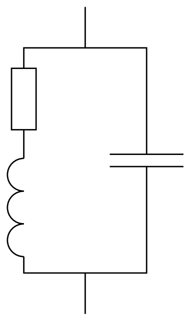
# 1 Capacitively coupled discharges – basic characterisation

Basic literature: [9, 1]

$$\omega_{pi} \quad < \quad \omega \quad \ll \quad \omega_{pe} \tag{1}$$

$$l \quad \ll \quad \lambda \tag{2}$$

# 2 RF plasma conductivity



$$\sigma \;=\; \frac{ne^2}{m(\nu + \mathrm{i}\omega)} + \mathrm{i}\omega\varepsilon_0 \tag{3}$$

$$\frac{1}{\sigma} \;=\; \frac{m(\nu+\mathrm{i}\omega)}{ne^2 + \mathrm{i}\omega\varepsilon_0 m(\nu+\mathrm{i}\omega)} = \frac{1}{\varepsilon_0}\,\frac{\nu+\mathrm{i}\omega}{\omega_{pe}^2 - \omega^2 + \mathrm{i}\nu\omega} \tag{4}$$

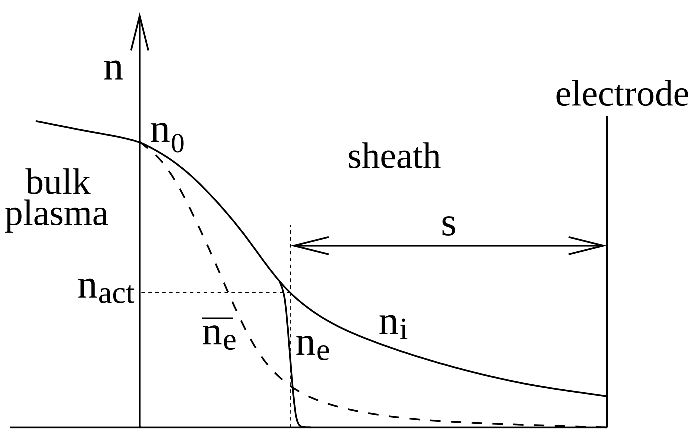
$$\omega_{pe} \;=\; e\sqrt{\frac{n}{m\varepsilon_0}} \tag{5}$$

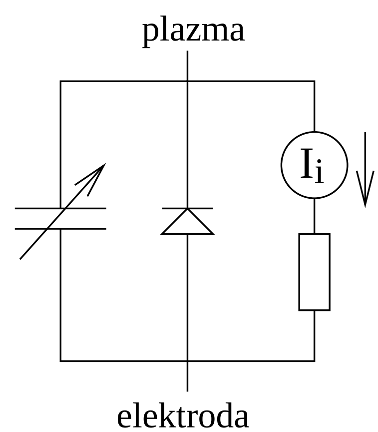
Ohmic heating:

$$\langle p\rangle = \frac{1}{2}\,j_1\,E_1\,\cos\alpha \;=\; \frac{1}{2}\,E_1^2\,\mathrm{Re}(\sigma) \;=\; \frac{E_1^2}{2}\,\frac{ne^2\nu}{m(\nu^2+\omega^2)} \;\xrightarrow{\nu\to 0}\; \frac{E_1^2}{2}\,\frac{ne^2}{m\omega^2}\,\nu \tag{6}$$

# 3 RF. sheath

Literature: [1, 8]




Sheath current density:

$$\begin{aligned} j &= \varepsilon_0\,\frac{\mathrm{d}E}{\mathrm{d}t} - \frac{en_0}{4}\sqrt{\frac{8kT_e}{\pi m}}\,\mathrm{e}^{-eU_{sh}(t)/(kT_e)} + en_0\sqrt{\frac{kT_e}{m_i}} \\ \varepsilon_0\,\frac{\mathrm{d}E}{\mathrm{d}t} &= n_{act}\,e\,\frac{\mathrm{d}s}{\mathrm{d}t} \end{aligned} \tag{7}$$

DC sheath voltage:

$$0 \;=\; -\frac{en_0}{4}\sqrt{\frac{8kT_e}{\pi m}}\,\left\langle \mathrm{e}^{-eU_{sh}(t)/(kT_e)}\right\rangle \;+\; en_0\sqrt{\frac{kT_e}{m_i}}$$

Let us assume $U_{sh} = U_0 + U_1 \sin\omega t$:

$$\mathrm{e}^{-\frac{eU_0}{kT_e}}\,\frac{\omega}{2\pi}\int\limits_0^{\frac{2\pi}{\omega}} \mathrm{e}^{-\frac{eU_1}{kT_e}\sin\omega t}\,\mathrm{d}t \;=\; \sqrt{\frac{2\pi m}{m_i}}$$

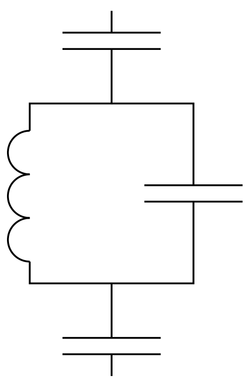
We will use

$$\frac{\omega}{2\pi}\int\limits_0^{\frac{2\pi}{\omega}} \mathrm{e}^{a\sin\omega t}\,\mathrm{d}t \;=\; \mathrm{I}_0(a),$$

where $\mathrm{I}_0(a)$ is the modified Bessel function of the order zero. We will obtain

$$\frac{eU_0}{kT_e} \;=\; \frac{1}{2}\ln\left(\frac{m_i}{2\pi m}\right) \;+\; \ln\left[\mathrm{I}_0\left(\frac{eU_1}{kT_e}\right)\right] \tag{8}$$

## 4 Series plasma-sheath resonance



$$Z_b \;\approx\; \frac{l_b}{\sigma S} \;\approx\; \frac{l_b}{\mathrm{i}\varepsilon_0 S\omega}\,\frac{1}{-\frac{\omega_{pe}^2}{\omega^2}+1}$$

$$Z_{sh} \;\approx\; \frac{1}{\mathrm{i}\omega C_{sh}} \;\approx\; -\mathrm{i}\,\frac{s_{tot}}{\omega\varepsilon_0 S}$$

$$Z \;\approx\; \frac{\mathrm{i}}{\varepsilon_0\omega S}\left(-s_{tot} + \frac{l_b}{\frac{\omega_{pe}^2}{\omega^2}-1}\right)$$

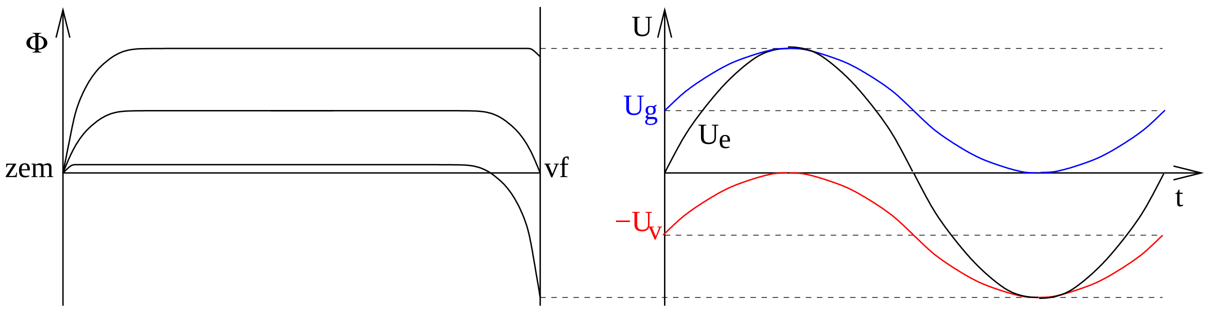
The resonance ($Z \approx 0$) occurs for the frequency

$$\omega_{sr} \;=\; \omega_{pe}\sqrt{\frac{s_{tot}}{l}}, \tag{9}$$

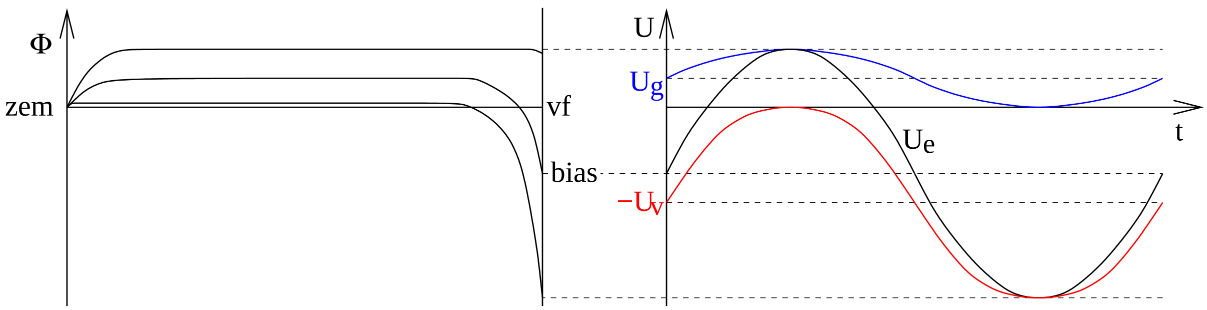
where $l_b$ is the length of the bulk plasma, $s_{tot}$ is the total thickness of the both sheaths and $l = l_b + s_{tot}$ is the distance of electrodes.

# 5 Discharge asymmetry

Symmetrical discharge:




Asymmetrical discharge:




**First approach:**

We will use $U_{sh} \propto s^\kappa$ and $U_{sh} \propto \frac{I}{C_{sh}} \propto \frac{I}{S} s$, so that $U_{sh} \propto \frac{U_{sh}^{1/\kappa}}{S}$ and we will obtain

$$U_{sh} \;\propto\; \frac{1}{S^{\frac{\kappa}{\kappa-1}}}$$

The index $g$ marks the sheath at the grounded electrode, the index $v$ sheath at the powered electrode and the index $e$ will mark the voltage at the powered electrode. We can write

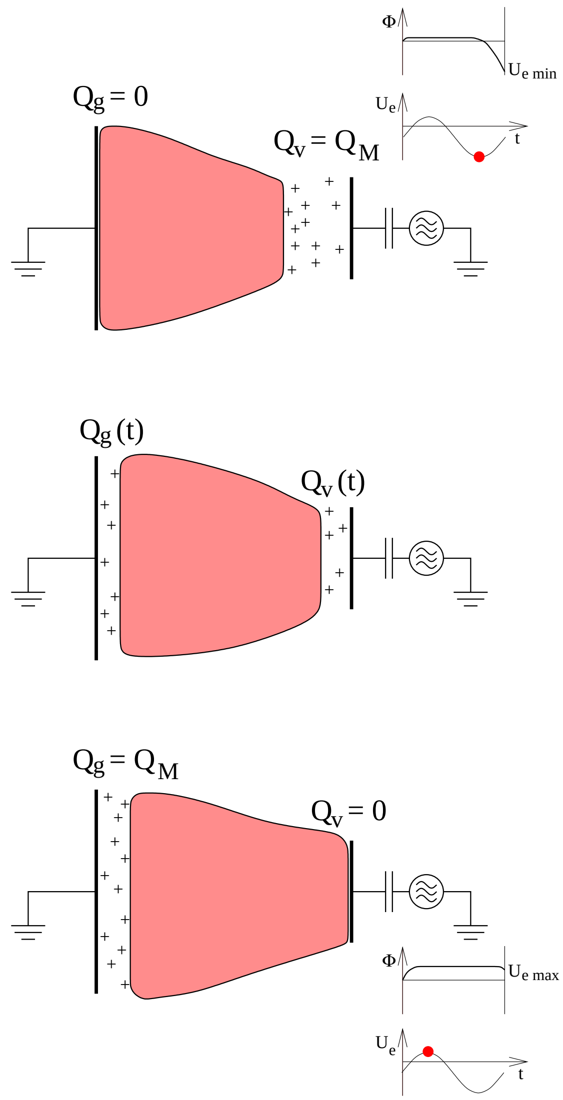
$$\begin{aligned} \frac{U_v}{U_g} &= \left(\frac{S_g}{S_v}\right)^\alpha \qquad (10) \\ \alpha &= \frac{\kappa}{\kappa - 1} \;\in\; \langle 1; 4 \rangle, \end{aligned}$$

frequently $\alpha \approx 2$ (valid for matrix sheath, $\kappa = 2$). The DC component of the voltage at the powered electrode can be calculated by

$$U_{e0} \;=\; U_{g0} - U_{v0} \;=\; -U_{e1}\, \frac{1 - \left(\frac{S_v}{S_g}\right)^\alpha}{1 + \left(\frac{S_v}{S_g}\right)^\alpha}, \qquad (11)$$

where the notation $U = U_0 + U_1 \sin \omega t$ was used.

**Second approach:**




$$E(x) = \frac{e}{\varepsilon_0} \int_0^x n_i(y)\mathrm{d}y \qquad (12)$$

$$U_{sh} = \frac{e}{\varepsilon_0} \int_0^{s(t)} \mathrm{d}x \int_0^x n_i(y)\mathrm{d}y \qquad (13)$$

For $n_i = konst.$ we would get

$$U_{sh} = \frac{e n_i s^2}{2\varepsilon_0} = \frac{Q^2}{2 e n_i \varepsilon_0 S^2},$$

where $Q = e n_i S s$. We can write the eq. (13) by means of the total sheath charge ($Q$) even in a more general case. We will define $\xi = x/s$ and we will label the actual averaged ion concentration in a sheath $\overline{n_i}$:

$$U_{sh} = \frac{Q^2}{2e\,\overline{n_i}\,\varepsilon_0\,S^2}\,\mathcal{I} \qquad (14)$$

$$\mathcal{I} = 2\int_0^1 \mathrm{d}\xi \int_0^\xi \frac{n_i(\xi')}{\overline{n_i}}\,\mathrm{d}\xi'$$

Because the total charge in both sheaths $Q_M = Q_g(t) + Q_v(t)$ is constant and because each sheath must almost collapse during each RF period, the maximum charge of each sheath is approximately equal to $Q_M$. we can write

$$U_{e\,max} = U_{g\,max} = \frac{Q_M^2}{2e\,\overline{n_{ig}}\,\varepsilon_0\,S_g^2}\,\mathcal{I}_g \qquad (15)$$

$$U_{e\,min} = -U_{v\,max} = -\frac{Q_M^2}{2e\,\overline{n_{iv}}\,\varepsilon_0\,S_v^2}\,\mathcal{I}_v \qquad (16)$$

and we can define the asymmetry parameter $\mathcal{E}$

$$\mathcal{E} = \frac{U_{g\,max}}{U_{v\,max}} = \left(\frac{S_v}{S_g}\right)^2 \frac{\overline{n_{iv}}}{\overline{n_{ig}}} \frac{\mathcal{I}_g}{\mathcal{I}_v} \qquad (17)$$

For the bias calculation we will mark $U_e = U_{e\,0} + U_{e\,RF}(t)$, where $U_{e\,0}$ is the spontaneously generated DC component of the voltage at the powered electrode (bias) and $U_{e\,RF}$ is the known RF voltage supplied from the RF generator. When we neglect the bulk-plasma voltage, we can write $U_e = U_g - U_v$. We can take advantage of the situation in the two extremes of the supplied voltage

$$
\begin{aligned}
U_{g\,max} &= U_{e\,0} + U_{e\,RF\,max} \\
-U_{v\,max} &= U_{e\,0} + U_{e\,RF\,min}
\end{aligned}
$$

and we can get

$$
U_{e\,0} = -\frac{U_{e\,RF\,max} + \mathcal{E} U_{e\,RF\,min}}{1+\mathcal{E}} \tag{18}
$$

For symmetrical supplied voltage ($U_{e\,RF\,max} = -U_{e\,RF\,min}$, e.g. $U_{e\,RF} = U_{e\,RF\,max} \sin \omega t$) we will get

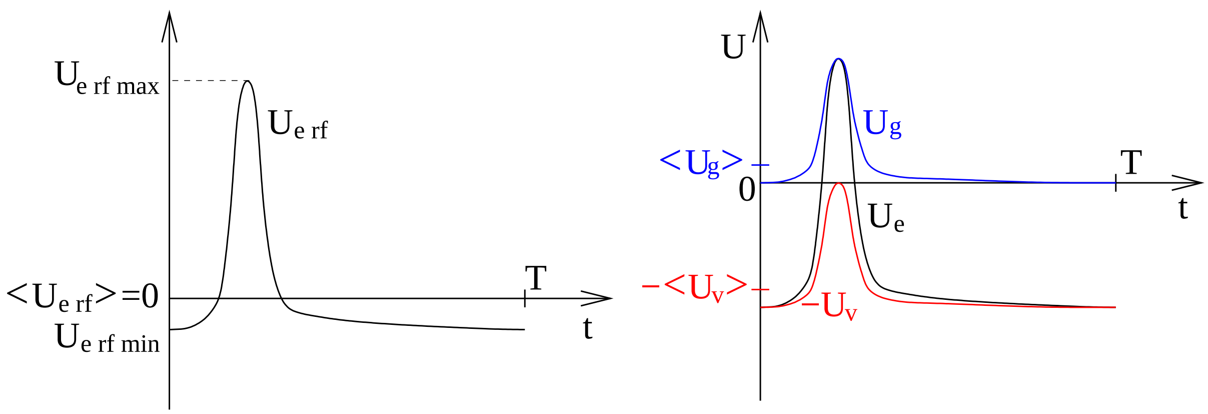
$$
U_{e\,0} = -U_{e\,RF\,max} \frac{1-\mathcal{E}}{1+\mathcal{E}} \tag{19}
$$

# 6 Electric asymmetric effect

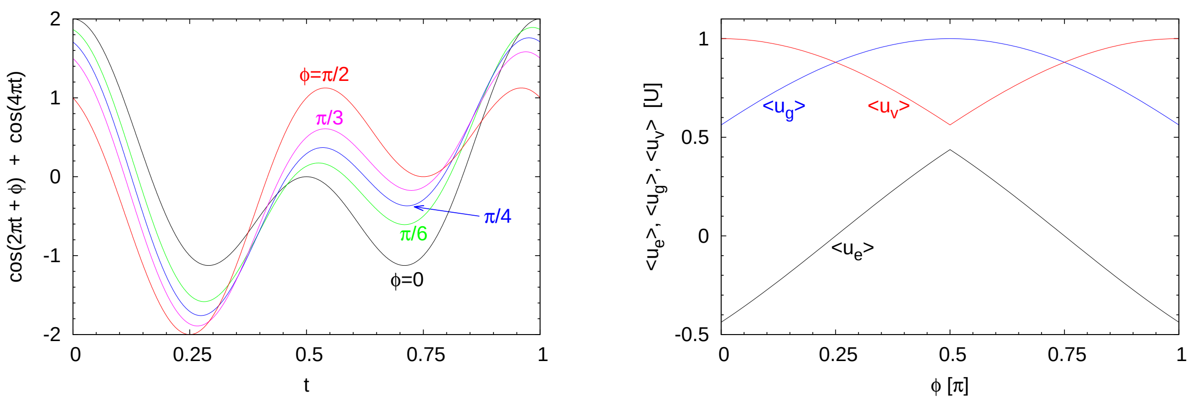
For symmetric discharges the eq. (18) has the following form:

$$
U_{e\,0} = -\frac{U_{e\,RF\,max} + U_{e\,RF\,min}}{2}.
$$

Consequently, if we use asymmetric waveform of the supplied voltage, we can generate an electric asymmetry (DC bias) in spite of geometric symmetry of the discharge [2].




*Electric asymmetrical effect for a strongly asymmetric supplied voltage.*




*An example of the electric asymmetric effect for $U_{e\,RF} = U\cos(\omega t + \Phi) + U\cos(2\omega t)$.*

# 7 Nonlinear nature of sheaths

Literature: [3, 5]

For $n_i = konst.$ we can approximate

$$E = \frac{nes}{\varepsilon_0}$$
$$U_{sh} = \frac{nes^2}{2\varepsilon_0}$$
$$j = \varepsilon_0 \frac{\mathrm{d}E}{\mathrm{d}t} = ne \frac{\mathrm{d}s}{\mathrm{d}t}$$

The two simplest cases are:

**1) Monofrequency current $I = I_1 \cos \omega t$:**

One sheath:

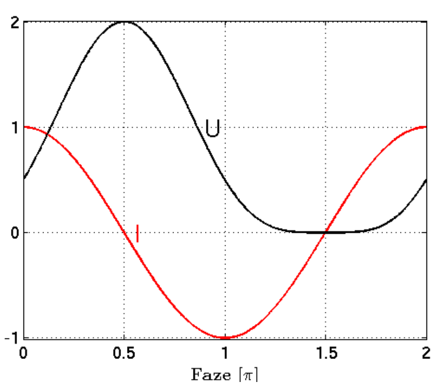
$$s = \frac{I_1}{Sne\omega} (\sin \omega t + 1)$$
$$U_{sh} = \frac{1}{\varepsilon_0 en} \left(\frac{I_1}{S\omega}\right)^2 \left(\frac{3}{4} + \sin \omega t - \frac{1}{4} \cos 2\omega t\right) \quad (20)$$

Two sheaths:

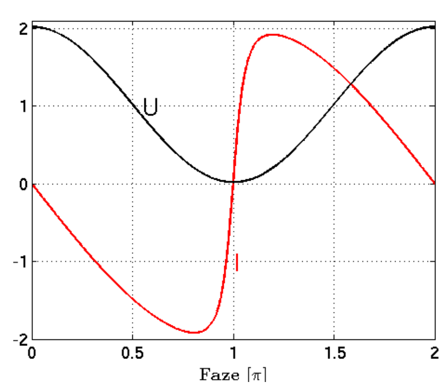
$$U_e(\omega t) = U_g(\omega t) - U_v(\omega t + \pi) \quad (21)$$
$$U_e = \frac{1}{\varepsilon_0 en} \left(\frac{I_1}{\omega}\right)^2 \left[\frac{3}{4}\left(\frac{1}{S_g^2} - \frac{1}{S_v^2}\right) + \left(\frac{1}{S_g^2} + \frac{1}{S_v^2}\right) \sin \omega t - \frac{1}{4}\left(\frac{1}{S_g^2} - \frac{1}{S_v^2}\right) \cos 2\omega t\right] \quad (22)$$
$$U_{e0} = -\frac{3}{4} U_{e1} \frac{1 - \left(\frac{S_v}{S_g}\right)^2}{1 + \left(\frac{S_v}{S_g}\right)^2} \quad (23)$$

**2) Monofrequency voltage $U_{sh} = U_0 + U_1 \cos \omega t$:**

$$I = Sne \frac{\mathrm{d}s}{\mathrm{d}t} = S\sqrt{\frac{\varepsilon_0 ne}{2}} \frac{1}{\sqrt{U_{sh}}} \frac{\mathrm{d}U_{sh}}{\mathrm{d}t} \quad (24)$$
$$I = -S\sqrt{\frac{\varepsilon_0 ne}{2}} \frac{U_1}{\sqrt{U_0}} \frac{\omega \sin \omega t}{\sqrt{1 + \frac{U_1}{U_0} \cos \omega t}} \quad (25)$$




*Monofrequency sheath current*




*Monofrequency sheath voltage*

## 8 Ion energy distribution function (IEDF)

Basic parameters:

- Ratio between the mean transit time of an ion through the sheath and the RF period:

$$\frac{T_i}{T} \approx \frac{3\bar{s}\omega}{2\pi}\sqrt{\frac{m_i}{2eU_0}} \tag{26}$$

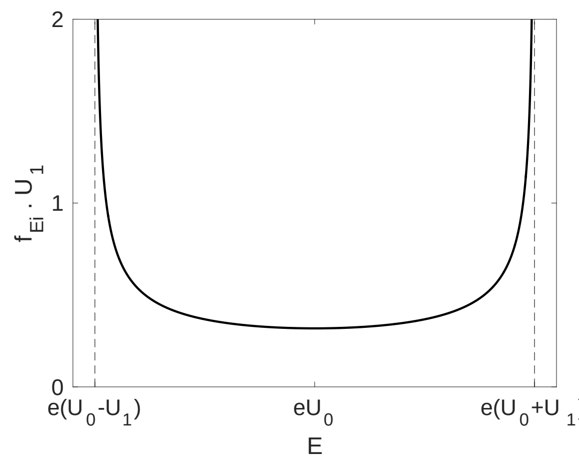
- Number of ion collisions inside the sheath $\approx 1/\left(\nu_i T_i\right)$

Literature: [7]

### 8.1 Collisionless low-frequency regime

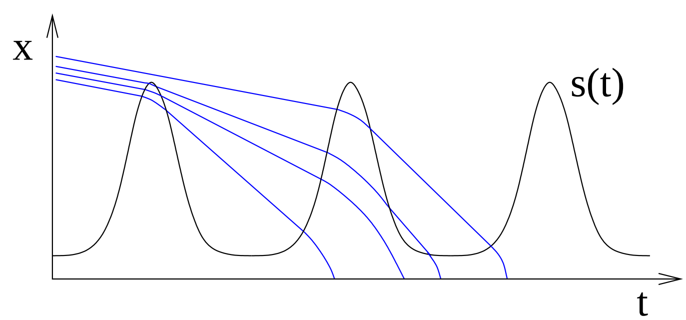
$T_i \ll T$, ion energy corresponds to the actual sheath voltage in the moment of ion impact. Let us assume $U_{sh} = U_0 + U_1 \cos\omega t$.

$$\begin{aligned}
E &= e\left(U_0 + U_1 \cos\omega t\right) \\
|\mathrm{d}t| &= \frac{\mathrm{d}E}{\omega e U_1 \sqrt{1-\left(\frac{E-eU_0}{eU_1}\right)^2}} \\
f_{Ei} &= \frac{1}{\pi e U_1 \sqrt{1-\left(\frac{E-eU_0}{eU_1}\right)^2}} \\
E &\in \left\langle e(U_0-U_1);\ e(U_0+U_1)\right\rangle
\end{aligned} \tag{27}$$




### 8.2 Collisionless middle-frequency regime

The saddle structure narrows with the increase of the $T_i/T$ ratio.



### 8.3 Collisionless high-frequency regime

$T_i \gg T$, for $\frac{T_i}{T} \to \infty$ the saddle structure $f_E$ transforms itself to a single peak at the energy $E = eU_0$.

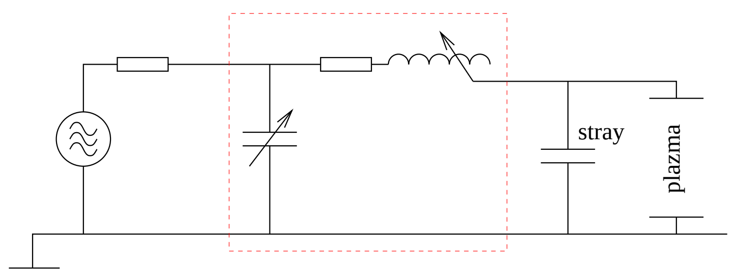
$$\begin{aligned} f_{Ei} &= \frac{1}{\pi \Delta E \sqrt{1 - \left(\frac{E - eU_0}{\Delta E}\right)^2}} \\ \Delta E &= \frac{2eU_1}{\pi} \left(\frac{T}{T_i}\right) \\ E &\in \langle eU_0 - \Delta E;\ eU_0 + \Delta E \rangle \end{aligned} \quad (28)$$

### 8.4 Collisions

- elastic collisions – continuous decrease of ion energy
- charge transfer – generation of new peaks in the EEDF ($f_{Ei}$)
- broadening of the ion angle distribution

## 9 Matching box

For example [1]:




## 10 Local/non-local plasma character

Local regime:

$$\begin{aligned} \vec{j}(\vec{r}, t) &= \sigma(\vec{r}, t)\, \vec{E}(\vec{r}, t) \\ f_E(\vec{r}, t) &= f_E\left[\vec{E}(\vec{r}, t)\right] \end{aligned}$$

Nonlocal regime:

$$\begin{aligned} \vec{j}(\vec{r}, t) &= \iiint_{\vec{r'}} \mathrm{d}\vec{r'} \int_{t' \le t} \mathrm{d}t'\ \sigma\left(\vec{r} - \vec{r'}, t - t'\right) \vec{E}\left(\vec{r'}, t'\right) \\ f_E(\vec{r}, t) &= f_E\left[\vec{E}\left(\vec{r'}, t'\right)\right], \qquad \vec{r'} \in V,\ t' \le t \end{aligned}$$

# 11 Plasma heating

- collisional (Ohmic) heating [9, 1, 6]
- stochastic heating [9, 1, 16]
  - bounce resonance [12]
- field reversal [15]
- $\gamma$-heating, $\alpha$ and $\gamma$ regimes [14, 18, 11, 13]

## 11.1 $\gamma$ regime

Potential emission – electron emission from electrode caused by an ion impact, $\sim 0{,}01$.

Electron avalanche in the sheath:

$$\begin{aligned}
\frac{\mathrm{d}j_e}{\mathrm{d}x} &= \alpha\left[E(x,t)\right] j_e \\
j_e(x) &= j_e(0)\, \mathrm{e}^{\int\limits_0^x \alpha[E(x',t)]\,\mathrm{d}x'} \\
j_e(0) &= \gamma j_i \\
\langle j_i \rangle &= \left\langle \gamma j_i \left\{ \mathrm{e}^{\int\limits_0^{s(t)} \alpha[E(x,t)]\,\mathrm{d}x} - 1 \right\} \right\rangle + env_B \qquad (29)
\end{aligned}$$

For negligible $nv_B$ we can use the last equation for calculation of the ignition voltage for the transition of the sheath from the $\alpha$ to the $\gamma$ regime. The current density for this transition can be estimated by means of

$$\begin{aligned}
j &= ne\,\frac{\mathrm{d}s}{\mathrm{d}t} \approx \frac{\varepsilon_0}{s}\,\frac{\mathrm{d}U}{\mathrm{d}t} \qquad (30) \\
j_1 &\approx \varepsilon_0\,\frac{\omega U_1}{s}
\end{aligned}$$

$\alpha \to \gamma$ transition:

- increase of electron concentration, plasma conductivity and current density
- decrease of sheath thickness, generation of a discharge structure that is analogous to the structure of the DC glow discharge
- discharge contraction to a smaller area, VA characteristics with a constant discharge voltage
- increase of supplied power
- in some cases an abrupt transition with hysteresis
- EEDF variations (shift to the Maxwell EEDF, increase of electron concentration, decrease of electron temperature)

## 12 Global models

Input parameters: pressure, electrode distance ($l$), angular frequency of the electric field ($\omega$), RF current amplitude ($I_1$), gas composition ($K_i$, $E_i$, $\nu$, $K_{exc}$, $E_{exc}$, $K_{el}$, $m_n$)
Output parameters: electron concentration ($n$), electron temperature ($T_e$), mean sheath thickness ($s$) [1].

- Balance of the number of electrons:

$$
\begin{aligned}
n_n \bar{n} K_i \,(l - s) &= 2 h_l n_c u_B && (31)\\
K_i &= K_{i0}\, \mathrm{e}^{-\frac{E_i}{kT_e}} && (32)\\
u_B &= \sqrt{\frac{kT_e}{m_i}} && (33)
\end{aligned}
$$

  ($n_n$ is the concentration of neutrals, $\bar{n}$ is the means electron concentration in the bulk plasma, $K_i$ is the rate constant for ionization, $n_c$ is the electron concentration in the discharge center, $h_l$ is the ratio between the electron concentration at the bulk-sheath border and in the plasma center, $u_B$ is the Bohm velocity, $E_i$ is the ionization energy of neutrals.)

- Balance of the mean electron energy:

$$
\frac{1}{2}\left(R_{ohm} + 2R_{stoch} + 2R_{ohm,sh}\right) I_1^2 = 2 h_l n_c u_B E_T(T_e) S \qquad (34)
$$

$$
\begin{aligned}
E_T &= E_i + \frac{K_{exc}}{K_i} E_{exc} + \frac{3m}{m_n}\frac{K_{el}}{K_i} kT_e + 2kT_e + e\Delta\Phi && (35)\\
R_{stoch} &= 0.72\,(mkT_e)^{1/2}\,\frac{\omega s}{eI_1} && (36)\\
R_{ohm} &= 1.55\, hm\nu\,(l - 2s)\left(\frac{\omega}{eI_1}\right)^{3/2}(S\varepsilon_0 s k T_e)^{1/2} && (37)\\
R_{ohm,sh} &= 0.33\, m\nu s \frac{\omega s}{eI_1} && (38)
\end{aligned}
$$

  ($R_{ohm}$, $R_{stoch}$ and $R_{ohm,sh}$ are resistivities caused by the collisional heating in the bulk plasma, stochastic heating and collisional heating in the sheath, $E_T$ is the mean energy supplied to one electron, $K_{exc}$ is the rate constant for excitation of neutrals, $E_{exc}$ is the excitation energy, $K_{el}$ is the rate constant for elastic collisions between electrons and neutrals, $m_n$ is the mass of neutrals, $\Delta\Phi$ is the average voltage that must be overcome by an electron that leaves plasma.)

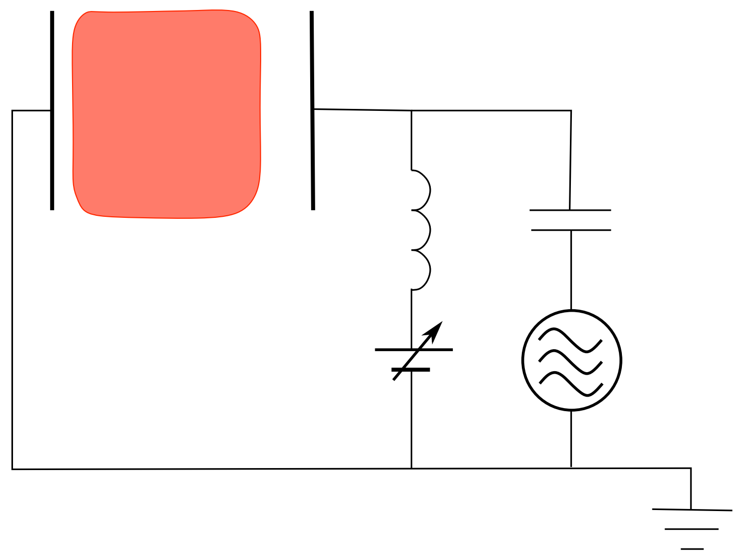
- Sheath thickness:

$$
s = \frac{5}{12 e h_l^2 n_c^2 \varepsilon_0 k T_e}\left(\frac{I_1}{S\omega}\right)^3 \qquad (39)
$$

The equations listed above are valid for low-pressure plasma with no negative ions and with no collisions in the sheaths.

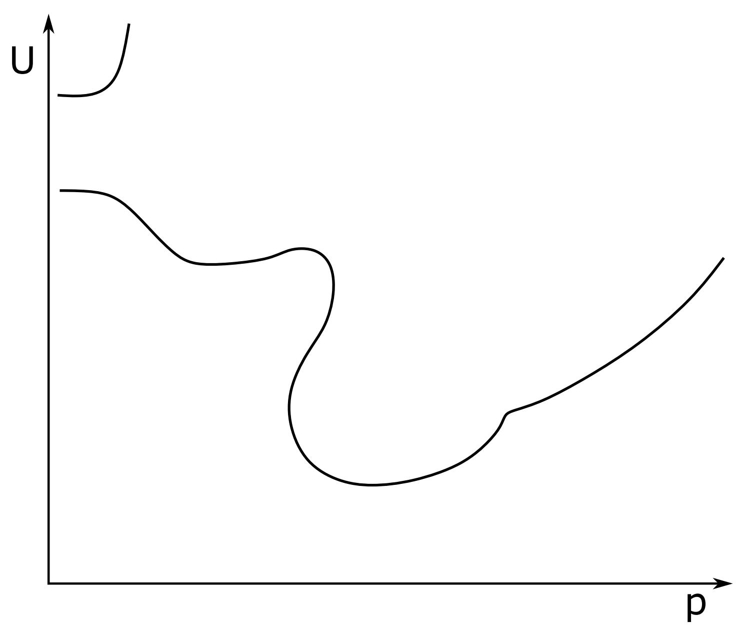
## 13 Independent control of the reactive species concentration and ion energy

- DC + RF [19, 10]



- Capacitive biasing of an electrode in a different discharge (ICP, MW)
- Double-frequency CCP [1, 4]
- Electric asymmetric effect [2, 4, 17]

## 14 CCP ignition



Breakdown voltage in the high-pressure branch:

$$\begin{aligned}
\frac{\mathrm{d}n}{\mathrm{d}t} &= \nu_i n + D\frac{\mathrm{d}^2 n}{\mathrm{d}x^2} \\
\frac{\mathrm{d}n}{\mathrm{d}t} &\geq 0 \\
n &\approx n_{\mathrm{centr}} \sin\left(\sqrt{\frac{\nu_i}{D}}\, x\right) \\
\nu_i &= D\left(\frac{\pi}{l}\right)^2 \\
\nu_i &= K_1 p\, \mathrm{e}^{-K_2 \frac{lp}{U}} \\
U &= \frac{K_2\, pl}{\ln\left(\frac{pl}{K_1 \pi^2}\, \frac{l}{D}\right)}
\end{aligned}$$

## Used marking of quantities

| | |
|---|---|
| $\omega_{pi}$ | plasma frequency of ions |
| $\omega$ | (angular) frequency of el. field |
| $\omega_{pe}$ | plasma frequency of electrons |
| $l$ | electrode separation |
| $\lambda$ | wavelength |
| $\sigma$ | plasma conductivity |
| $n$ | electron concentration |
| $e$ | elementary charge |
| $m$ | electron mass |
| $\nu$ | mean collisional frequency of transition of momentum of the electron (to neutrals) |
| $\varepsilon_0$ | vacuum permittivity |
| $p$ | power density |
| $j$ | current density |
| $j_1$ | current density amplitude |
| $E$ | electric field intensity |
| | energy |
| $E_1$ | amplitude of electric field intensity |
| $n_0$ | electron concentration at the plasma-sheath border |
| $n_i$ | ion concentration |
| $k$ | Boltzmann constant |
| $T_e$ | electron temperature |
| $U_{sh}$ | sheath voltage |
| $m_i$ | ion mass |
| $s$ | sheath thickness |
| $U_0$ | DC voltage component |
| $U_1$ | amplitude of the fundamental voltage component |
| $\mathrm{I}_0$ | modified Bessel function of the 1. kind, order 0 |
| $Z_b$ | bulk plasma impedance |
| $l_b$ | bulk plasma length |
| $S$ | electrode area |
| $Z_{sh}$ | sheath impedance |
| $C_{sh}$ | sheath(s) capacity |
| $s_{tot}$ | total thickness of both sheaths |
| $Z$ | discharge impedance |
| $\omega_{sr}$ | (angular) frequency of the plasma-sheath resonance |
| $U_g$ | sheath voltage (at the grounded electrode) |
| $U_v$ | sheath voltage (at the powered electrode) |
| $U_e$ | powered electrode voltage |
| $\kappa$ | power in the dependence of the sheath voltage on the sheath thickness |
| $\alpha$ | phase difference between current and voltage |
| | power in the dependence of the electric and geometric discharge asymmetry |

designation of the CCP regime with negligible role of $\gamma$-electrons
1. Towsend coefficient

| | |
|---|---|
| $S_g$ | grounded electrode area |
| $S_v$ | powered electrode area |
| $Q$ | el. charge |
| $Q_g$ | sheath charge at the grounded electrode |
| $Q_v$ | sheath charge at the powered electrode |
| $Q_M$ | total charge in both sheaths |
| $\Phi$ | el. potential |
| $U_{x\,max}$ | maximum value of the voltage $U_x$ |
| $U_{x\,min}$ | minimum value of the voltage $U_x$ |
| $U_{e\,RF}$ | RF component of the powered electrode voltage (i.e. $U_e - U_{e0}$) |
| $\mathcal{I}$ | quantity that describes profile of ion concentration inside a sheath |
| $\mathcal{E}$ | discharge asymmetry parameter |
| $I$ | electric current |
| $T_i$ | mean transit time of an ion through a sheath |
| $T$ | discharge period |
| $\nu_i$ | mean collisional frequency of an ion |
| $f_{Ei}$ | IEDF |
| $f_E$ | EEDF (electron energy distribution function) |
| $\nu_i$ | ionization frequency |
| $D$ | coefficient of diffusion |

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