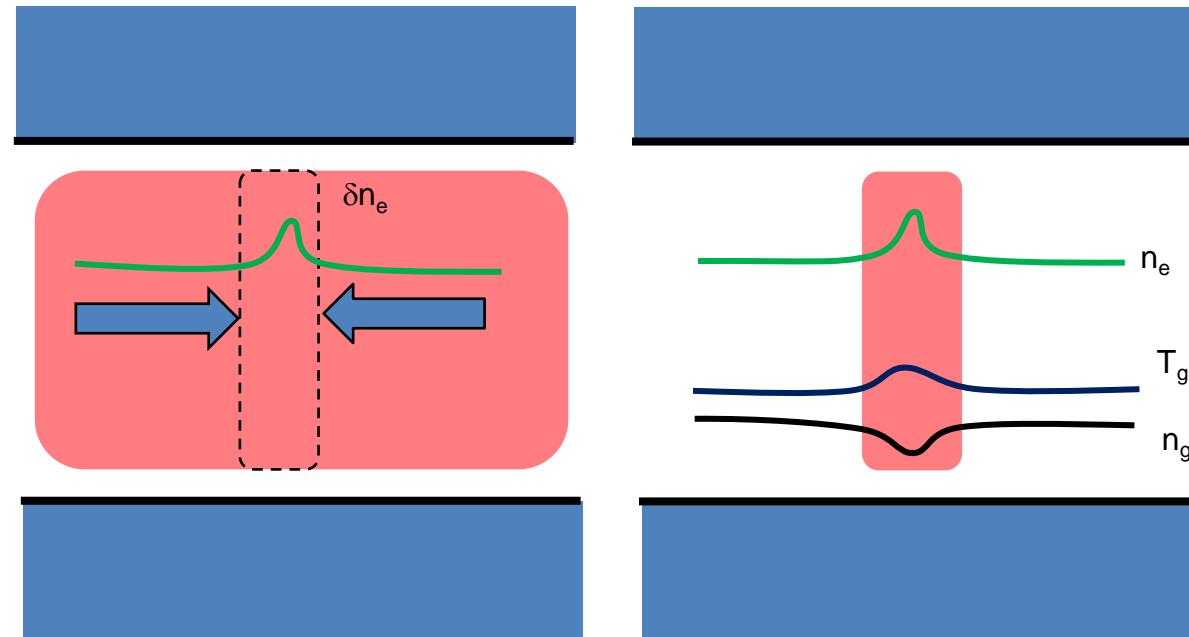
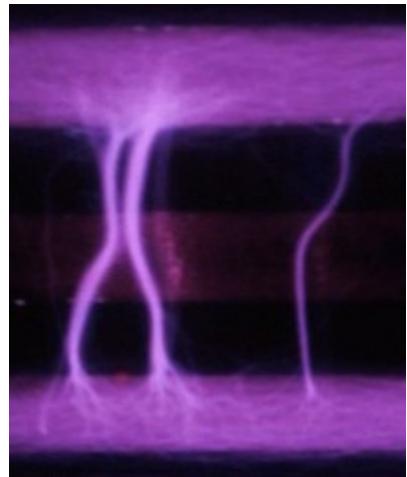
# Sustaining a plasma – ICP discharges - hysteresis



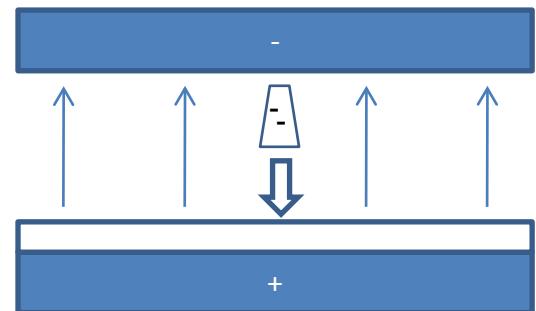
# Sustaining a plasma – electron cyclotron discharges



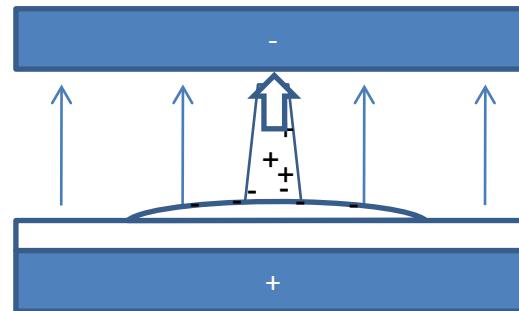
# Sustaining a plasma – high pressure discharges - filamentation



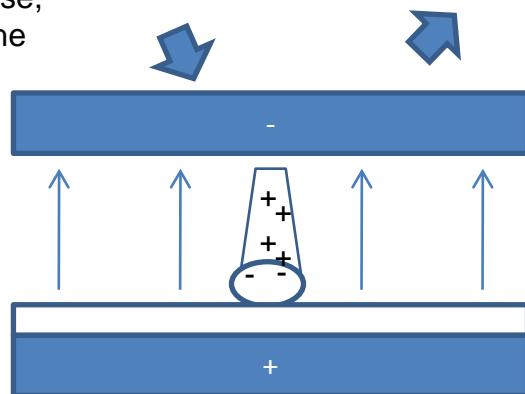
# Sustaining a plasma – barrier discharges



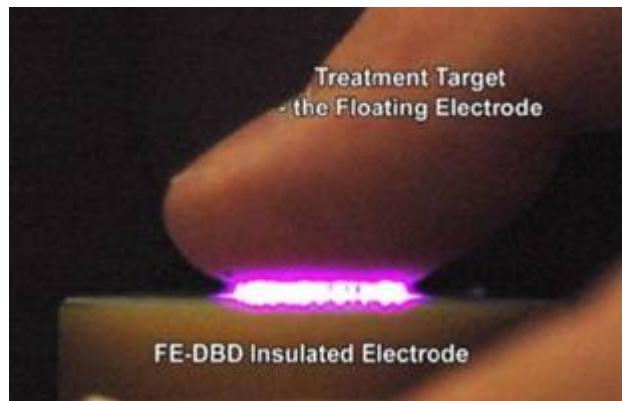
1. Townsend-Phase,  
electron avalanche



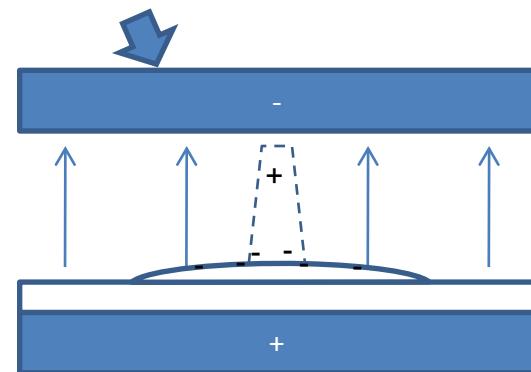
Return stroke,  
ions move to cathode



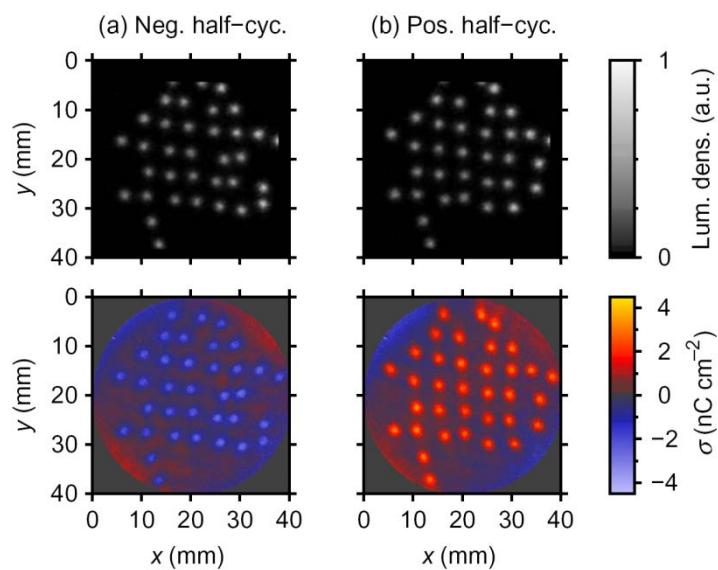
2. streamer



3. Charging up dielectricum



4. extinction



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

## 1. What is a plasma ?

- Temperature
- Debye shielding
- Plasma frequency

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

## 2. The edge of a plasma

- Sheath physics

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

## 4. How to ignite a plasma

## 3. Transport on a plasma

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

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

- 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

## 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](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

