بسم الله الرحمن الرحيم

Transition from non-neutral regime to neutral regime for capacitively coupled plasma reactors

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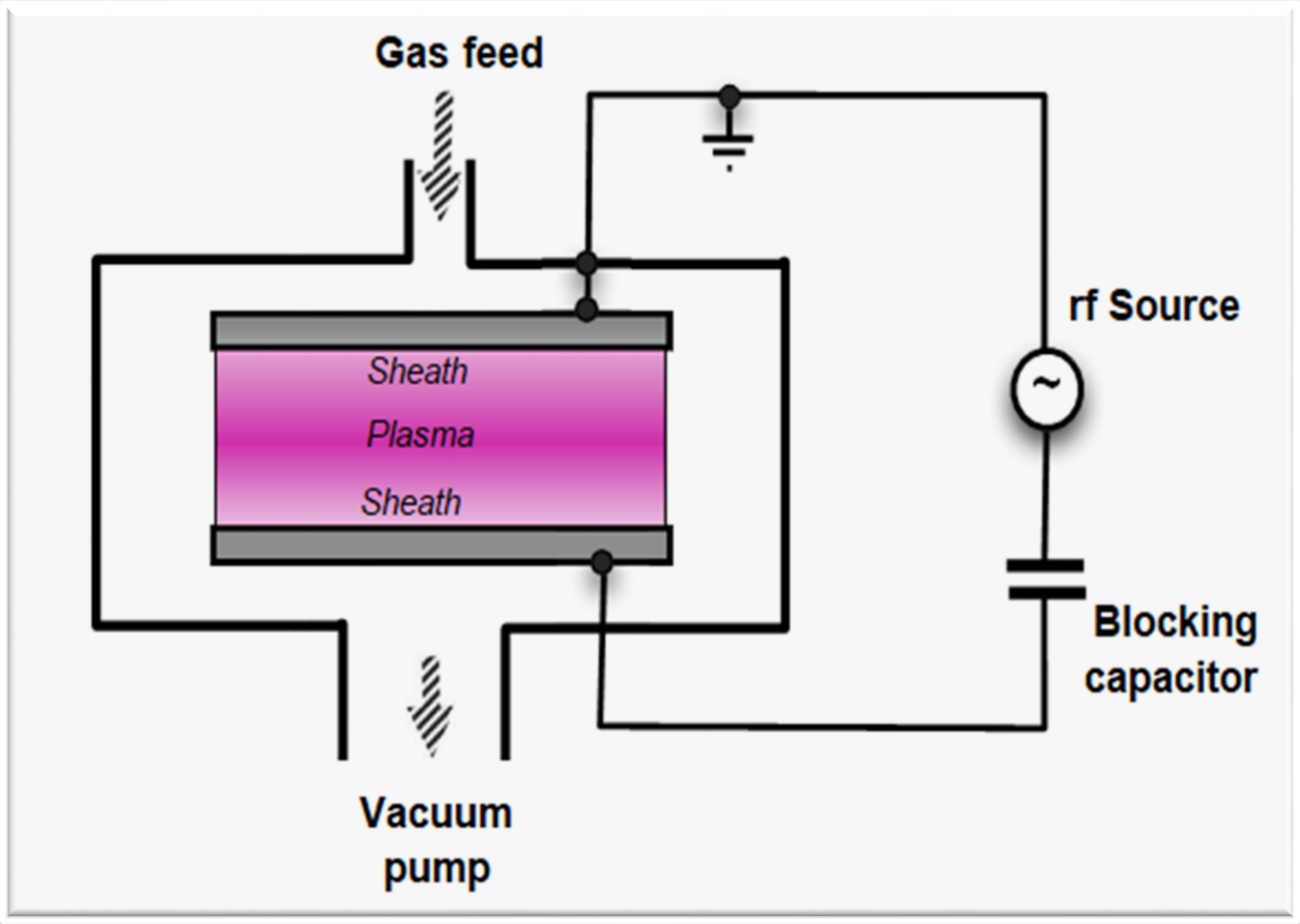
Outlines

- Introduction to Capacitive coupled plasma
- PIC simulation
- PIC simulation parameters for He RF-CCP
- PIC simulation parameters for Ar RF-CCP
- Ion Acoustic modes and solitons
- KdV equation
- Conclusion

Motivation

- Studying the effect of pressure, applied voltage and frequency on the properties of the formed plasma.
- Studying the conditions for the transition from neutral plasma to non-neutral plasma.
- Studying the possibility of generating sound waves for ions and generating soliton waves when moving from the neutral plasma to the non-neutral plasma.

Capacitive coupled plasma CCP



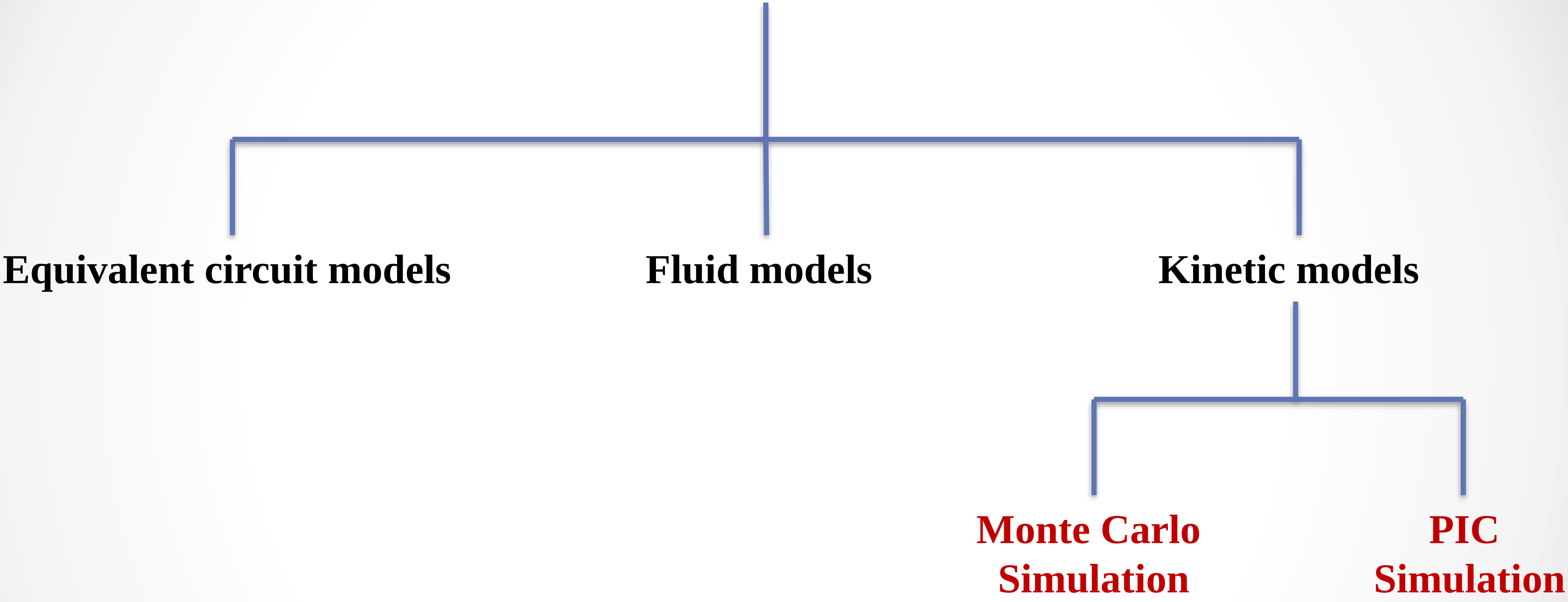
Plasma deposition

Plasma etching

Capacitive coupled plasma applications

Plasma sputtering

Plasma modeling and simulation



Equivalent circuit models

Fluid models

Kinetic models

Monte Carlo Simulation

PIC Simulation

Particle in cell simulation (PIC)

- An RF-CCP simulation is conducted using a 1d3v PIC code in Cartesian coordinates.
- The code solves the motion equation of plasma super particles in a self-consistent manner, employing an electrostatic approximation and Poisson’s equation.

PIC simulation parameters for He RF-CCP

- The distance between the two planar electrodes is 5 cm and the gap size is discretized into 129 grids.
- The simulation runs for 5000 RF periods of the 60 MHZ cycles.
- The driven frequencies are 60 MHz and 1 MHz,

$$\boldsymbol{V_{RF} = V_{60}\,\mathbf{sin}(2\pi 60\mathbf{MHz}t) + V_1\mathbf{sin}(2\pi\mathbf{MHz}t).}$$

- The voltages of the frequencies change, where the total is constant, . $V_{60} + V_1 = 500\mathrm{V}$

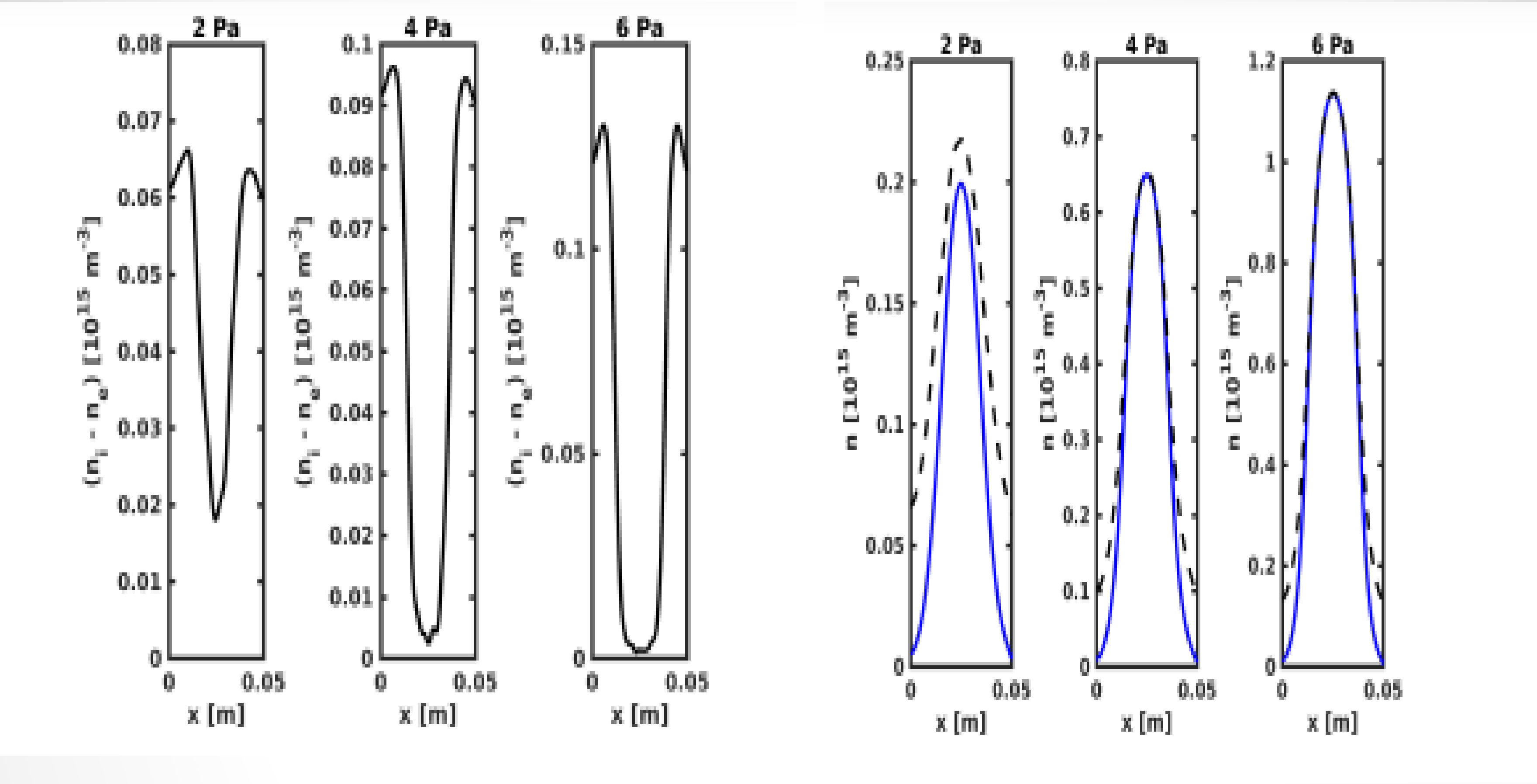


Figure 1: (Left) The time averaged charge density separation. (Right) the time averaged density.

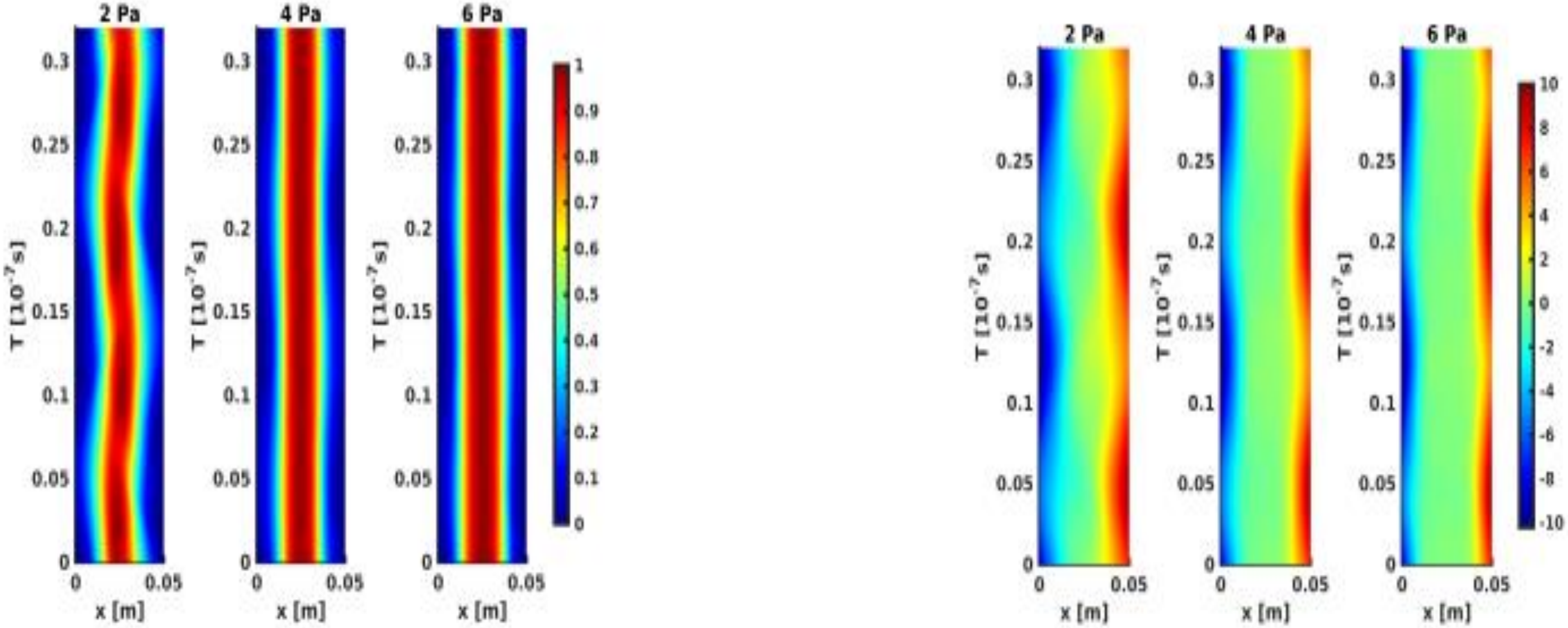


Figure 2: (Left) The electron density as a function of time and position. (Right) the electric field as a function of time and position.

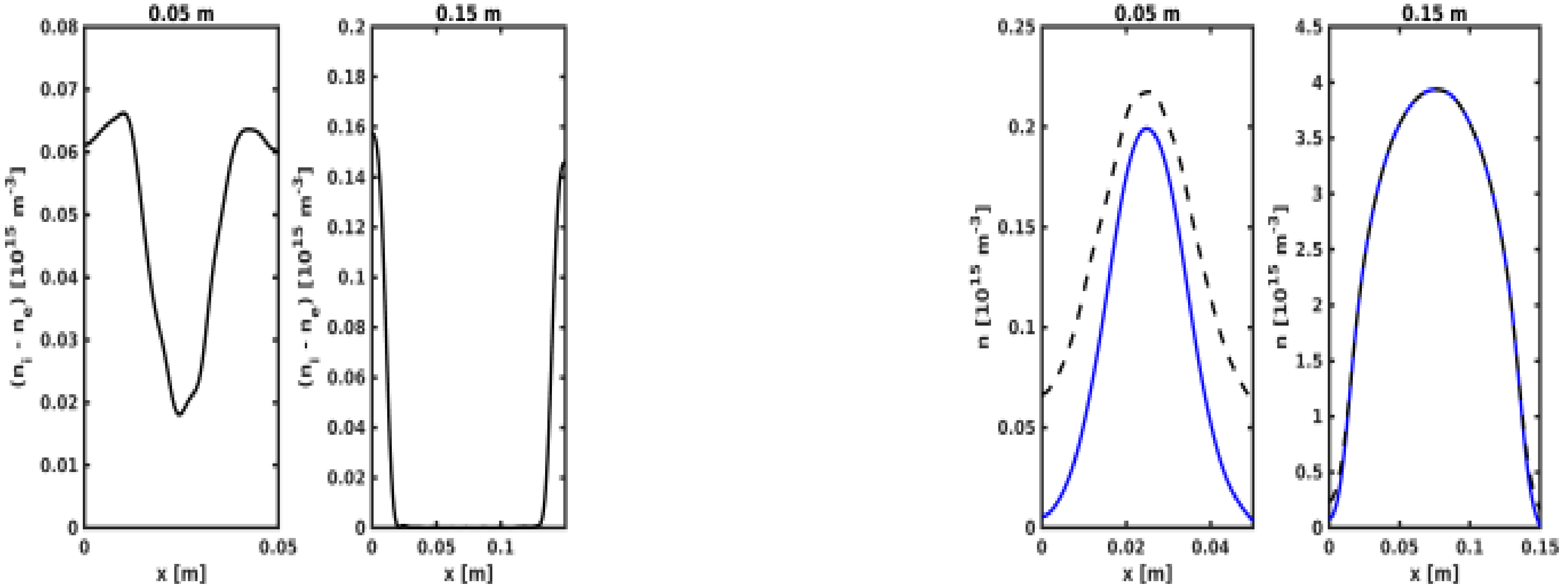


Figure 3: (Left) The time averaged charge density separation. (Right) the time averaged density.

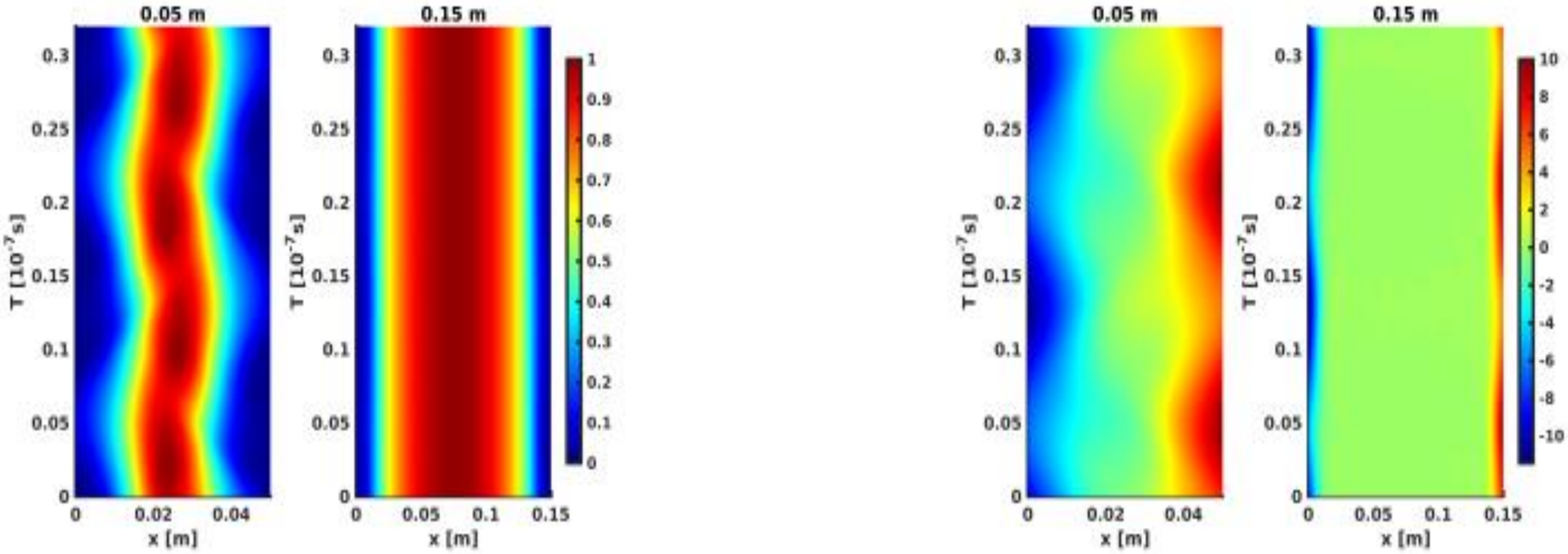


Figure 4: (Left) The electron density as a function of time and position. (Right) the electric field as a function of time and position.

Ion Acoustic modes and solitons

- The intermediate radio frequency regime holds the inequality $\omega_{pe} >> \omega_{RF} \approx \omega_{pi}$.

Where ω_{pe}, ω_{RF} and ω_{pi} are the electron plasma frequency, the radio frequency and the ion plasma frequency, respectively.

- The ionization degree in low temperature plasma is very low. Therefore, the main collision term is the momentum transfer between the charged species and the background gas.

$$\frac{\partial n_\mathrm{i}}{\partial t} + \frac{\partial n_\mathrm{i} u_\mathrm{i}}{\partial x} = 0 \tag{1}$$

$$m_\mathrm{i} n_\mathrm{i} \left(\frac{\partial u_\mathrm{i}}{\partial t} + u_\mathrm{i} \frac{\partial u_\mathrm{i}}{\partial x} \right) = -e n_\mathrm{i} \frac{\partial \phi}{\partial x} - m_\mathrm{i} n_\mathrm{i} u_\mathrm{i} \nu_\mathrm{i} \tag{2}$$

$$\frac{\partial n_\mathrm{e}}{\partial t} + \frac{\partial n_\mathrm{e} u_\mathrm{e}}{\partial x} = 0 \tag{3}$$

$$m_\mathrm{e} n_\mathrm{e} \left(\frac{\partial u_\mathrm{e}}{\partial t} + u_\mathrm{e} \frac{\partial u_\mathrm{e}}{\partial x} \right) = e n_\mathrm{e} \frac{\partial \phi}{\partial x} - m_\mathrm{e} n_\mathrm{e} u_\mathrm{e} \nu_\mathrm{e} \tag{4}$$

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{-e}{\epsilon_0} (n_\mathrm{i} - n_\mathrm{e}) \tag{5}$$

The normalization of the dynamical quantities gives dimensionless forms. Two dimension-less parameters appear: $\Omega = \omega_\mathrm{rf}/\omega_\mathrm{i}$ and $\Omega' = (\omega_\mathrm{rf}/\omega_\mathrm{e})\sqrt{m_\mathrm{e}/m_\mathrm{i}}$

- By making the normalization by using:

$$t = t/\omega_{\mathrm{rf}},\ x = x\lambda_{\mathrm{D}},\ u_{\mathrm{i}} = u_{\mathrm{i}}\sqrt{T_{\mathrm{e}}/m_{\mathrm{i}}},\ n_{\mathrm{i}} = n_0 n_{\mathrm{i}},\ n_{\mathrm{e}} = n_0 n_{\mathrm{e}},\ \phi = T_{\mathrm{e}}\phi/e,\ u_{\mathrm{e}} = u_{\mathrm{e}}\sqrt{T_{\mathrm{e}}/m_{\mathrm{e}}}.$$

We found :

$$\Omega\frac{\partial n_{\mathrm{i}}}{\partial t} + \frac{\partial n_{\mathrm{i}} u_{\mathrm{i}}}{\partial x} = 0 \qquad (6)$$

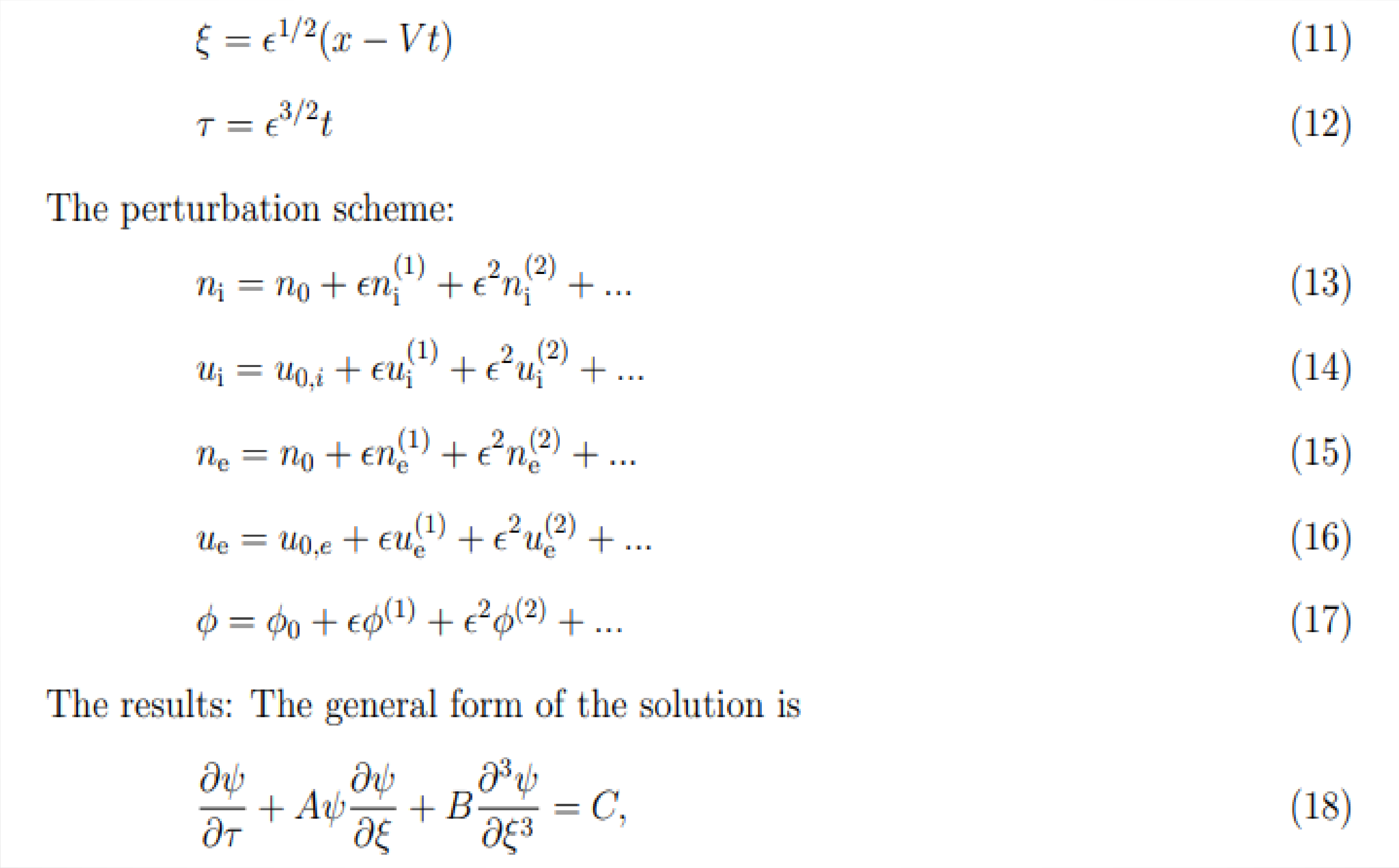
$$\Omega\left(\frac{\partial u_{\mathrm{i}}}{\partial t} + u_{\mathrm{i}}\frac{\partial u_{\mathrm{i}}}{\partial x}\right) = -\frac{\partial \phi}{\partial x} - \Omega u_{\mathrm{i}}\nu_{\mathrm{i}} \qquad (7)$$

$$\Omega'\frac{\partial n_{\mathrm{e}}}{\partial t} + \frac{\partial n_{\mathrm{e}} u_{\mathrm{e}}}{\partial x} = 0 \qquad (8)$$

$$\Omega'\left(\frac{\partial u_{\mathrm{e}}}{\partial t} + u_{\mathrm{e}}\frac{\partial u_{\mathrm{e}}}{\partial x}\right) = \frac{\partial \phi}{\partial x} - \Omega' u_{\mathrm{e}}\nu_{\mathrm{e}} \qquad (9)$$

$$\frac{\partial^2 \phi}{\partial x^2} = -(n_{\mathrm{i}} - n_{\mathrm{e}}) \qquad (10)$$

- In order to find the KdV equation a transformation is made with a first order perturbation:



$$\xi = \epsilon^{1/2}(x - Vt) \tag{11}$$

$$\tau = \epsilon^{3/2}t \tag{12}$$

The perturbation scheme:

$$n_{\mathrm{i}} = n_0 + \epsilon n_{\mathrm{i}}^{(1)} + \epsilon^2 n_{\mathrm{i}}^{(2)} + \dots \tag{13}$$

$$u_{\mathrm{i}} = u_{0,i} + \epsilon u_{\mathrm{i}}^{(1)} + \epsilon^2 u_{\mathrm{i}}^{(2)} + \dots \tag{14}$$

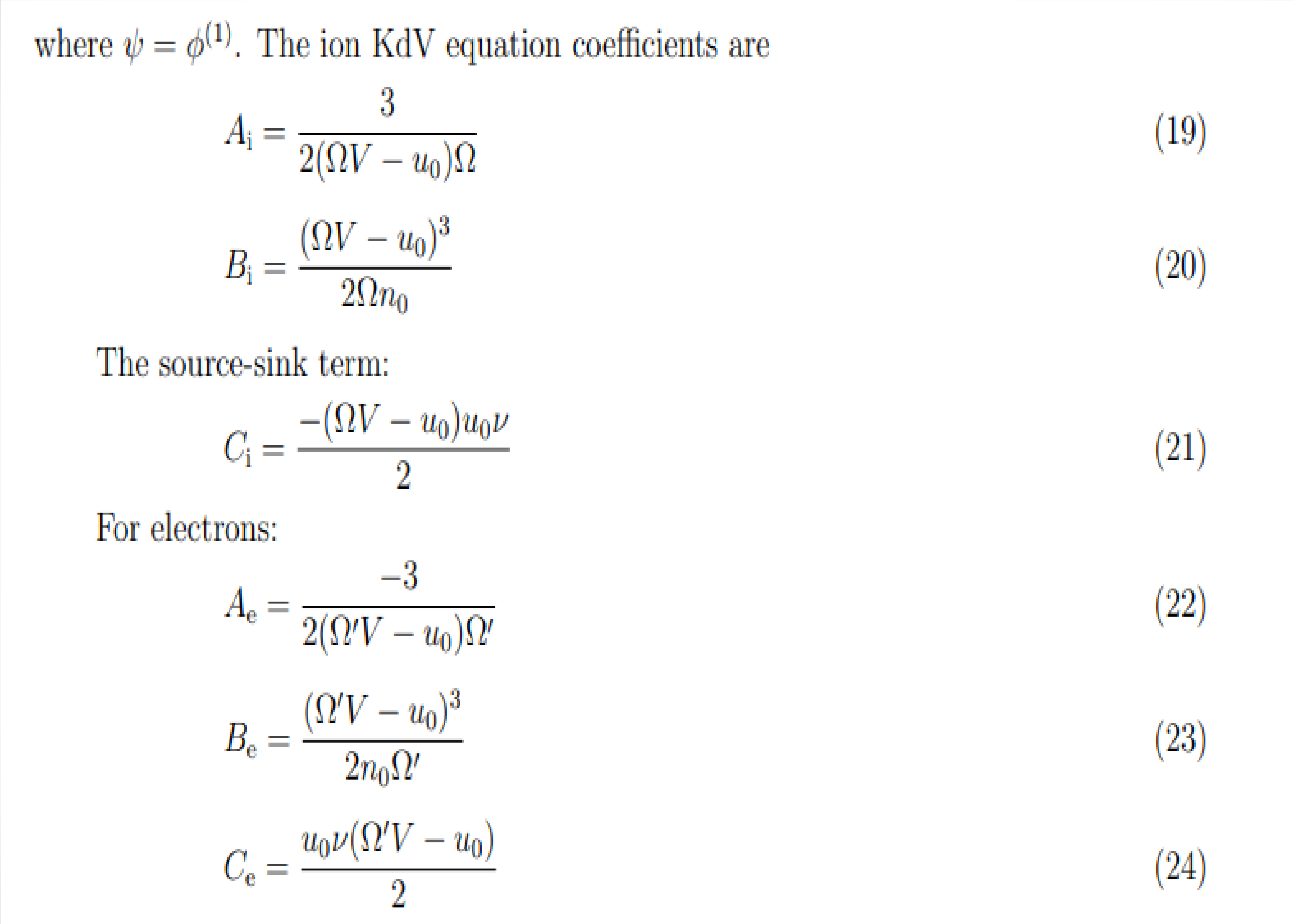
$$n_{\mathrm{e}} = n_0 + \epsilon n_{\mathrm{e}}^{(1)} + \epsilon^2 n_{\mathrm{e}}^{(2)} + \dots \tag{15}$$

$$u_{\mathrm{e}} = u_{0,e} + \epsilon u_{\mathrm{e}}^{(1)} + \epsilon^2 u_{\mathrm{e}}^{(2)} + \dots \tag{16}$$

$$\phi = \phi_0 + \epsilon \phi^{(1)} + \epsilon^2 \phi^{(2)} + \dots \tag{17}$$

The results: The general form of the solution is

$$\frac{\partial \psi}{\partial \tau} + A\psi \frac{\partial \psi}{\partial \xi} + B\frac{\partial^3 \psi}{\partial \xi^3} = C, \tag{18}$$



where $\psi = \phi^{(1)}$. The ion KdV equation coefficients are

$$A_{\mathrm{i}} = \frac{3}{2(\Omega V - u_0)\Omega} \tag{19}$$

$$B_{\mathrm{i}} = \frac{(\Omega V - u_0)^3}{2\Omega n_0} \tag{20}$$

The source-sink term:

$$C_{\mathrm{i}} = \frac{-(\Omega V - u_0)u_0\nu}{2} \tag{21}$$

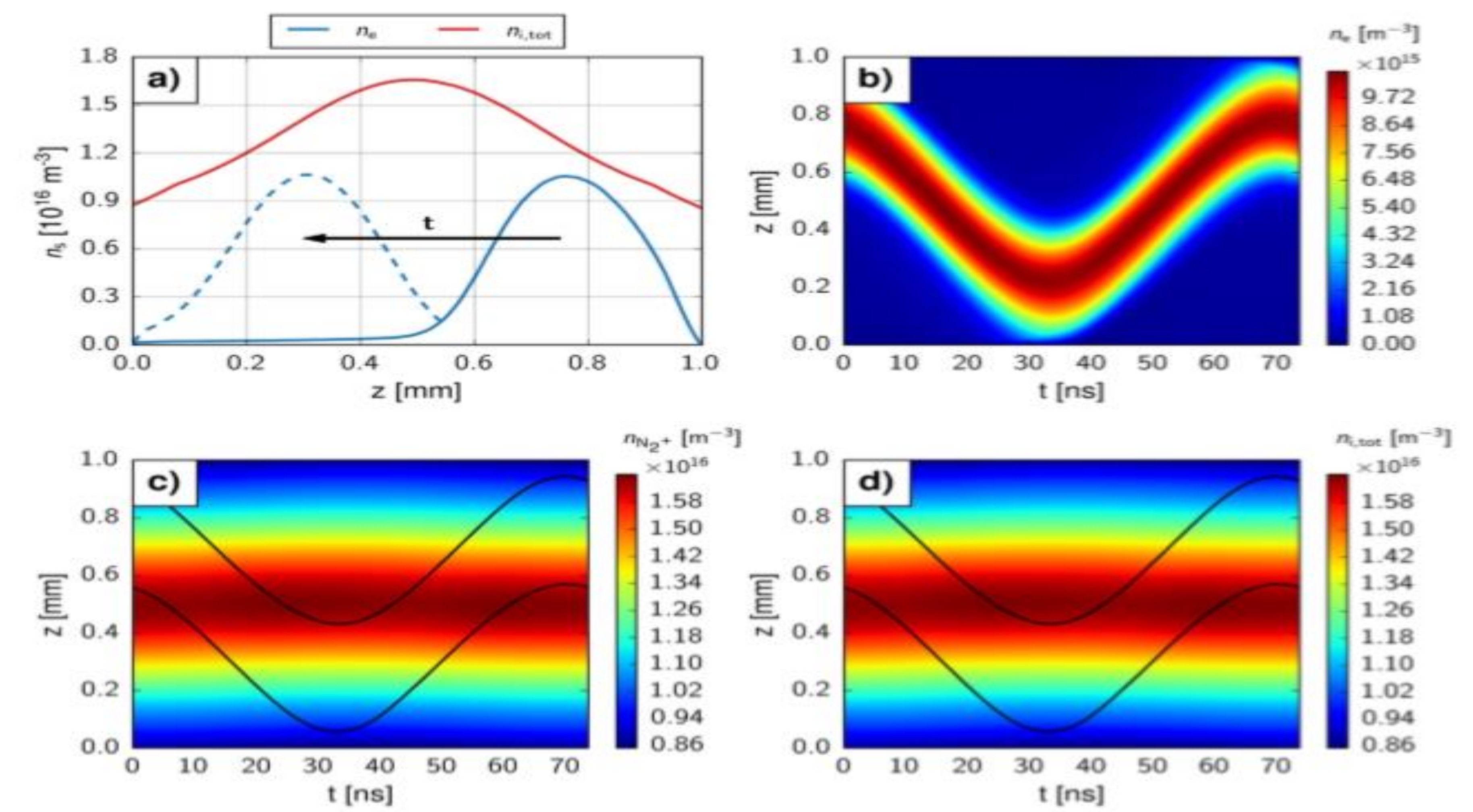
For electrons:

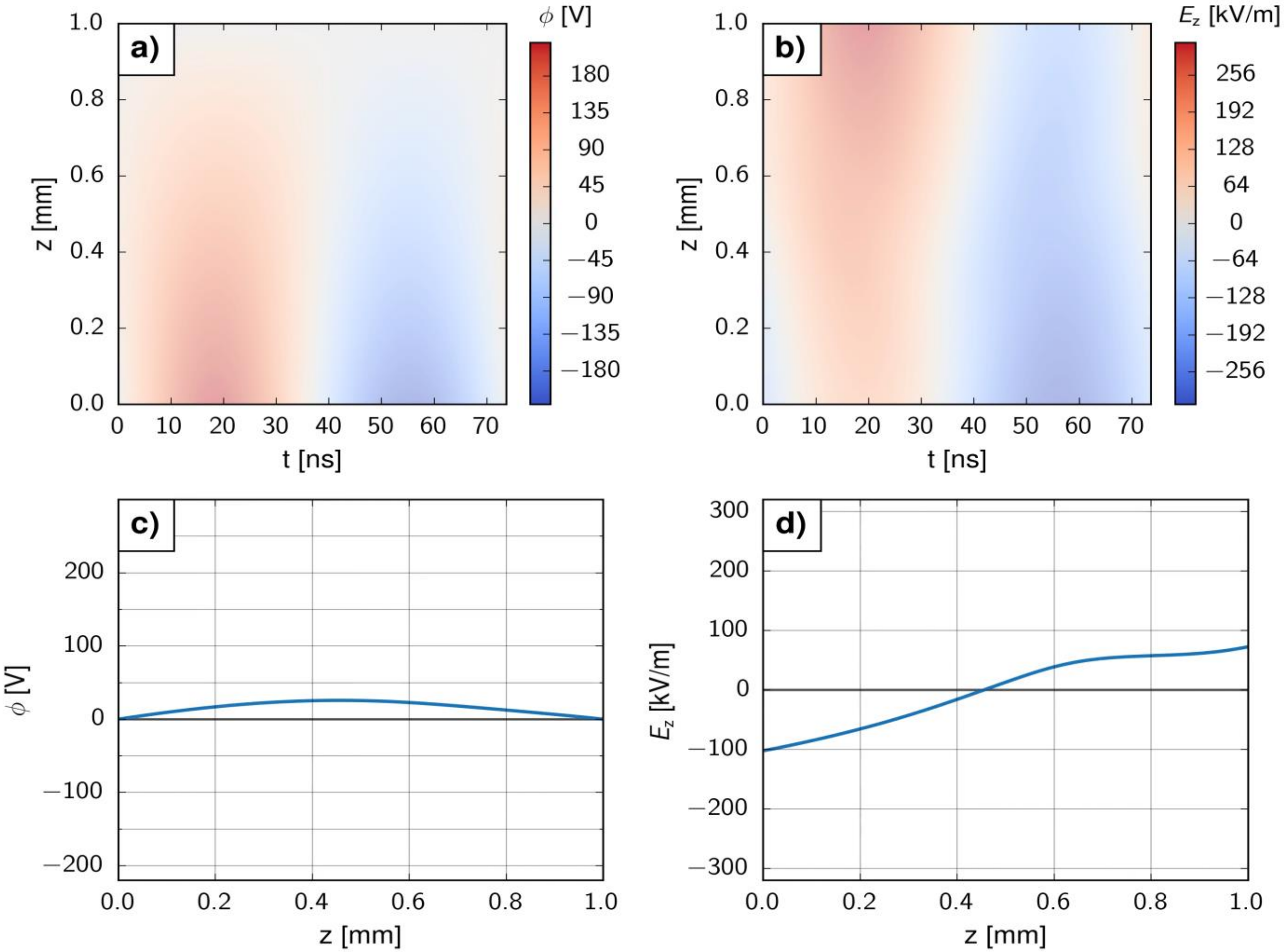
$$A_{\mathrm{e}} = \frac{-3}{2(\Omega' V - u_0)\Omega'} \tag{22}$$

$$B_{\mathrm{e}} = \frac{(\Omega' V - u_0)^3}{2n_0\Omega'} \tag{23}$$

$$C_{\mathrm{e}} = \frac{u_0\nu(\Omega' V - u_0)}{2} \tag{24}$$

The conditions for the transition from neutral plasma to non-neutral plasma in plasma jet at atmospheric pressure




a)
b)
c)
d)
ϕ [V]
180
135
90
45
0
−45
−90
−135
−180
E_z [kV/m]
256
192
128
64
0
−64
−128
−192
−256
z [mm]
1.0
0.8
0.6
0.4
0.2
0.0
t [ns]
0
10
20
30
40
50
60
70
ϕ [V]
200
100
0
−100
−200
E_z [kV/m]
300
200
100
0
−100
−200
−300
z [mm]
0.0
0.2
0.4
0.6
0.8
1.0

Conclusion

- The capacitively coupled plasma is investigated kinetically utilizing the particle-in- cell technique.
- The He plasma is generated via two radio-frequencies.
- An oscillatory soliton like structures are excited for electrons. An electron density pulse oscillates between the two electrodes. Ions are almost stationary.
- By increasing the gas pressure, the amplitude of high radiofrequency, the gape size, or replacing the He gas with Ar gas a quasineutral region known as plasma bulk is formed.

Conclusion

- In the neutral discharge regime, the oscillation of electrons exist only in the sheath. Before the creation of plasma bulk, the discharge is known as a non-neutral discharge, where, electron soliton like structures are always exist.
- An analytical model is presented. The KdV equations predict a damping ion soliton like structures.
- Supersonic electron solitons are exist in the non-neutral discharge regime.
- At different pressure 2 pa, 3 pa,4 pa,5 pa and 6 pa respectively, plasma bulk not excited at small pressure as shown in the next figures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Thank you