Electrical models of CCPs

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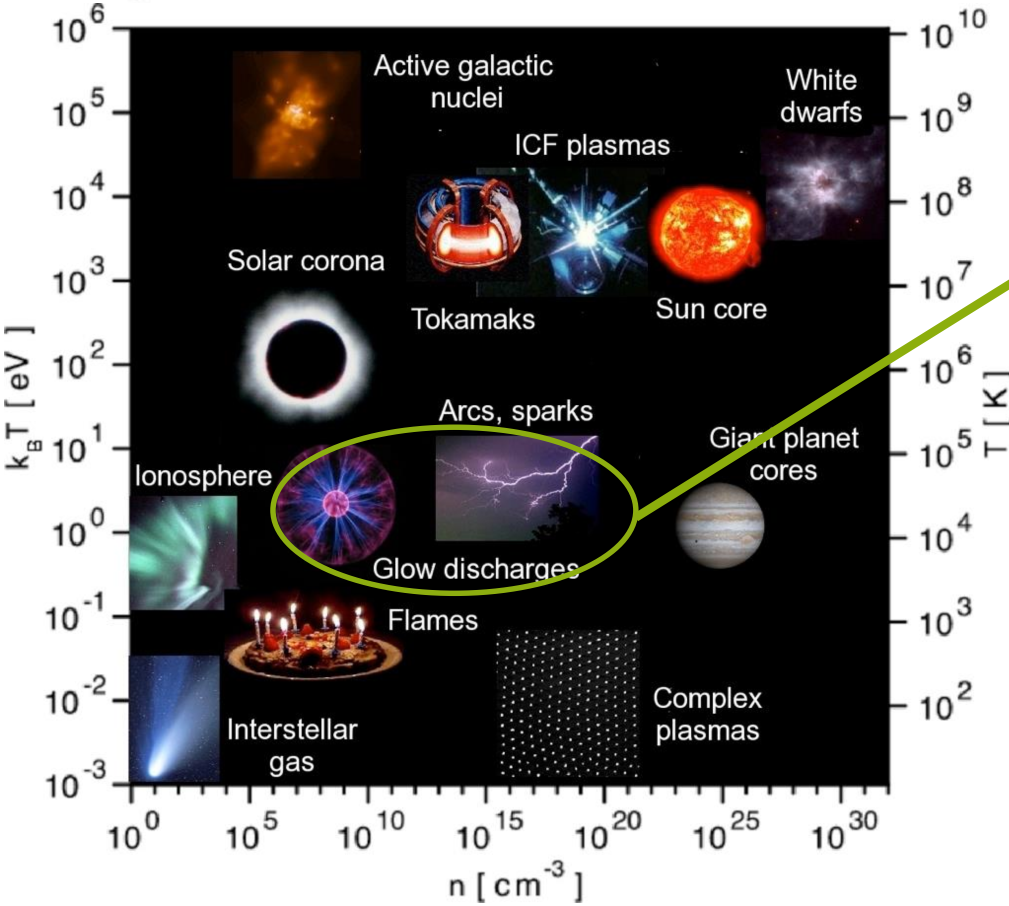
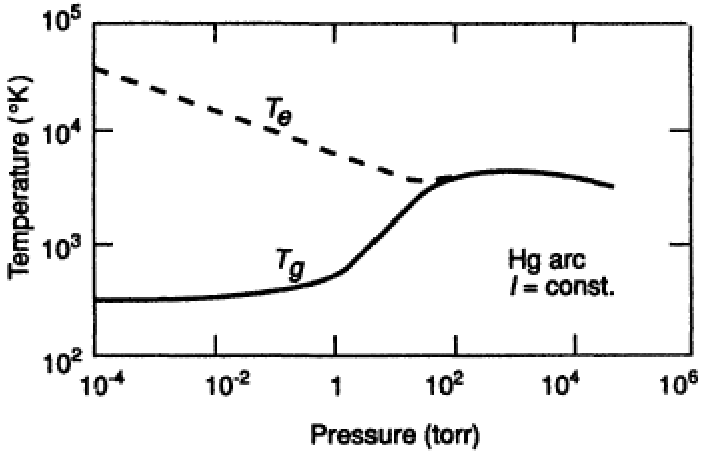
Low Temperature Plasma



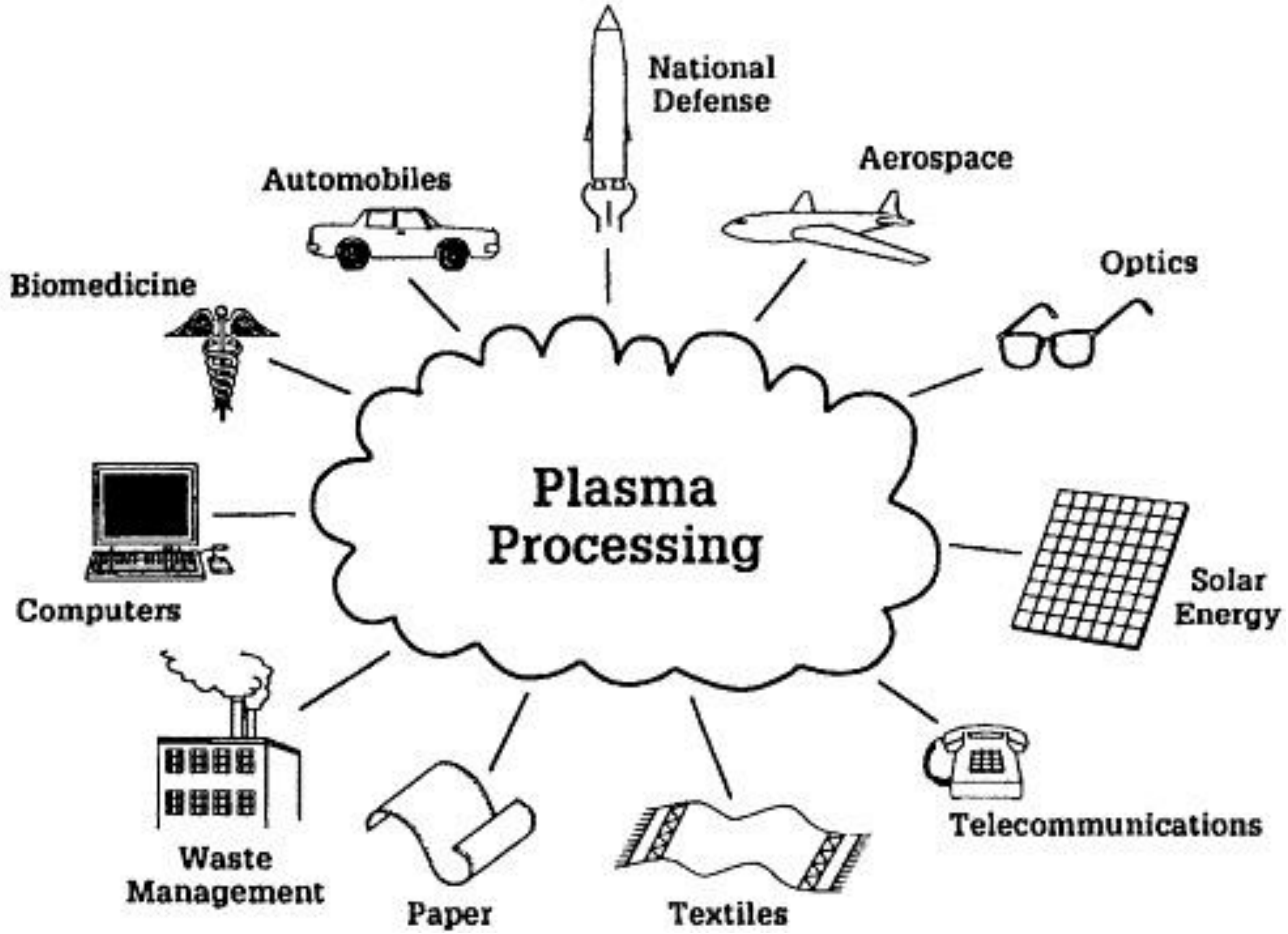
- Low degree of ionization
- Neutral background 10^6 the ion and electron density
- Collisions with the background gas is dominant compared to electron ion collisions



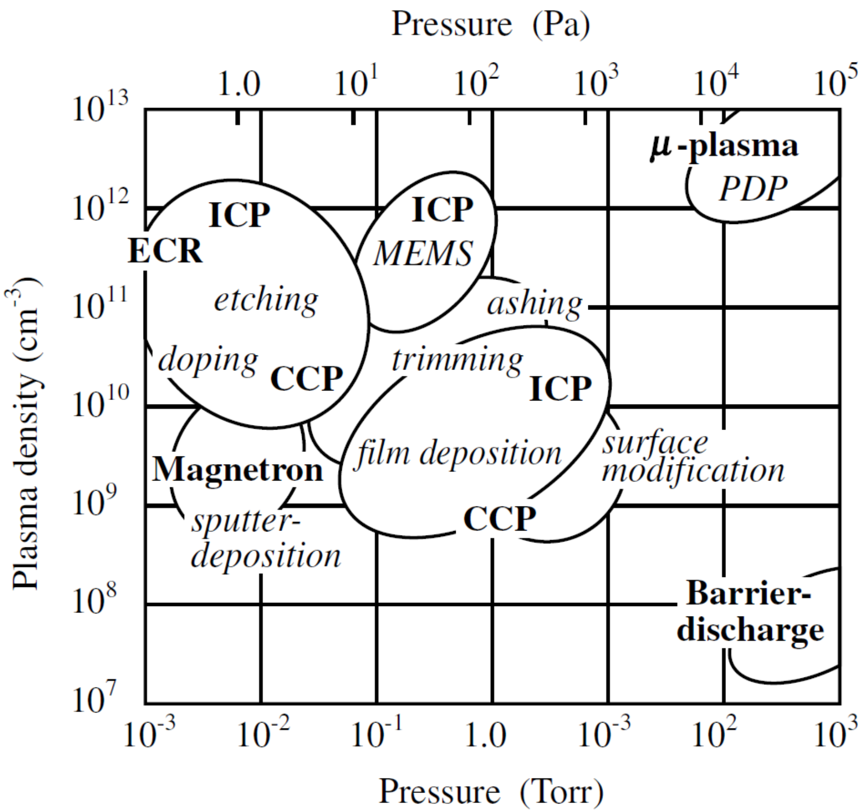
- Non-equilibrium plasmas at low pressures

$T_{\mathrm{e}} = 11000 - 60000\mathrm{K}$ $\quad$ $T_{\mathrm{e}} = 1 - 5\mathrm{eV}$ $\quad$ $T_{\mathrm{i}} = 300\mathrm{K}$

Various applications

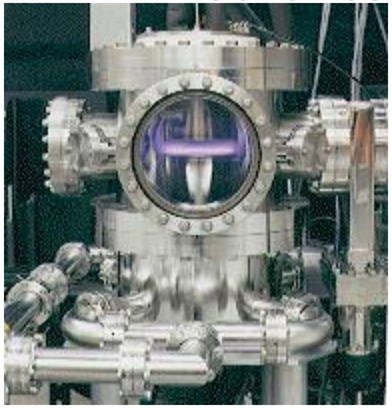


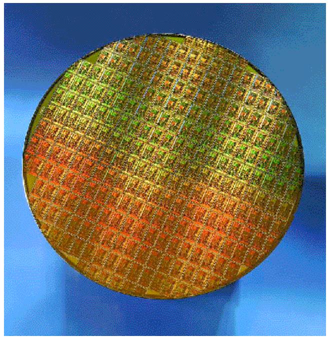
Devices

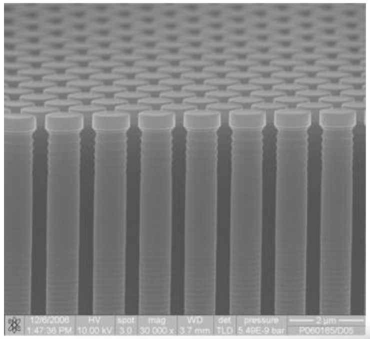


Plasma electronics,
Applications in Microelectronic Device Fabrication

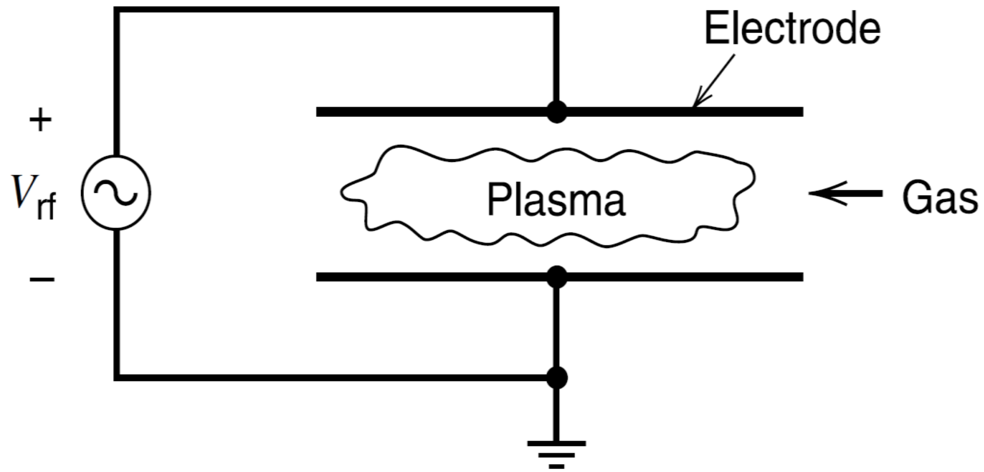
- **Capacitive coupled plasma** are used in plasma etching and deposition process for production of:
  - Integrated circuits
  - Sollar cells

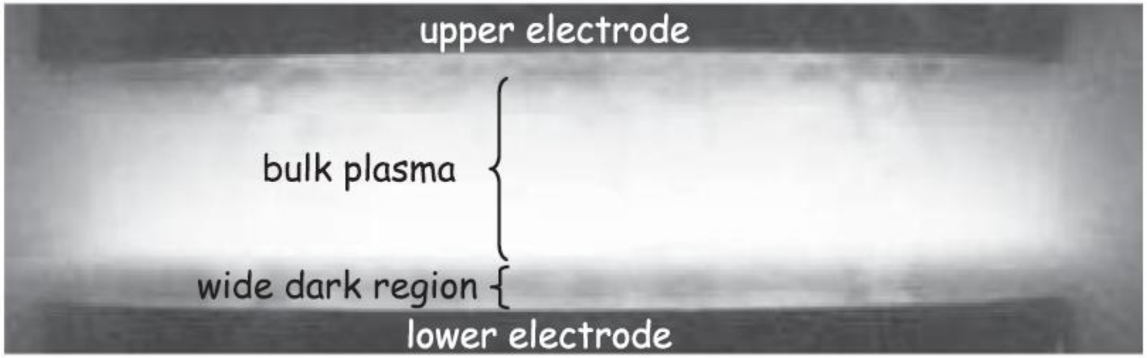






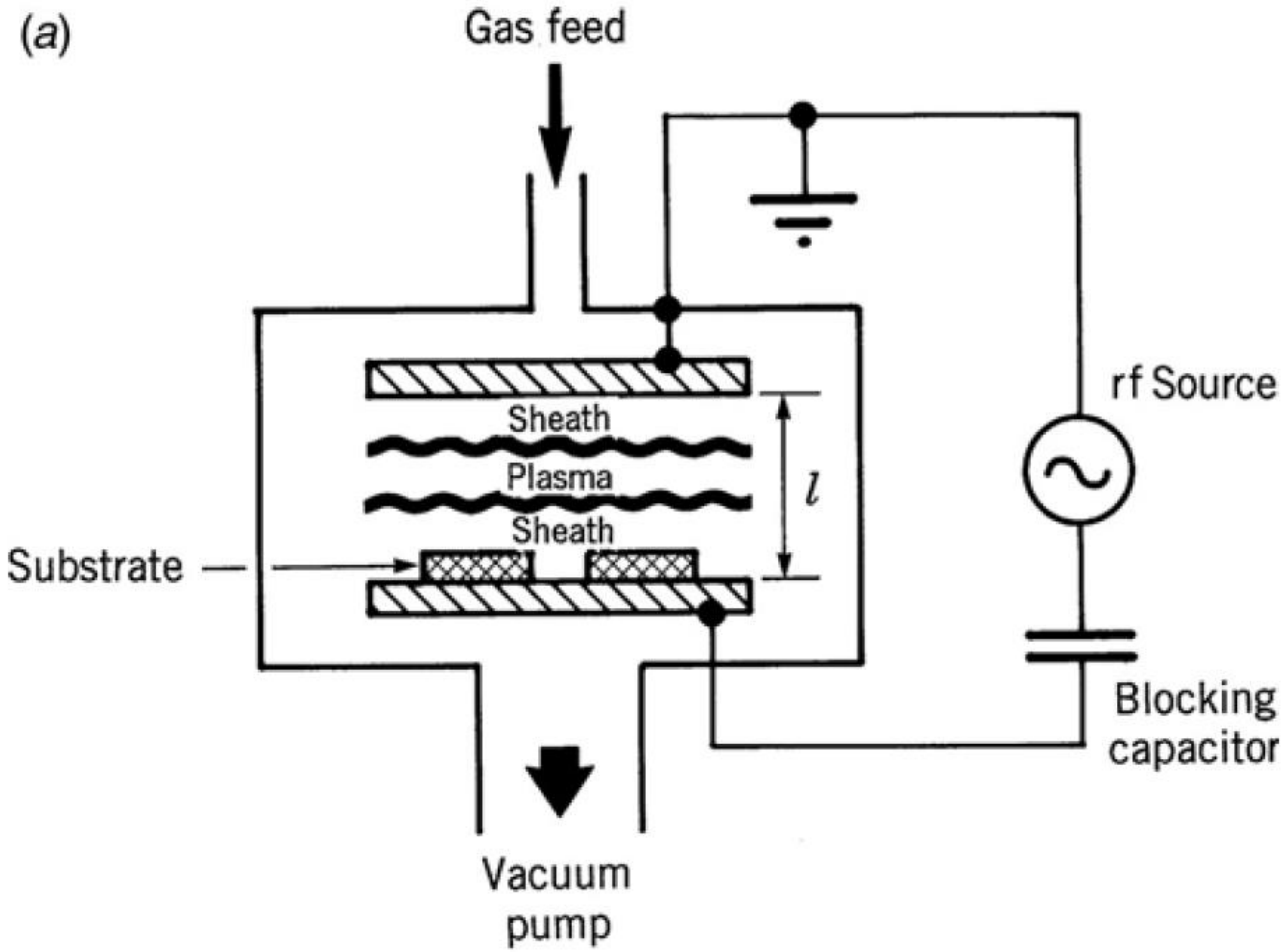
Symmetric CCP discharge





- **The ion flux and the ion energies increase (decreases) by increasing (decreasing) the dreving frequency.**

CCPs & blocking a Capacitor



Geometrically Asymmetric

- **The RF current is constant.**
- **But the ground electroge**

Area is greater then the powered electrode area.

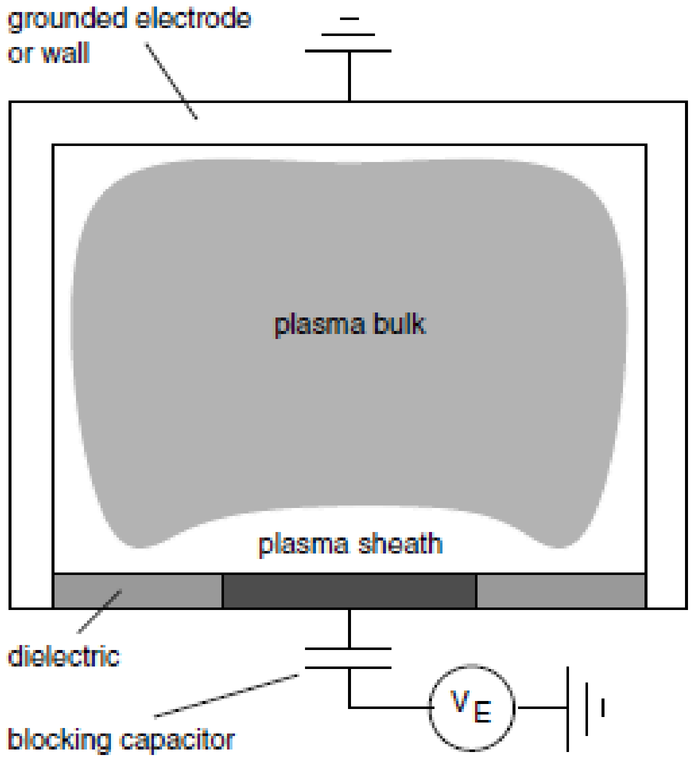
$$J_{\mathrm{g}} = I_{\mathrm{rf}}/A_g$$

$$J_{\mathrm{p}} = I_{\mathrm{rf}}/A_p$$

$$J_{\mathrm{p}} \gg J_{\mathrm{g}}$$

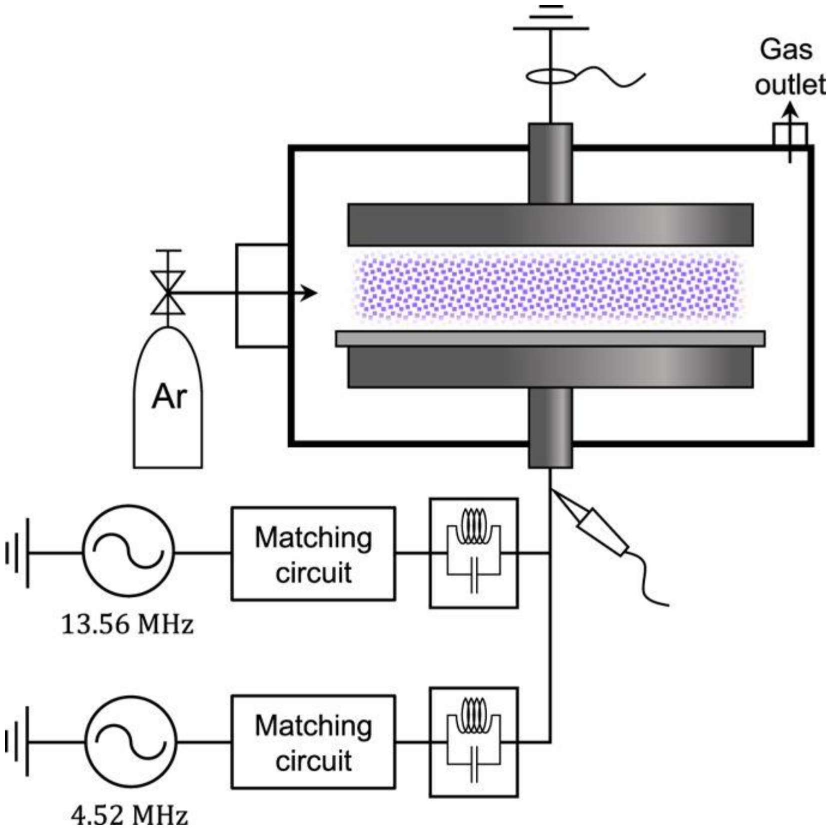
- The blocking capacitor blocks DC currents:

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{g}}} = (\frac{A_{\mathrm{g}}}{A_{\mathrm{p}}})^4$$

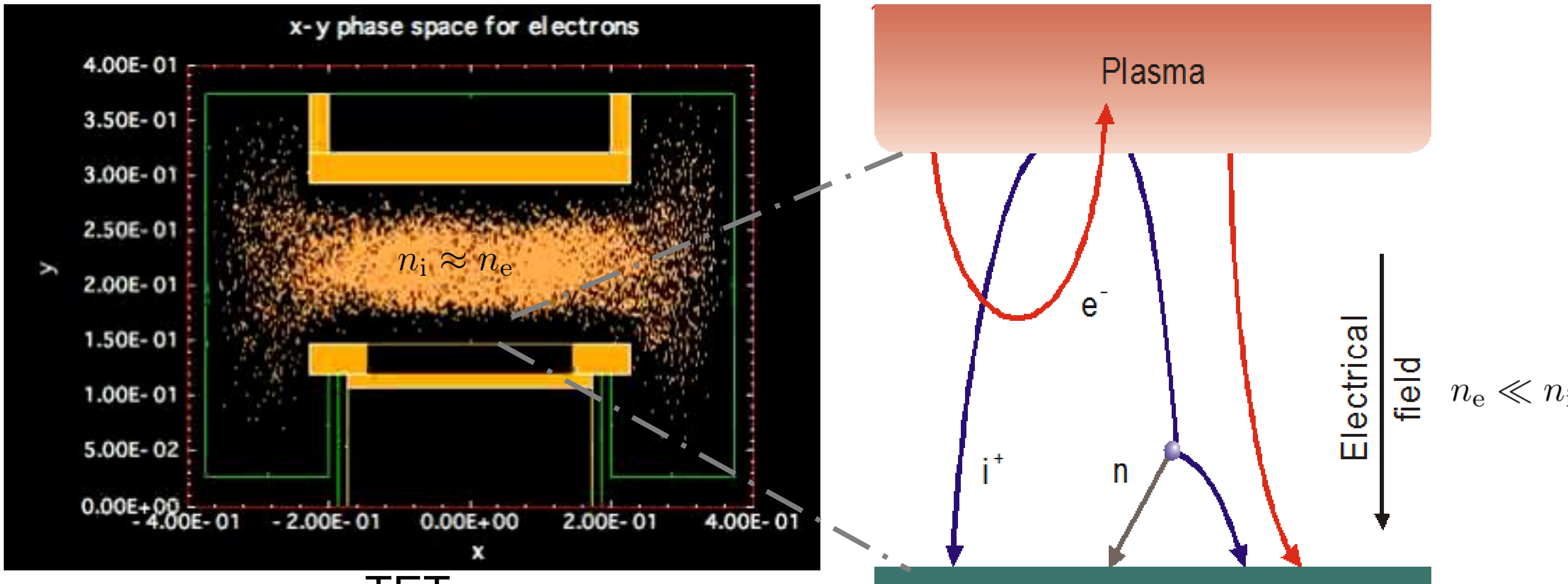


Electrically Asymmetric

- The high frequency controls the ion plasma bulk (ion flux).
- The lower frequency controls the plasma sheath.
- The phase shift between the two sources controls also the sheath potential.
- The independent control is not always perfect.



Plasma Sheaths



TET

- RF sheaths:
  - High frequency regime
  - Intermediate frequency regime
  - Low frequency regime

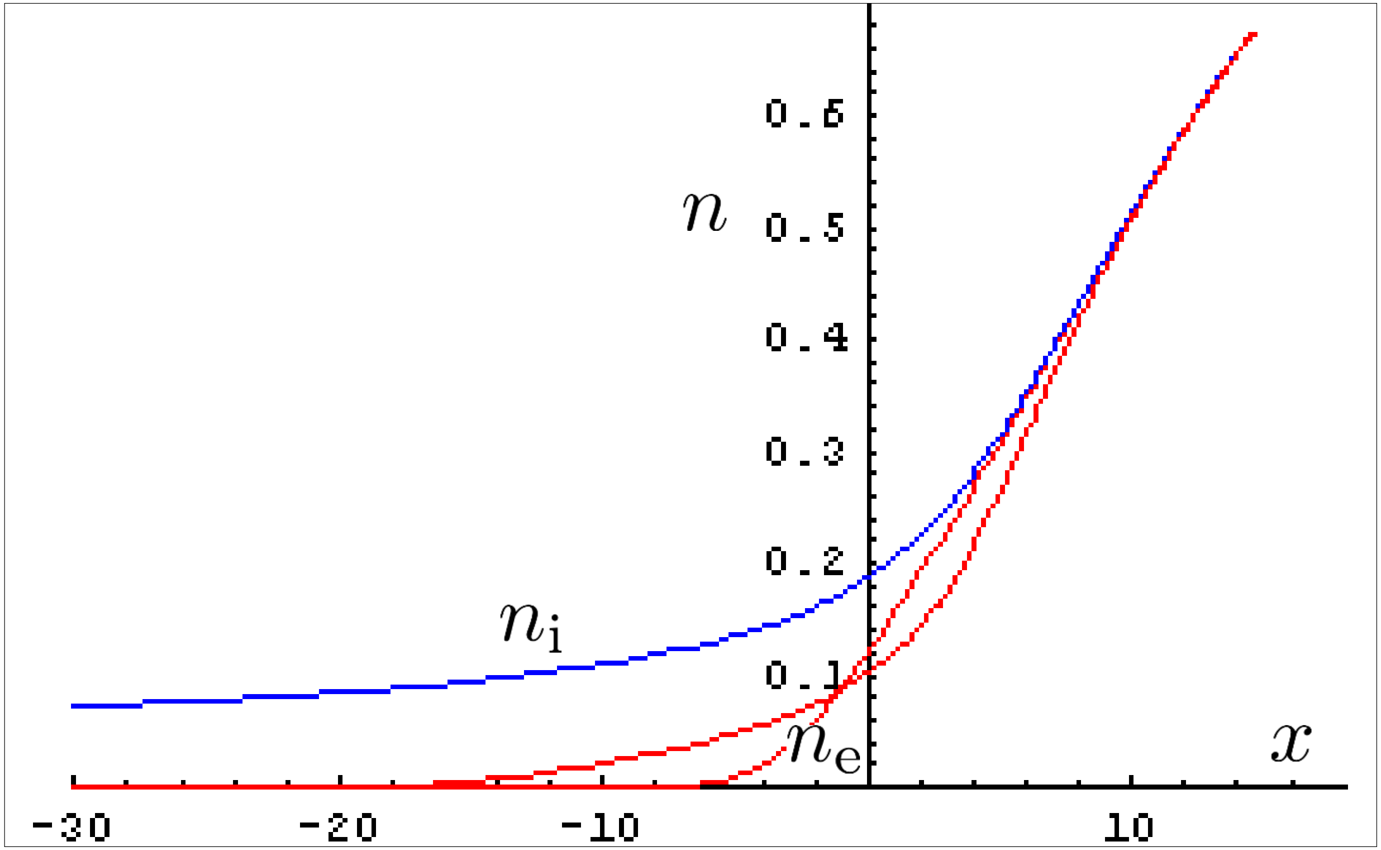
$$\omega_{RF} \gg \omega_{pi} \qquad n_i(x) \Leftrightarrow \bar{E}(x)$$

$$\omega_{RF} \approx \omega_{pi}$$

$$\omega_{RF} \ll \omega_{pi} \qquad n_i(x,t) \Leftrightarrow E(x,t)$$

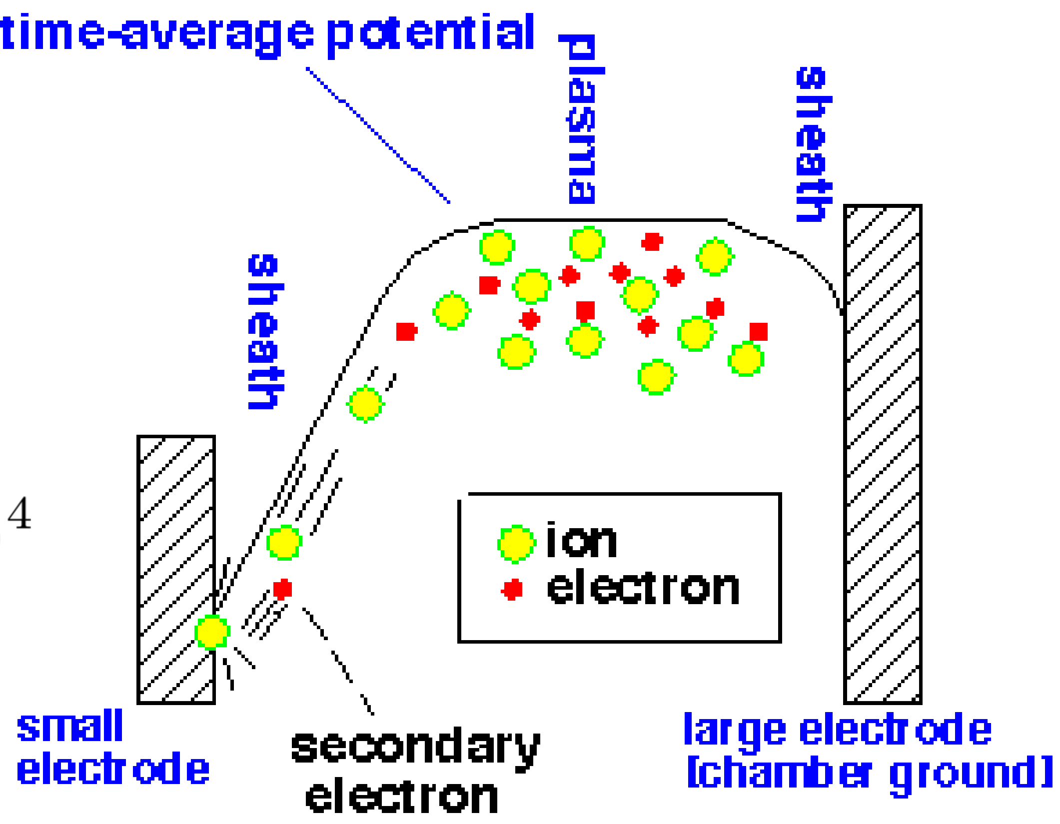
Plasma Sheaths

$$\omega_{\rm pe} \gg \omega_{\rm RF} \gg \omega_{\rm pi}$$

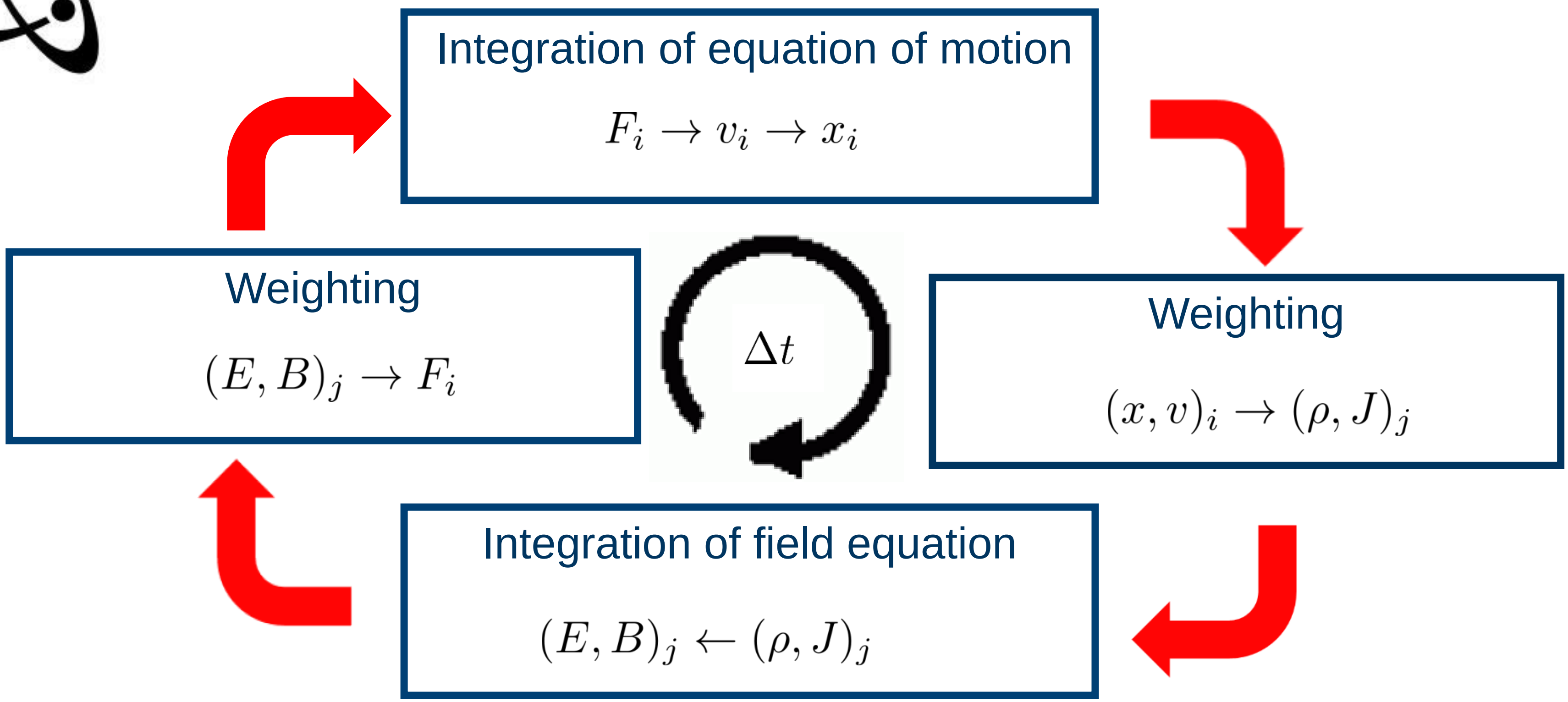


Particle and Potential distribution

$$\frac{V_p}{V_g} = \left(\frac{A_g}{A_p}\right)^4$$



Particle in Cell



- Kinetically self-consistent and no constraints.
- Simulate the whole discharge.
- Follow the time evolution until the system is converged,

i.e. the solution is periodic.

Fluid Models

- Transport =free flights + collisions
- Look from a distance at the ensemble of particles : transport coeffecients
- Fluid models: hydrodynamic transport

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = S$$

$$\rho \left(\frac{\partial}{\partial t} + \vec{u} \cdot \vec{\nabla} \right) \vec{u} = qn(\vec{E} + \vec{u} \times \vec{B}) - \vec{\nabla} \cdot \Pi + \vec{S}_c$$

.....

- Open set of equations even with Maxwell equations.
- Provide macroscopic description.
- Transport coeffecients are functions of local (E/n) or on local mean free energy.

$$\frac{dE}{dx} \lambda \ll E \qquad \frac{dE}{dt} \nu^{-1} \ll E$$

- Transport coeffecients can be derived from cross-sections, however, such calculations are zero-dimentional .

Plasma Chemistry I

- **Dissociation of feedstock gas into active neutral free radicals:**

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$$e^- + CF_4 \rightarrow CF_2 + 2F + e^-$$

$$e^- + CF_4 \rightarrow CF_{+}F_2 + F + e^-$$

- **Dissociation of the free radicals**

$$e^- + CF_3 \rightarrow CF_2 + F + e^-$$

$$e^- + CF_2 \rightarrow CF + F + e^-$$

Plasma Chemistry II

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

$$e^- + CF_3 \rightarrow CF_3 + F^-$$

- **Chlorine discharge**

$$e^- + Cl_2 \rightarrow Cl_2^+ + 2e^-$$

$$e^- + Cl_2 \rightarrow Cl^+ + Cl + 2e^-$$

Plasma Chemistry III

- **Chemical reactions between neutrals in the presence of a third body**

$$CF_3 + F + M \rightarrow CF_4 + M$$
$$CF_2 + F + M \rightarrow CF_3 + M$$
$$CF + F + M \rightarrow CF_2 + M$$

- **At the substrate**
- **Removing**

$$Cl(g) + Cl(ads) \rightarrow Cl_2(g)$$

- **Etching**

$$Cl(g) + SiCl_3(s) \rightarrow SiCl_4(g) \uparrow$$

- **Deposition or growth**

$$SiH(g) \rightarrow Si(s) \downarrow + H(g) \uparrow$$

Wet and Dry etching

- **Carbon Floride (CF4) does not react with Silicin (Si).**

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

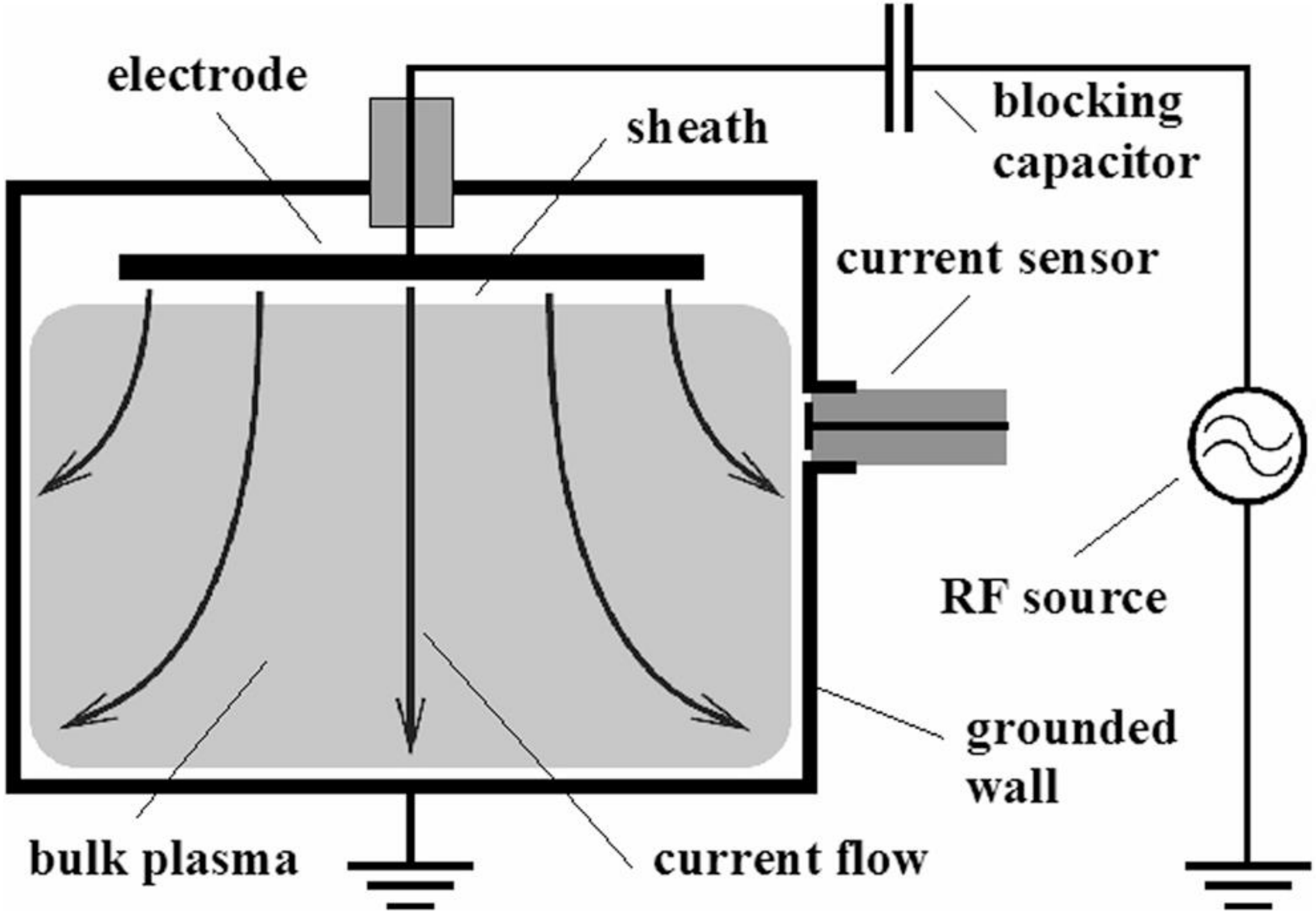
$$e^- + CF_3 \rightarrow CF_3 + F^-$$

- **Wet etching**

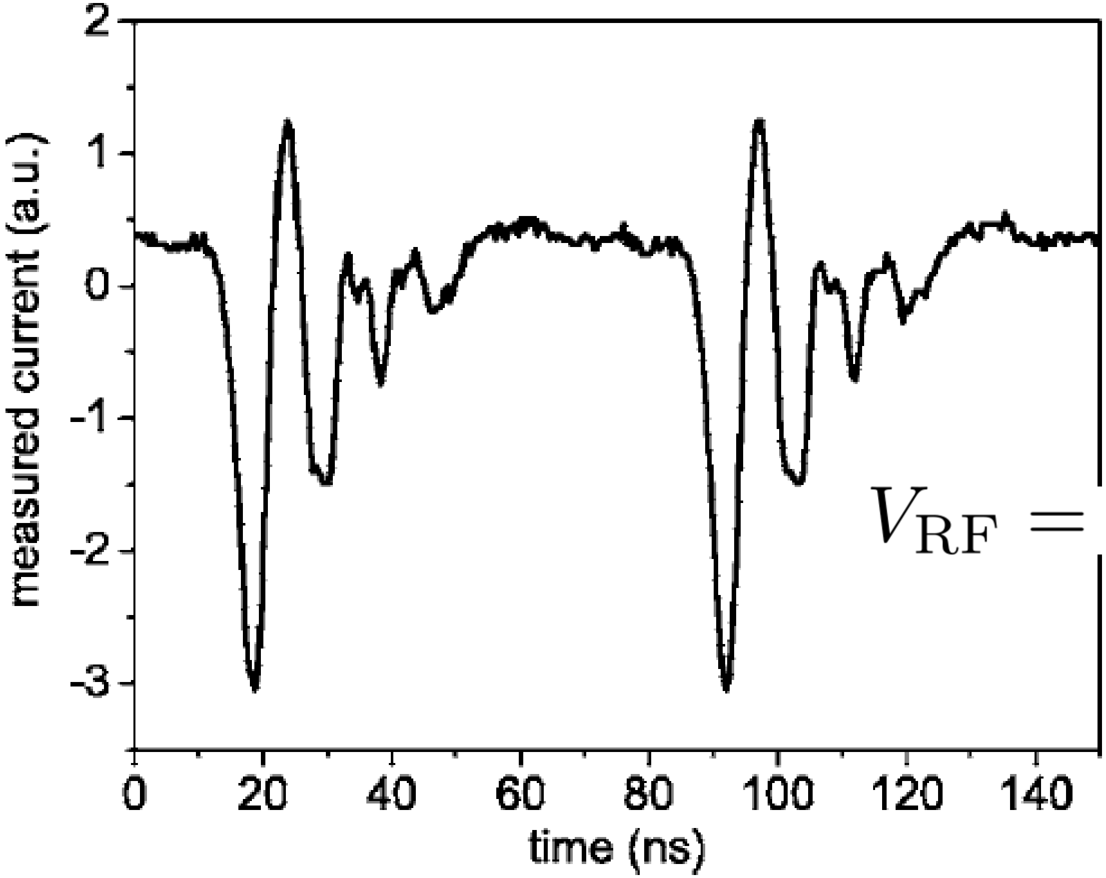
$$Si(s) + 4F(g) \rightarrow SiF_4(g) \uparrow$$

- **Dry etching: Accelerate CF_3^+ toward the Silicon substrate**

Why do we need an electrical model?



Measured Current

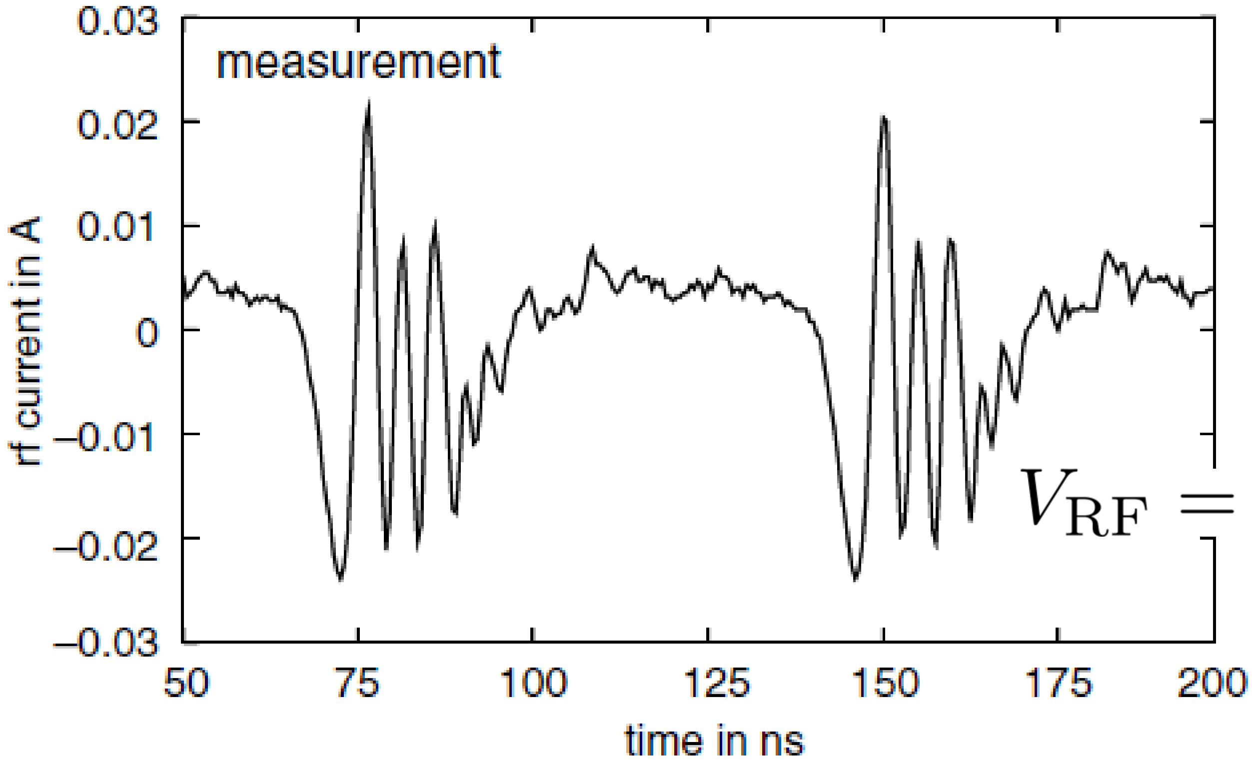


$V_{\mathrm{RF}} = 13.56\mathrm{MHz}$

123503-2 Czarnetzki, Mussenbrock, and Brinkmann Phys. Plasmas **13**, 123503 (2006)

[21] E. Semmler and P. Awakowicz, private communication (2006).

Measured Current



$V_{\mathrm{RF}} = 13.56\mathrm{MHz}$

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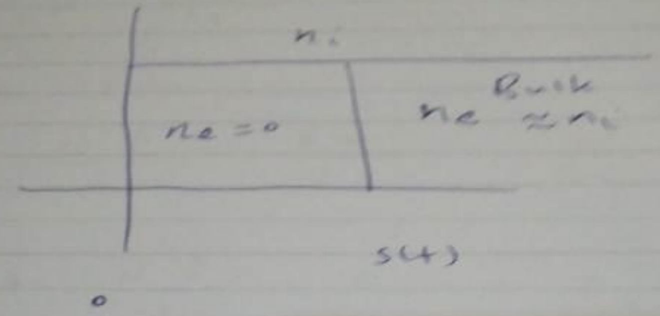
Plasma Sources Sci. Technol. **16** (2007) 377–385 doi:10.1088/0963-0252/16/2/022

[14] Semmler E and Awakowicz P 2006 private communication

Sheath Model

sheath model



$$\frac{d^2\phi}{dx^2} = \frac{-e}{\varepsilon_0} n_i \longrightarrow (1)$$

let $\alpha = e \int n_i \, dx \longrightarrow (2)$

then from (1)

$$\frac{d\phi}{dx} = \frac{-e}{\varepsilon_0} n_i \, dx$$

$$\therefore \quad \frac{d\phi}{dx} = -\frac{\alpha}{\varepsilon_0} \longrightarrow (3)$$

Sheath Model

$\therefore \quad \sigma = e \int n_i \, dx$

$\therefore \quad \frac{d\sigma}{dx} = e n_i$

then from (3)

$$\frac{d\phi}{d\sigma} \cdot \frac{d\sigma}{dx} = -\frac{\sigma}{\varepsilon_0}$$

$$\therefore \quad \frac{d\phi}{d\sigma} \cdot e n_i = \frac{-\sigma}{\varepsilon_0}$$

$$\therefore \quad \frac{d\phi}{d\sigma} = \frac{-\sigma}{e \varepsilon_0 n_i}$$

$$\therefore \quad \phi_{sheath} = \frac{-\sigma^2}{2 \varepsilon_0 n_i}$$

σ is charge density

$$\therefore \quad \phi_{sheath} = \frac{-Q^2}{2 \varepsilon_0 n_i A^2}$$

Bulk Model

Title: Bulk model

start from momentum equation

$$m \frac{\partial v}{\partial t} + m_e v_e \frac{\partial v_e}{\partial x} = -eE - m_e v_e \nu_e$$

the plasma bulk is homogeneous

$$\therefore \frac{\partial v_e}{\partial x} = 0$$

$$\therefore m \frac{\partial v}{\partial t} = -eE - m_e v_e \nu_e$$

$$E = -\frac{\partial \phi}{\partial x}$$

$$m_e \frac{\partial v}{\partial t} = e \frac{\partial \phi}{\partial x} - m_e v_e \nu_e$$

$$\therefore m_e \frac{\partial v}{\partial t} + m_e v_e \nu_e = e \frac{\partial \phi}{\partial x}$$

from definition $\Rightarrow J = e n_e v_e$

Bulk Model

Title:

$$\therefore \; I(t) = e\, n_e\, v_e\, A \;\Rightarrow\; v_e = \frac{I(t)}{e\, n_e\, A}$$

$$\therefore \; v_e = \frac{I(t)}{e\, n_e\, A}$$

$$m_e \frac{\partial v}{\partial t} + m_e\, v_e\, \nu_e = e \frac{d\varphi}{dx}$$

$$\left(m_e \frac{\partial}{\partial t} + m \nu\right) v = e \frac{d\varphi}{dx}$$

$$\int_{x_1}^{x_2} \frac{m_e}{e} \left[\frac{\partial}{\partial t} + \nu \right) v \, dx = \varphi_{21}$$

$$\frac{m_e}{e} \left[\frac{\partial}{\partial t} + \nu \right) \Big] \int \frac{I(t)}{e\, n_e\, A}\, dx = \varphi_{21}$$

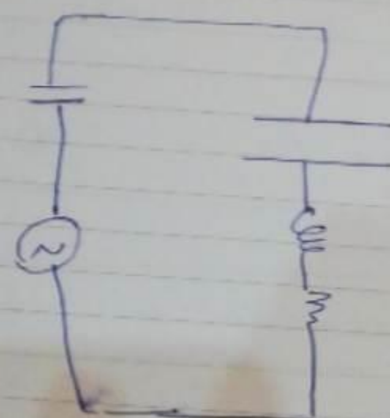
$$\therefore \; \frac{m_e L}{e^2 n_e A} \left[\frac{\partial}{\partial t} + \nu \right) I(t) = \varphi_{21}$$

Bulk Model

Title:

$$V_{Source} = V_{Bulk} + V_{sheath}$$

$$\frac{m_e L}{e^2 n_e A}\left[\frac{dI(t)}{dt} + \nu I(t)\right] - \frac{Q^2}{2\varepsilon_0 n_i A^2} = V_{Source}$$



So finally

$$V_{Source} = \frac{m_e L}{e^2 n_e A}\left[\ddot{Q} + \nu \dot{Q}\right] - \frac{Q^2}{2\varepsilon_0 n_i A^2} + V_{D}$$

Bulk Model

Title:

which is $\Phi = a\ddot{Q} + b\dot{Q} + cQ^2$

where Q is the net positive charge.

If the sheath is a linear element then

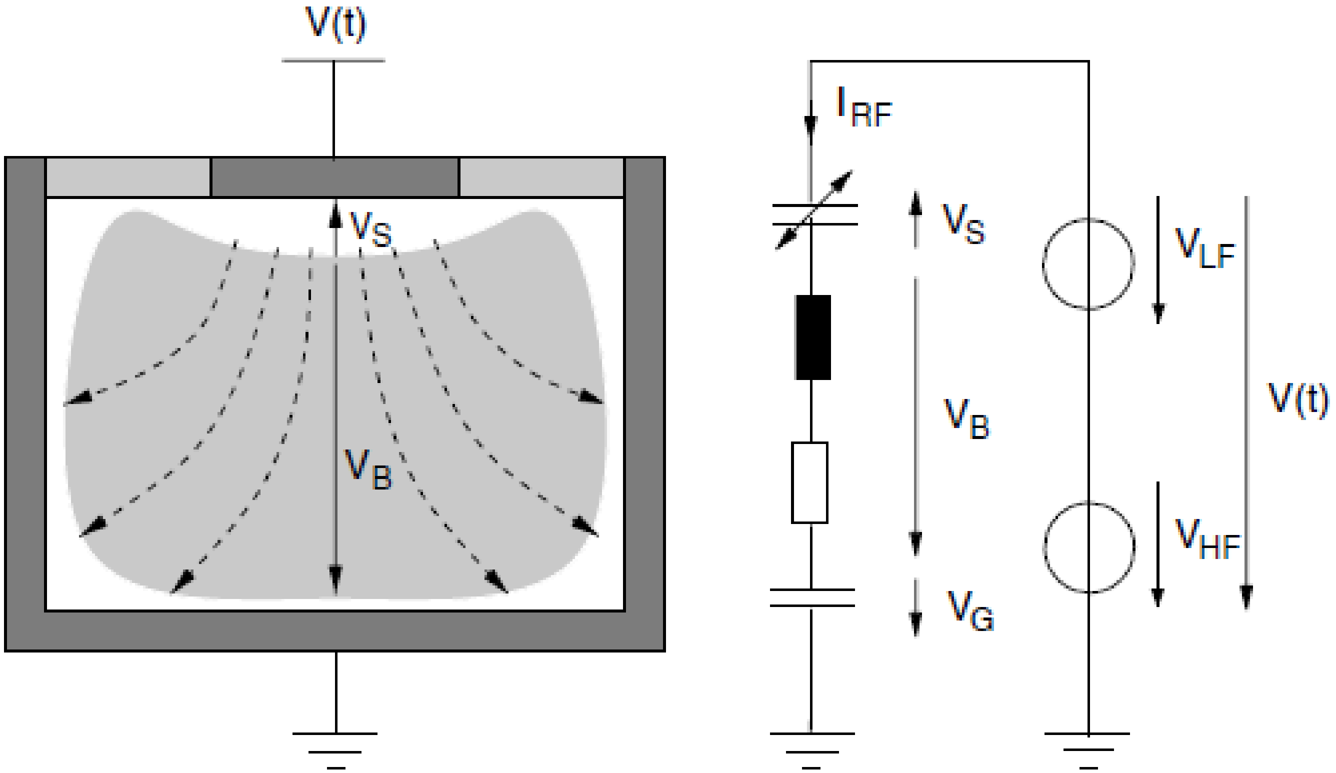
$$\Phi = a\ddot{Q} + b\dot{Q}$$

or

$$\Phi = a\ddot{Q} + b\dot{Q} + cQ$$

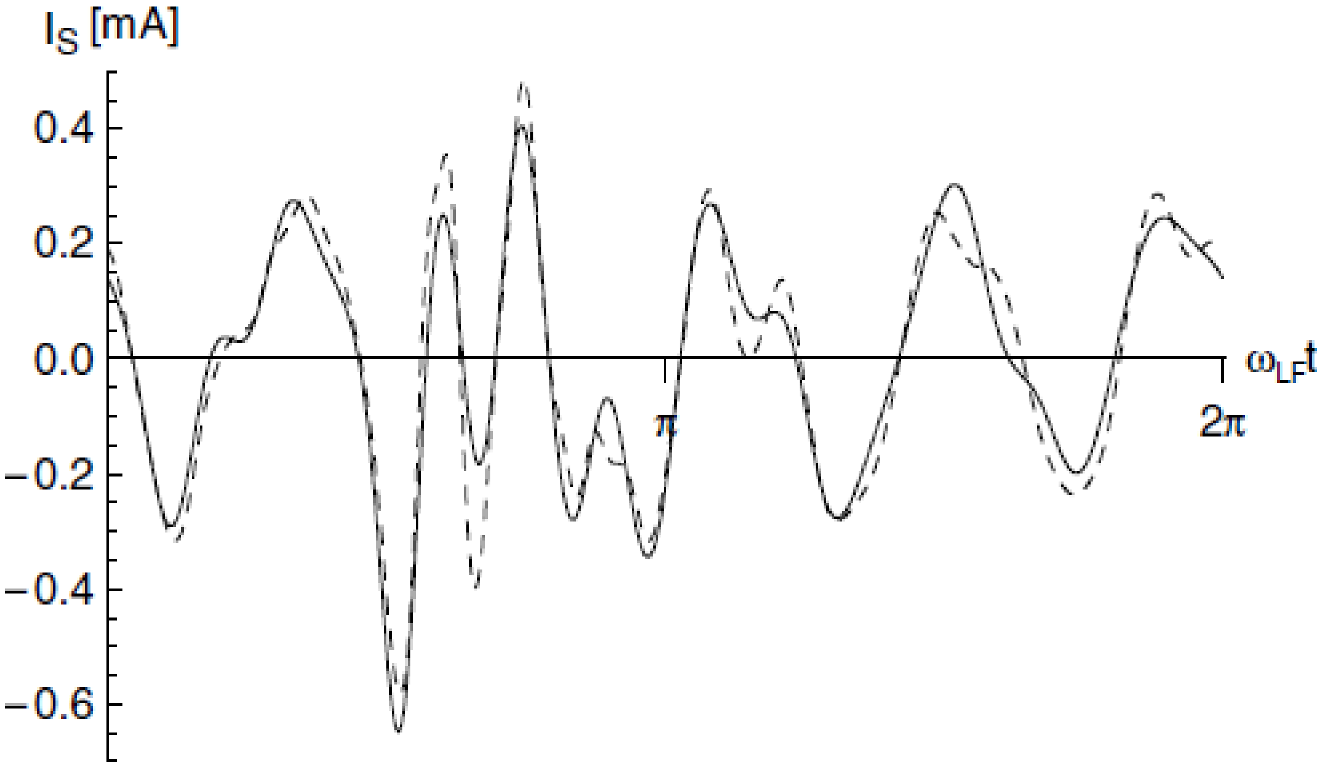
the solution will be like hormonic oscillator. so $Q(t)$ and $\Phi(t)$ have the same frequency.

2 RF discharge



Plasma Sources Sci. Technol. **17** (2008) 045011 D Ziegler *et al*

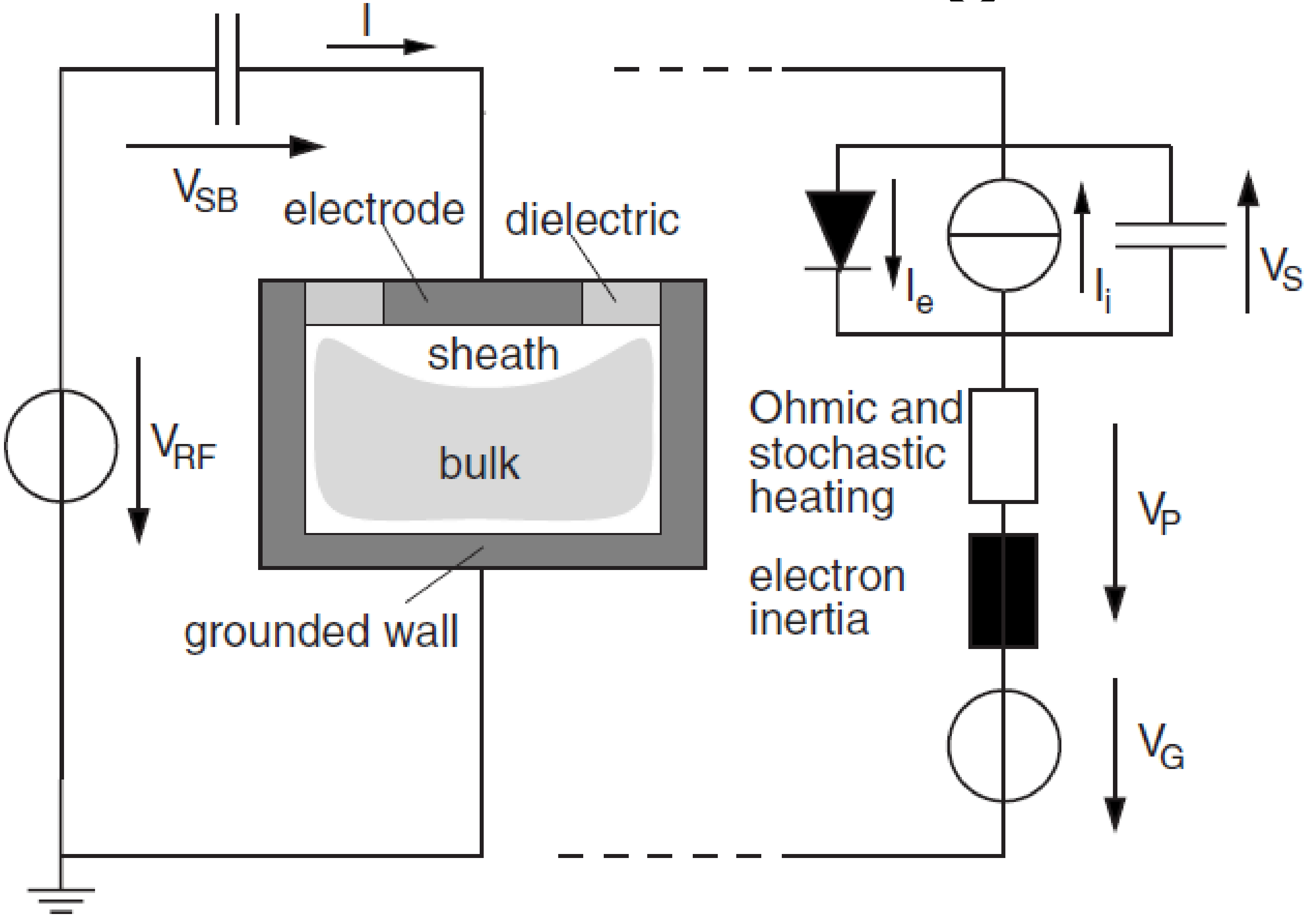
2 RF discharge



Plasma Sources Sci. Technol. **17** (2008) 045011 D Ziegler *et al*

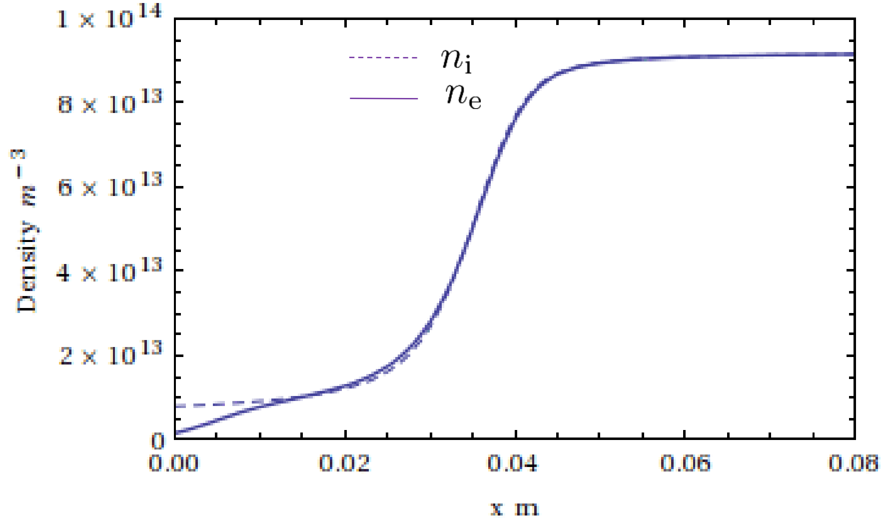
$$L_P \frac{d^2 Q}{dt^2} + \nu_m L_P \frac{dQ}{dt} + \sum_{k=2}^{M} V_k Q^k - V_{SB} - V_G$$
$$+ V_{LF} \cos(\omega_{LF} t + \phi_{LF}) + V_{HF} \cos(\omega_{HF} t + \phi_{HF}) = 0. \quad (31)$$

2 RF discharge



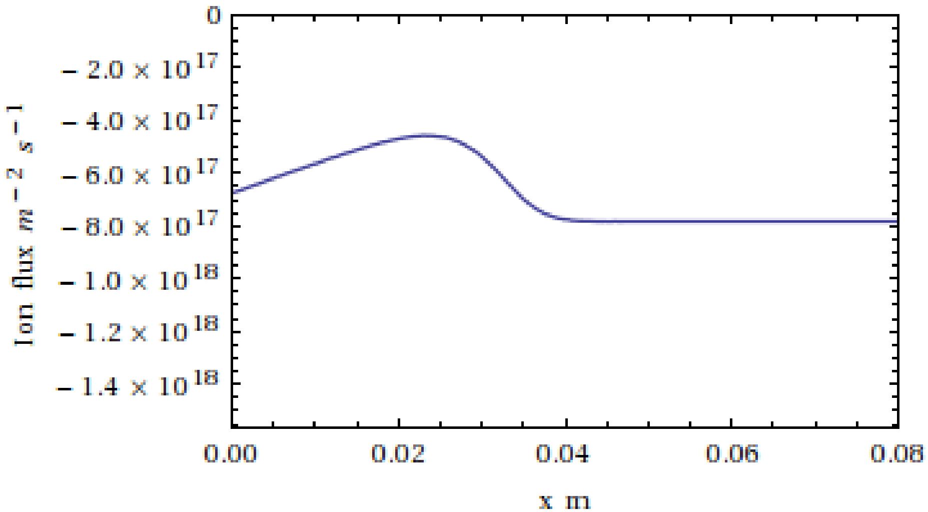
023503-2 Ziegler, Mussenbrock, and Brinkmann Phys. Plasmas **16**, 023503 (2009)

Ion Dynamics

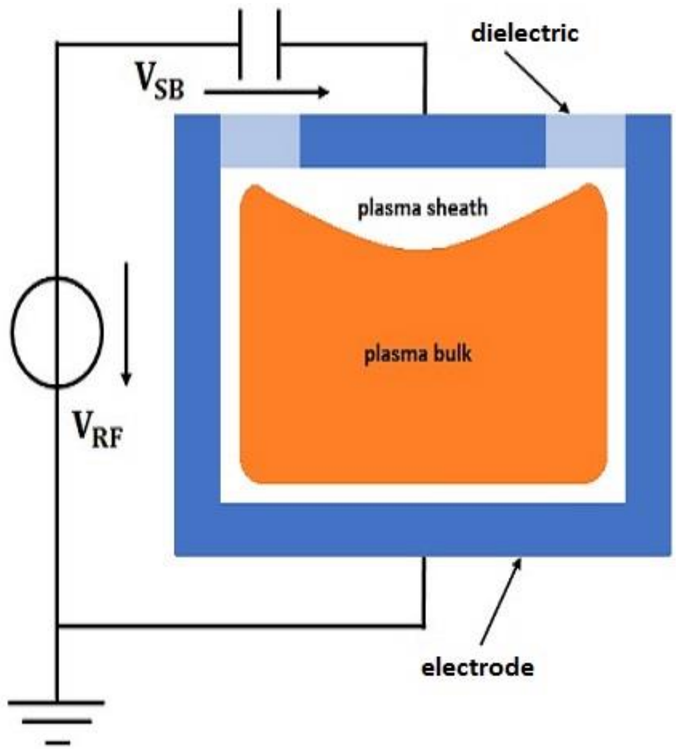


- The intermediate regime

$$\omega_{\rm RF} \approx \omega_{\rm pi}$$



lumped model circuit of CCPs at the intermediate radio-frequencies



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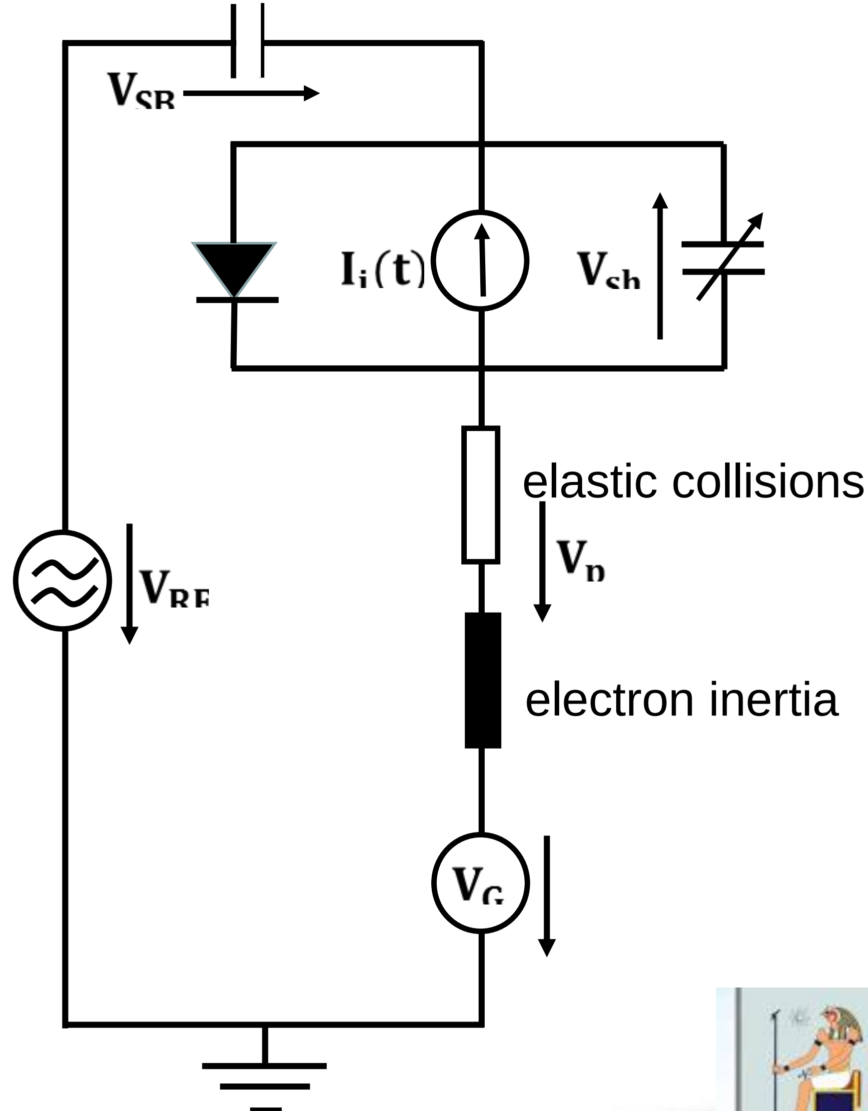

Model equations

$$\frac{dQ(t)}{dt} = -I - en_{\mathrm{s}}(t)A_{\mathrm{s}}u_{\mathrm{s}}(t) + en_{\mathrm{B}}\sqrt{(T_{\mathrm{e}}/2\pi m_{\mathrm{e}})}A_{\mathrm{s}}\exp(-eV_{\mathrm{s}}(t)/T_{\mathrm{e}})$$

$$V_{\mathrm{s}}(t) = \frac{Q^2(t)}{2\epsilon_0 en_{\mathrm{s}}(t)A_{\mathrm{s}}^2}$$

$$\frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}}\left(\frac{dI(t)}{dt} + \nu_{\mathrm{eff}}I(t)\right) = V_{\mathrm{s}}(t) - V_{\mathrm{G}} - V_{\mathrm{SB}}(t) + V_{\mathrm{RF}}(t)$$

$$V_{\mathrm{G}} = \frac{T_{\mathrm{e}}}{2e}\ln\left(\frac{m_{\mathrm{i}}}{2\pi m_{\mathrm{e}}}\right)$$

$$C\frac{dV_{\mathrm{SB}}(t)}{dt} = I(t)$$

$$P(t) = \frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}}\nu_{\mathrm{eff}}I^2(t) \qquad \bar{P}(t) = \frac{m_{\mathrm{e}}L_{\mathrm{B}}}{e^2 n_{\mathrm{B}}A_{\mathrm{B}}\tau}\int_0^t \nu_{\mathrm{eff}}I^2(t)dt$$

Model equations

In order to include the ion dynamics in the RF sheath self-consistently, the collisionless-sheath equations should be coupled to the system of equations:

$$\frac{\omega_{\mathrm{RF}}}{\omega_{\mathrm{pi}}}\frac{\partial n_{\mathrm{s}}}{\partial t}+\frac{\partial n_{\mathrm{s}}u_{\mathrm{s}}}{\partial s}=0, \tag{12}$$

$$\frac{\omega_{\mathrm{RF}}}{\omega_{\mathrm{pi}}}\frac{\partial u_{\mathrm{s}}}{\partial t}+u_{\mathrm{s}}\frac{\partial u_{\mathrm{s}}}{\partial s}=-\frac{\partial V_{\mathrm{s}}(t)}{\partial s}. \tag{13}$$

Assuming a first order perturbation approach, $n_{\mathrm{s}}=\bar{n}_{\mathrm{s}}+\delta n_{\mathrm{s}}$, $u_{\mathrm{s}}=\bar{u}_{\mathrm{s}}+\delta u_{\mathrm{s}}$, and $V_{\mathrm{s}}=\bar{V}_{\mathrm{s}}+\delta V_{\mathrm{s}}$. Where $\bar{n}_{\mathrm{s}}$, $\bar{u}_{\mathrm{s}}$, $\bar{V}_{\mathrm{s}}$ are the time averaged ion density, ion speed, and sheath potential, respectively. While δn_{s}

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$$n_s(t) = n_B + \delta n_s(t),$$

$$u_s(t) = u_B + \delta u_s(t).$$

The modulation of the ion density and the ion speed can be calculated approximately via

$$\frac{\omega_{RF}}{\omega_{pi}} \frac{\partial \delta n_s}{\partial t} + \frac{\bar{u}_s \delta n_s + \bar{n}_s \delta u_s}{s} = 0, \tag{14}$$

$$\frac{\omega_{RF}}{\omega_{pi}} \frac{\partial \delta u_s}{\partial t} + \frac{\bar{u}_s \delta u_s + \delta V_s}{s} = 0, \tag{15}$$

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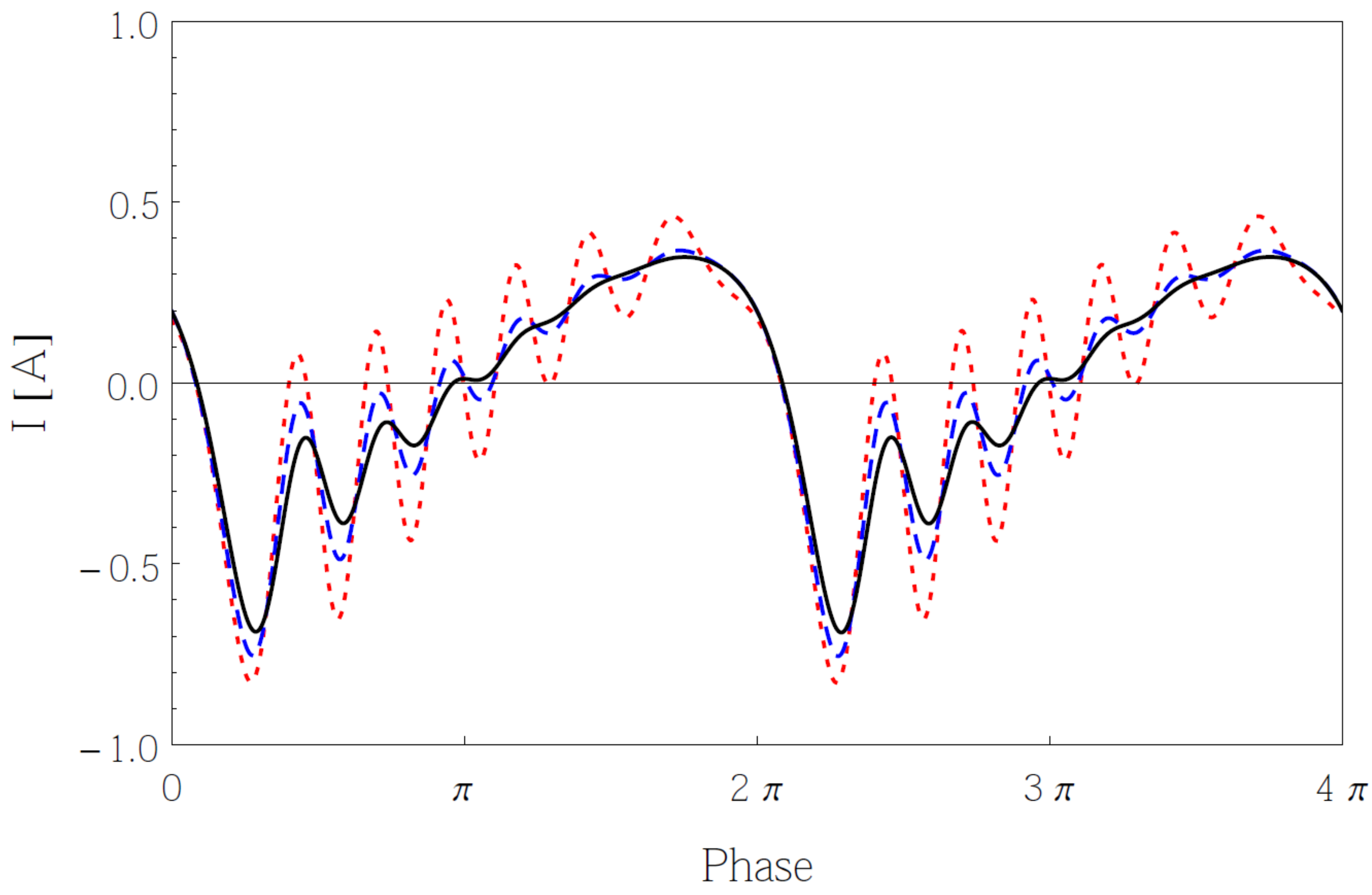
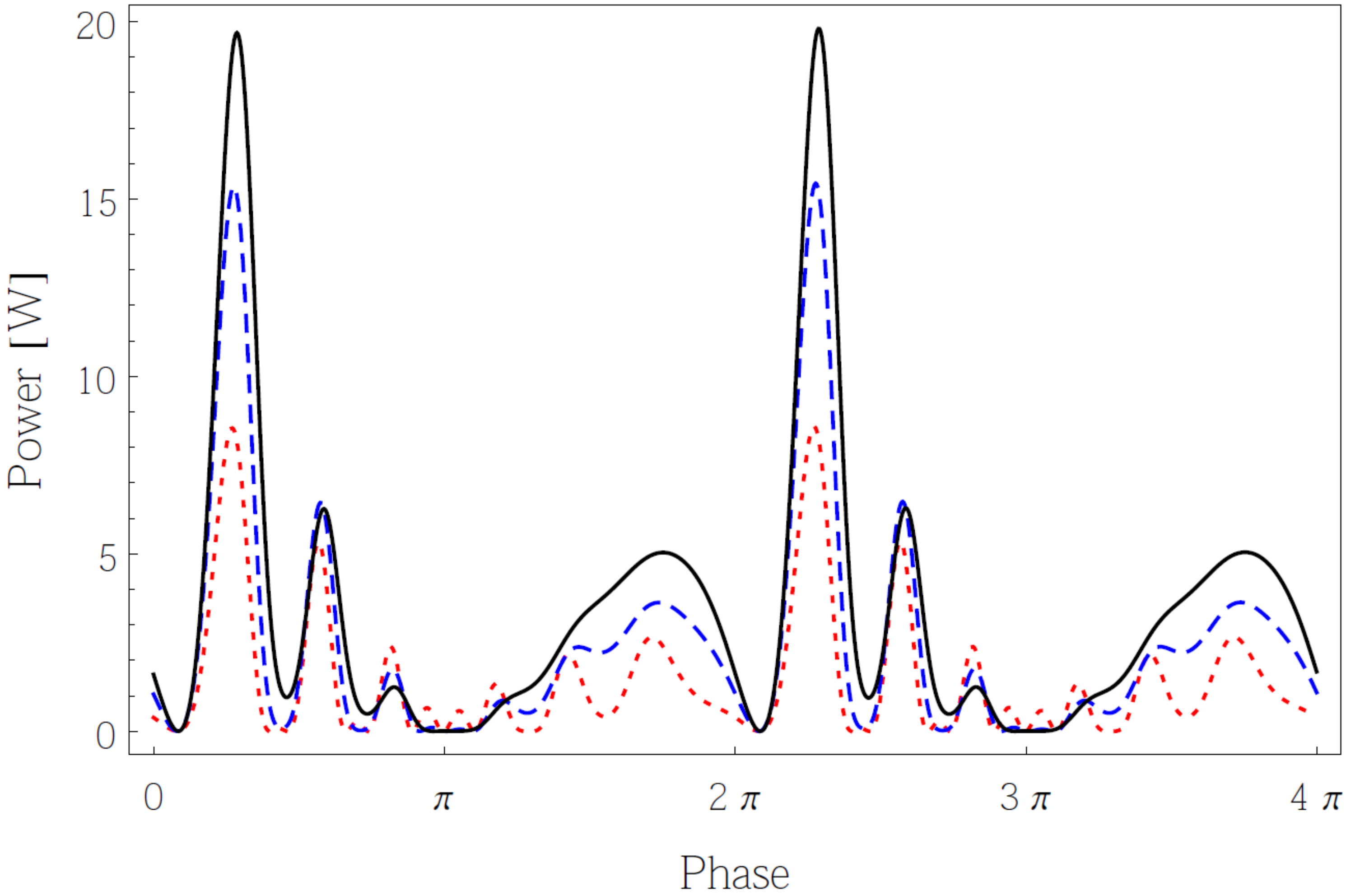


- 50 mTorr Black, 30 mTorr Blue, 10 mTorr Red
- 13.56 MHz



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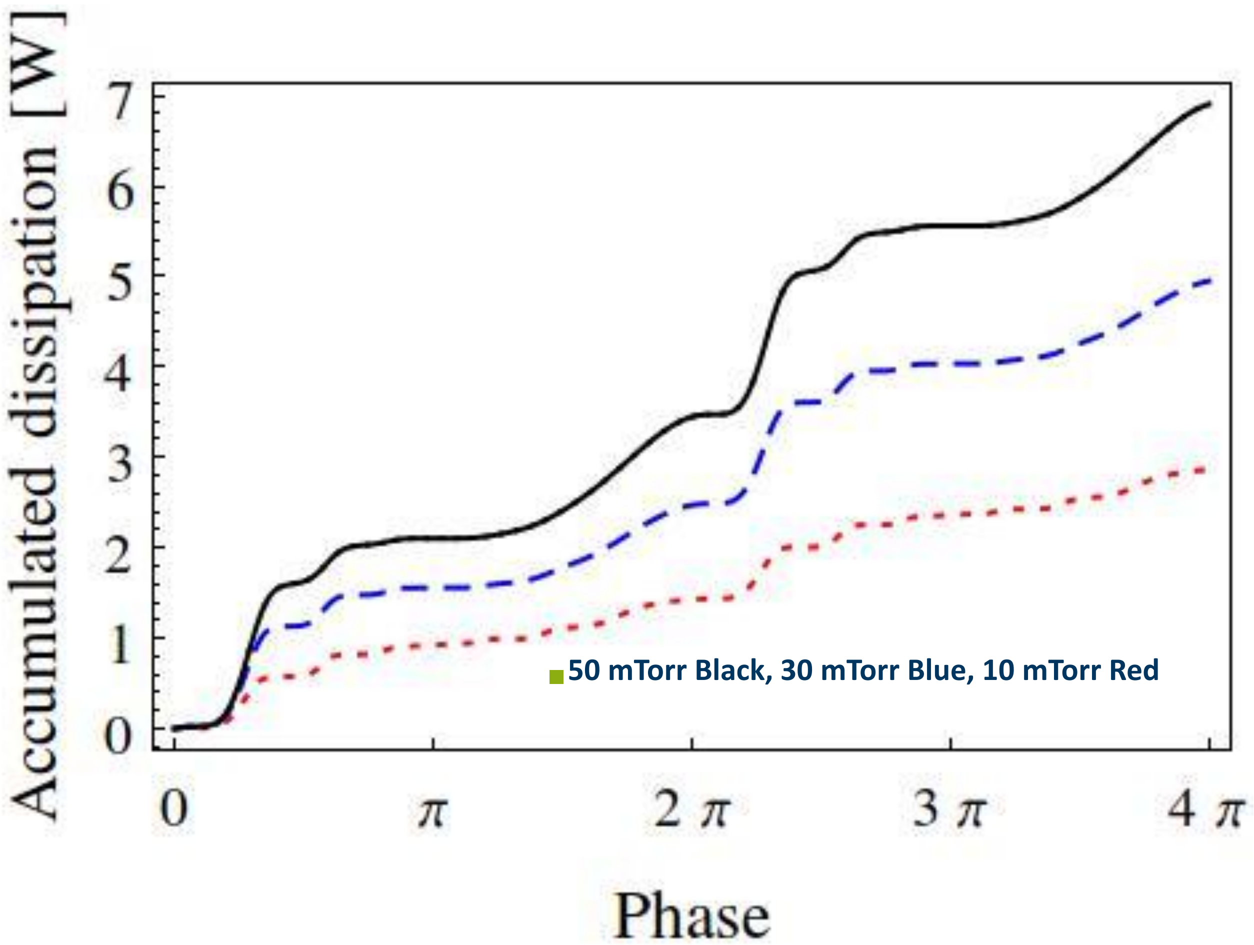

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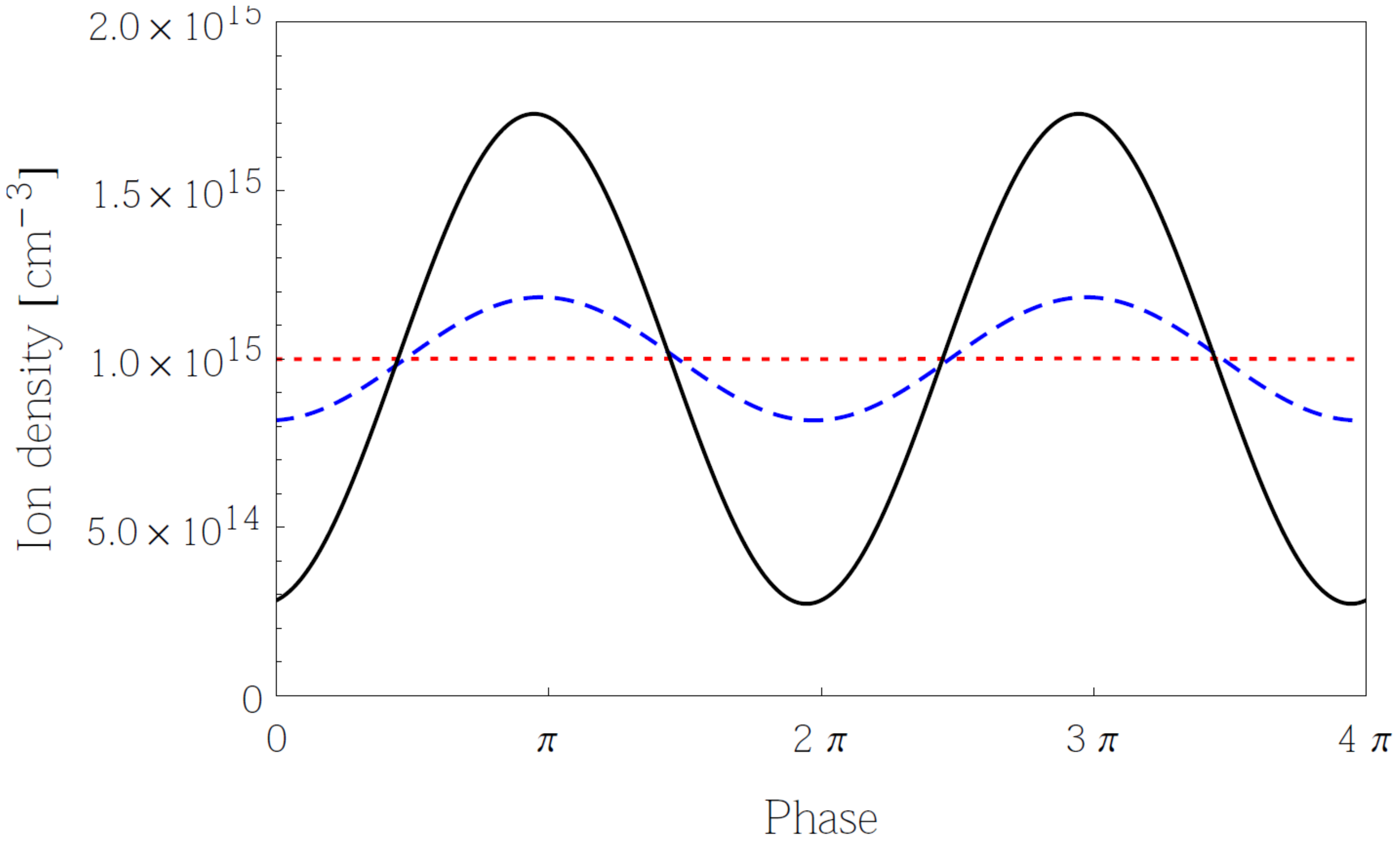
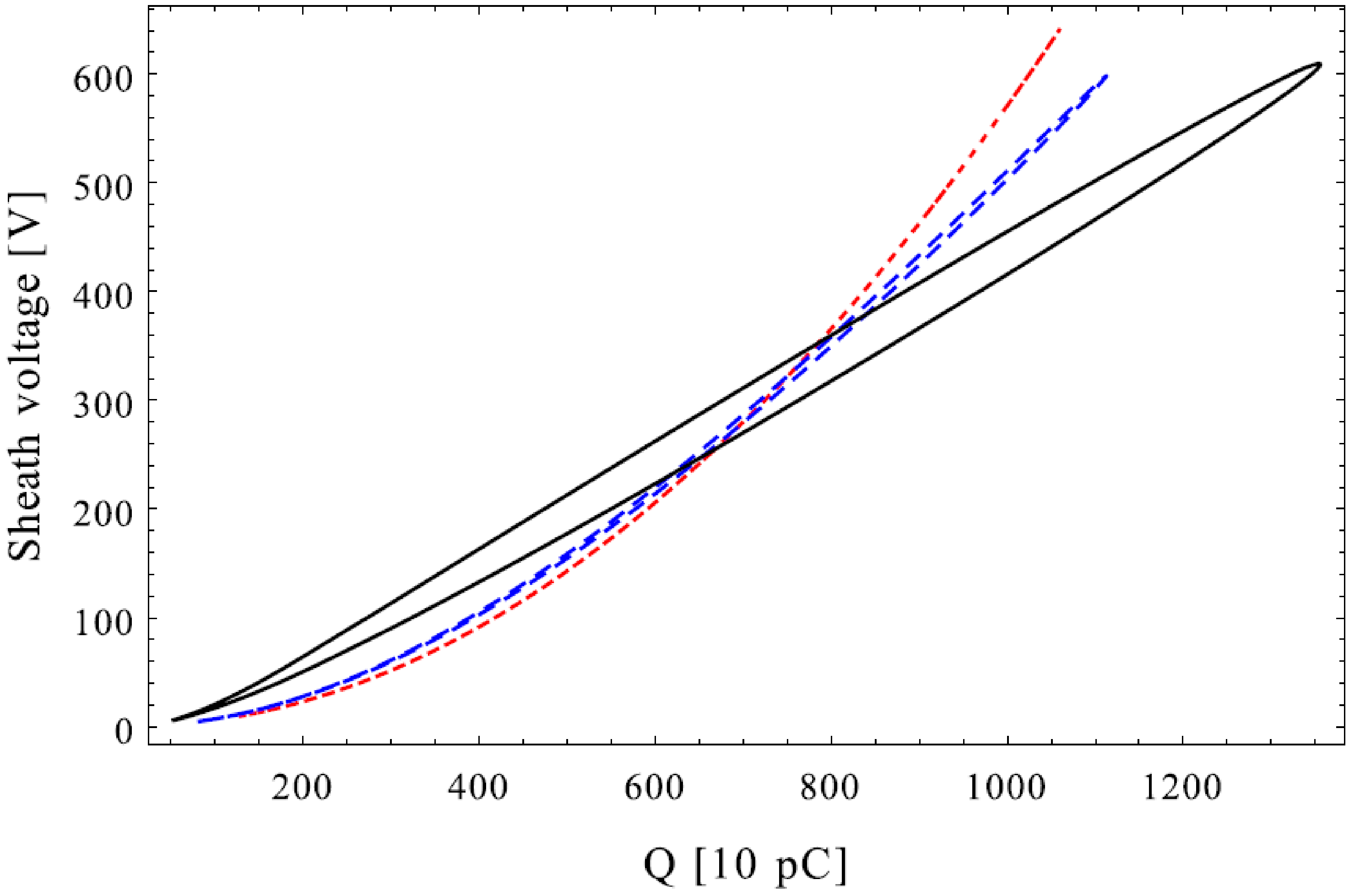


- 13.56 MHz dotted, 1MHz dashed, 0.5 MHz solid



- 13.56 MHz dotted, 1MHz dashed, 0.5 MHz solid

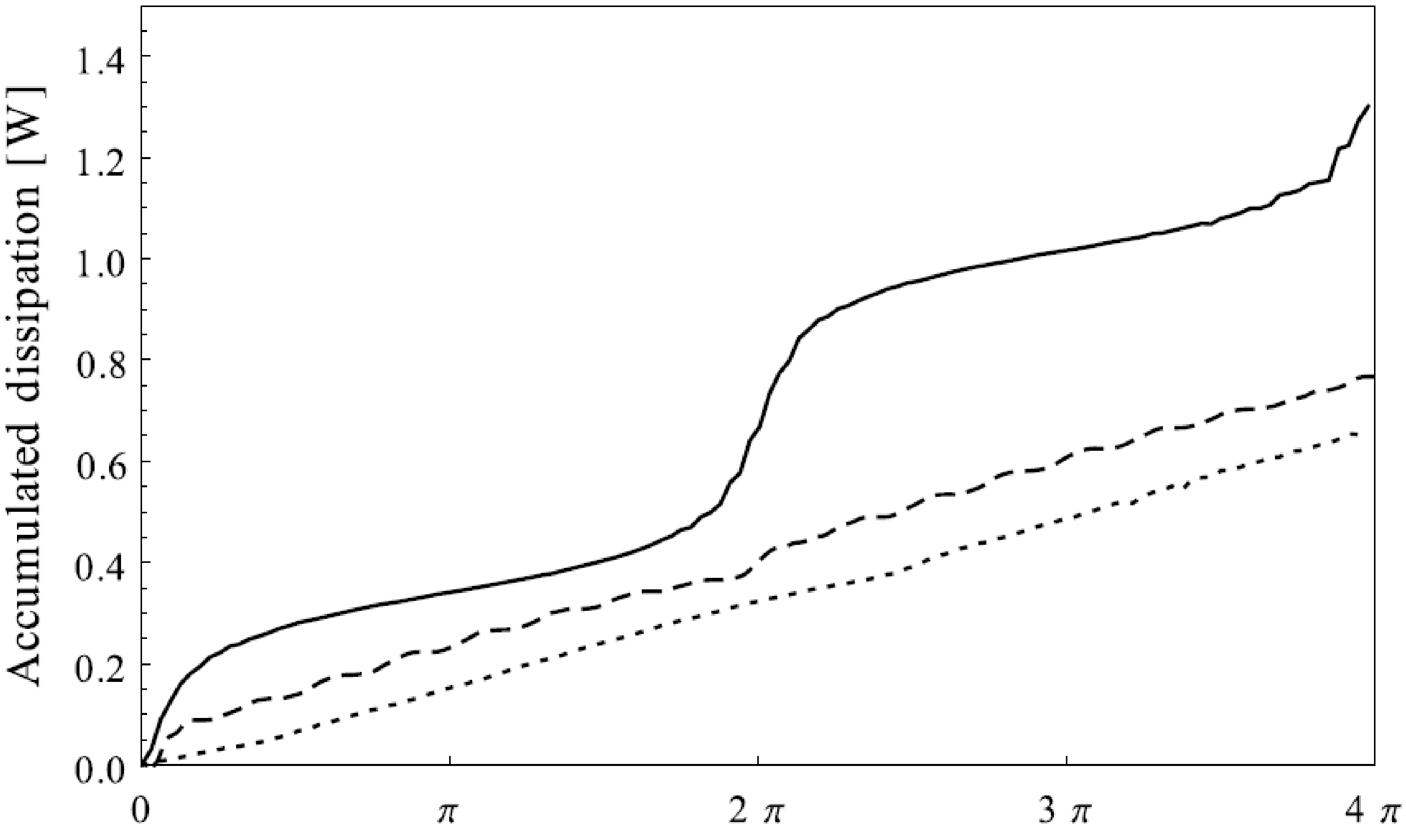


Fig. 8. The phase-accumulated power when $V_{RF} = 300[\cos(0.5\ \text{MHz}\ t + \theta) + \cos(13.56\ \text{MHz}\ t)]$ V. Dashed-black, dotted-black represent the cases $\theta = 0$ and $\theta = -\pi/2$, respectively. The solid-black line represents the results when the ion modulation is ignored and $\theta = 0$.

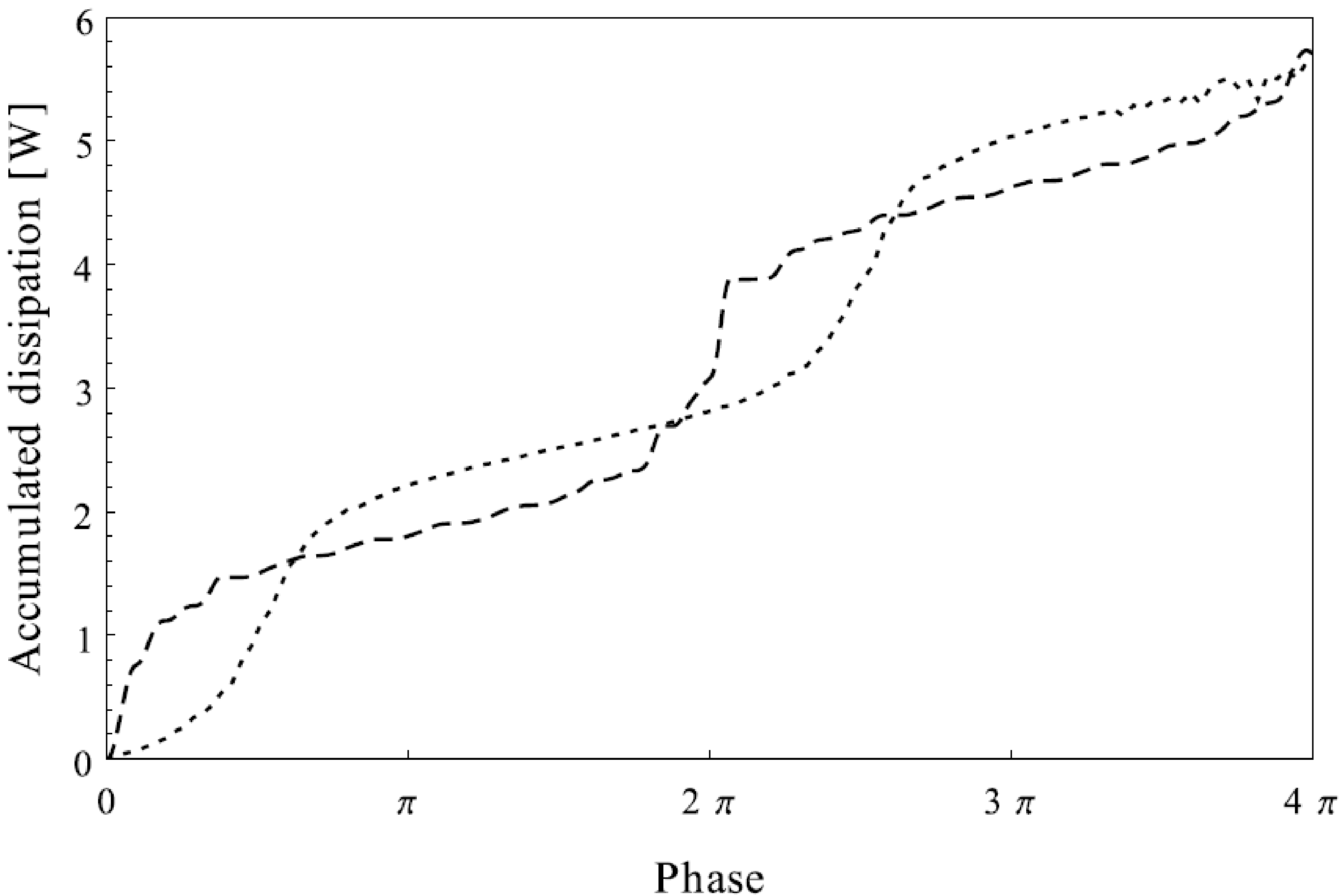
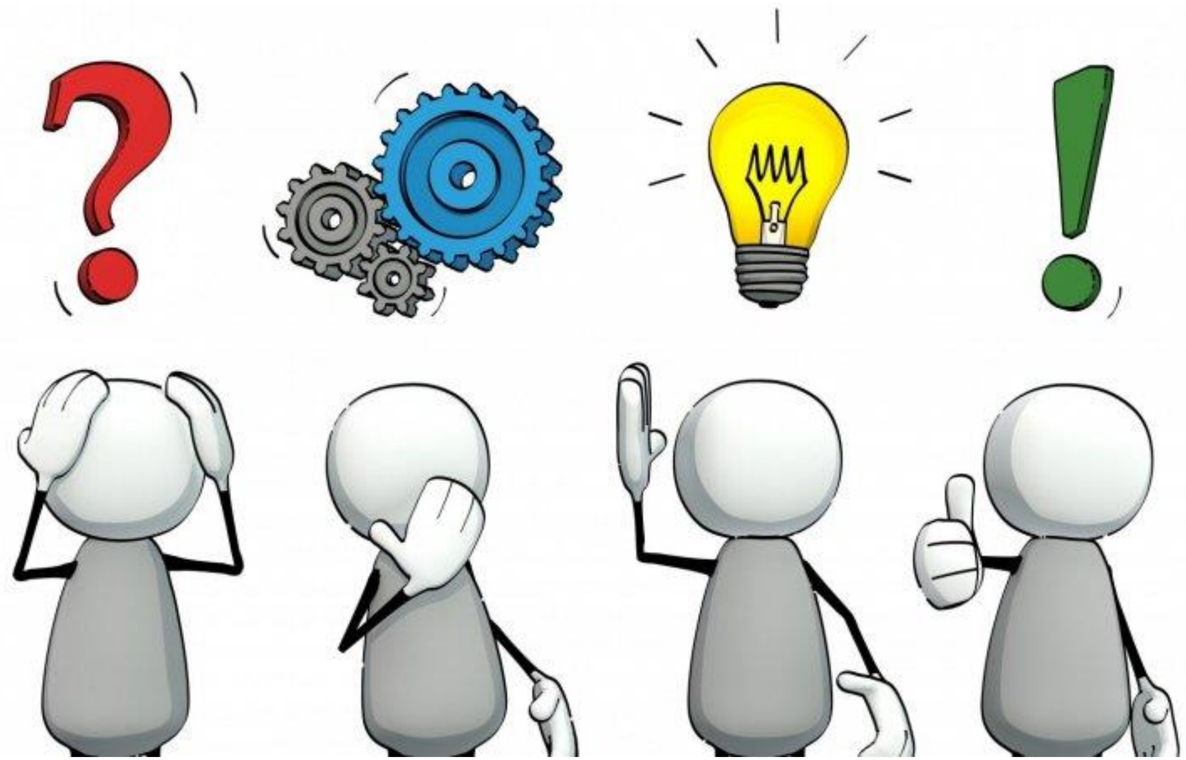


Fig. 9. The phase-accumulated power when $V_{RF} = 300[\cos(1 \text{ MHz } t + \theta) + \cos(13.56 \text{ MHz } t)]$ V. Dashed-black, dotted-black represent the cases $\theta = 0$ and $\theta = -\pi/2$, respectively.

Open Discussion

- ***Can the ion modulation heat the plasma?***



Thanks!