Fundamentals of Plasma Physics III

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outline

3.1. Gas discharge plasmas

electric breakdown in gases
Townsend mechanism
micro discharges / streamers
Paschen’s law

3.2. Stationary gas discharges

Townsend discharge
glow discharge
structures of a glow discharge
hollow cathode effect, magnetron effect
arc discharge

3.3. Plasma surface interaction

stationary plasma boundary sheath
Child-Langmuir law
Bohm criterion

3.1. Gas Discharge Plasmas

mechanical compression

- gas is heated by shock waves (*ballistic compression*)

electromagnetic compression

- gas heating for short duration by high-current pulse discharges to very high temperatures
- special form of electromagnetic compression at ***Pinch effect*** where a rapidly increasing magnetic field compresses the plasma

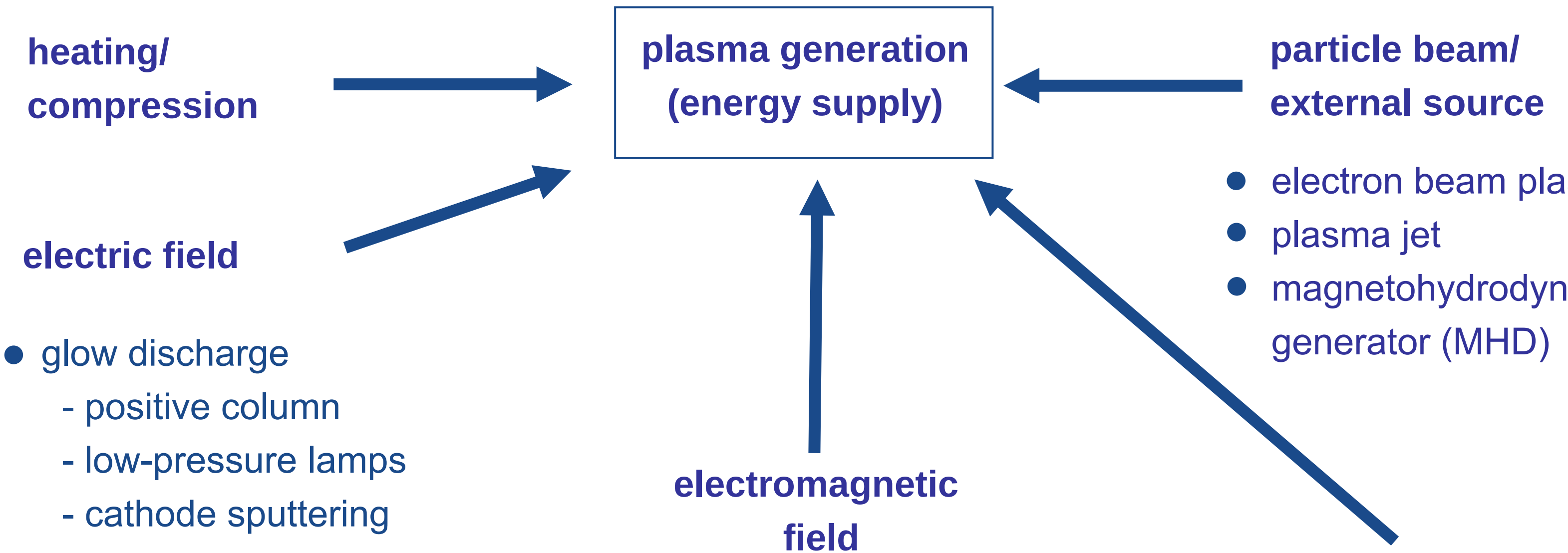
plasma generation by electric fields

- plasmas are mostly generated by ***electrical discharges***
- in principle, a gas becomes ionized by an electric field (ignition) and a self-sustaining mechanism stabilizes the plasma at a certain current
- time regime (frequency) of the field, gas pressure and electrode material are of great importance

plasma generation by waves / radiation

- for ionization of a gas also ***waves*** or ***particle beams*** can be used
- e.g. microwave radiation, electron beams, laser, radioactive radiation

3.1. Gas Discharge Plasmas



plasma generation (energy supply)

heating/ compression

particle beam/ external source

- electron beam plasma
- plasma jet
- magnetohydrodynamic generator (MHD)

electric field

- glow discharge
  - positive column
  - low-pressure lamps
  - cathode sputtering
  - hollow cathode

- arc discharge
  - high-pressure lamps
  - plasma welding
- corona discharge
- dielectric barrier discharge (DBE)
  - plasma display panel (PDP)
- capacitively coupled plasma (CCP)

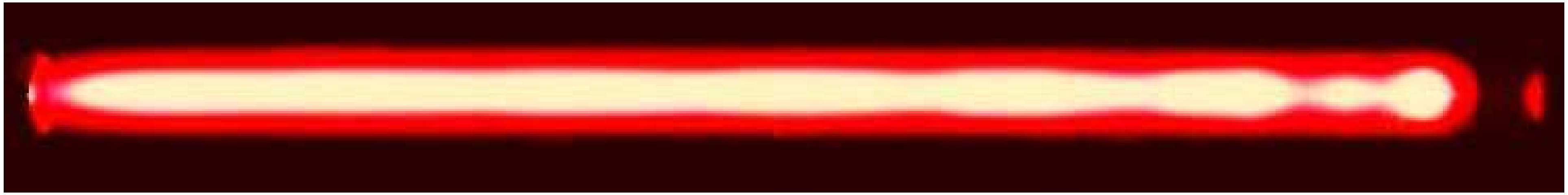
electromagnetic field

- inductively coupled plasma (ICP)
  - plasma torch
- magnetron discharge
- plasma focus

electromagnetic waves

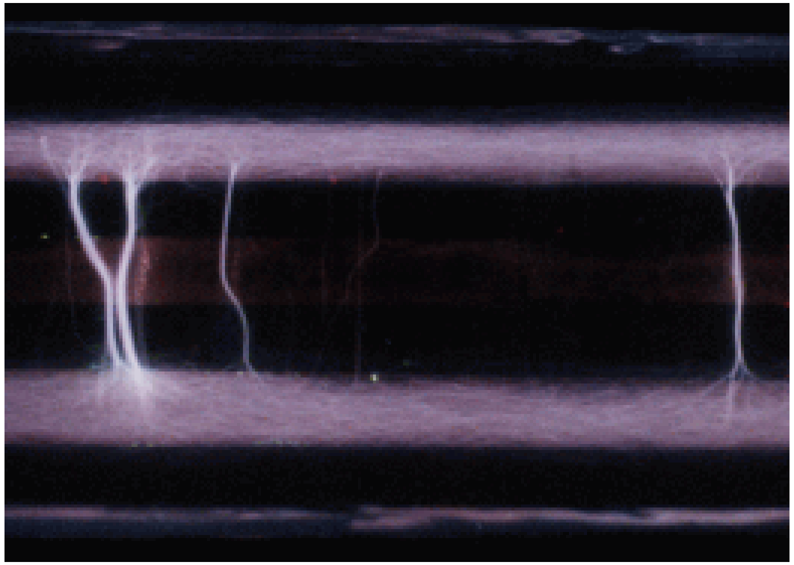
- microvwave plasma
  - electron cyclotron resonance (ECR)
- surface wave plasma
- helicon wave plasma

3.1. Gas Discharge Plasmas



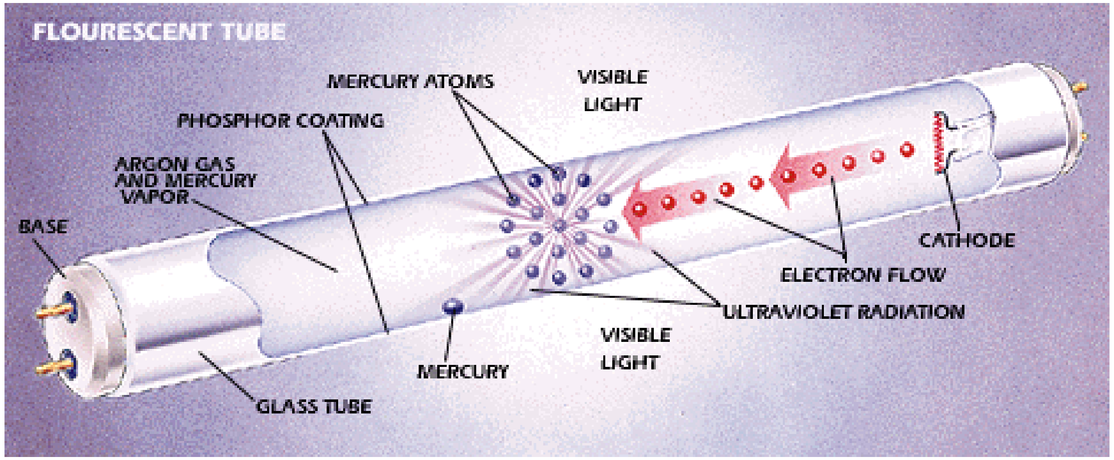
low pressure dc glow discharge in neon (positive column)

low pressure rf discharge in argon

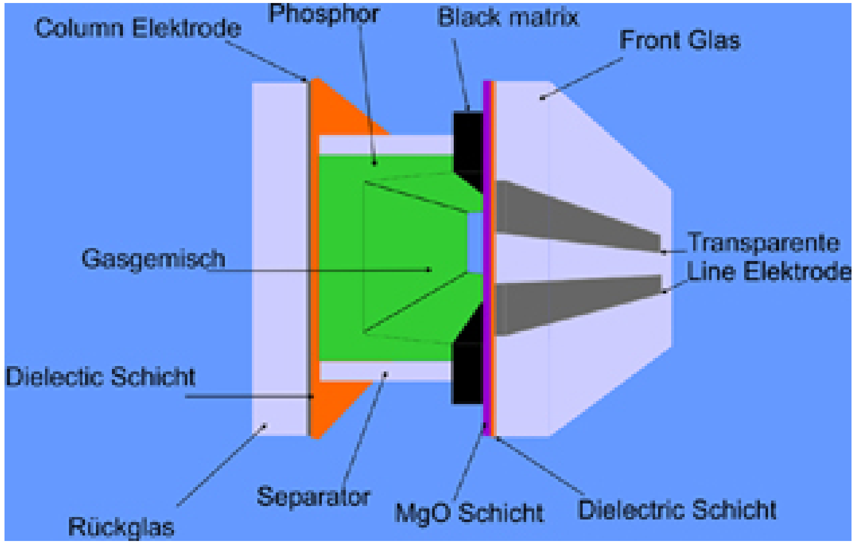


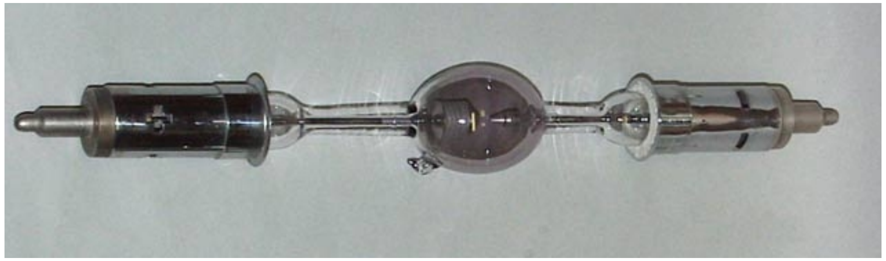
atmospheric pressure discharge

3.1. Gas Discharge Plasmas



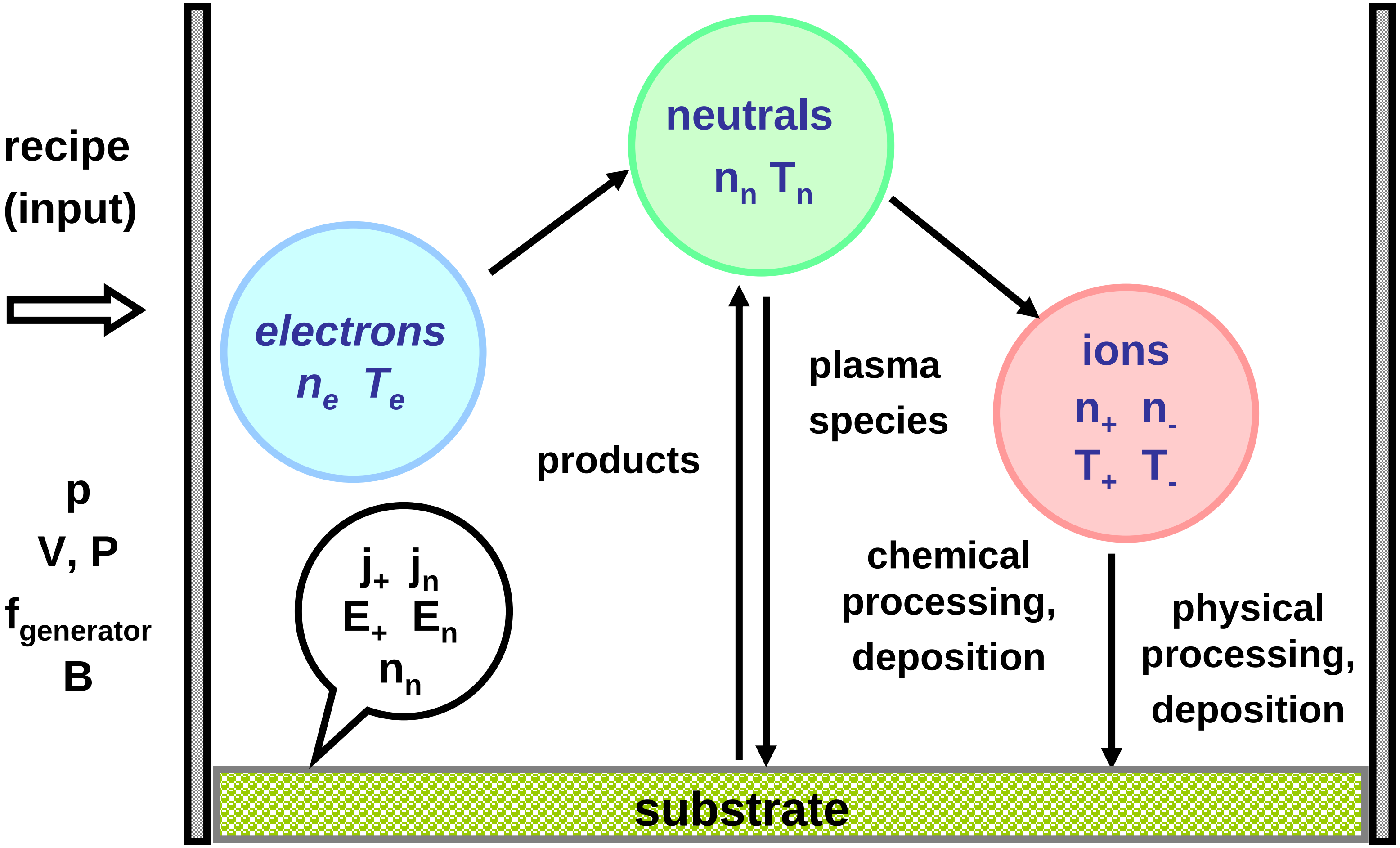
plasma application:
for example for illumination





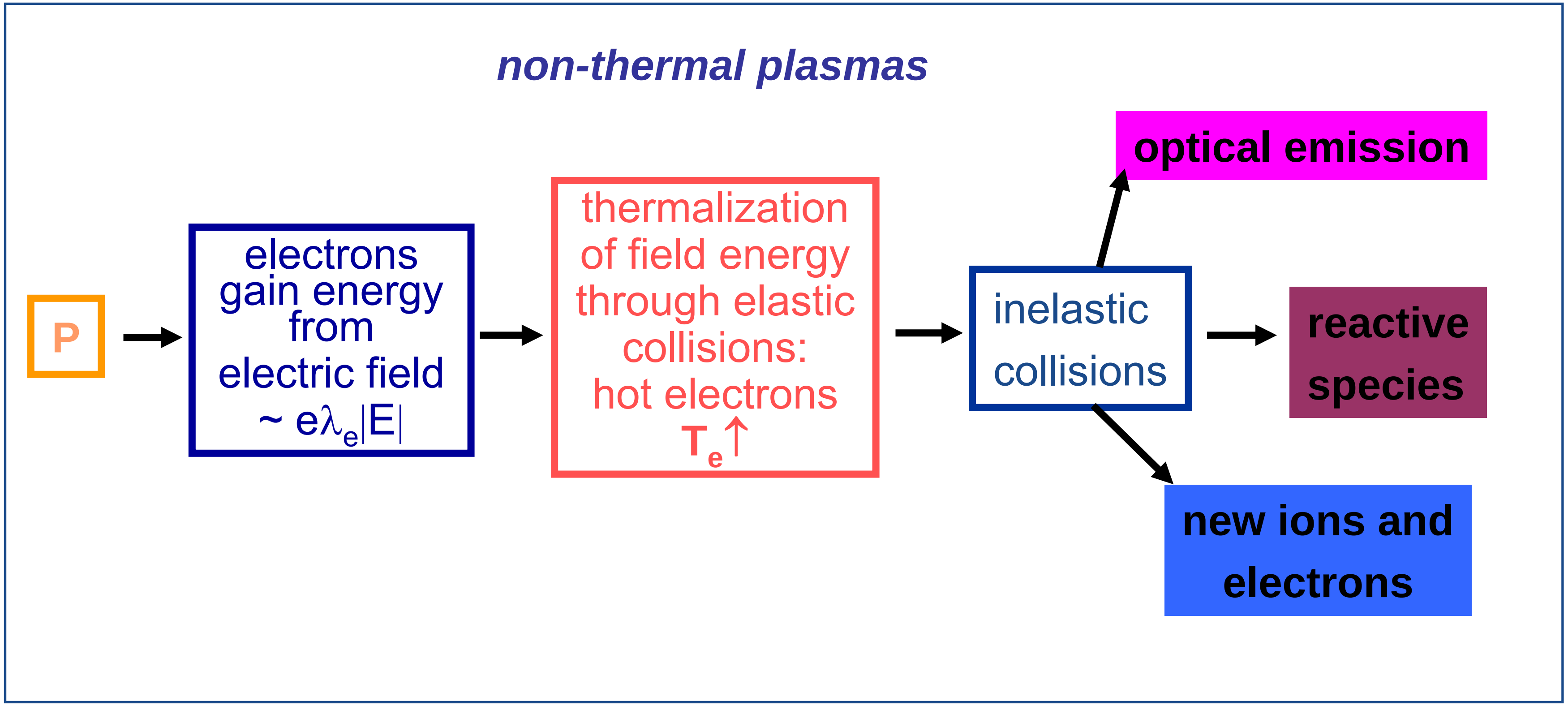
3.1. Gas Discharge Plasmas

energy conversion : field, plasma, surface



3.1. Gas Discharge Plasmas

particle interaction: charge carriers in plasma



non-thermal plasmas

P

electrons gain energy from electric field $\sim e\lambda_e|E|$

thermalization of field energy through elastic collisions: hot electrons $T_e\uparrow$

inelastic collisions

optical emission

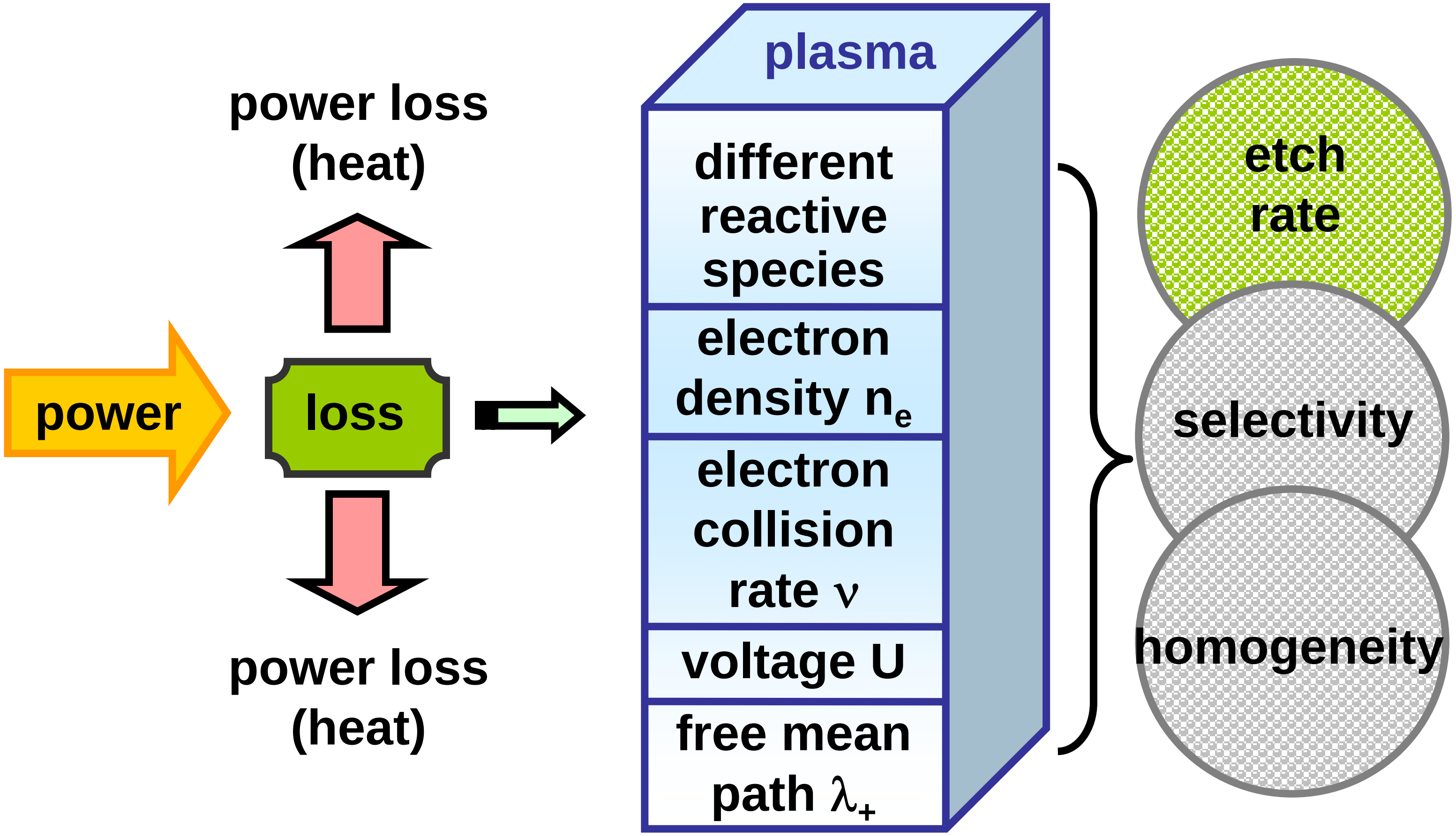
reactive species

new ions and electrons

electrons and their collisions carry and distribute the energy
from the matchbox to process gas (neutrals, ions) to the substrate

3.1. Gas Discharge Plasmas

energy conversion : field, plasma, surface



power loss (heat)

power

loss

power loss (heat)

plasma

different reactive species

electron density n_e

electron collision rate ν

voltage U

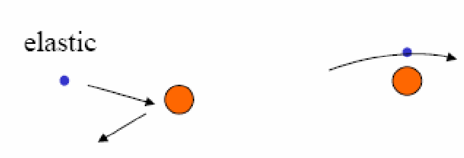
free mean path λ_+

etch rate

selectivity

homogeneity

plasma application:
for example semiconductor etching



3.1. Gas Discharge Plasmas

collision processes in non-isothermal plasmas

- electron-electron interaction
- electron collisions with heavy particles
- heavy particle reactions

electron collisions with heavy particles:

elastic collision
$e^- + A \Rightarrow e^- + A$

excitation
$e^- + A \Rightarrow e^- + A^*$
$e^- + A^* \Rightarrow e^- + A^{**}$
(source of radiation:
$A^* \Rightarrow A + h\nu$)

deexcitation
$e^- + A^* \Rightarrow e^- + A$

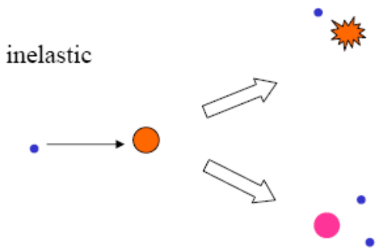
recombination
$e^- + A^+ \Rightarrow A + h\nu$
$e^- + A_2^+ \Rightarrow A + A$

dissociation
$e^- + AB \Rightarrow e^- + A + B$
$e^- + AB \Rightarrow e^- + A^+ + B^-$

attachment
$e^- + A + B \Rightarrow A^- + B$
$e^- + A_2 \Rightarrow A + A^-$

ionization
$e^- + A \Rightarrow 2e^- + A^+$
$e^- + A^+ \Rightarrow 2e^- + A^{++}$
$e^- + A_2 \Rightarrow 2e^- + A + A^+$

collsion processes : generation of charge carriers



no change of particle number

change of particle number

3.1. Gas Discharge Plasmas

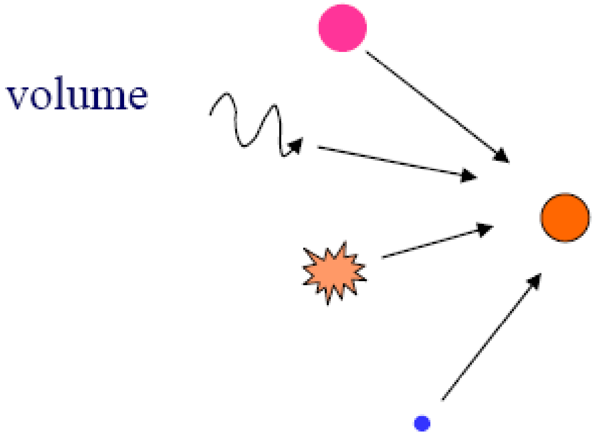
collsion processes : generation of charge carriers

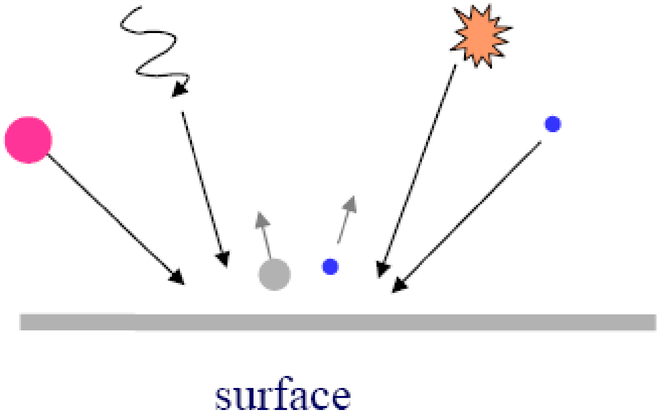
$$A + B^{\pm} \rightarrow A^{+} + B^{\pm} + e^{-}$$

$$A + h\nu \rightarrow A^{+} + e^{-}$$

$$A + B^{*} \rightarrow A^{+} + B + e^{-}$$

$$e^{-}_{fast} + A \rightarrow A^{+} + e^{-}_{slow} + e^{-}_{slow}$$





3.1. Gas Discharge Plasmas

collsion processes : generation of charge carriers

dominant at high energy

- Direct electron impact ionization

$$M + e^- \xrightarrow{K_i} M^+ + 2e^-$$

- Ionization from excited levels

$$M^* + e^- \xrightarrow{K_i^*} M^+ + 2e^-$$

- Penning Ionization

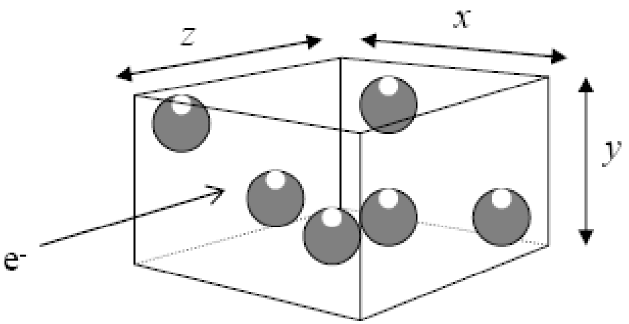
$$Ar^* + M \xrightarrow{K_p} M^+ + Ar + e^-$$

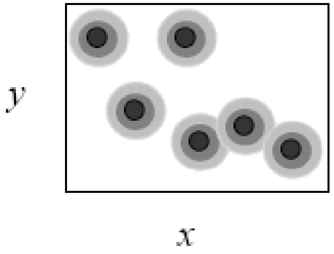
dominant at low energy

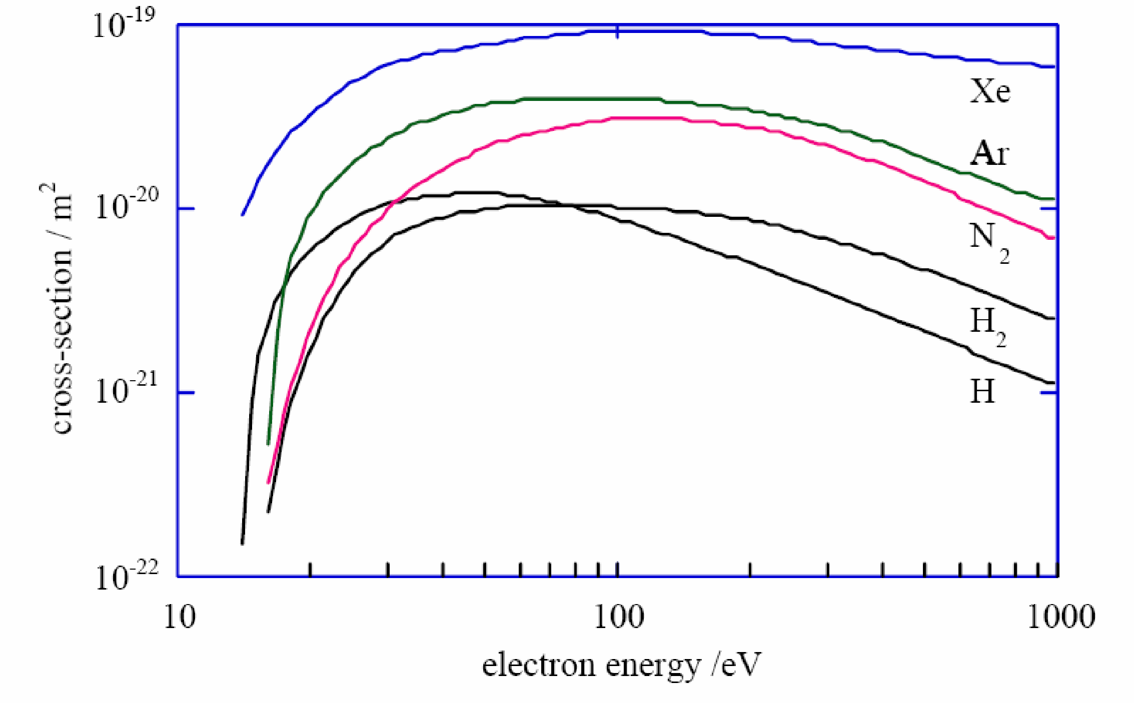
channels of ionization (→ α)

3.1. Gas Discharge Plasmas

collsion processes : generation of charge carriers

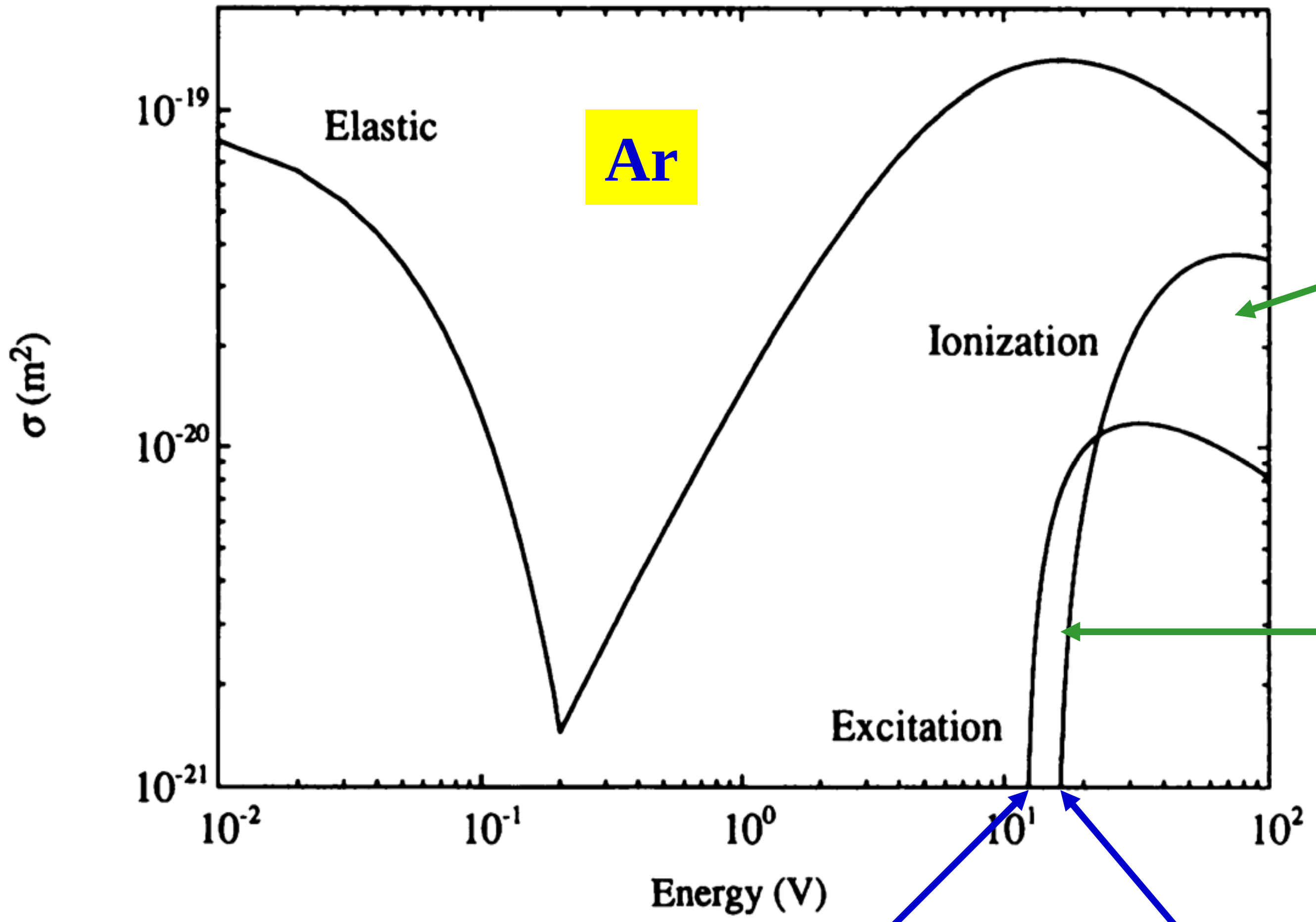






3.1. Gas Discharge Plasmas

collsion processes : generation of charge carriers



ionization via impact ionization

ionization via excited states and Penning effect

excitation energy

ionization energy

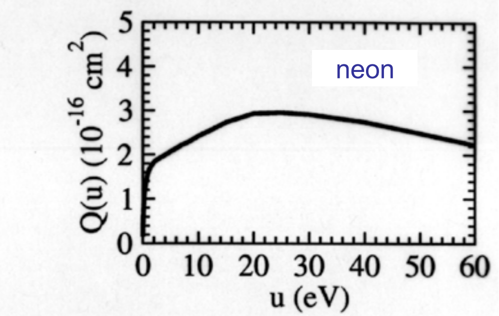
3.1. Gas Discharge Plasmas

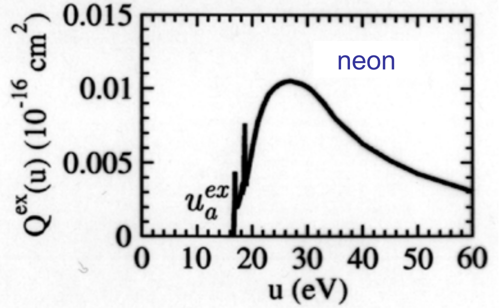
energy and momentum conservation

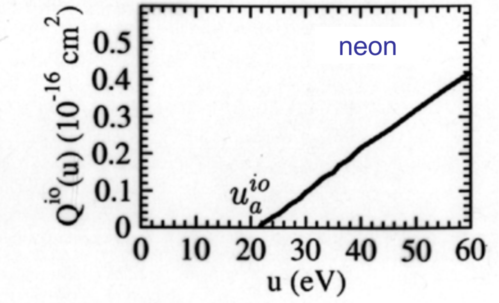
collision of an electron (m_e and $\vec{v}_e$) and an atom (m_a and $\vec{v}_a$)

$(m_a >> m_e\, , v_a << v_e)$

typical total cross section $Q\,(u = \frac{m_e}{2}v_e^2)$:







- **elastic collision**

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e\vec{v}_e' + m_a\vec{v}_a'$$

$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}v_e'^2 + \frac{m_a}{2}v_a'^2$$

- **exciting collision**

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e\vec{v}_e' + m_a\vec{v}_a'$$

$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}v_e'^2 + \frac{m_a}{2}v_a'^2 + u_a^{ex}$$

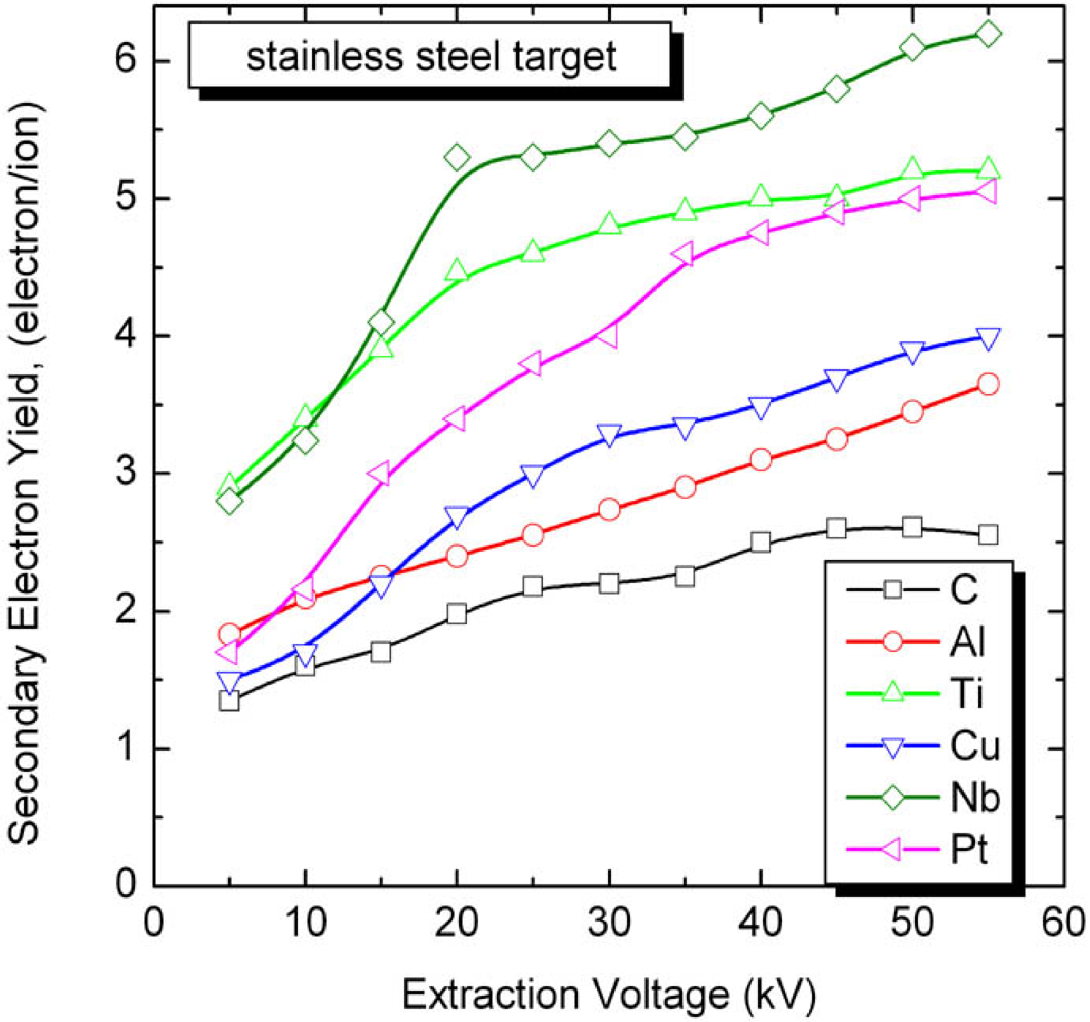
- **ionizing collision**

$$m_e\vec{v}_e + m_a\vec{v}_a = m_e(\vec{v}_e' + \vec{v}_e'') + m_a\vec{v}_a'$$

$$\frac{m_e}{2}v_e^2 + \frac{m_a}{2}v_a^2 = \frac{m_e}{2}(v_e'^2 + v_e''^2) + \frac{m_a}{2}v_a'^2 + u_a^{io}$$

3.1. Gas Discharge Plasmas

collsion processes : generation of charge carriers

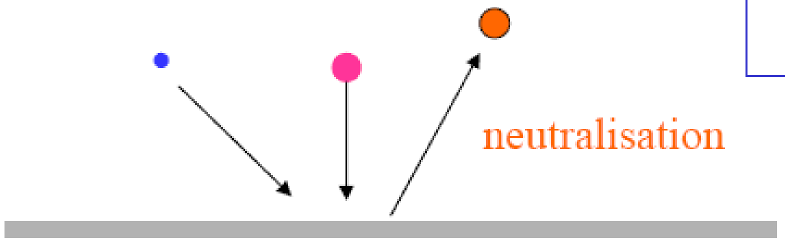


3.1. Gas Discharge Plasmas

collsion processes : losses of charge carriers

$A + e^- \rightarrow A^- + h\nu$	radiative attachment
$AB^* + e^- \rightarrow A^- + B$	dissociative attachment
$e^- + A^+ + e^- \rightarrow A + e^-_{faster}$	3 body recombination
$e^- + AB \rightarrow AB^-$	associative attachment
$AB^- + C^+ \rightarrow AB + C$	ion-ion recombination

Volume loss rate depends on concentrations



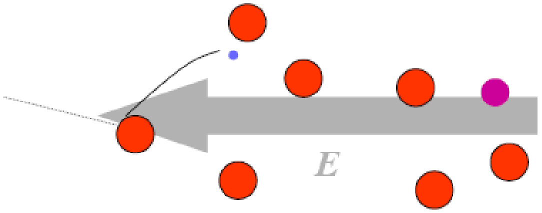
neutralisation

Surface loss rate depends on fluxes

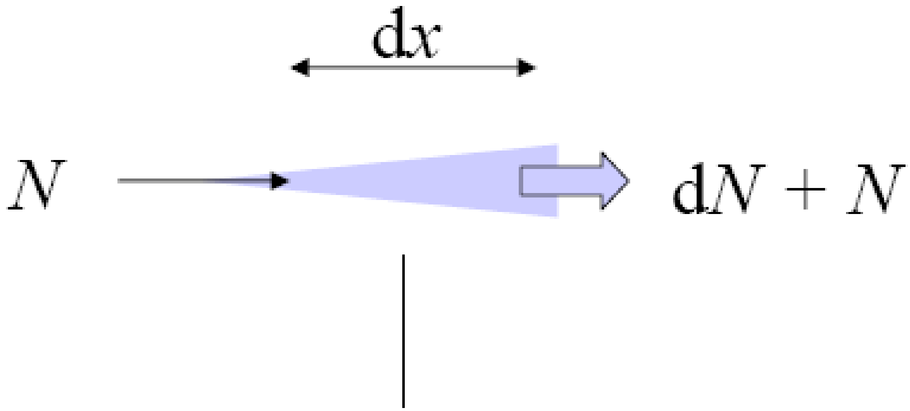
3.1. Gas Discharge Plasmas

multiplication of charge carriers

drift



$$v_d = \mu_e E = \frac{e_0 \tau}{m_e} E$$



$$\mathrm{d}N = N\mathrm{d}x / \lambda_\mathrm{i}$$

$$N = N_0 \exp(x / \lambda_\mathrm{i})$$

or

$$N = N_0 \exp(\alpha x)$$

3.1. Gas Discharge Plasmas

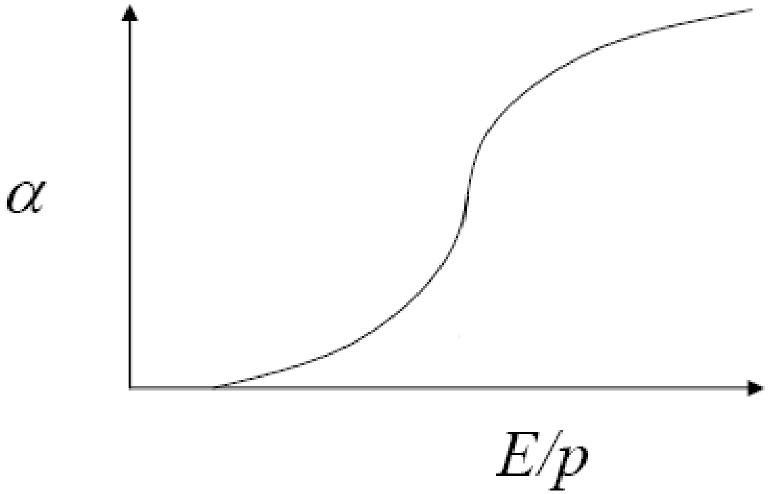
Townsend's coefficient

Drift energy activates the ionisation process

cf: $R = R_o \exp(-\varepsilon_a/kT)$

$$\alpha = \lambda_i^{-1} = const.\ \lambda^{-1} \exp(-V_i/E\lambda)$$

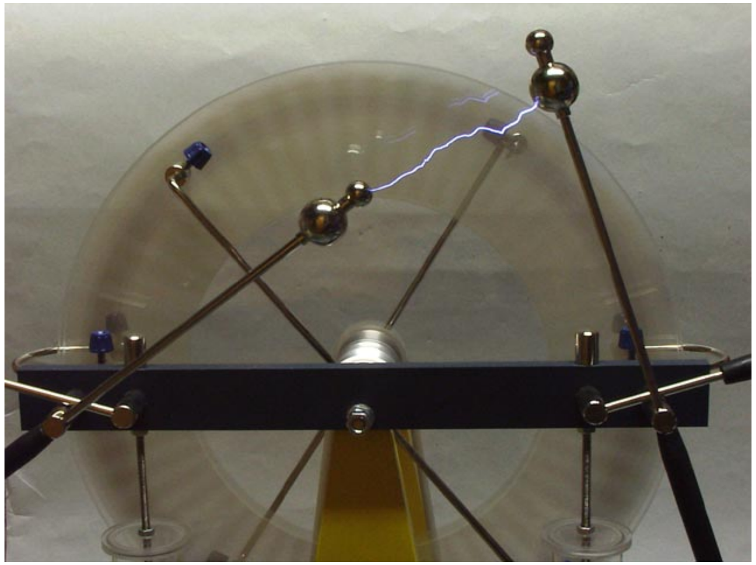
$$\alpha = Ap.\exp(-Bp/E)$$



3.1. Gas Discharge Plasmas

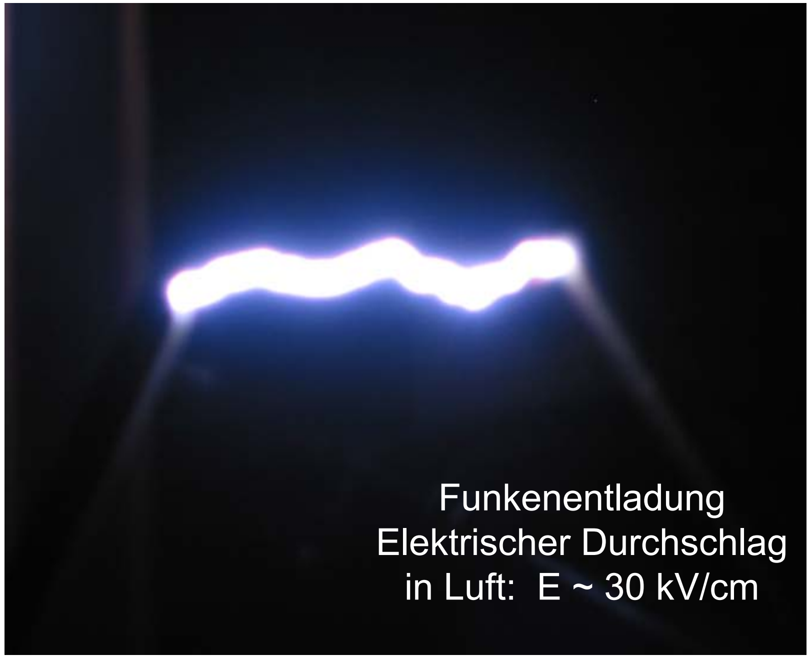
Streamers

Pieter van Musschenbroek (1692-1761)
Leiden jar‘s



3.1. Gas Discharge Plasmas

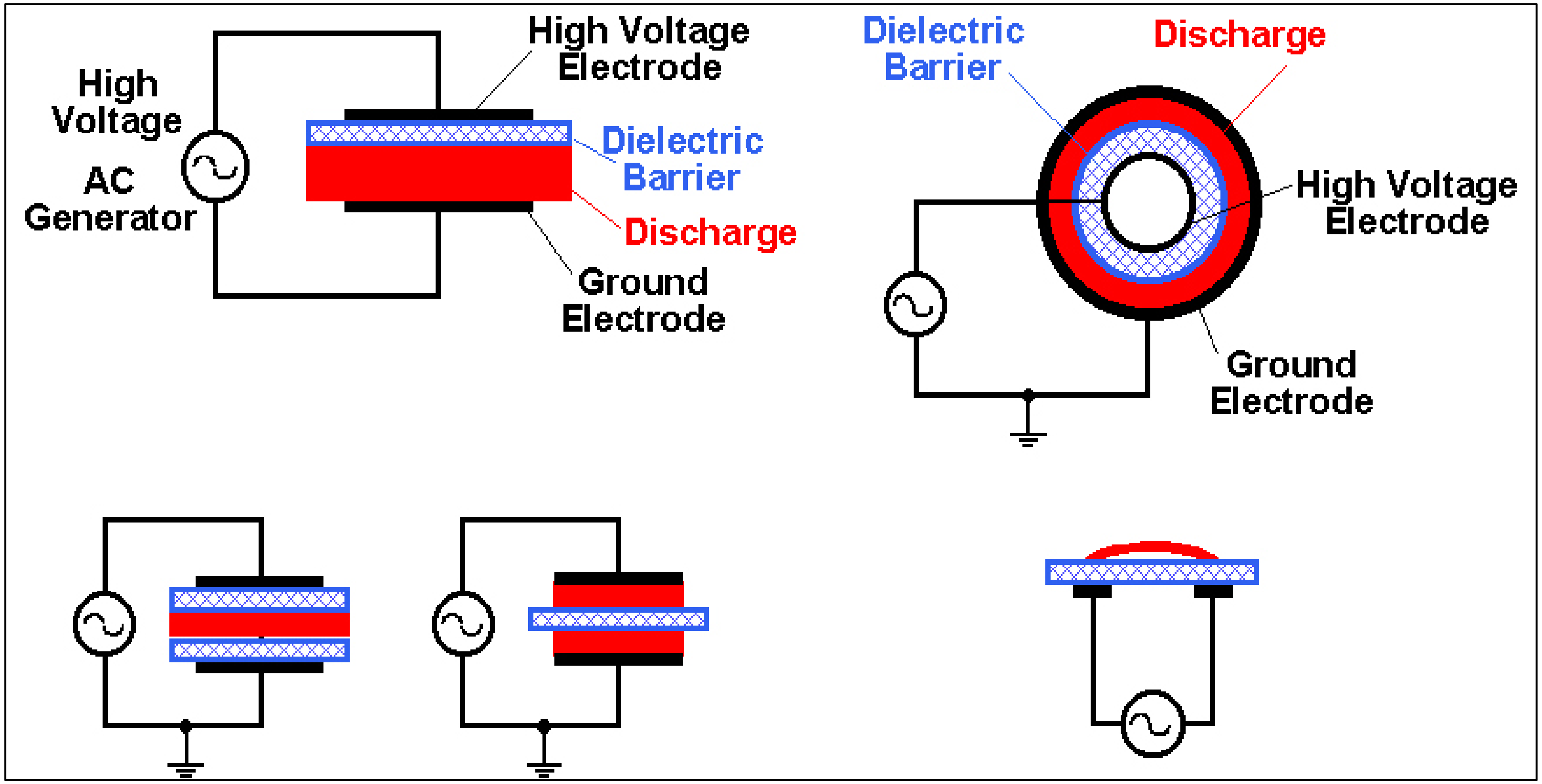
streamers

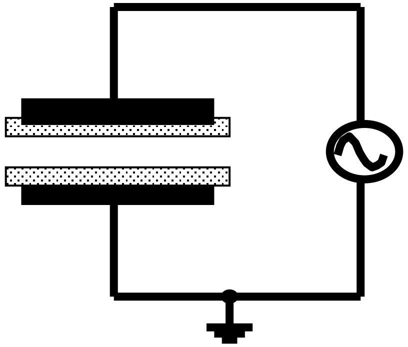


Funkenentladung
Elektrischer Durchschlag
in Luft: E ~ 30 kV/cm

3.1. Gas Discharge Plasmas

micro discharges : DBD





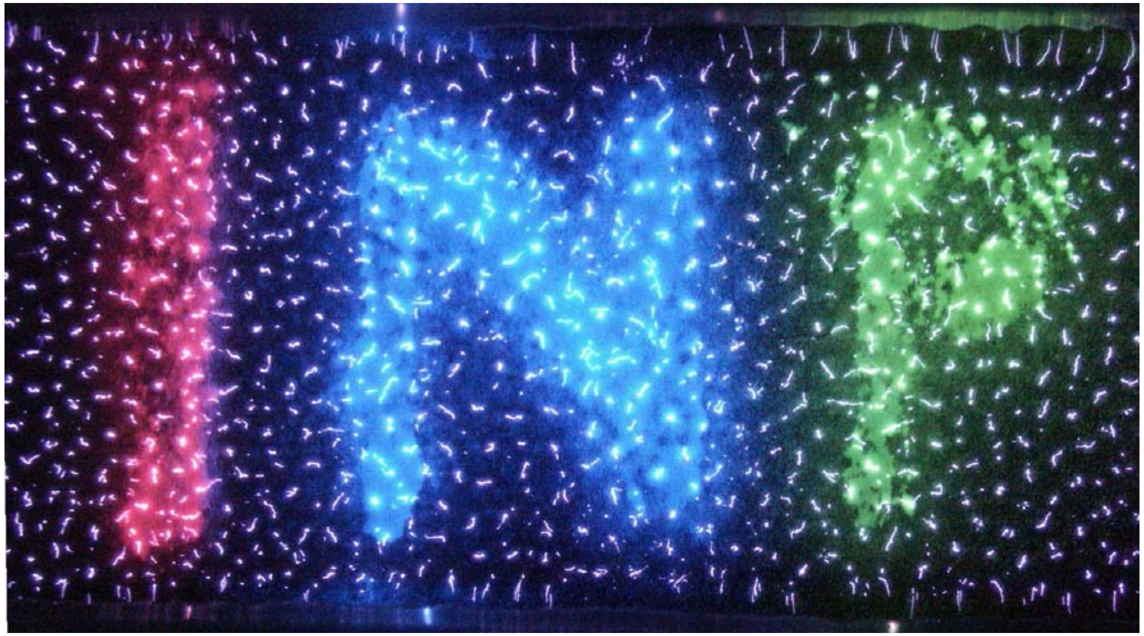
presence of at least one dielectric in the discharge space

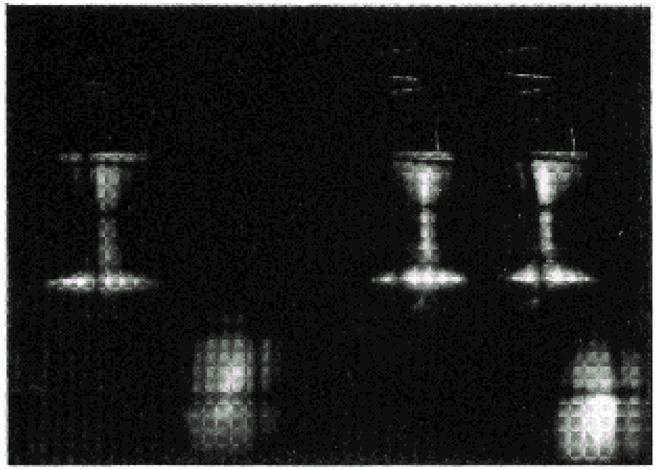
3.1. Gas Discharge Plasmas

micro discharges : DBD

Microdischarges of short duration

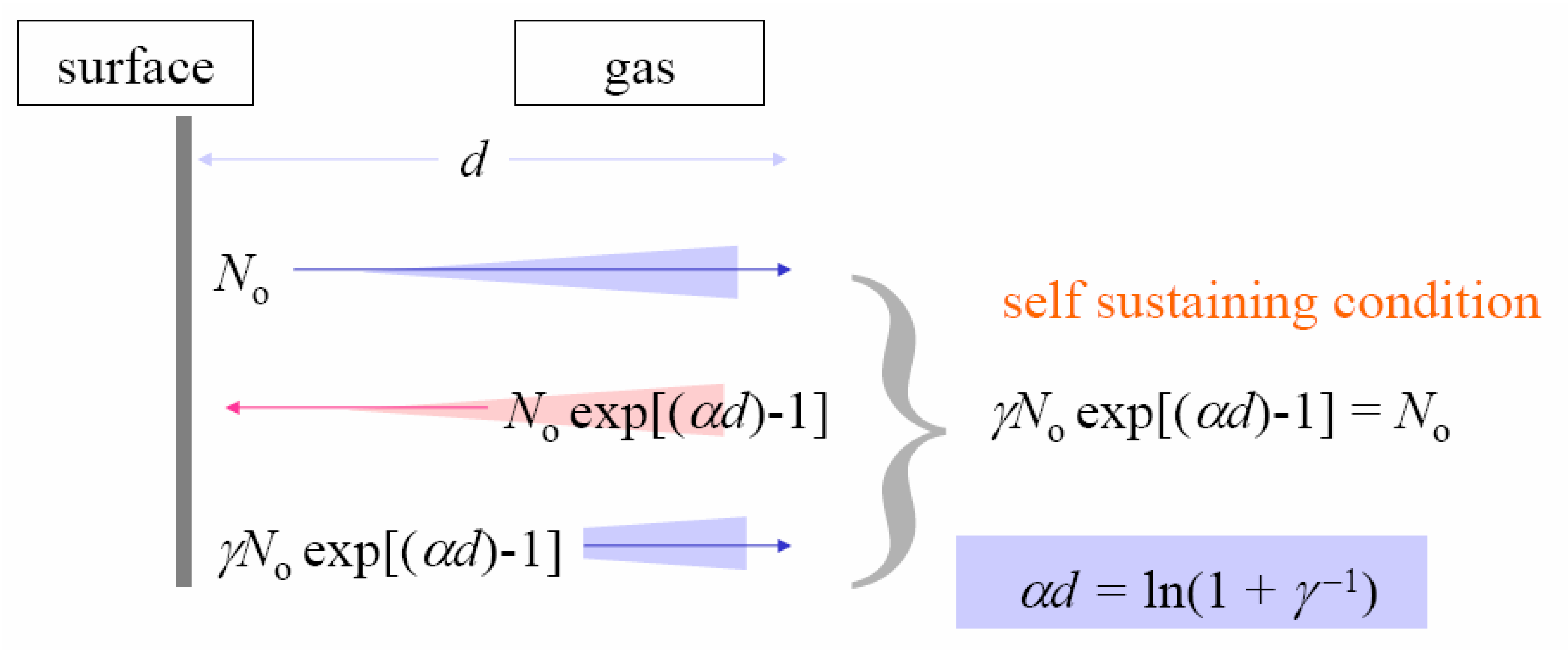
- thin cylindrical weakly ionized plasma columns, $\varnothing \approx 200\ \mu m$
- electron densities: $10^{14} \ldots 10^{15}\ cm^{-3}$
- duration: 1 .. 10 ns
- non-equilibrium plasmas ($T_e >> T_{gas}$) $\Rightarrow$ well suited for initiation of plasma-chemical reactions





3.1. Gas Discharge Plasmas

electric breakdown



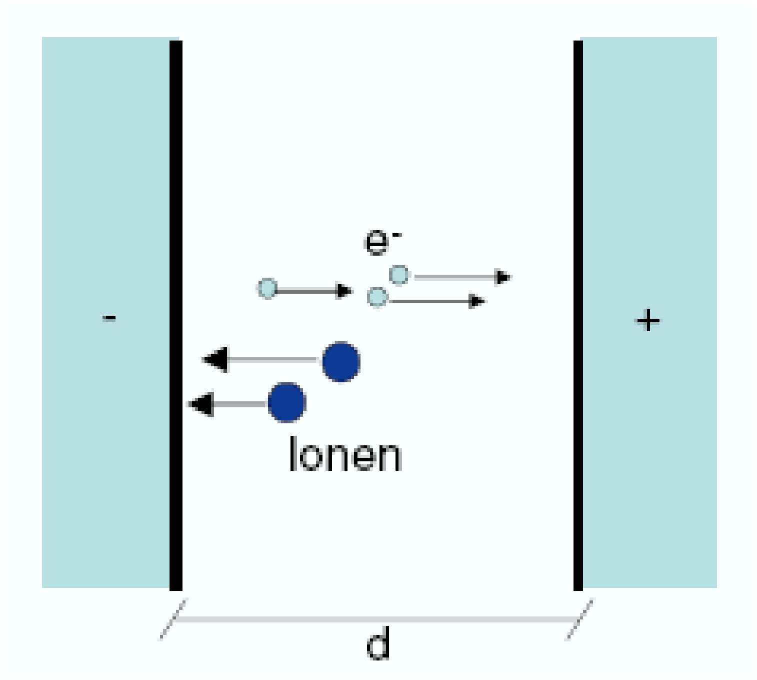
self sustaining condition

$$\gamma N_o \exp[(\alpha d)-1] = N_o$$

$$\boxed{\alpha d = \ln(1+\gamma^{-1})}$$

3.1. Gas Discharge Plasmas

multiplication of charge carriers



ignition of discharge

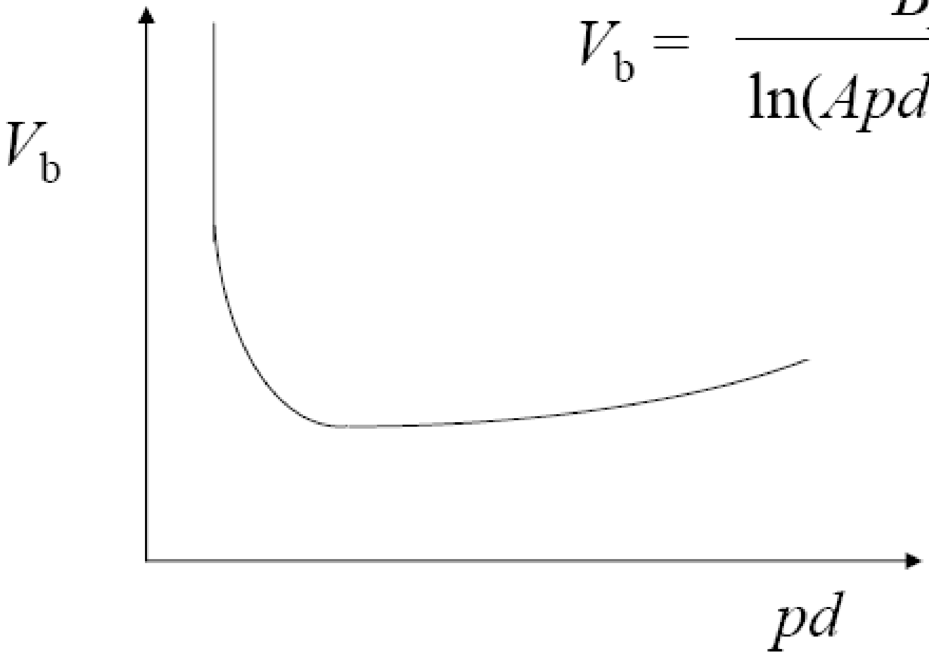
3.1. Gas Discharge Plasmas

Paschen‘s law

$$\left.\begin{array}{r} \alpha = Ap.\exp(-Bp/E) \\[2em] \alpha d = \ln(1+\gamma^{-1}) \end{array}\right\} \quad Apd.\exp(-Bp/E) = \ln(1+\gamma^{-1})$$

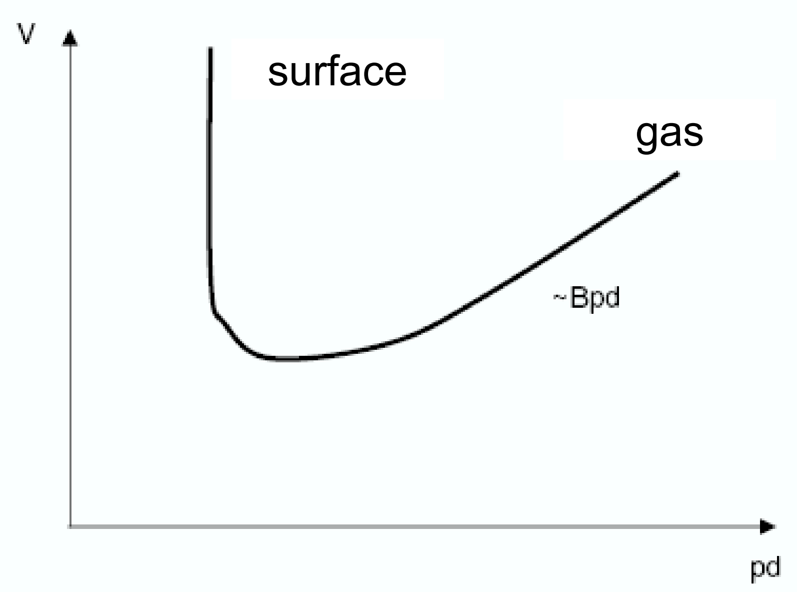
V_b/d (planar geometry)

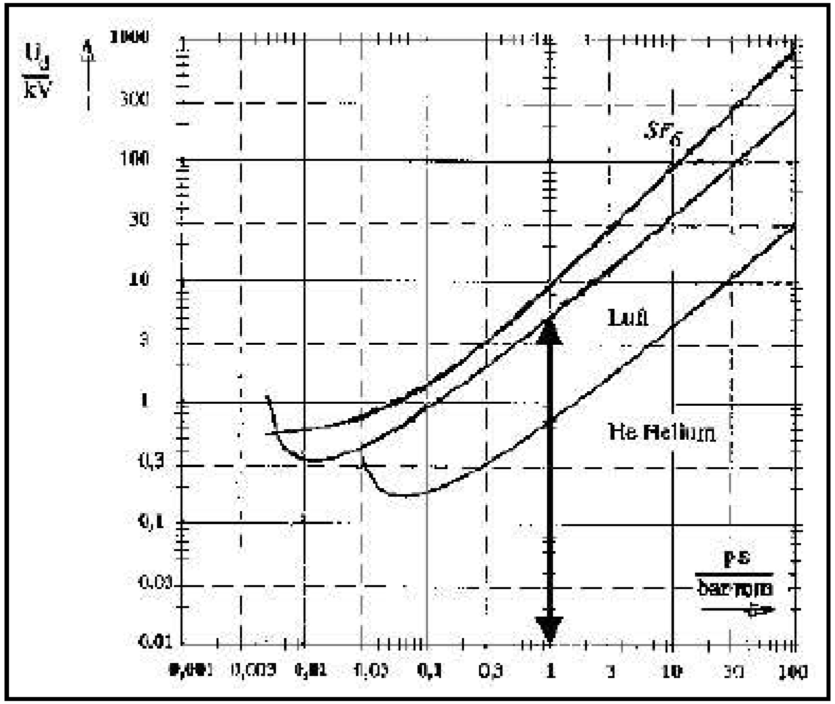
$$V_b = \frac{Bpd}{\ln(Apd)\text{-}\ln\ln(1+\gamma^{-1})}$$



3.1. Gas Discharge Plasmas

Paschen‘s law

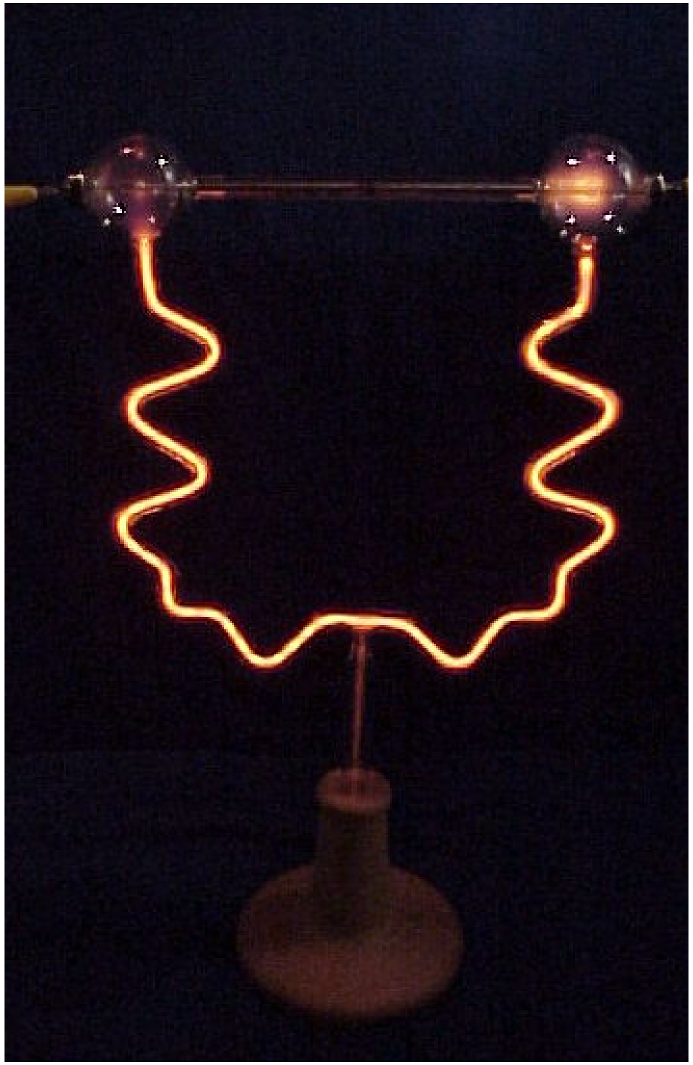


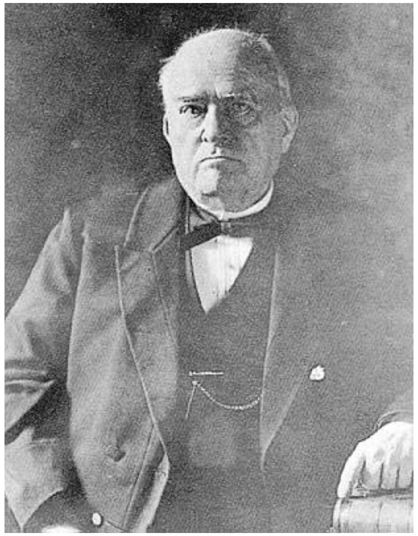


breakdown voltage depends on pressure, distance and gas

3.1. Gas Discharge Plasmas

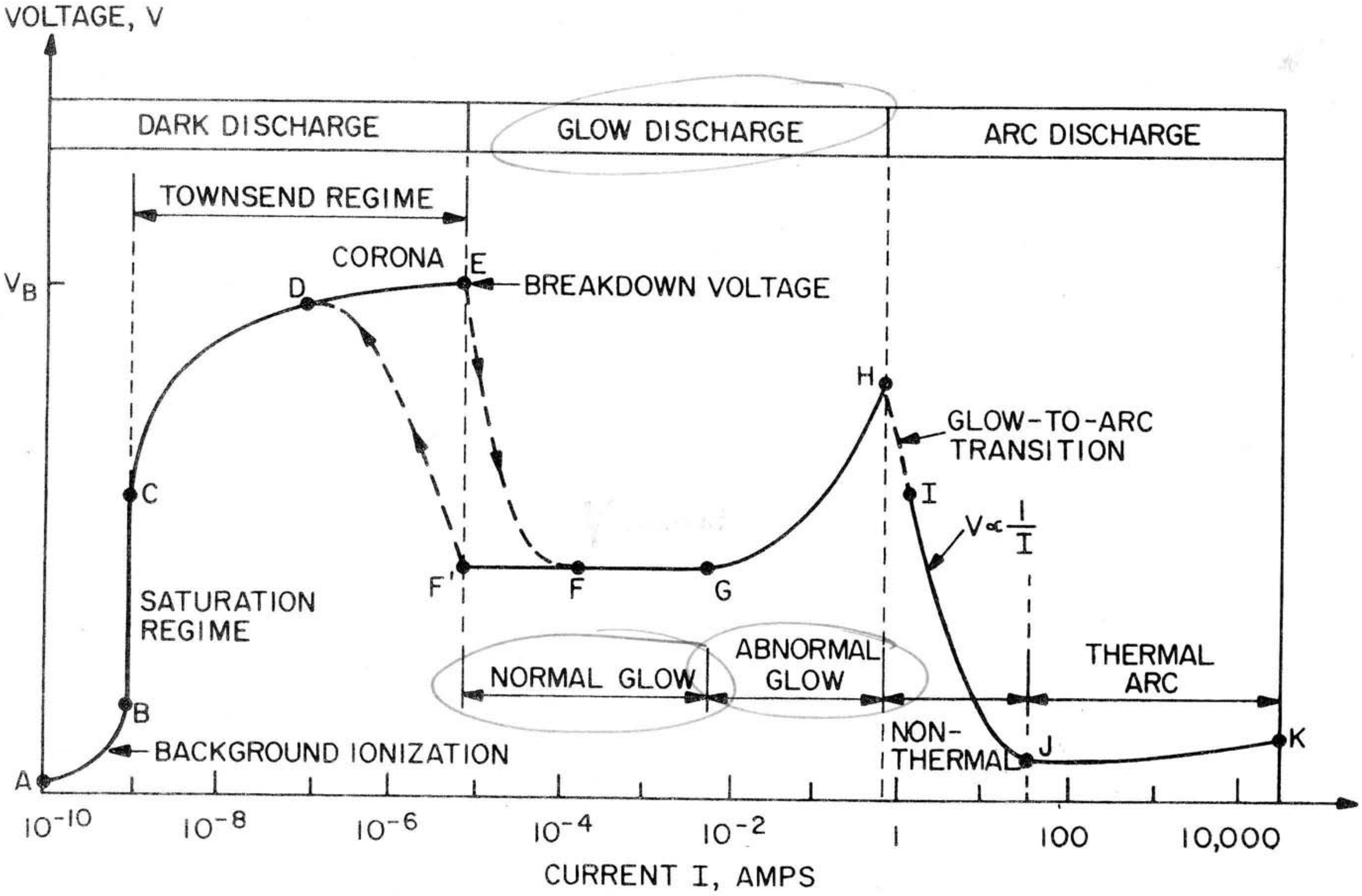
Paschen‘s law





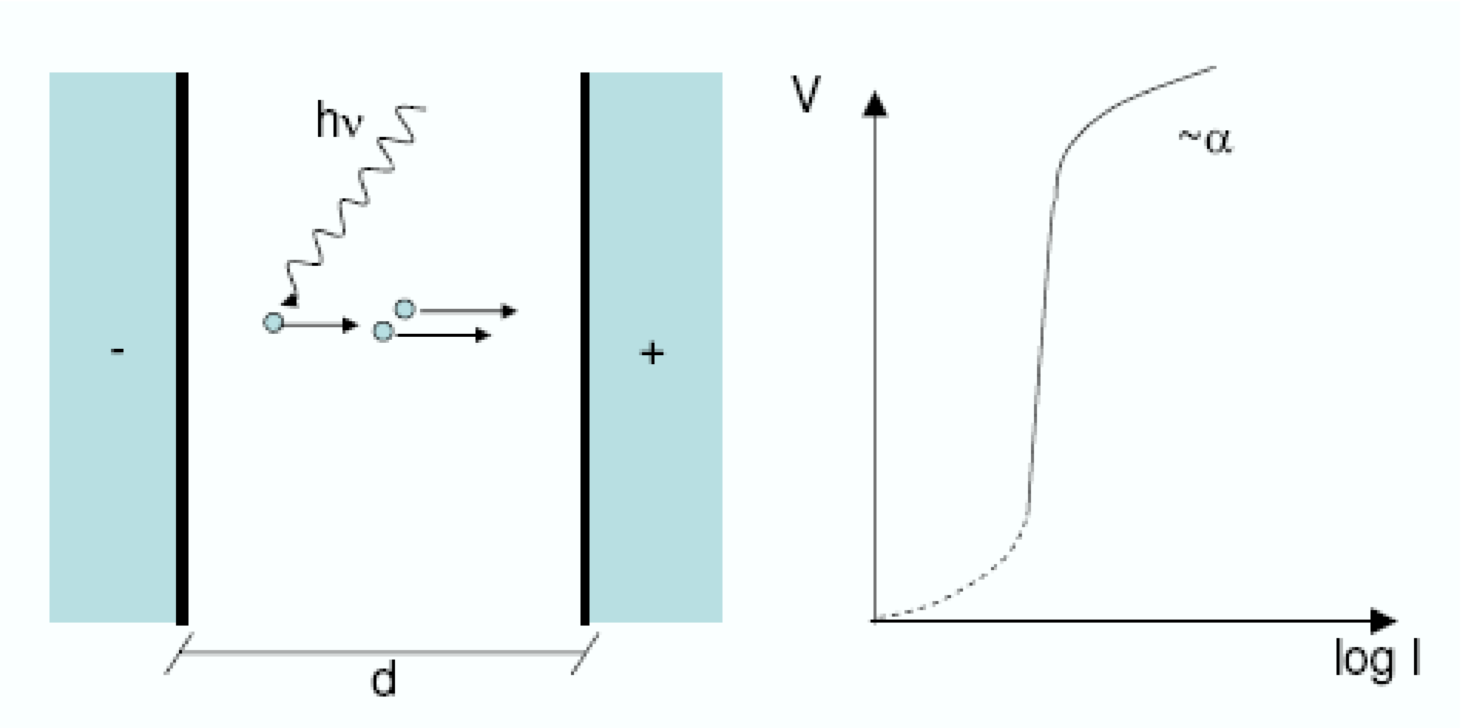
Johann W. Hittorf (1824-1914)

3.2. Stationary Gas Discharges

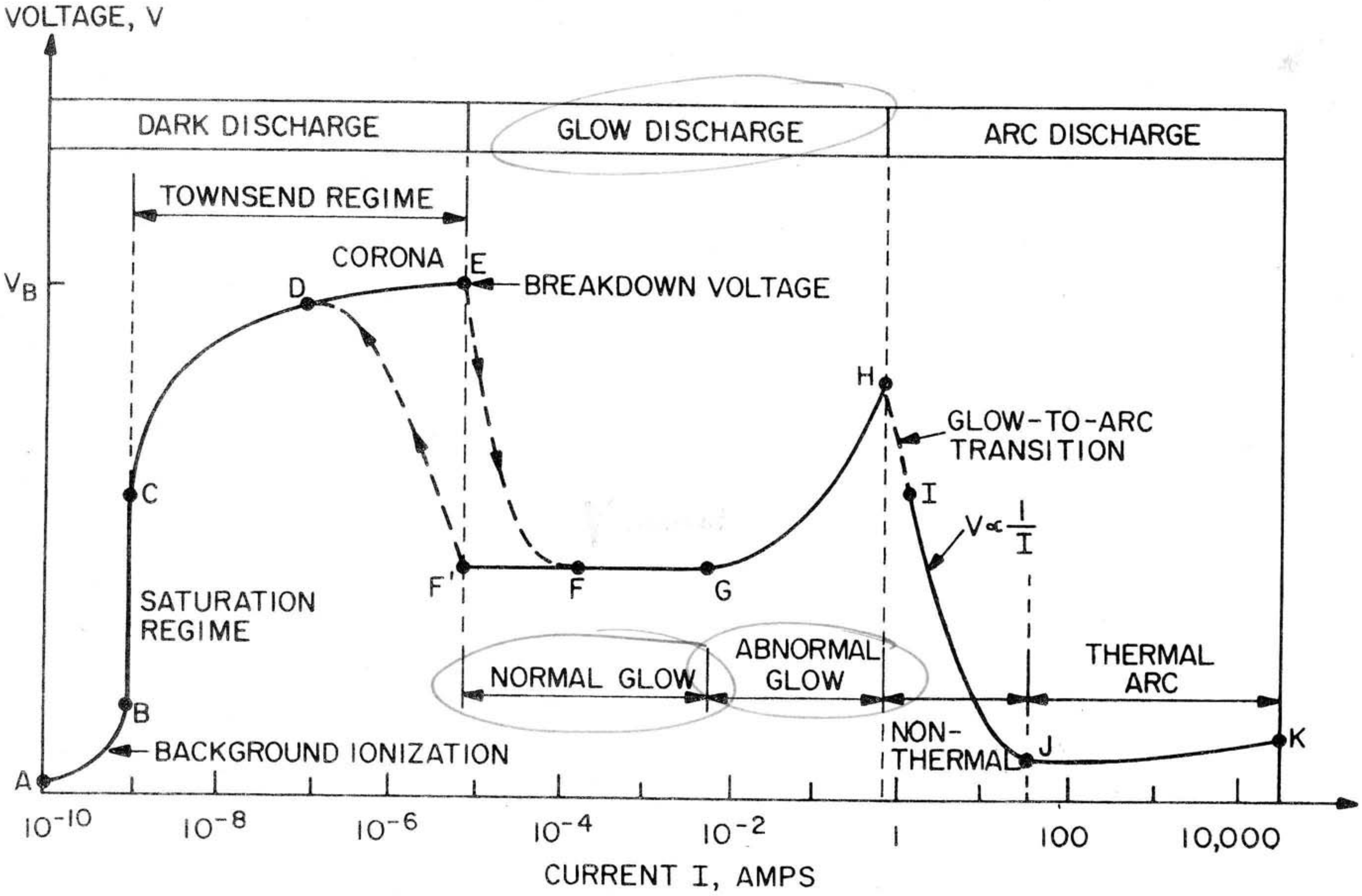


3.2. Stationary Gas Discharges

Townsend discharge

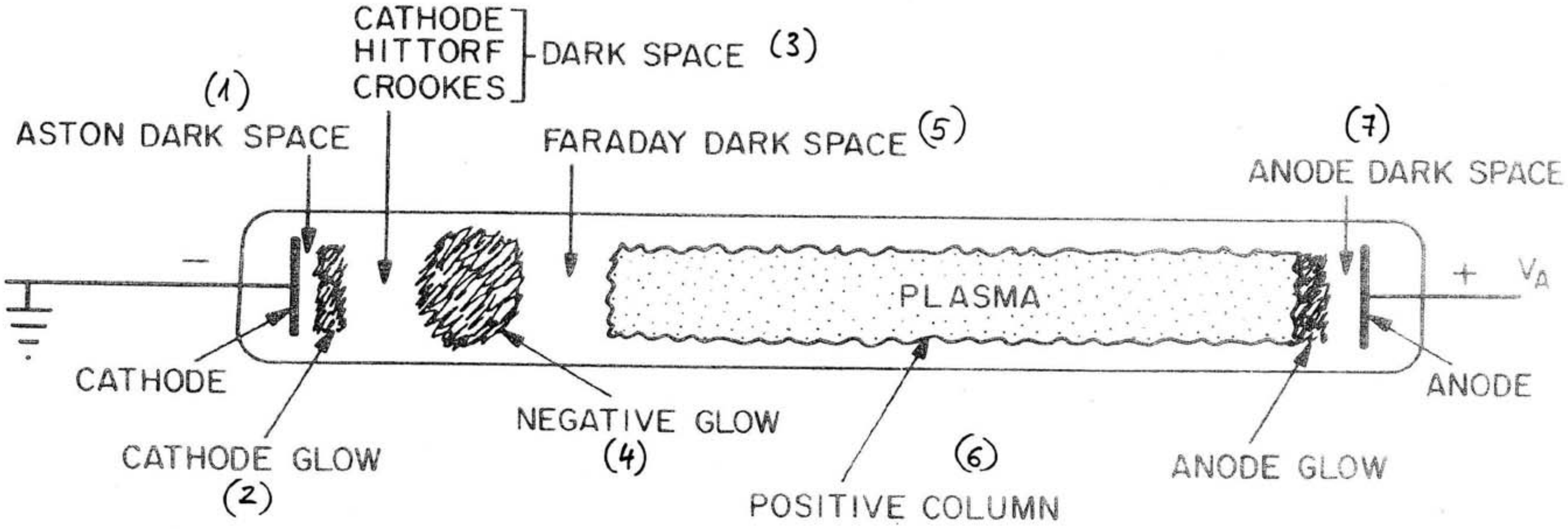


3.2. Stationary Gas Discharges



3.2. Stationary Gas Discharges

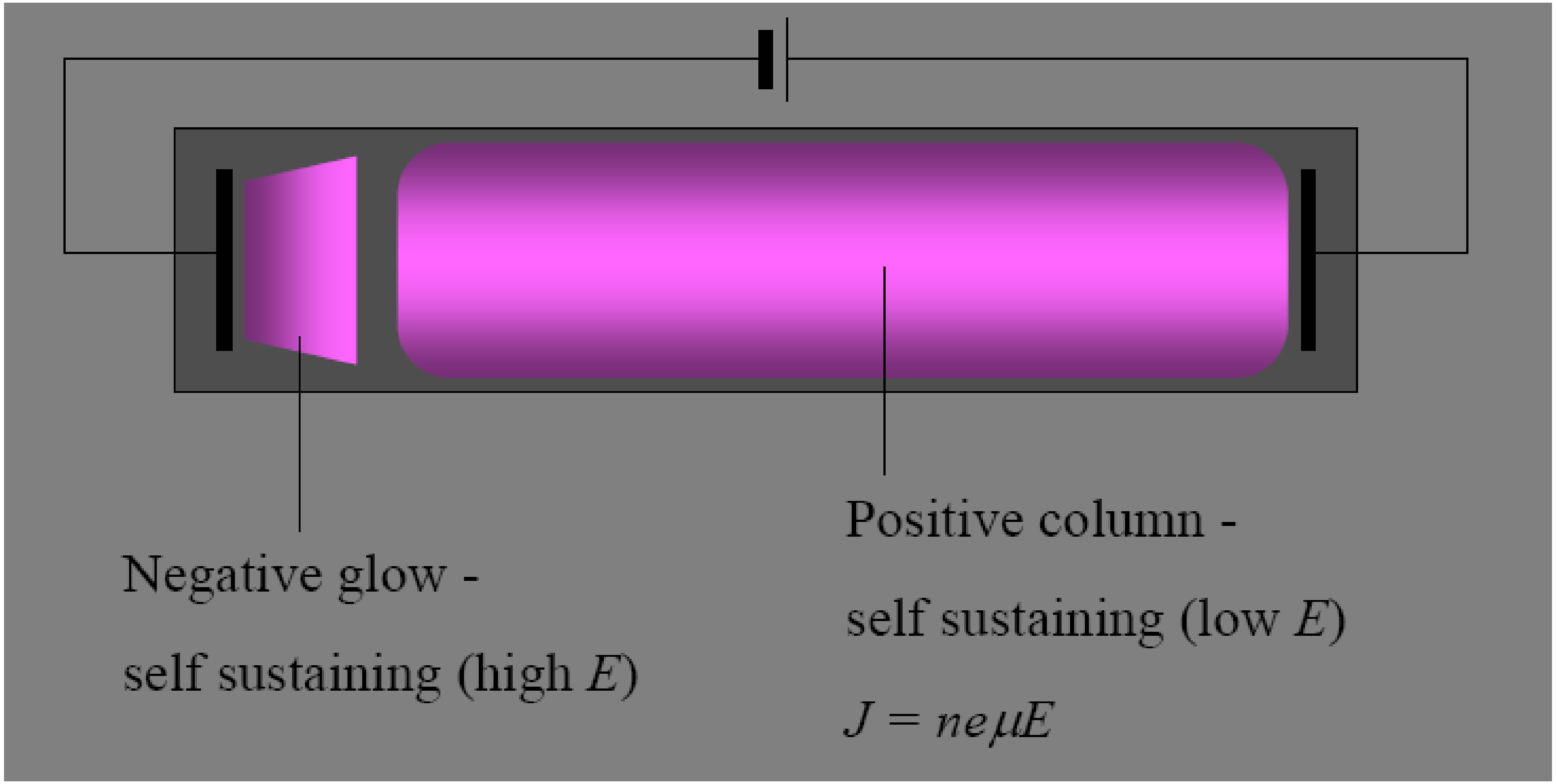
glow discharge



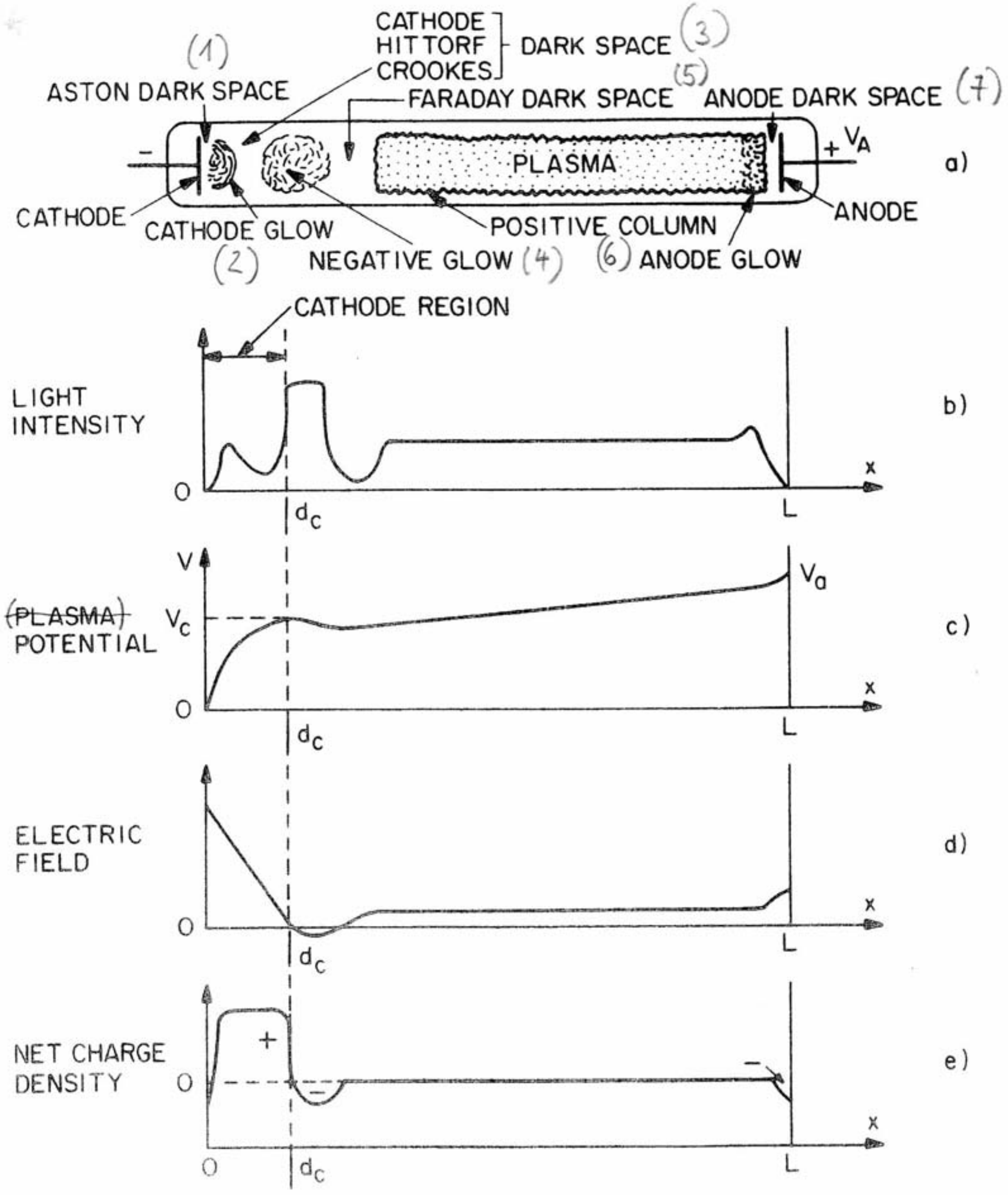
A schematic drawing of the visible regions of the normal glow discharge.

3.2. Stationary Gas Discharges

glow discharge



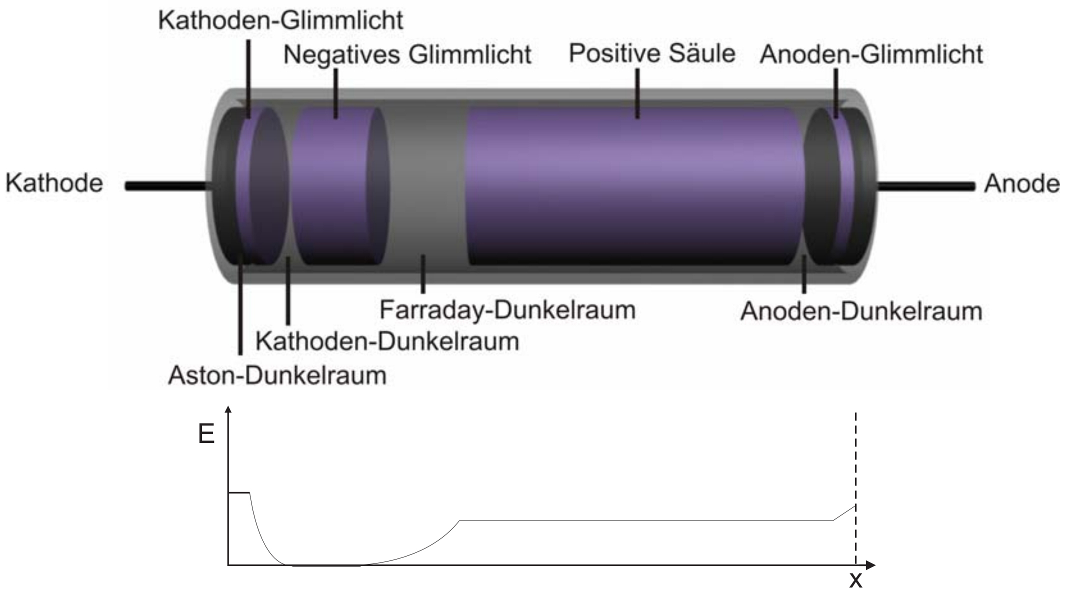
glow discharge



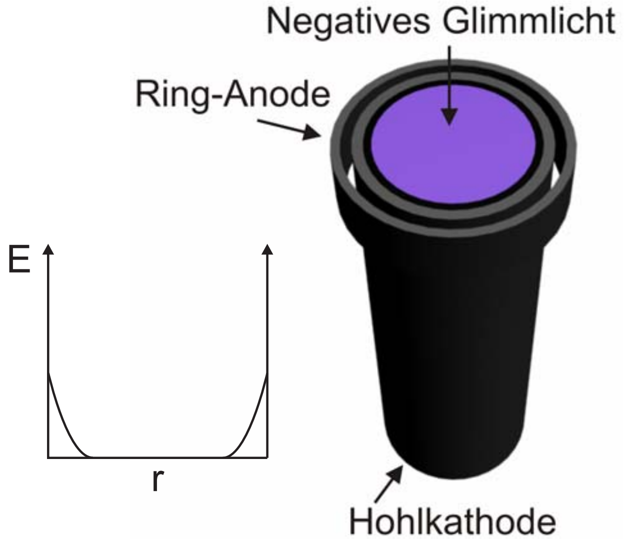
Axial variation of the characteristics of the normal glow discharge.

3.2. Stationary Gas Discharges

hollow cathode discharge

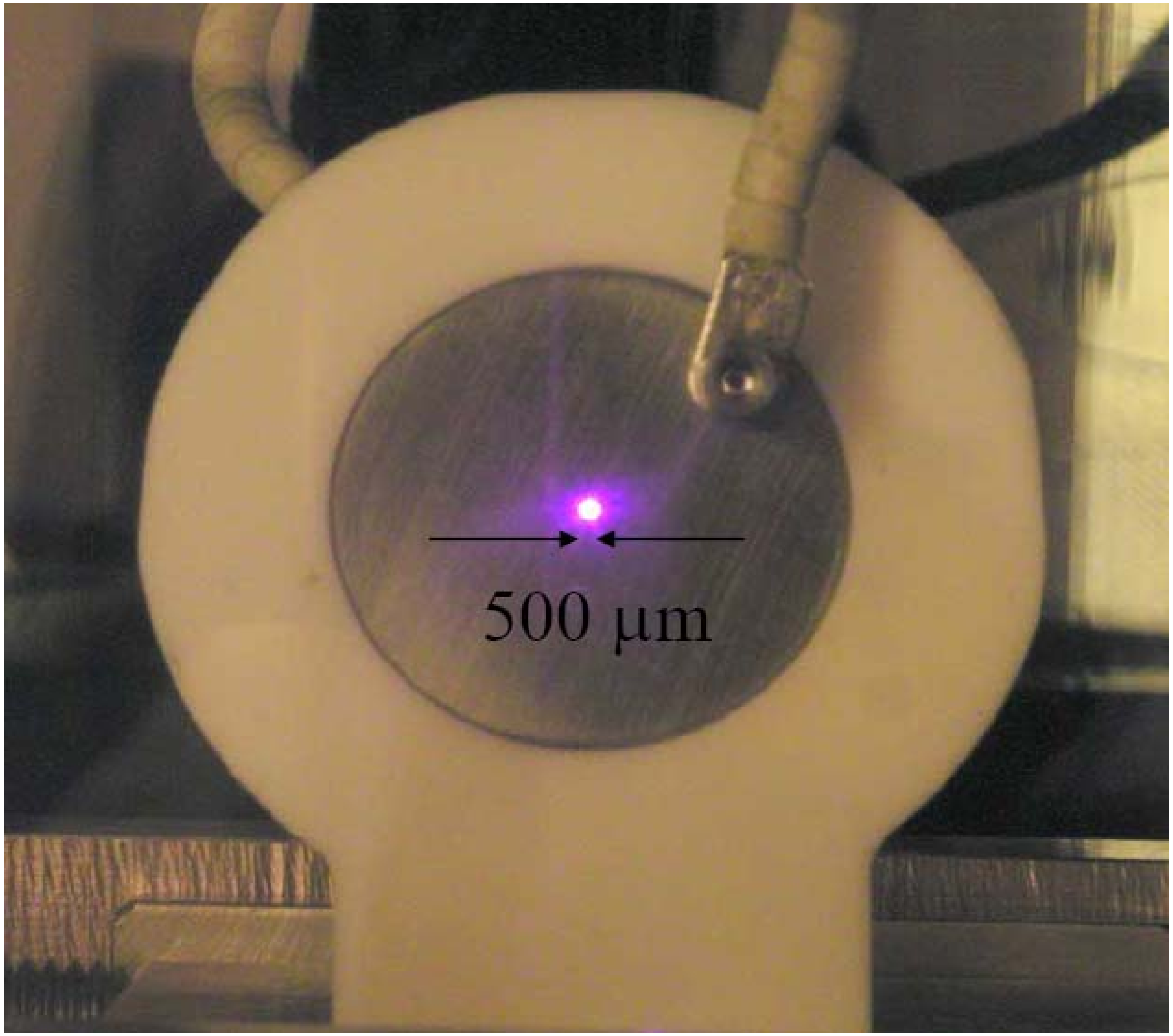


- cylindric cathode,
  ring shaped anode
  (at positive potential)
- merging of of glow edge
- „ideal plasma“: only negative glow
- oscillation of electrons → increase of
  ionization and dissociation
- hollow cathode effect



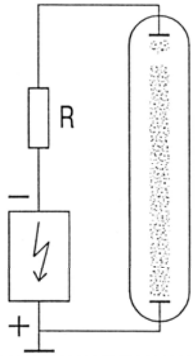
3.2. Stationary Gas Discharges

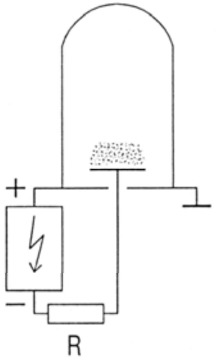
micro hollow cathode discharge

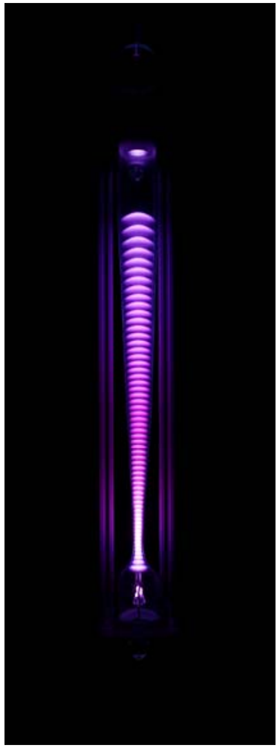


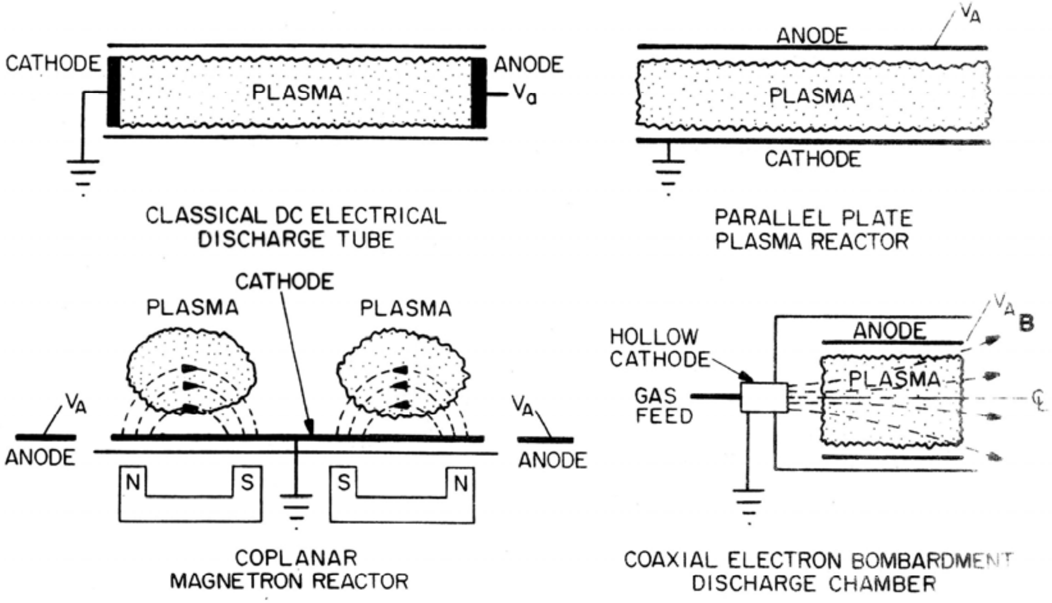
3.2. Stationary Gas Discharges

glow discharge









Various forms of the DC glow discharge.

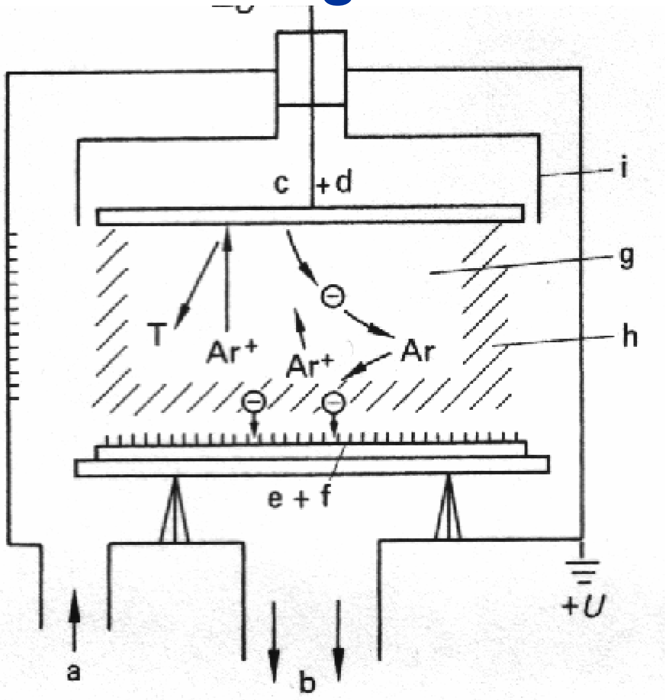
3.2. Stationary Gas Discharges

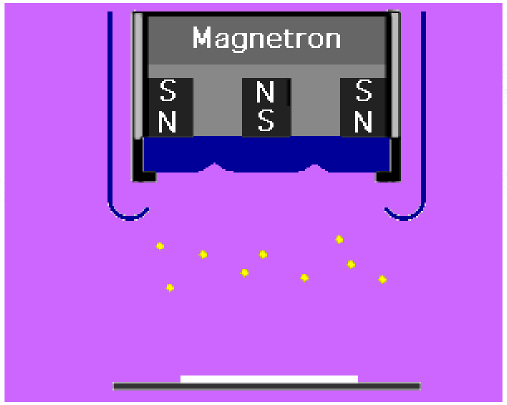
magnetron discharge

principle of dc cathode sputtering,
diode system

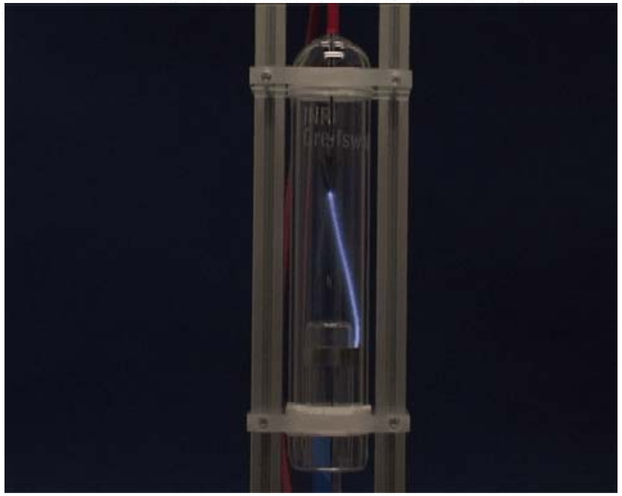
a gas flow
b pump
c cathode
d target
e anode
f deposited layer
g cathode fall
h positive column
I screening, shield

diode system (E)





magnetron system (E X B)

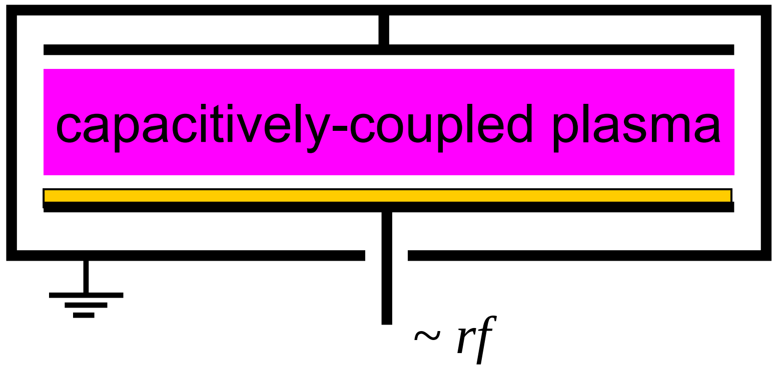


influence of magnetic field

3.2. Stationary Gas Discharges

rf discharge

- Capacitive discharges are used in etching and deposition



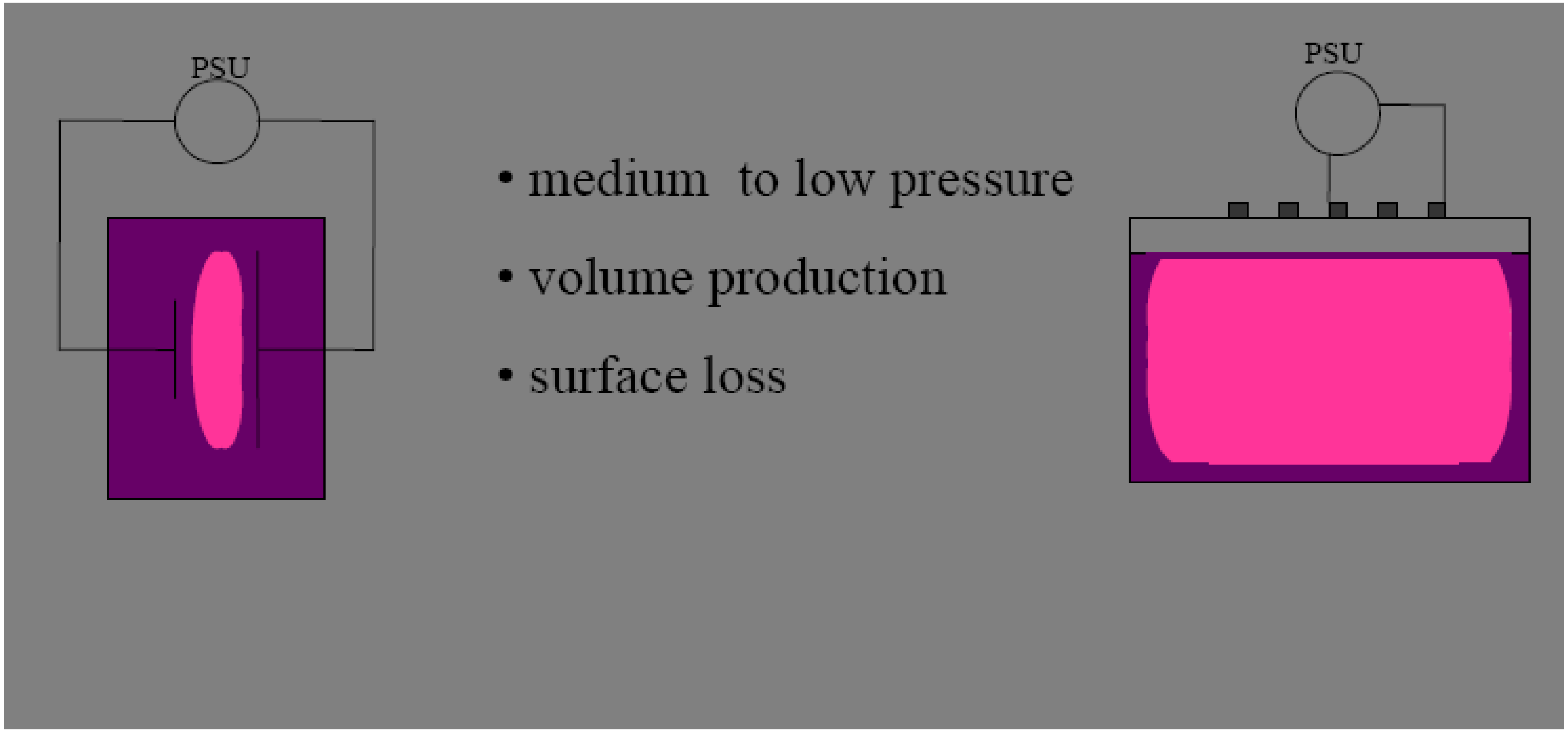
- Radiofrequency domain is such that electrons follow the rf field wile ions follow time-averaged field

- Ionization degree is small (<0.001)

- Gas pressure is low (a few Pa); collisionless heating is often dominant

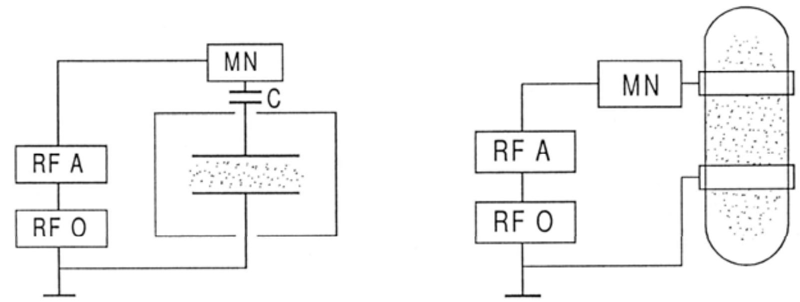
3.2. Stationary Gas Discharges

rf discharge : CCP, ICP

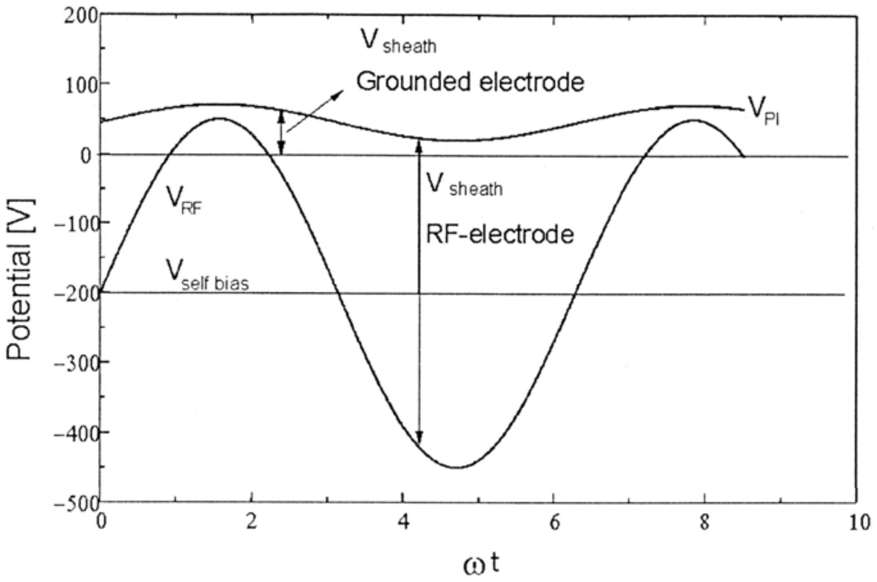


- medium to low pressure
- volume production
- surface loss

3.2. Stationary Gas Discharges

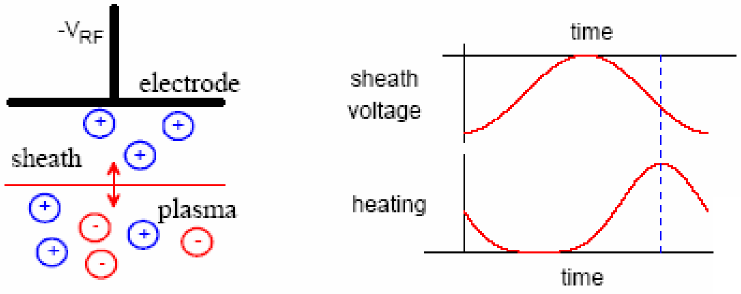


rf discharge : CCP, ICP



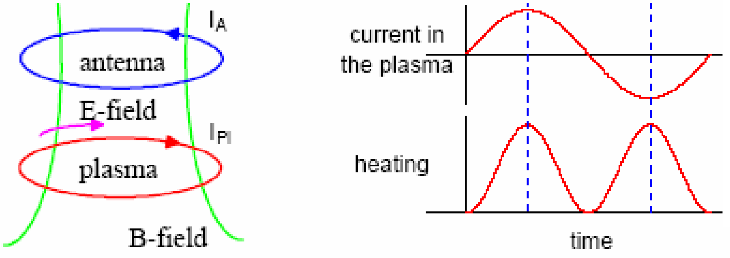
CCP-mode:

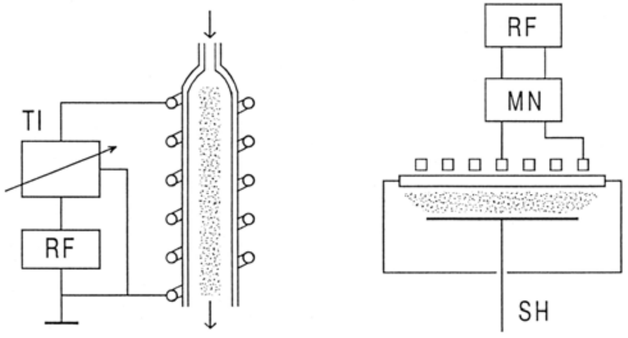
„piston“-principle



ICP-mode:

transformer-principle

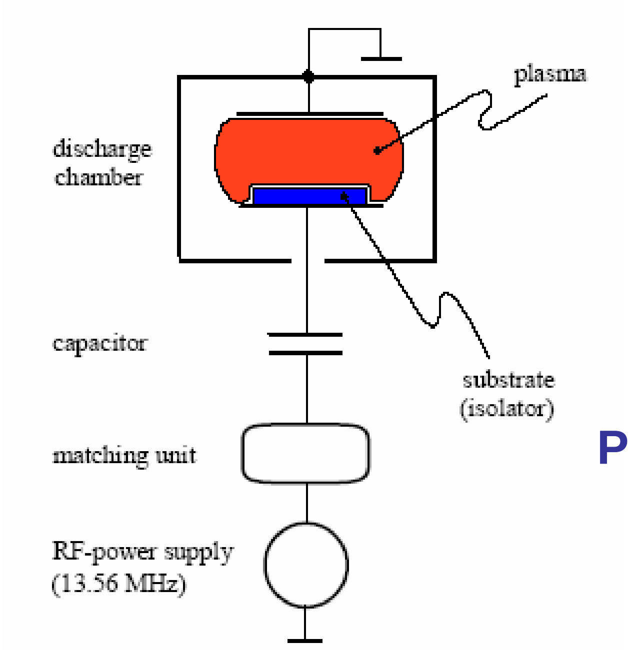




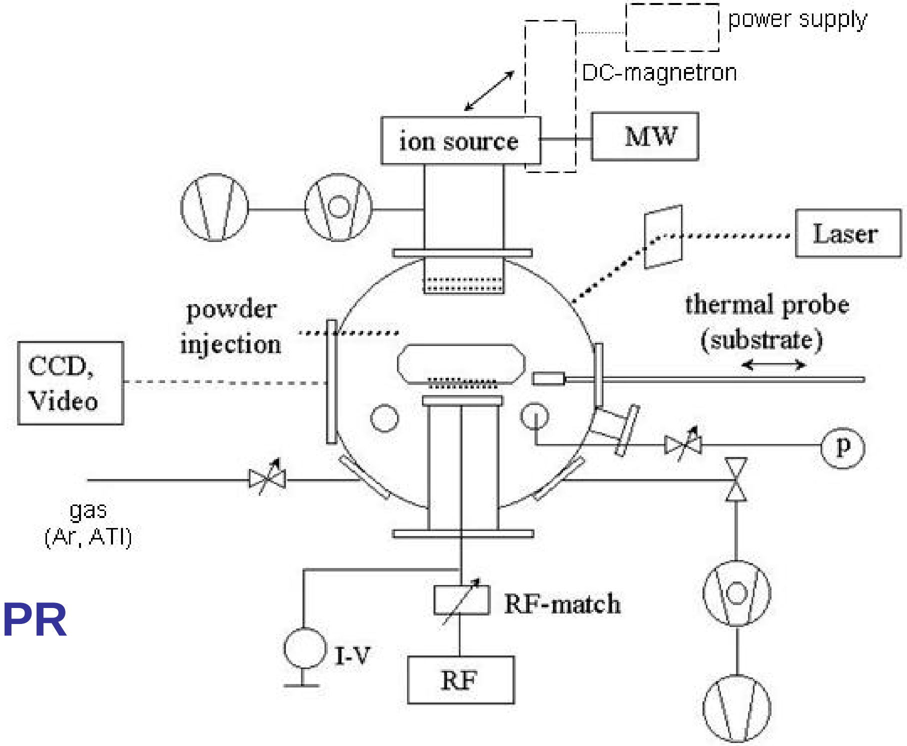
3.2. Stationary Gas Discharges

rf discharge : CCP

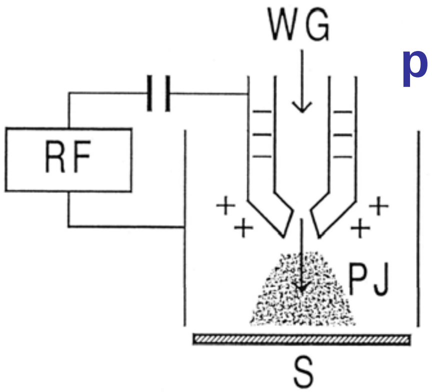
symmetric, asymmetric

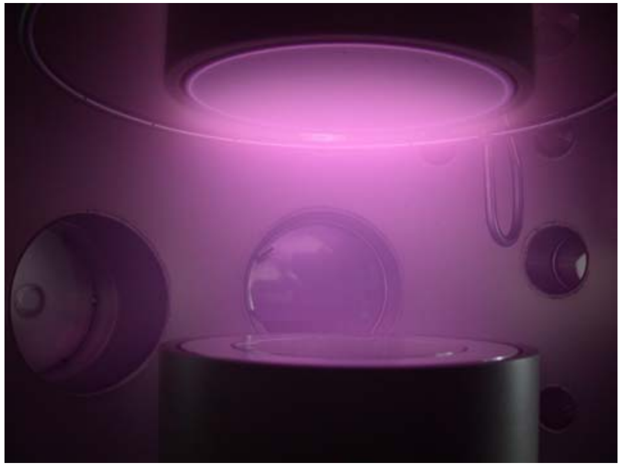


PPR



plasma jet

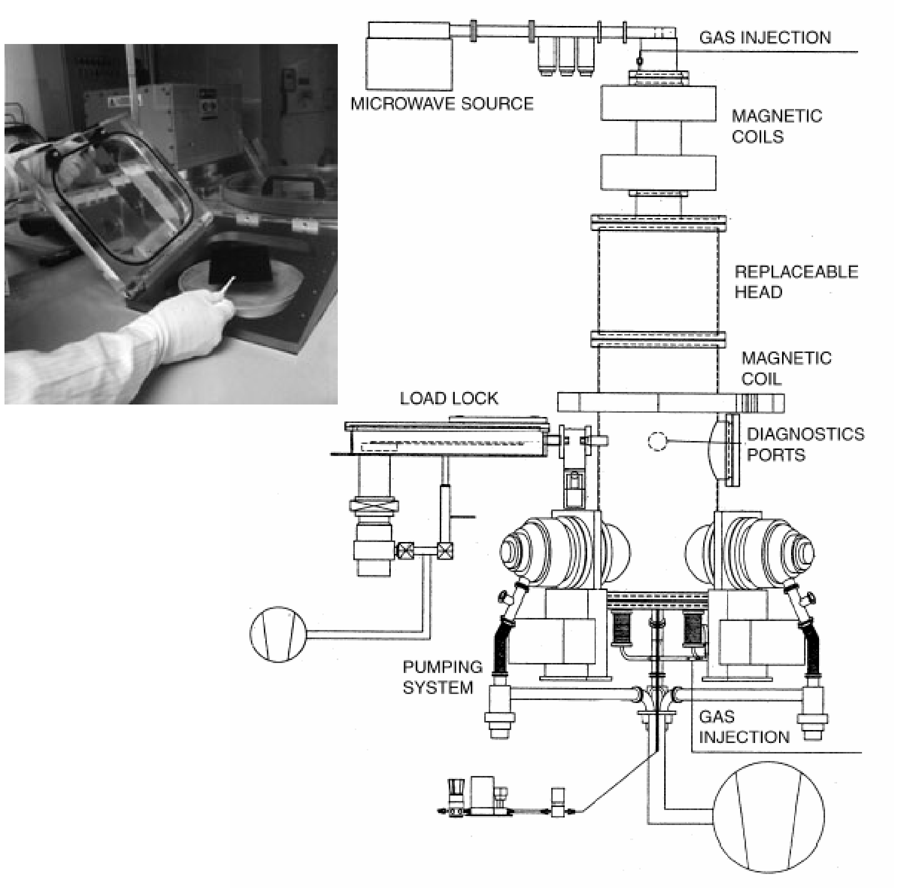


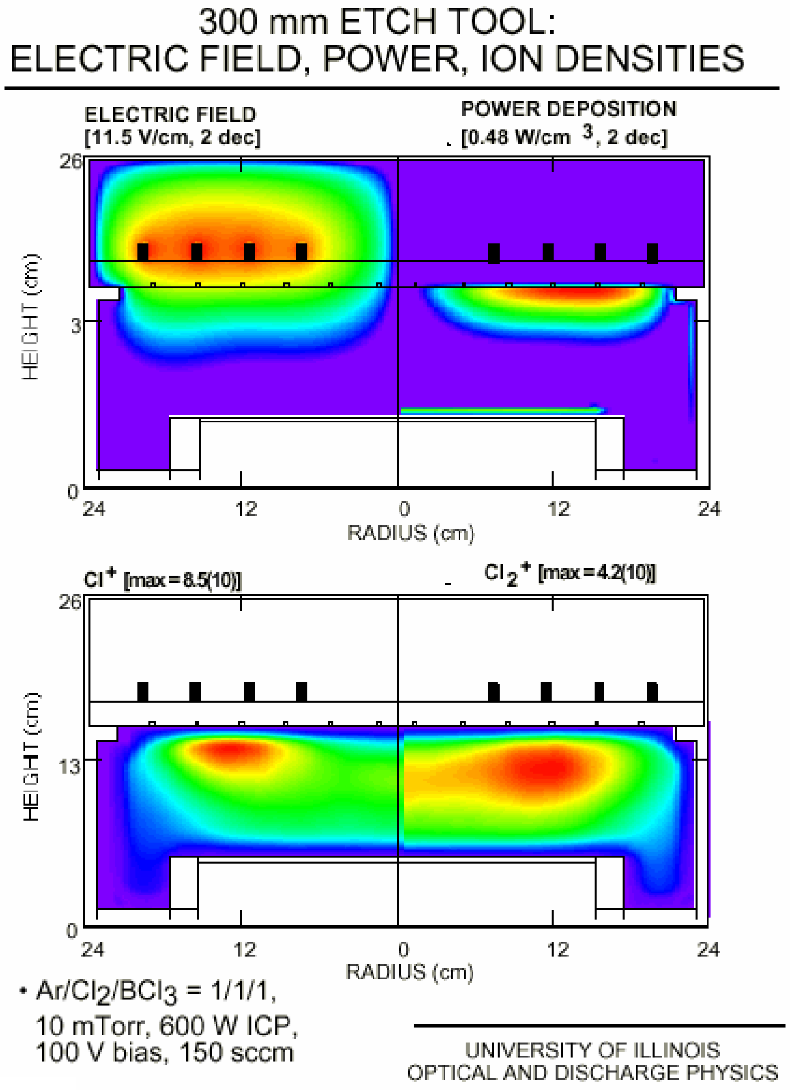


3.2. Stationary Gas Discharges

rf discharge : ICP

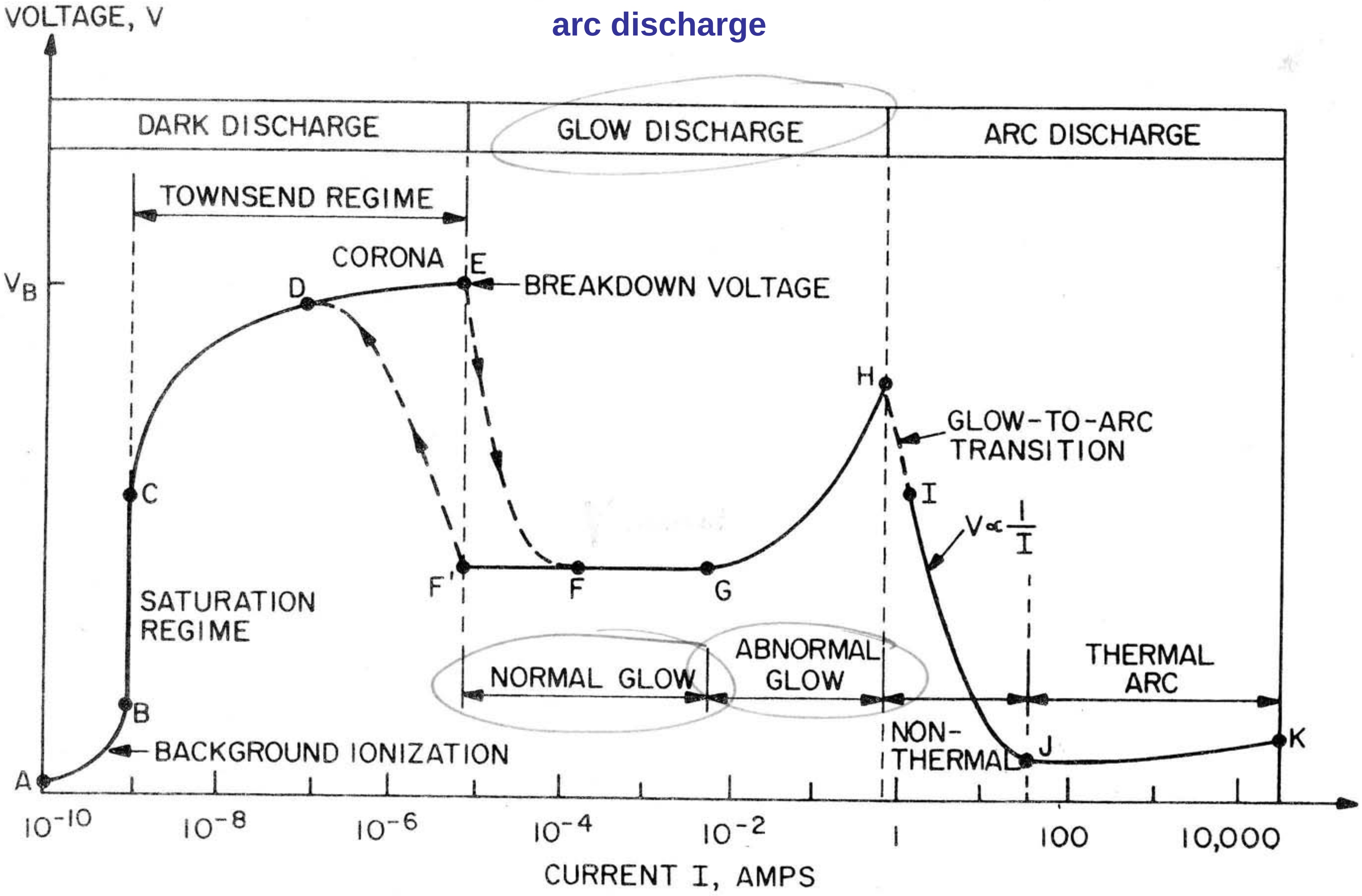
- plasma excitation by an electric field generated by the transformer principle
- changing magnetic field of the conductor induces an electric field in which the electrons are accelerated
- high plasma density





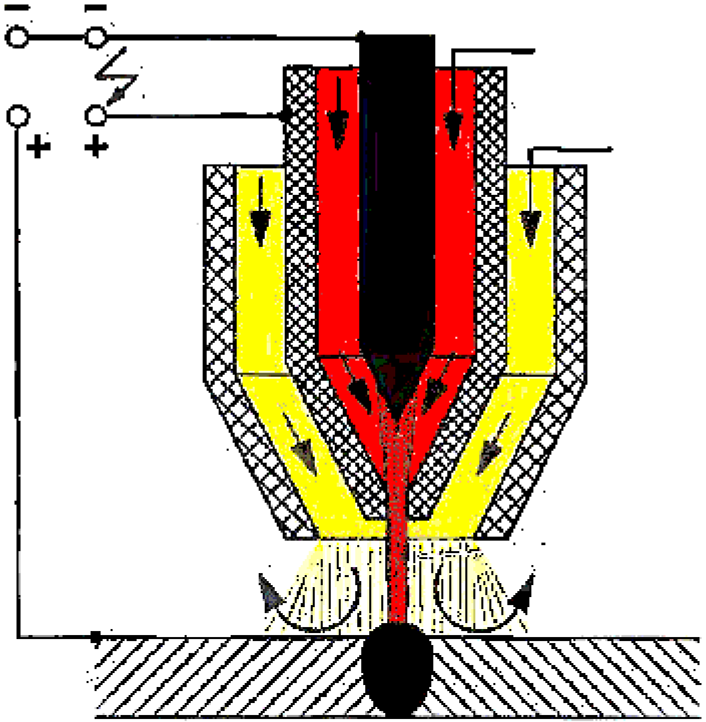
3.2. Stationary Gas Discharges

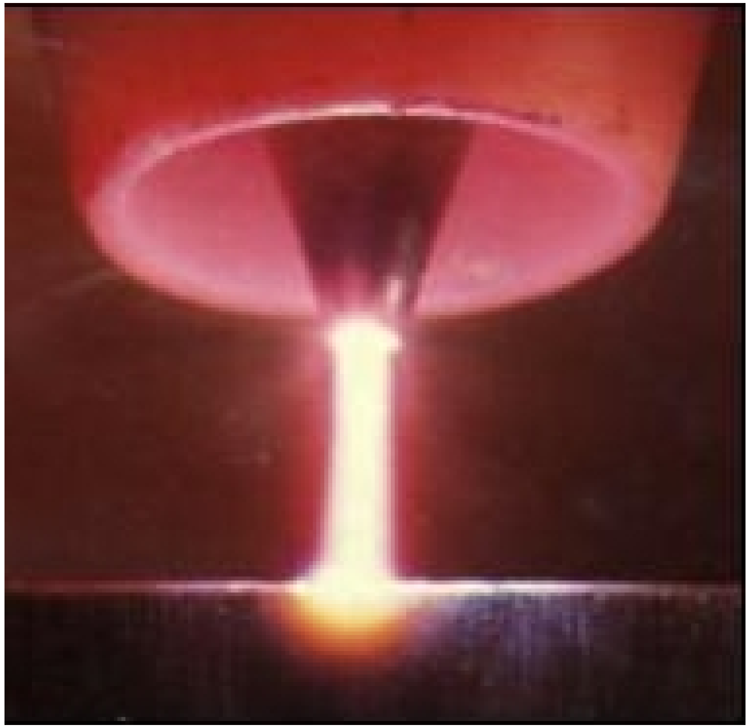
arc discharge



3.2. Stationary Gas Discharges

arc discharge



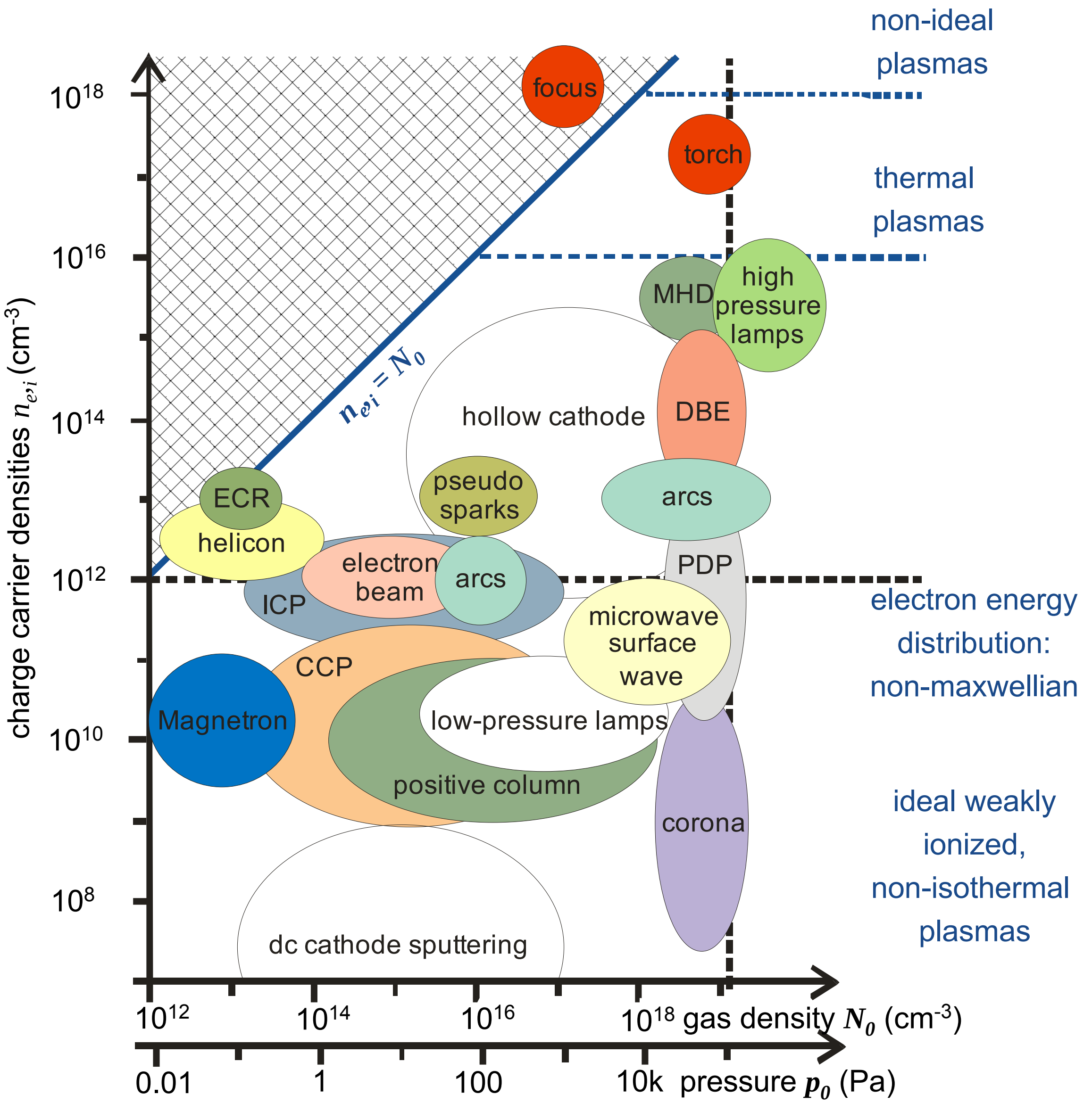


plasma welding and cutting

3.2. Stationary Gas Discharges

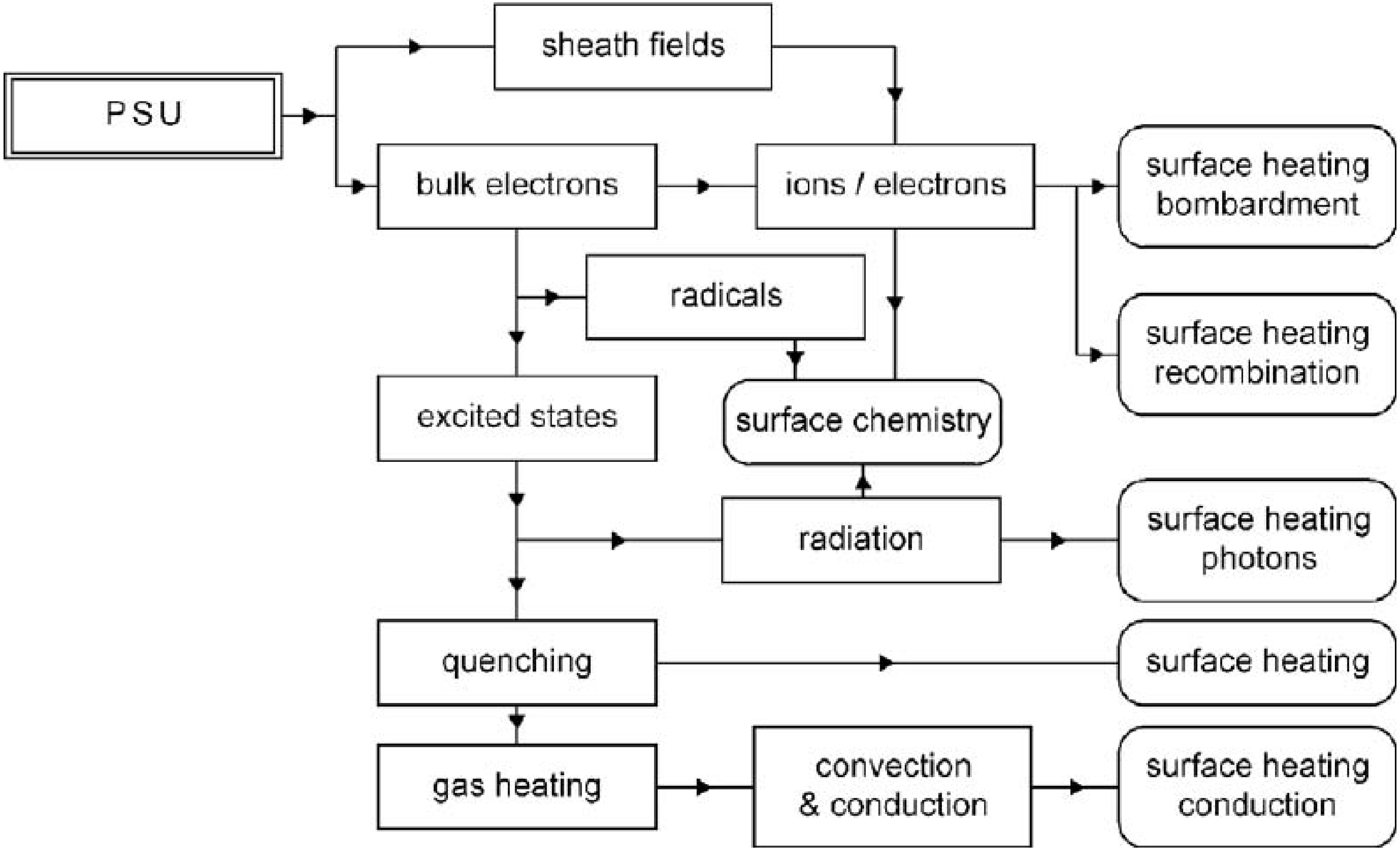
plasma sources at different gas and charge carrier densities

Coulomb-dominated plasmas



„reactive“ neutral-dominated plasmas

3.3. Plasma Surface Interaction



PSU

sheath fields

bulk electrons

ions / electrons

surface heating bombardment

radicals

surface heating recombination

excited states

surface chemistry

radiation

surface heating photons

quenching

surface heating

gas heating

convection & conduction

surface heating conduction

3.3. Plasma Surface Interaction

plasma bulk

role of charge carriers in plasma :

- occurrence of electrical conductivity
- screening of electric fields
- occurrence of oscillations and waves, and corresponding instabilities
- interaction with magnetic fields
- formation of characteristic boundary sheaths due to contact with walls

characteristic dimensions / time constants :

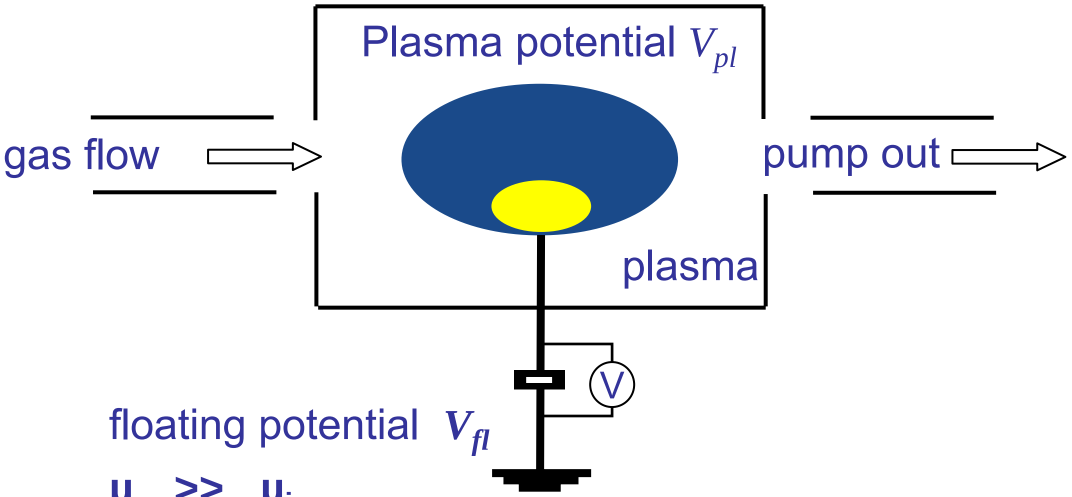
Debye length λ_D is the shielding length for the long range Coulomb interaction. It is the distance over which thermal motion causes significant deviations from quasi-neutrality

The **plasma frequency** ω_P is critical for the propagation of electromagnetic waves in plasmas (supply of energy).

3.3. Plasma Surface Interaction

plasma boundary sheath

plasma in contact with floating wall:



μ_e >> μ_i

$\Rightarrow$ wall charges up until ion flux equals electron flux

$$\boxed{j_j = \frac{n_i e v_i}{4} = j_e = \frac{n_e e v_e}{4}}$$

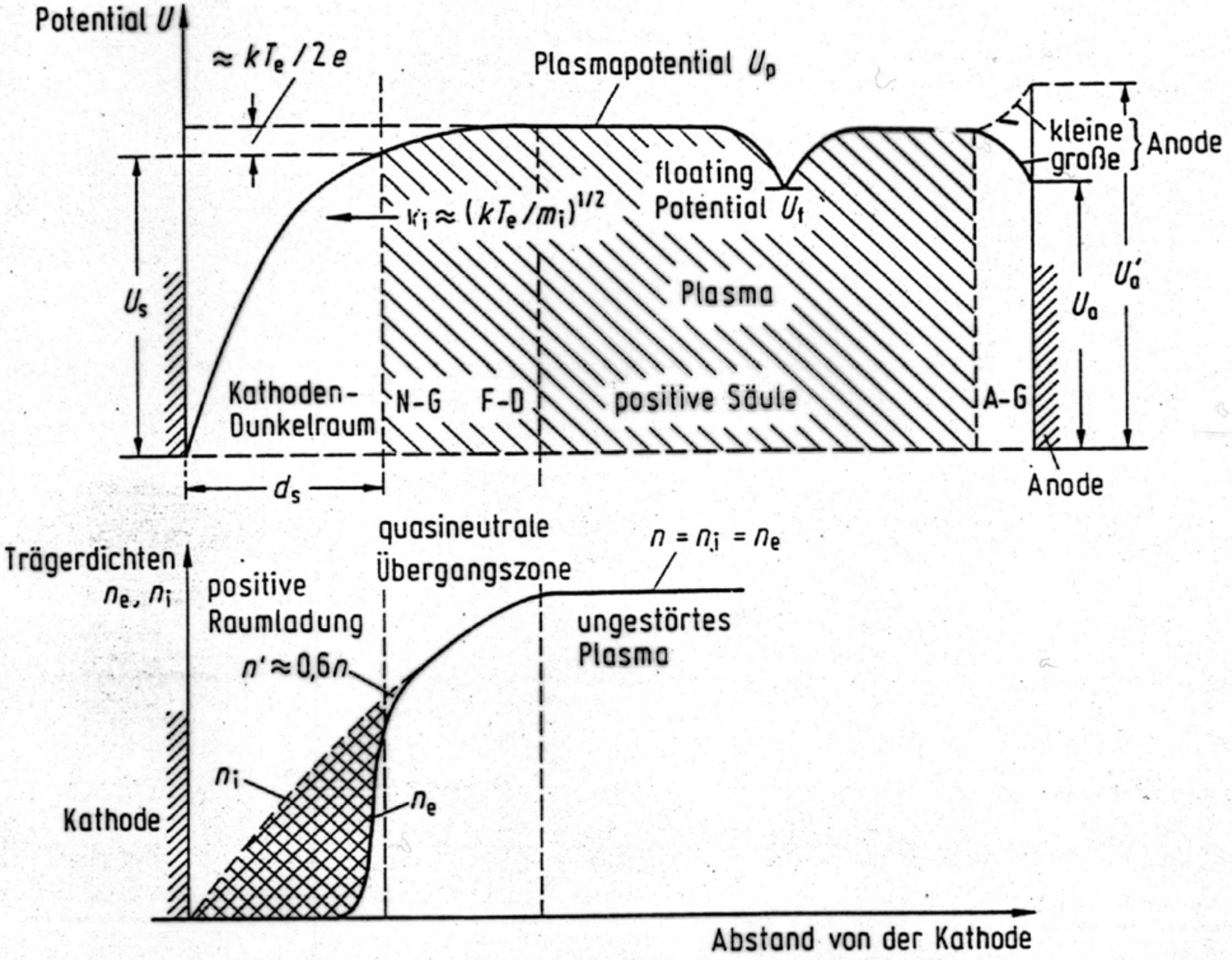
sheath formation: $\boxed{n_e = n_i \exp(-e(V_{pl} - V_{fl})/kT_e)}$

sheath potential: $\boxed{V_{bias} = V_{fl} - V_{pl} = -\frac{kT_e}{2}\ln(m_i/m_e)}$

or for additional V_s, then : $V_{bias} = V_s - V_{pl}$

3.3. Plasma Surface Interaction

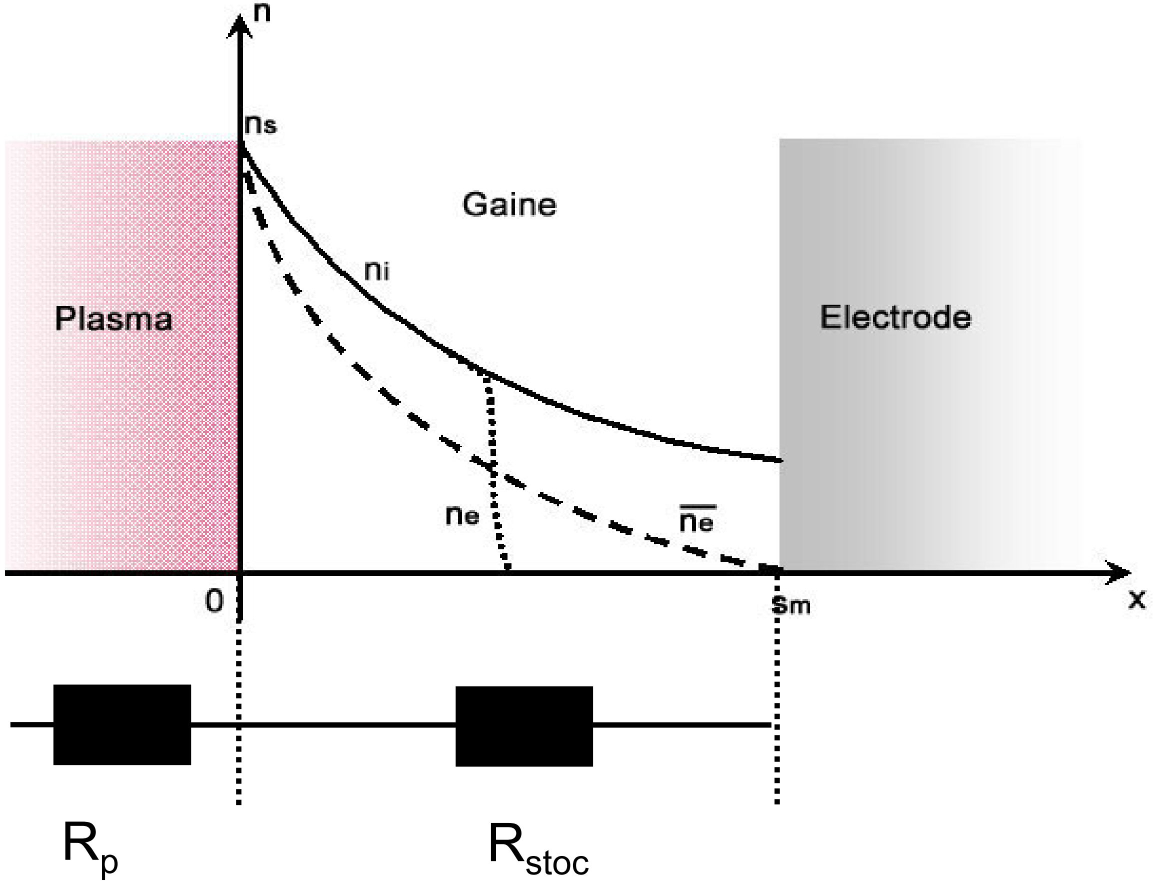
plasma boundary sheath



potential and charge carrier density for a typical glow discharge

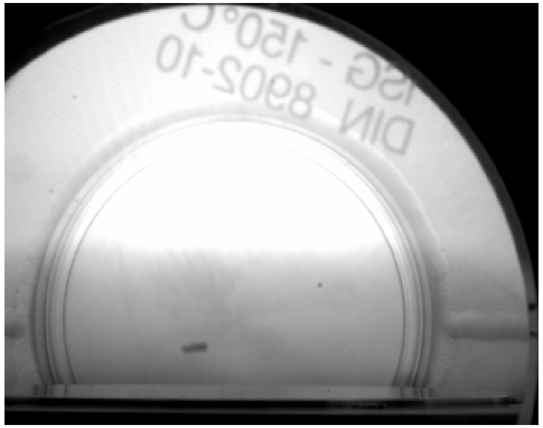
3.3. Plasma Surface Interaction

plasma boundary sheath

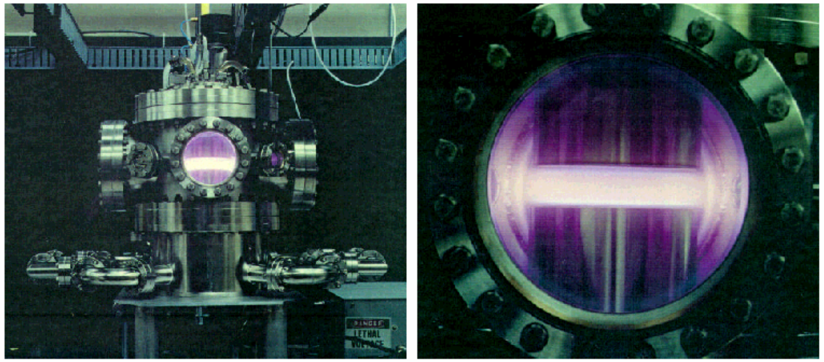


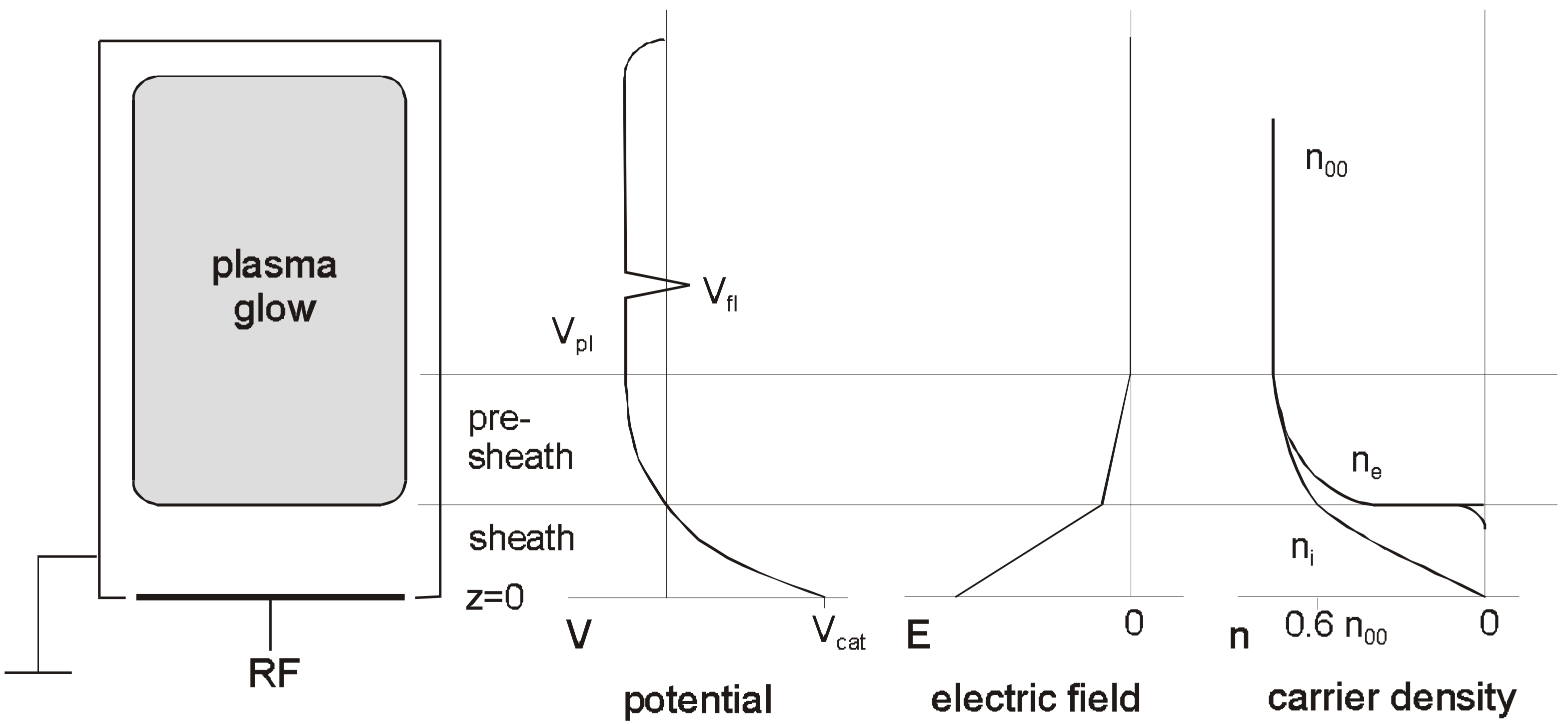
collisionless power
dissipation in the sheath

3.3. Plasma Surface Interaction



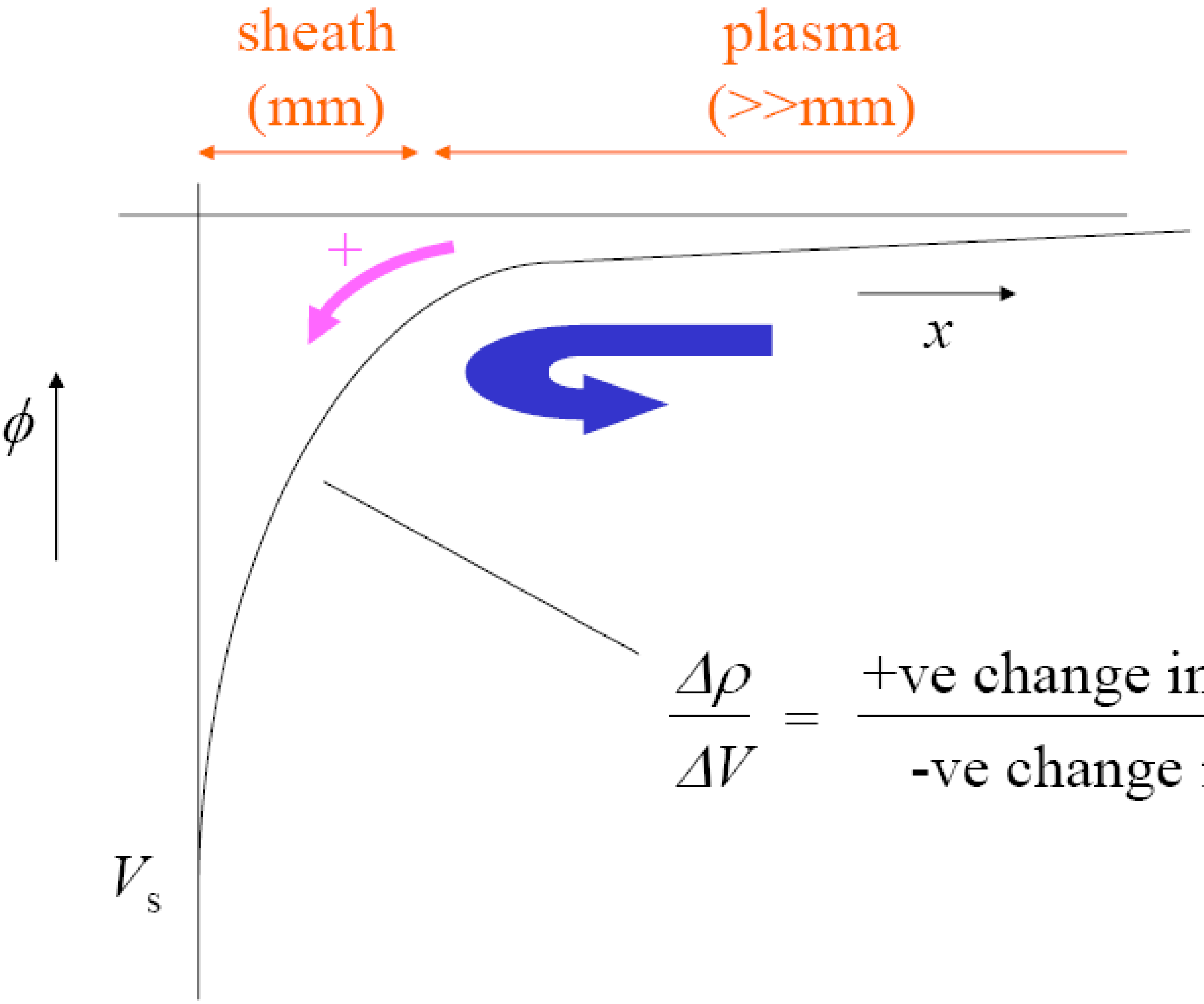
Gaseous Electronics Conference Reference Cell





3.3. Plasma Surface Interaction

plasma boundary sheath



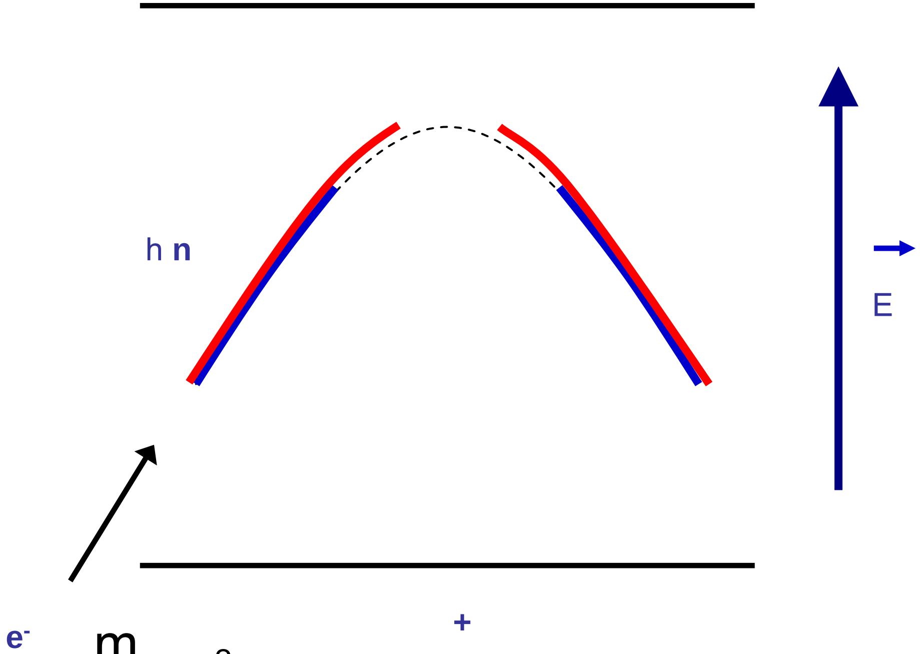
$$\frac{\Delta\rho}{\Delta V} = \frac{\text{+ve change in space charge}}{\text{-ve change in potential}}$$

3.3. Plasma Surface Interaction

plasma boundary sheath

Rudolf Seeliger
Universität Greifswald
1918 -1955

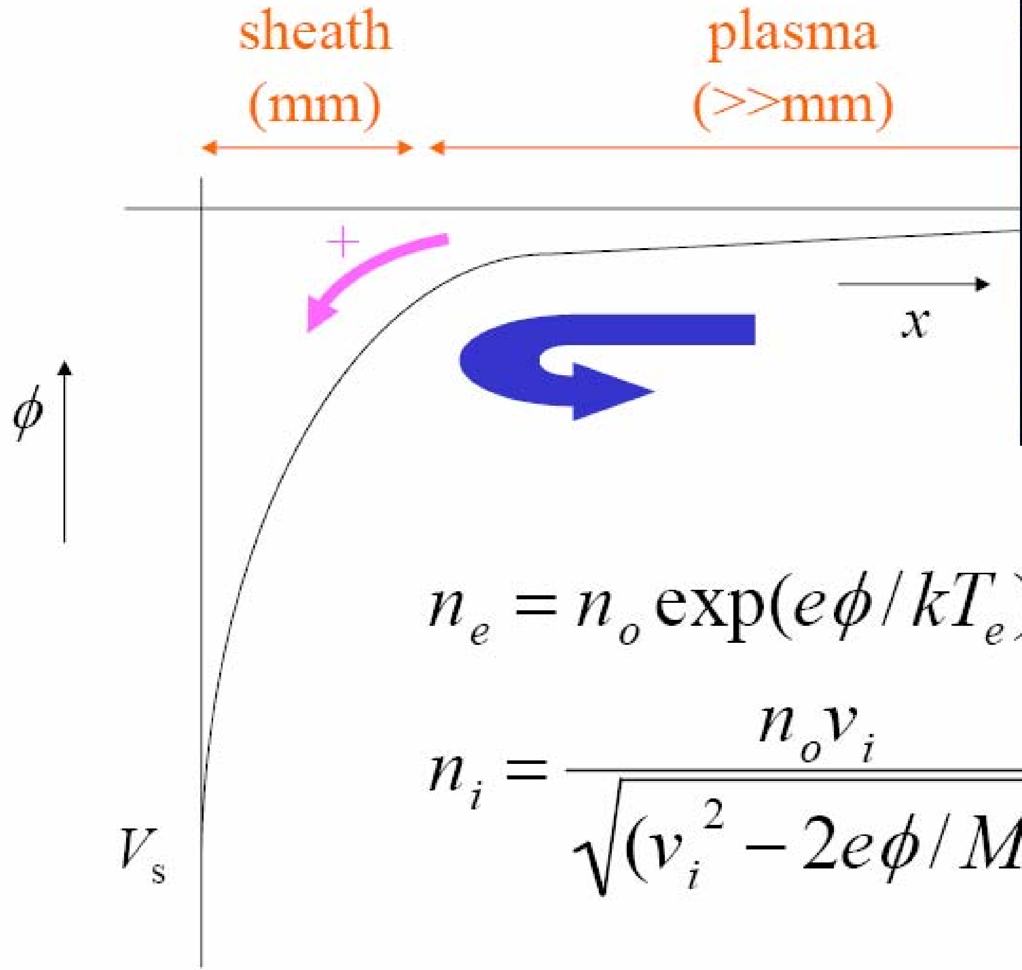
Gehrcke-Seeliger-Demo.exe



$$\frac{m_e}{2} \cdot v^2 = e \cdot U$$

3.3. Plasma Surface Interaction

plasma boundary sheath



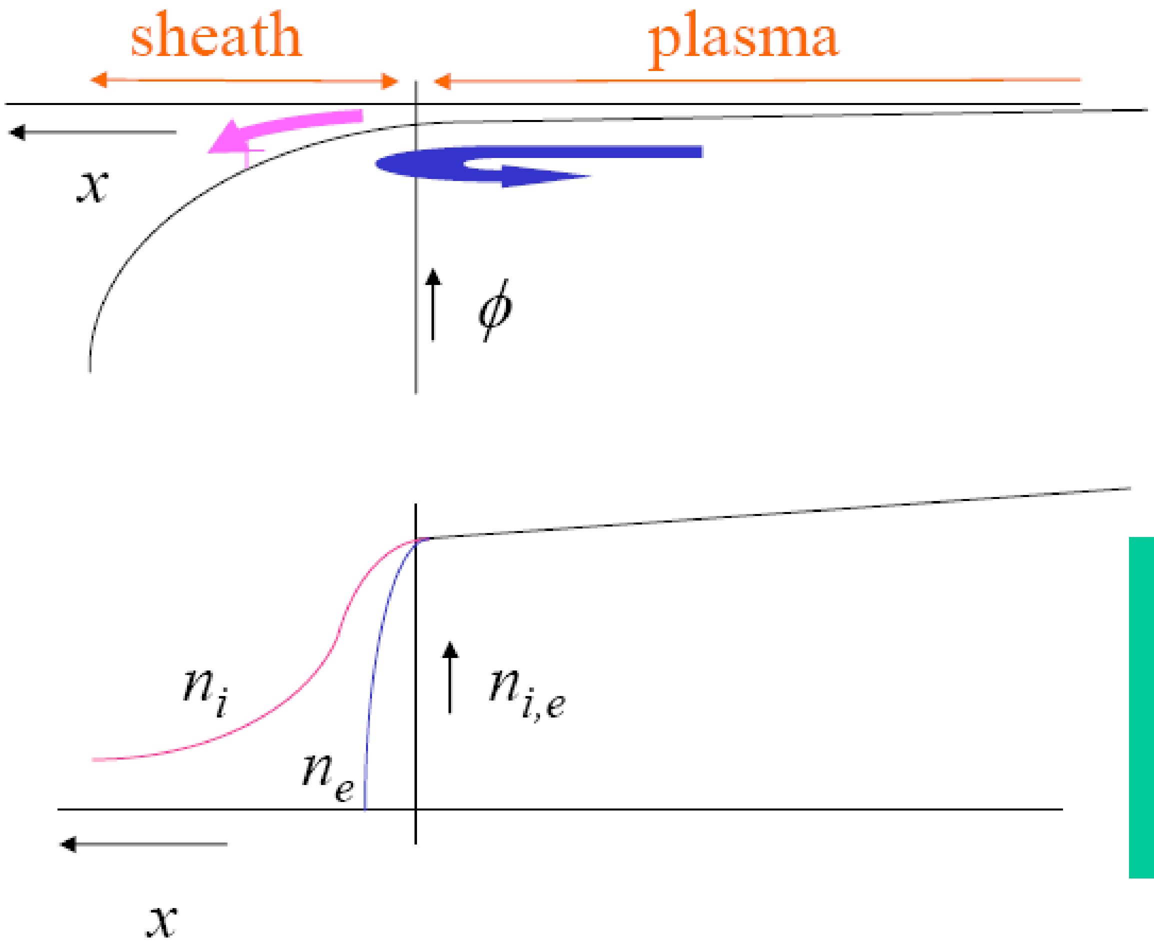
G. Arnell Williams: www.dramainnature.com

$$n_e = n_o \exp(e\phi / kT_e)$$ Boltzmann

$$n_i = \frac{n_o v_i}{\sqrt{(v_i^2 - 2e\phi / M)}}$$ Free-fall

3.3. Plasma Surface Interaction

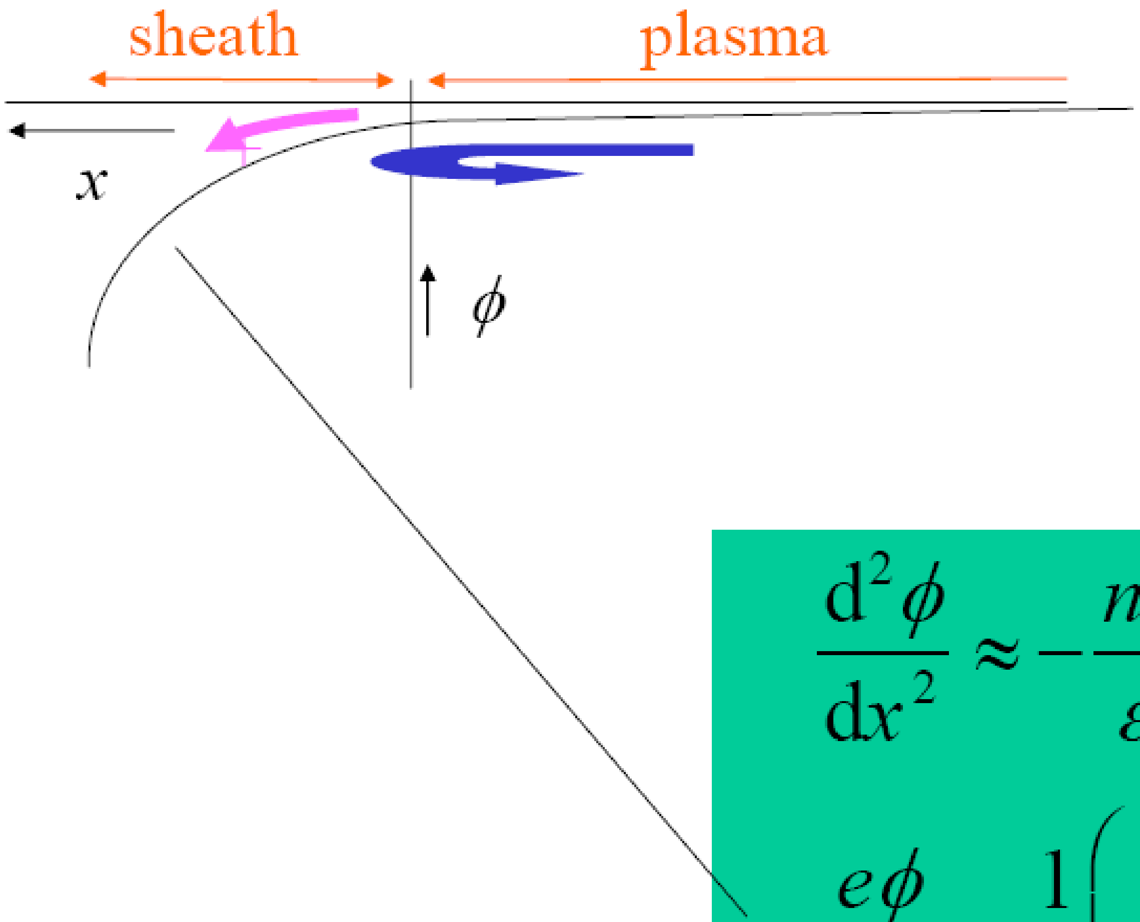
plasma boundary sheath



$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} \approx -\frac{n_i e}{\varepsilon_o}$$

3.3. Plasma Surface Interaction

plasma boundary sheath : Child-Langmuir



Child-Langmuir

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} \approx -\frac{n_i e}{\varepsilon_o}$$

$$\frac{e\phi}{kT_e} = \frac{1}{2}\left(\frac{3}{\sqrt{2}}\frac{x}{\lambda_D}\right)^{4/3}$$

3.3. Plasma Surface Interaction

plasma boundary sheath : Child-Langmuir

Negative voltage pulse applied:

- *electrons are repelled*

  → ion matrix sheath

$$\omega_{pl,e}^{-1} = \left(\varepsilon_0 \, m_e / e^2 \, n_e\right)^{1/2}$$

- *ions are attracted*

  → expanding sheath

$$\omega_{pl,i}^{-1} = \left(\varepsilon_0 \, m_i / e^2 \, n_i\right)^{1/2}$$

- energetic ions arrive at substrate
- stationary sheath position may be reached if

ion current in plasma = space-charge limited current (Child current for given voltage and actual sheath thickness)

3.3. Plasma Surface Interaction

plasma boundary sheath : Child-Langmuir

- The transition zone between bulk plasma and a surface, the SHEATH, is fundamental in plasma-surface interaction, plasma-assisted deposition of films, and ion extraction in ion sources.
- Child Law (1911):

$$\boxed{j_i = \frac{4}{9}\left(\frac{2e\overline{Q}}{m_i}\right)^{1/2} \frac{\varepsilon_0 \left|\phi_{wall}\right|^{3/2}}{d^2}}$$

- Can be interpreted as
  - limited current density, *j*, for given distance, *d*, or
  - **adjusting sheath** thickness for given current density and voltage.

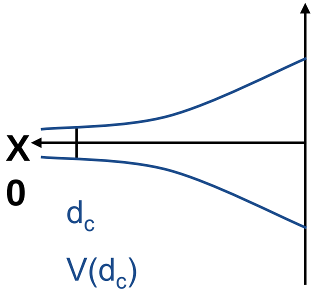
plasma boundary sheath : Child-Langmuir

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} = \frac{e_0}{\varepsilon_0}\left(n_e - n_i\right) \qquad \text{with } n_e = \frac{j_e}{e_0 v_e} = \frac{j_e}{-e_0 b_e E} \quad \text{and } n_i = \frac{j_i}{e_0 v_i} = \frac{j_i}{e_0\sqrt{\frac{2e_0V}{m_i}}}$$

$$\frac{d^2V}{dx^2} = -\frac{e_0}{\varepsilon_0}\left(\frac{j_e}{e_0 b_e E} + \frac{j_i}{\varepsilon_0\sqrt{\frac{2e_0V}{m_i}}}\right) = -\frac{dE}{dx} \qquad c_1 = \frac{j_e}{b_e\varepsilon_0} \qquad c_2 = \frac{j_i\sqrt{m_i}}{\varepsilon_0\sqrt{2e_0}}$$

$$\frac{dE}{dx} = \frac{c_1}{E} + \frac{c_2}{\sqrt{V}} \longrightarrow \frac{1}{2}\frac{d}{dx}\left[\left(\frac{dV}{dx}\right)^2\right] = c_1 + 2c_2\frac{d}{dx}\left(V^{\frac{1}{2}}\right) \quad = \frac{1}{2}d\left[\left(\frac{dV}{dx}\right)^2\right] = c_1 dx + 2c_2 d\left[\left(V^{\frac{1}{2}}\right)\right]$$

integration limits ?



d$_c$

V(d$_c$)

E(d$_c$)

$$\int_{E(d_c)}^{E(x)} d\left[\underset{\substack{\uparrow\\ E}}{\left(\frac{dV}{dx}\right)}^2\right] = 2c_1\int_{d_c}^{x} dx + 4c_2\int_{V(d_c)}^{V(x)} d\left[V^{\frac{1}{2}}\right]$$

$$\underset{\substack{\uparrow\\ \left(\frac{dV}{dx}\right)^2}}{E(x)^2} - E(d_c)^2 = 2c_1\left(x - d_c\right) + 4c_2\left(V(x)^{\frac{1}{2}} - \underset{\substack{\uparrow\\ \approx 0}}{V(d_c)^{\frac{1}{2}}}\right)$$

x : d$_c$ ... x

V : V(d$_c$) ... V(x)

E : E(d$_c$) ... E(x)

plasma boundary sheath : Child-Langmuir

$$\Rightarrow \frac{dV}{dx} = \left(2c_1\left(x-d_c\right)+4c_2\left(V\left(x\right)^{\frac{1}{2}}\right)+E\left(d_c\right)^2\right)^{\frac{1}{2}}$$

if sheath determined by positive space charges, then : $\mathrm{j_i} >> \sqrt{\frac{\mathrm{m_e}}{\mathrm{m_i}}}\ \mathrm{j_e} \Rightarrow c_1 << c_2 \Rightarrow c_1 \approx 0$

$$\frac{dV}{dx} \approx \left(4c_2\left(V\left(x\right)^{\frac{1}{2}}\right)+E\left(d_c\right)^2\right)^{\frac{1}{2}}$$

$$dV = \left(4c_2\left(V\left(x\right)^{\frac{1}{2}}\right)+E\left(d_c\right)^2\right)^{\frac{1}{2}} dx \longrightarrow dV \approx 2\sqrt{c_2}V\left(x\right)^{\frac{1}{4}}dx \qquad \int_0^{V_c}\frac{dV}{V\left(x\right)^{\frac{1}{4}}} = 2\sqrt{c_2}\int_{d_c}^{0}dx$$

$$\uparrow$$

$$\frac{\mathrm{V}\left(\mathrm{d_c}\right)^{\frac{1}{2}}}{d_c^{\ 2}} \approx 0$$

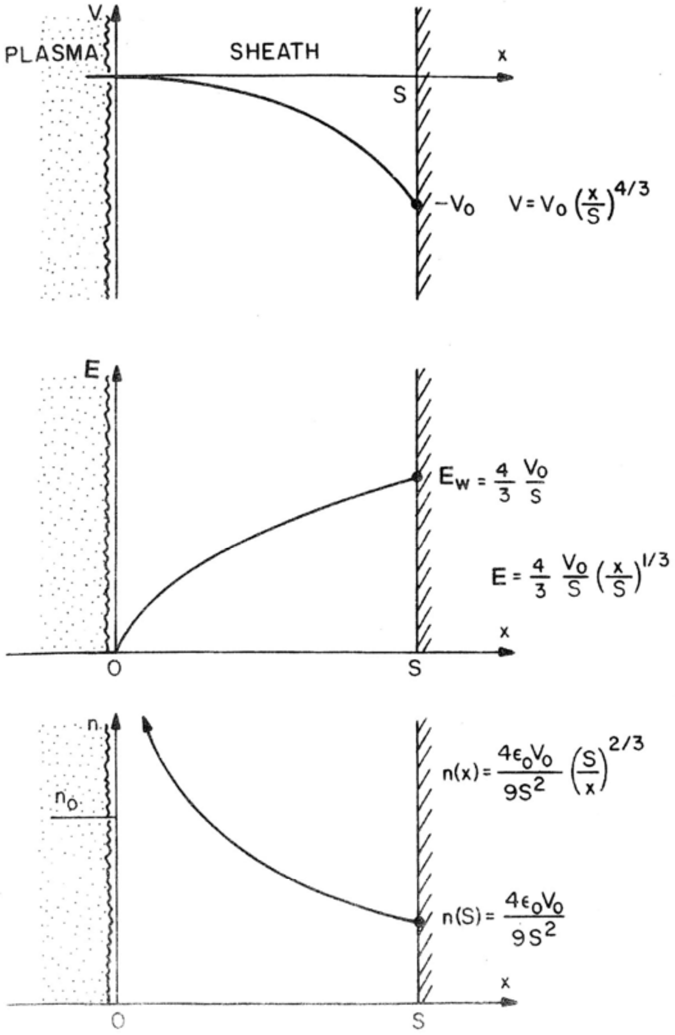
$$\frac{4}{3}V_c^{\frac{3}{4}} = -2\sqrt{c_2}dc \Rightarrow d_c^2 = \frac{4}{9}\frac{1}{c_2}V_c^{\frac{3}{2}}$$

$$d_c^2 = \frac{4}{9}V_c^{\frac{3}{2}}\frac{\varepsilon_0\sqrt{2e_0}}{j_i\sqrt{m_i}}$$

$$\left(p \le 10\,Pa\right) \leftrightarrow d_c \ge \lambda_{mpf}$$

$$\boxed{d_c^{\ 2} = \frac{4}{9}\frac{V_c^{\frac{3}{2}}}{j_i}\sqrt{\frac{2\varepsilon_0^{\ 2}e_0}{m_i}}} \longleftrightarrow \mathrm{j} = \frac{4\varepsilon_0}{9}\left(\frac{2e_0}{m_i}\right)^{\frac{1}{2}}\frac{V^{\frac{3}{2}}\left(x\right)}{d_c^{\ 2}} \qquad \mathrm{d_c} \sim d_{sh}$$

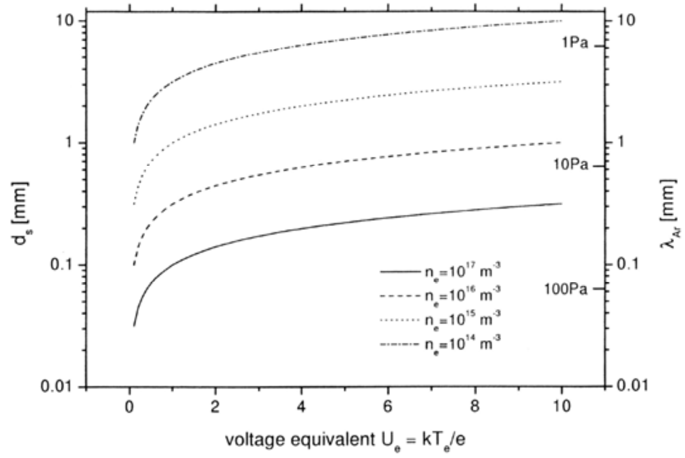
plasma boundary sheath : Child-Langmuir



A schematic of the potential, electric field, and electron number density profiles across a Child law sheath.

$V_0 = V_c$

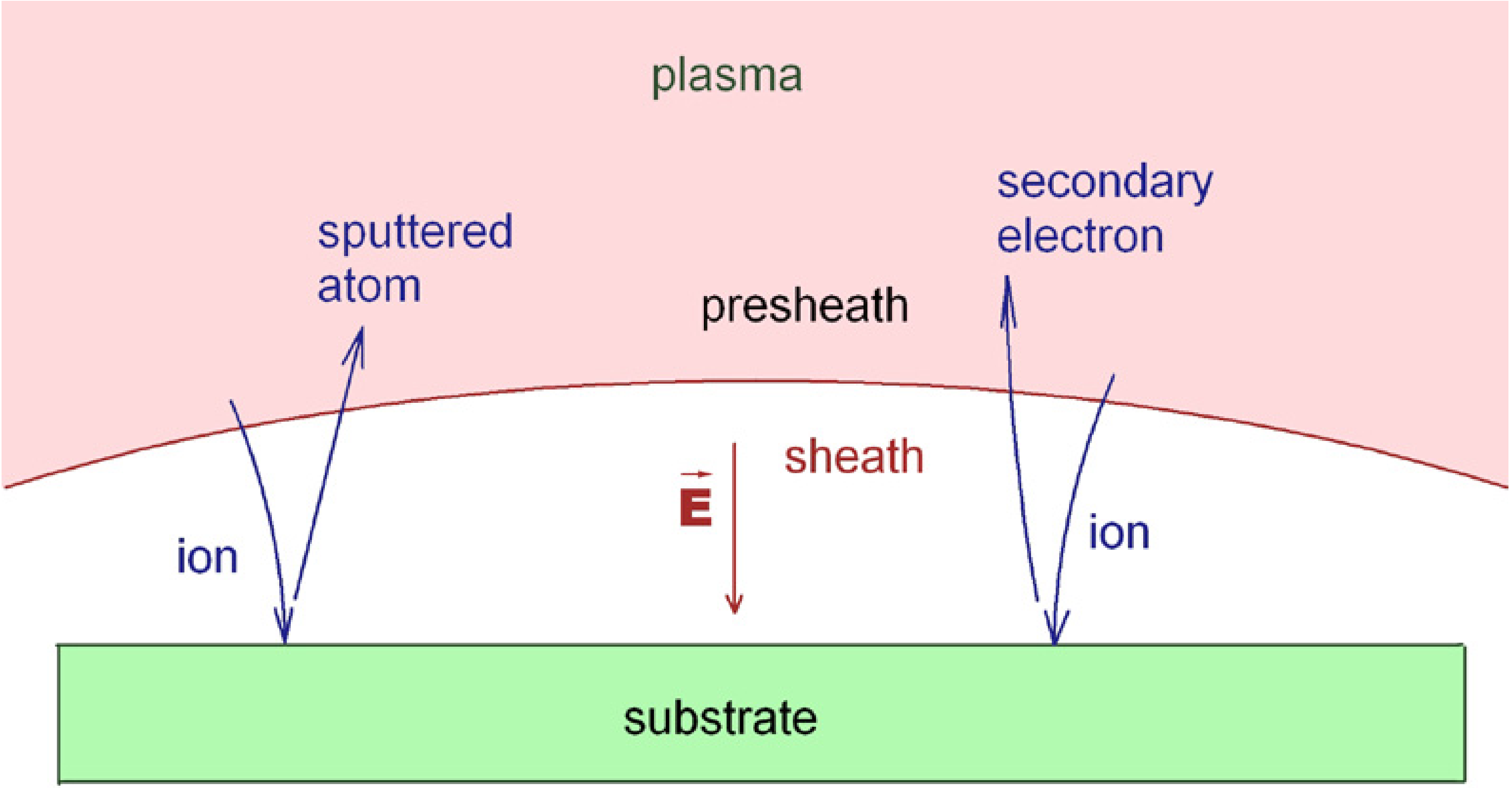
$S = d_c$



Thickness of the plasma sheath d_s versus electron temperature T_e for different electron densities. This is valid only for lower pressures when the ion mean free path is longer than the thickness of the plasma sheath. On the right axes the mean free path λ of Ar atoms for selected pressures is shown.

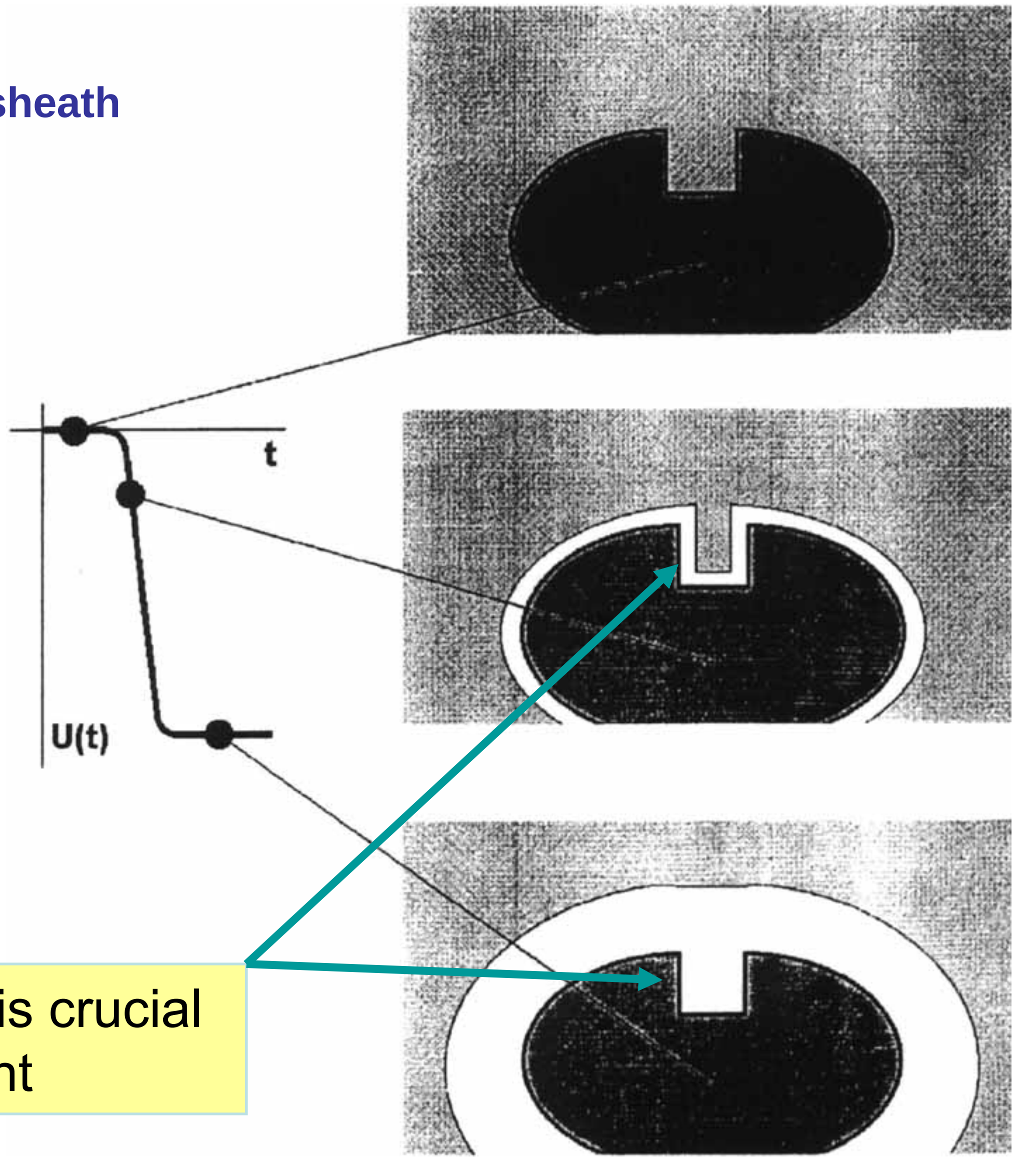
3.3. Plasma Surface Interaction

plasma boundary sheath



3.3. Plasma Surface Interaction

plasma boundary sheath

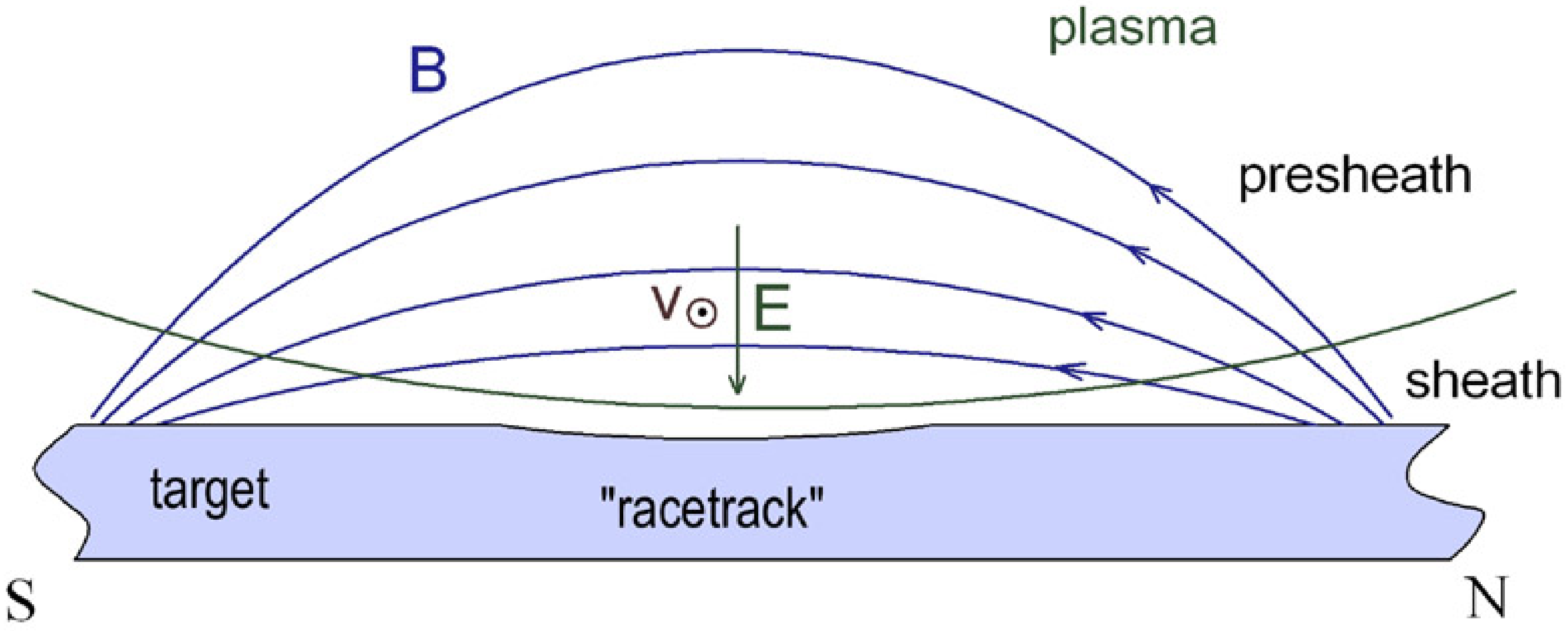


trench-to-sheath size is crucial for conformal treatment

3.3. Plasma Surface Interaction

plasma boundary sheath : magnetron

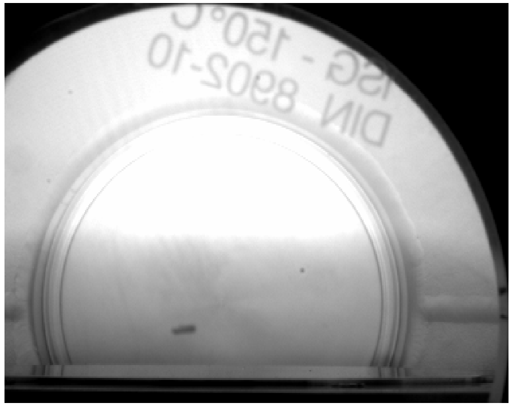
not to scale



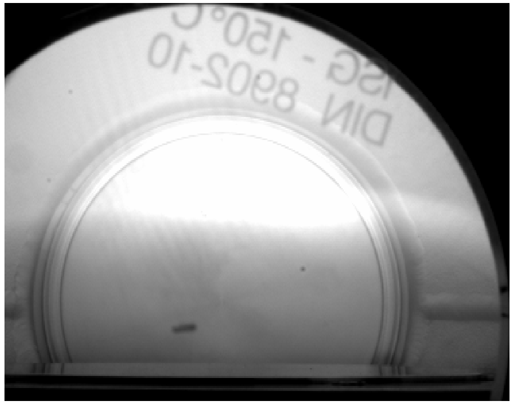
3.3. Plasma Surface Interaction

plasma boundary sheath

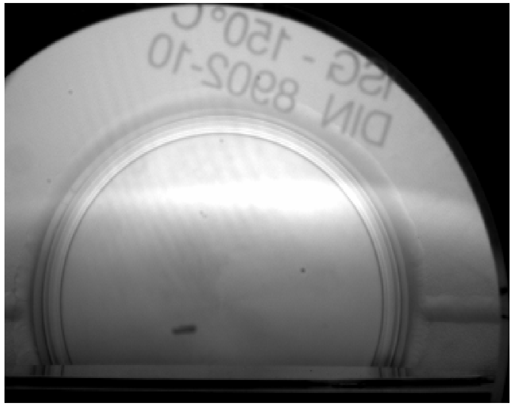
depends on discharge power and pressure



Argon, 0.005mbar, 10W

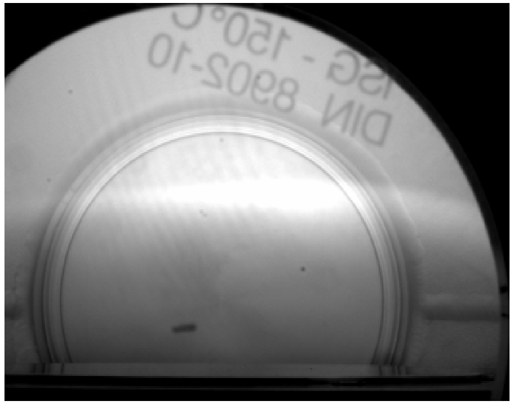


30W

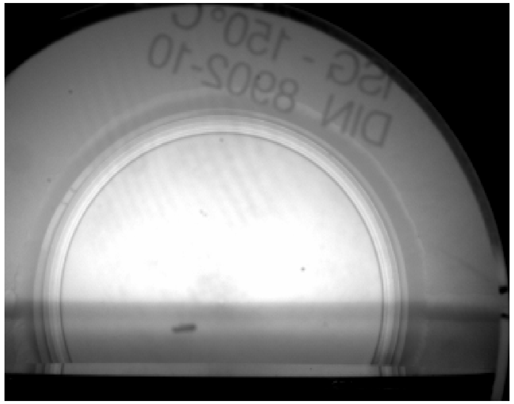


50W

Argon, 50W



0.005mbar



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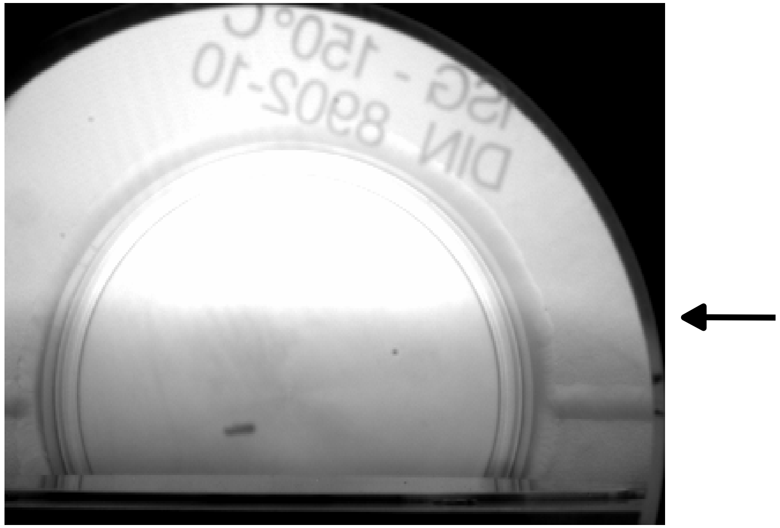
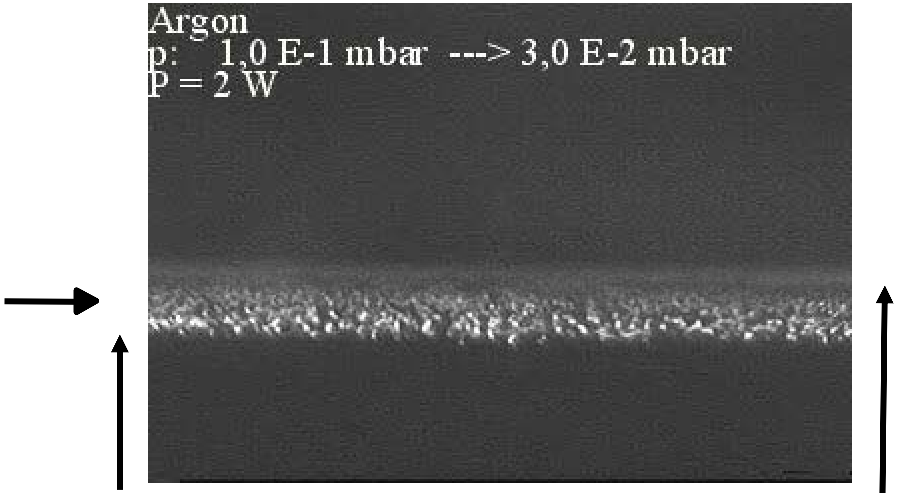
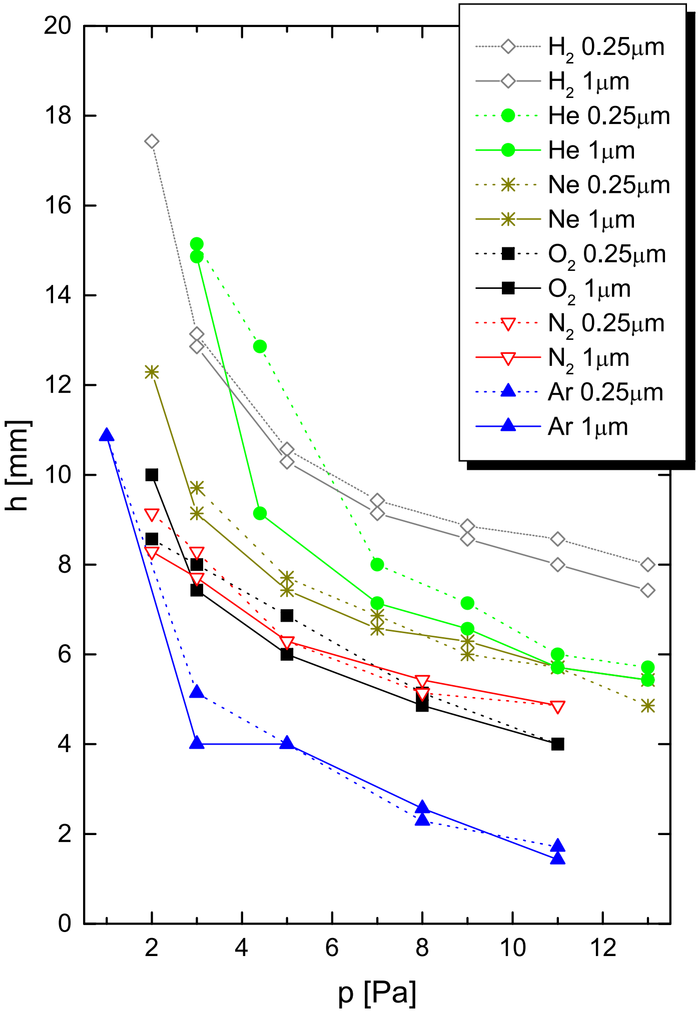
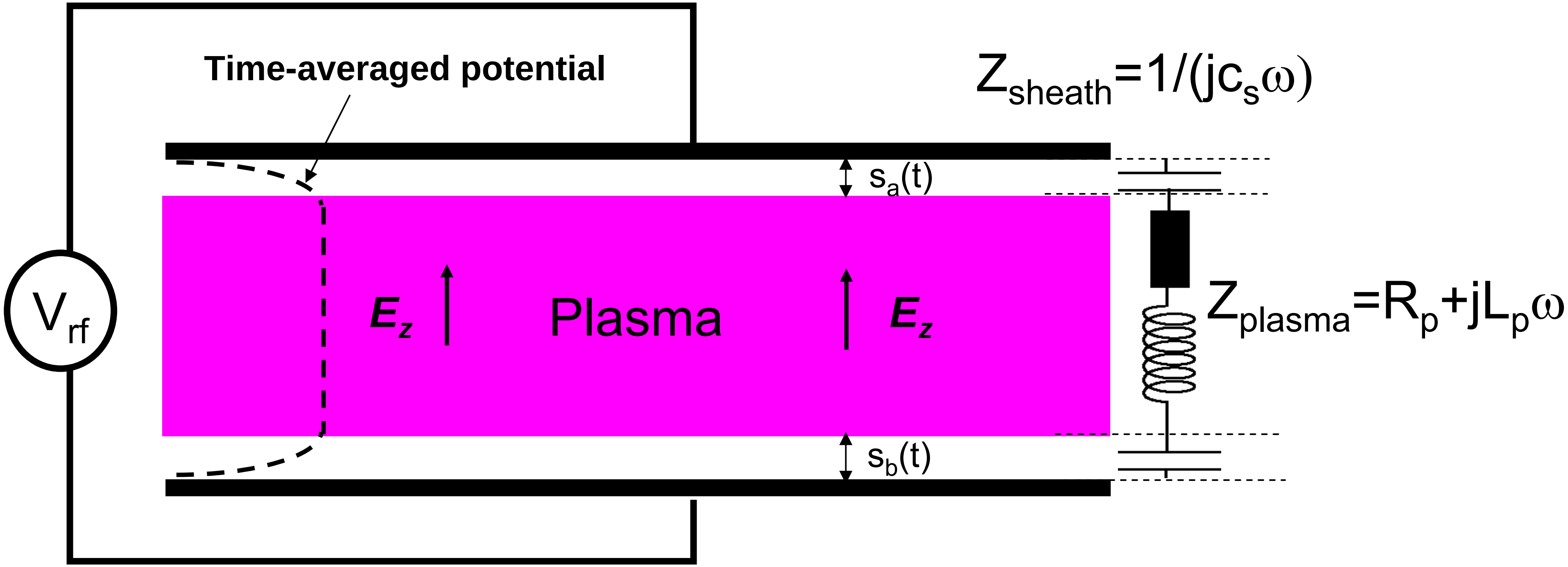
3.3. Plasma Surface Interaction









Impedance depends on :

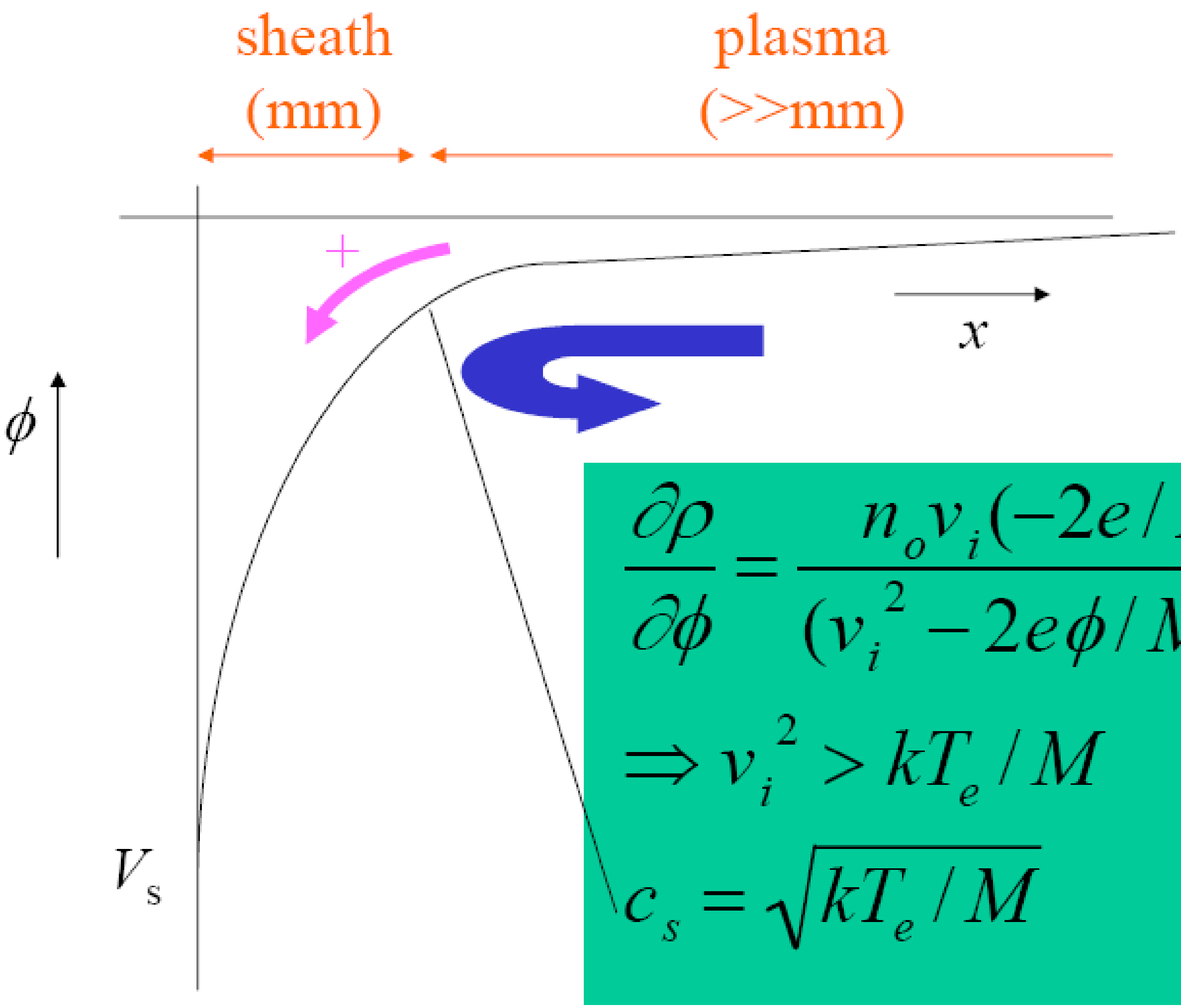
- Voltage, V_{rf}
- Electron density, n_e
- Sheath size, s_m

To find a self-consistent solution:

- Child law
- Particle balance
- Power balance

3.3. Plasma Surface Interaction

plasma boundary sheath : Bohm



$$\frac{\partial\rho}{\partial\phi} = \frac{n_o v_i(-2e/M)}{(v_i^2 - 2e\phi/M)^{3/2}} + \frac{e}{kT_e} n_e < 0$$

$$\Rightarrow v_i^2 > kT_e/M$$

$$c_s = \sqrt{kT_e/M}$$ Bohm speed

plasma boundary sheath : Bohm

$x = 0 \ldots x = d_{sh} = (S)$ no ionization in the sheath

—— sheath ⟶

continuity equation of ions: $n_i(x)v_i(x) = n_i(0), v_i(0)$

conservation of energy: $\frac{1}{2}m;v_i{}^2(0) = \frac{1}{2}kT_i + e_0V_{pl}$ $\quad \mathrm{x} = 0 \quad kT_i << e_0V_{pl} \Rightarrow v_i(0) = \sqrt{\frac{2e_0V_{pl}}{m_i}}$

v$_i$(x) between 0 and d$_{sh}$: $v_i(x) = \sqrt{\frac{2e_0(V_{pl} - V(x))}{m_i}}$

$$n_i(x)\sqrt{\frac{2e_0(V_{pl} - V(x))}{m_i}} = n_i(0)\sqrt{\frac{2e_0V_{pl}}{m_i}}$$

$$n_i(x) = n_i(0)\sqrt{\frac{V_{pl}}{V_{pl} - V(x)}}$$

Boltzmann : $n_e(x) = n_e(0)e^{\frac{e_oV(x)}{kT_e}}$

Poisson-equation : $\frac{d^2V}{dx^2} = -\frac{e_0}{\varepsilon_0}[n_i(x) - n_e(x)] \Rightarrow \frac{d^2V}{dx^2} = -\frac{e_0n_e(0)}{\varepsilon_0}\left[\left(\frac{V_{pl}}{V_{pl} - V(x)}\right)^{\frac{1}{2}} - e^{\frac{e_0V(x)}{kT_e}}\right]$

plasma boundary sheath : Bohm

$$\longrightarrow \qquad E^2(x)=\frac{2e_0 n_e(0)}{\varepsilon_0}\left\{2V_{pl}\left[\left(1-\frac{V(x)}{V_{pl}}\right)^{\frac{1}{2}}-1\right]+\frac{kT_e}{e_0}\left[e^{\frac{e_0 V(x)}{kT_e}}-1\right]\right\}$$

with

$$(1-x)^{\frac{1}{2}}\approx 1-\frac{1}{2}x-\frac{1}{8}x^2 \quad \text{and} \quad \mathrm{e}^{\mathrm{x}}\approx 1+x+\frac{x^2}{2}$$

$$\mathit{for} \quad \mathrm{V}(\mathrm{x}) << V_{pl} \quad \text{and} \quad \mathrm{e}_0 V(x) << kT_e \qquad ???$$

$$E^2(x)\approx\frac{2e_0 n_e(0)}{\varepsilon_0}\left\{2V_{pl}\left(1-\frac{1}{2}\frac{V(x)}{V_{pl}}-\frac{1}{8}\frac{V^2(x)}{V_{pl}^{\;2}}-1\right)+\frac{kT_e}{e_0}\left(1+\frac{e_0 V(x)}{kT_e}+\frac{e_0^{\;2}V^2(x)}{2k^2 T_e^{\;2}}-1\right)\right\}$$

$$E^2(x)\approx\frac{e_0 n_e(0)}{\varepsilon_0}\left\{-V(x)-\frac{1}{4}\frac{V^2(x)}{V_{pl}}+V(x)+\frac{e_0 V^2(x)}{2kT_e}\right\}$$

$$E^2(x)\approx\frac{e_0 n_e(0)V^2(x)}{\varepsilon_0}\left\{\frac{e_0}{kT_e}-\frac{1}{2V_{pl}}\right\}$$

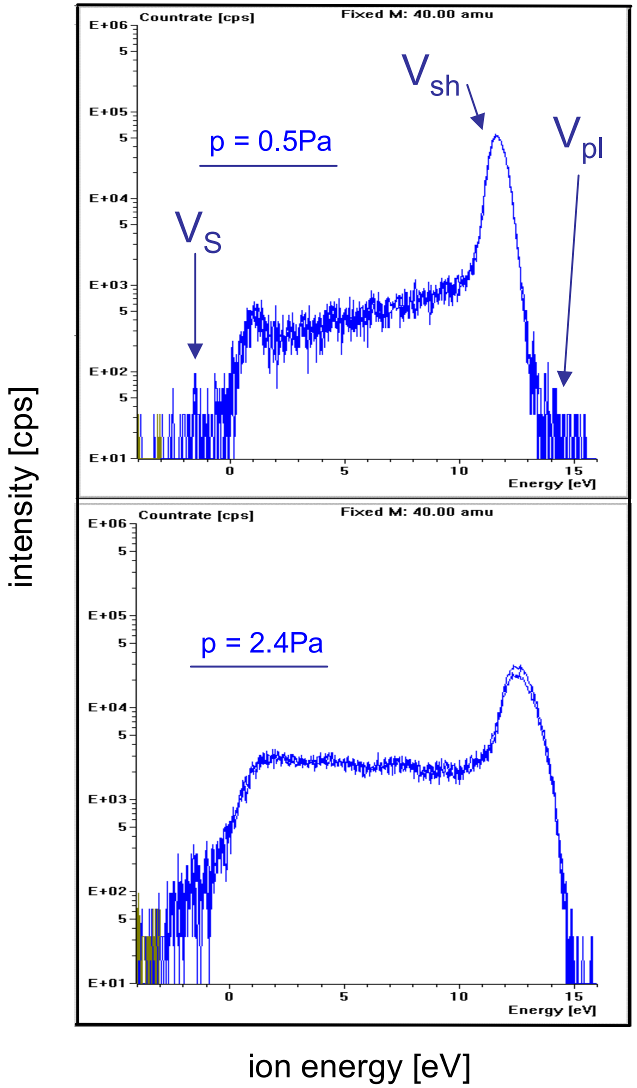
in order to have a real solution, it must

$$\frac{e_0}{hT_e}\geq\frac{1}{2V_{pl}}\Rightarrow \qquad \boxed{e_0 V_{pl}\geq\frac{1}{2}kT_e}$$

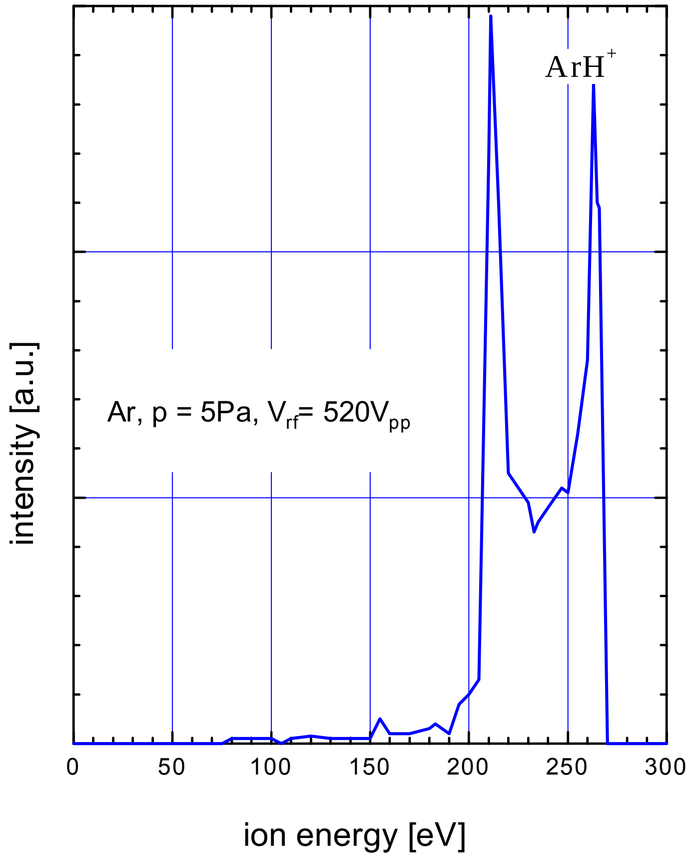
Bohm criterion

3.3. Plasma Surface Interaction

plasma boundary sheath

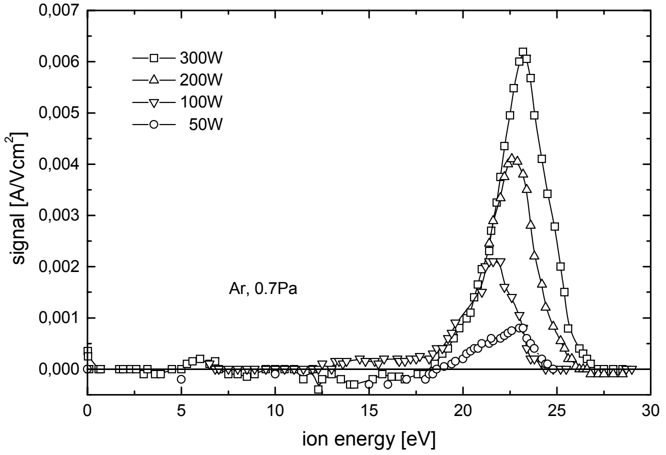


IEDF



3.3. Plasma Surface Interaction

plasma boundary sheath

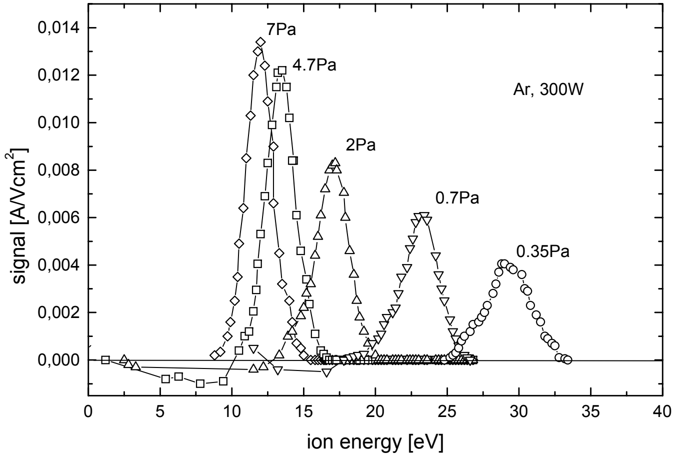


IEDF : dependence on power

⟶ intensity

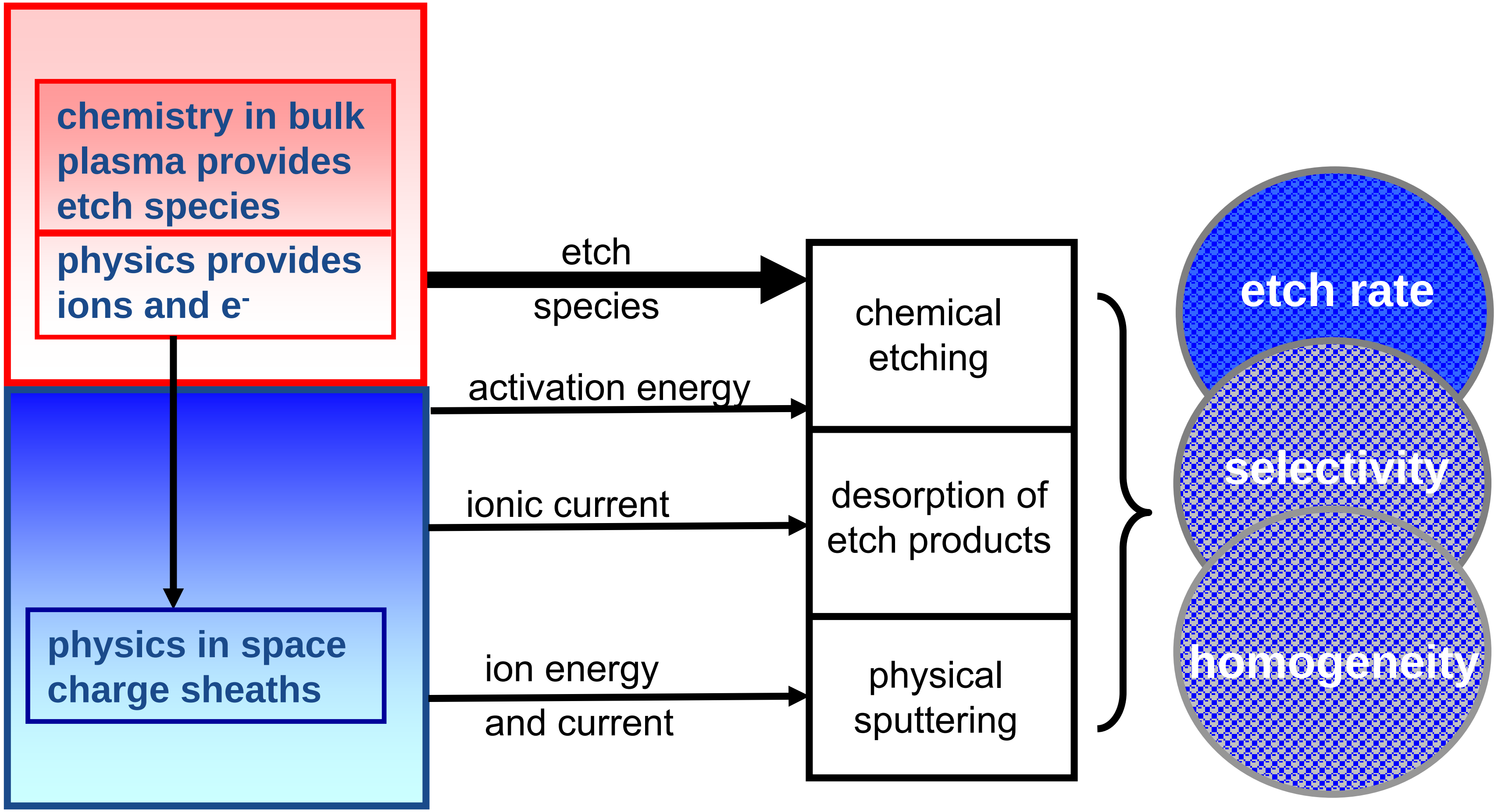
IEDF : dependence on pressure

⟶ intensity, mean energy



3.3. Plasma Surface Interaction

plasma boundary sheath : etching



chemistry in bulk plasma provides etch species

physics provides ions and e$^-$

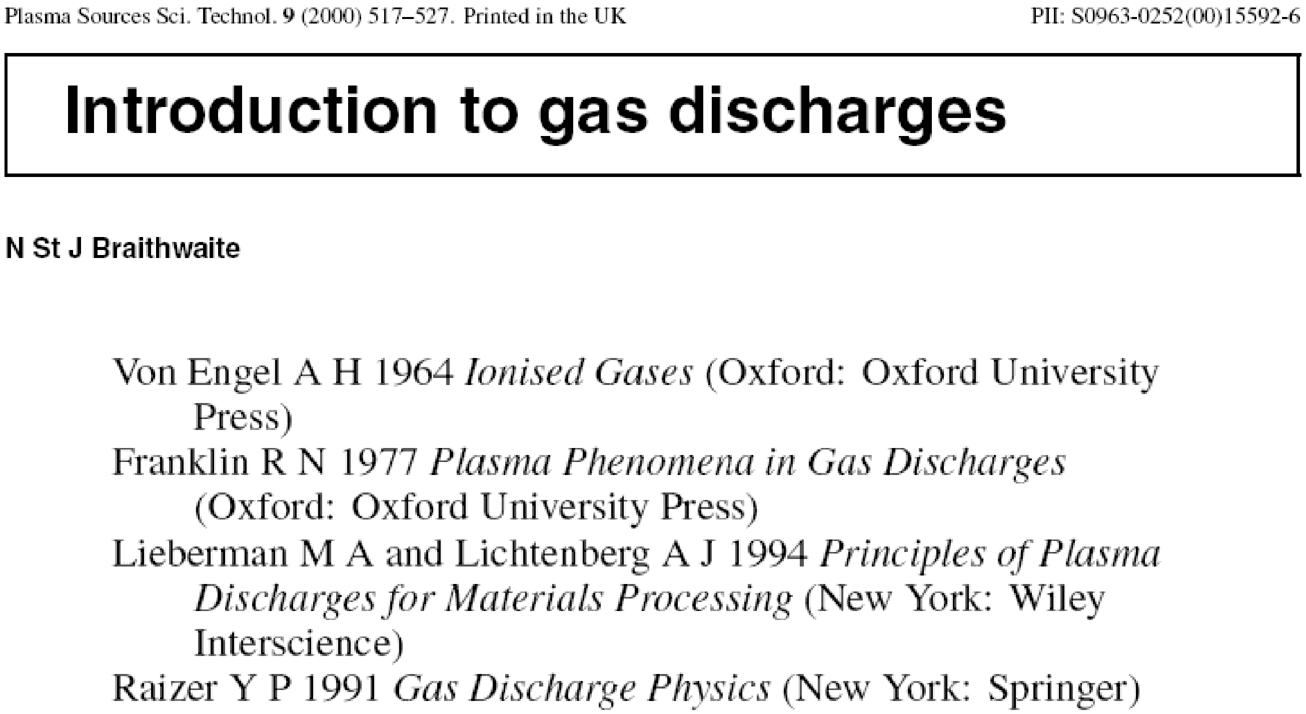
physics in space charge sheaths

chemical etching

desorption of etch products

physical sputtering

References



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Introduction to gas discharges

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