Electron heating mode transitions in a capacitively coupled oxygen discharge

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Abstract

We use the one-dimensional object-oriented particle-in-cell Monte Carlo collision code oopd1 to explore the evolution of the electron heating mechanism in a capacitively coupled oxygen discharge. We have demonstrated an electron heating mode transition from drift-ambipolar (DA) mode to α-mode as the operating pressure [1,2,3], electrode separation [4], and driving frequency [5] are increased. At low driving frequency and low pressure (10 mTorr) a combination of stochastic (α-mode) and drift ambipolar (DA) heating in the bulk plasma (the electronegative core) is observed and the DA-mode dominates the time averaged electron heating. At higher pressures (> 50 mTorr) stochastic heating dominates.

Introduction

Here we explore the influence of pressure and electrode spacing on on the electron heating mechanism in a capacitively coupled oxygen discharge.

When operating at low pressure (10 mTorr) the electron heating within the discharge is due to combined drift-ambipolar-mode (DA-mode) and α-mode and at higher pressures (50 – 500 mTorr) the discharge is operated in a pure α-mode [1,2,3,4].

Earlier we have also explored the role of surface quenching coefficients for the singlet metastable molecule $O_2(a^1\Delta_g)$ [6] and the secondary electron emission [7] on the electron power absorption of the capacitively coupled oxygen discharge.

The simulation

For this current study we assume the discharge to be operated with voltage amplitude of $V_0 = 400$ V with an electrode separation of 45 mm, while the discharge pressure is varied in the range 10 – 100 mTorr, and when varying the electrode spacing from 25 to 60 mm at fixed operating pressure at 50 mTorr.

The kinetics of the charged particles (electrons, O_2^+-ions, O^+-ions and O^--ions) was followed for all energies. The kinetics of the neutrals are followed when their energy exceeds a preset energy threshold value. To determine the partial pressures of the background thermal neutral species we applied a global (volume averaged) model of the oxygen discharge.

Results and discussion

Figure 1 shows the spatio-temporal behaviour of the electron power absorption at 50 mTorr for varying electrode separation at fixed pressure and applied voltage.

For 25 mm electrode spacing a significant electron power absorption (red and yellow areas) and small energy loss (dark blue areas) are evident in the plasma bulk region as seen in Figure 1 (a).

At 30 mm electrode spacing, seen in Figure 1 (b), the electron power absorption within the bulk region has decreased somewhat, and there is strong power absorption during during sheath expansion while the cooling during sheath collapse has decreased.

At 35 mm electrode spacing, the electron power absorption is observed almost solely within the sheath regions and there is almost no electron power absorption within the plasma bulk. Similar behavior is observed for electrode spacing of 45 mm seen in Figure 1 (d).

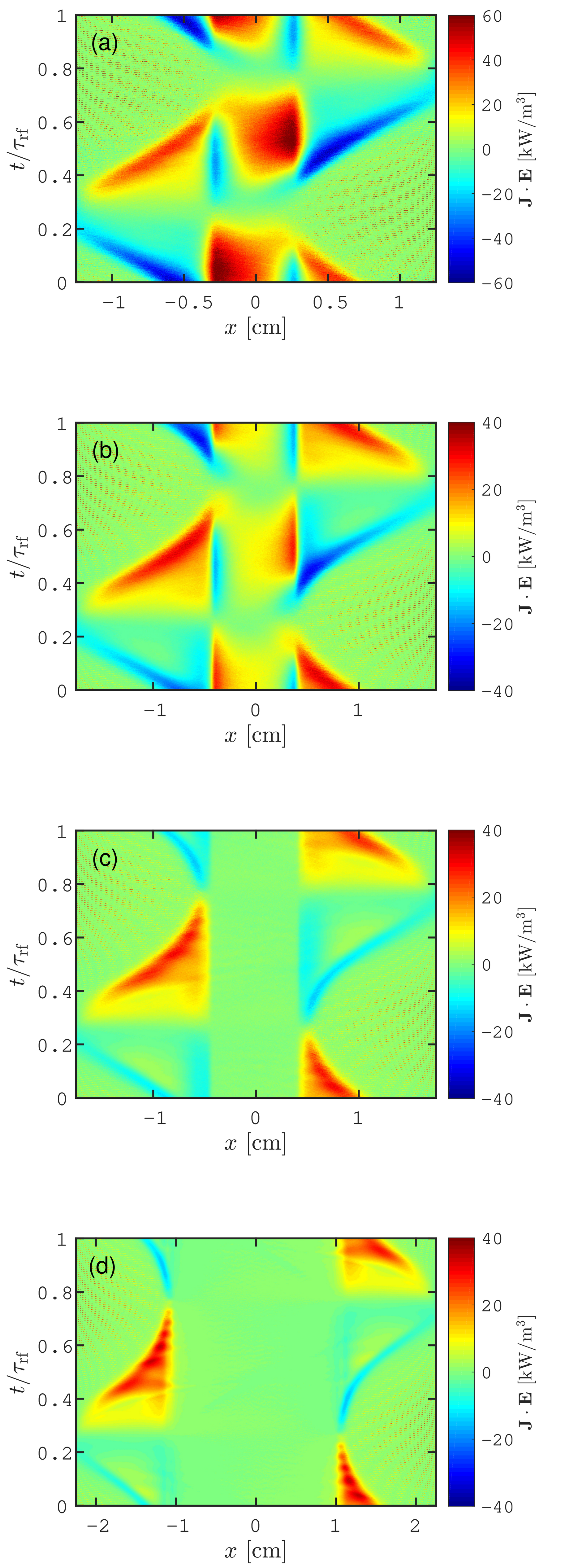

Figure 1: The spatio-temporal behaviour of the electron power absorption at 50 mTorr for a parallel plate capacitively coupled oxygen discharge with electrode separation of (a) 25 mm, (b) 30 mm, (c) 35 mm, and (d) 45 mm driven by a 400 V voltage source at driving frequency of 13.56 MHz.

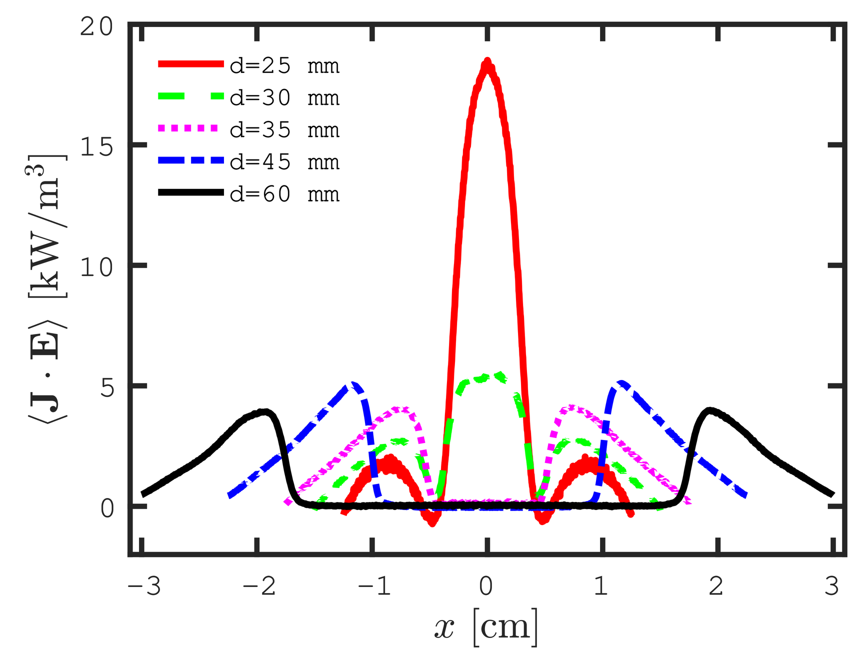

Figure 2: The time averaged electron power absorption for a parallel plate capacitively coupled oxygen discharge at 50 mTorr driven by a 400 V voltage source at driving frequency of 13.56 MHz as the gap separation is varied.

Figure 2 shows the time averaged electron heating profile between the electrodes $\langle \mathbf{J}_e \cdot \mathbf{E}\rangle$. At 25 mm almost all the electron heating occurs in the plasma bulk (the electronegative core). As the electrode spacing is increased the electron heating in the bulk region decreases and the heating in the sheath regions increases.

The center electron density and the center electronegativity are plotted as a function of the gap separation in Figure 3. The electron density increases while the electronegativity decreases with increased gap separation.

When the gap separation is 35 mm the electronegativity (electron density) has drastically reduced (enhanced). At 45 mm and 60 mm the electronegativity (electron density) approaches its lowest (highest) values.

This is consistent with the findings of You et al. [8], who find the electron density to depend on the electrode separation, observed both experimentally and through PIC/MCC simulation.

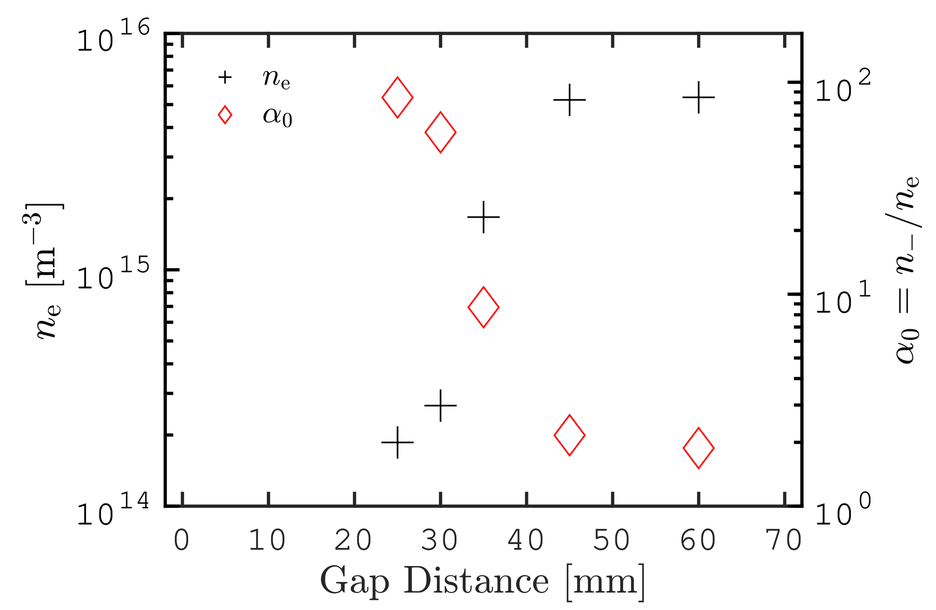

Figure 3: The electron density in the discharge center (left y axis) and the electronegativity in the discharge center (right y axis) as a function of the gap separation for a parallel plate capacitively coupled oxygen discharge at 50 mTorr driven by a 400 V voltage source at driving frequency of 13.56 MHz.

The center electron density and the center electronegativity are shown as a function of pressure in Figure 5. The electron density increases while the electronegativity decreases with increased pressure.

At low presure the effective electron temperature is high [1,2] and effective procuction of the negative ions through electron impact dissociative attachment, while due to low density of the singlet metastable molecules the detachment processes are not very efficient.

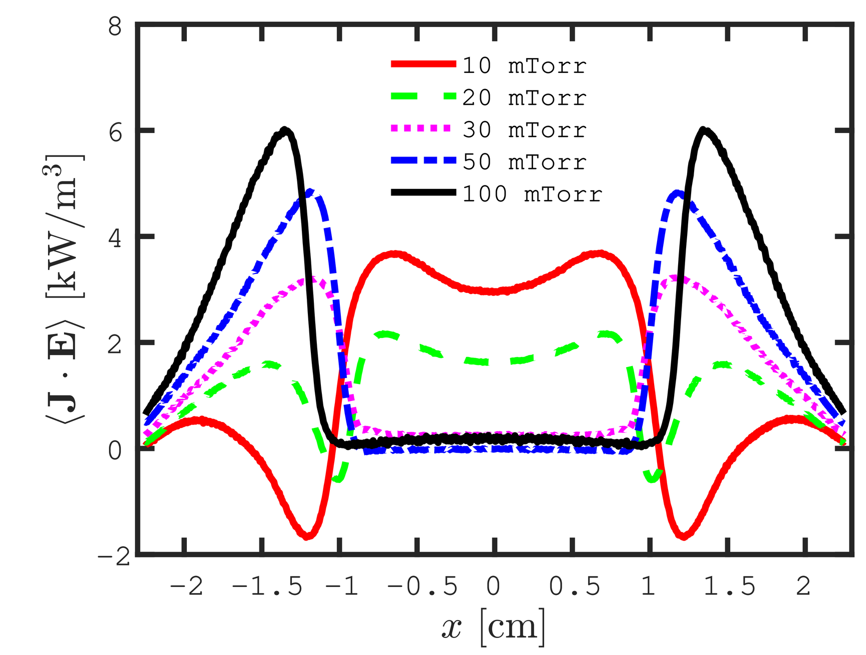

Figure 4: The time averaged electron power absorption for a parallel plate capacitively coupled oxygen discharge at 45 mm of gap distance driven by a 400 V voltage source at driving frequency of 13.56 MHz as the pressure is varied.

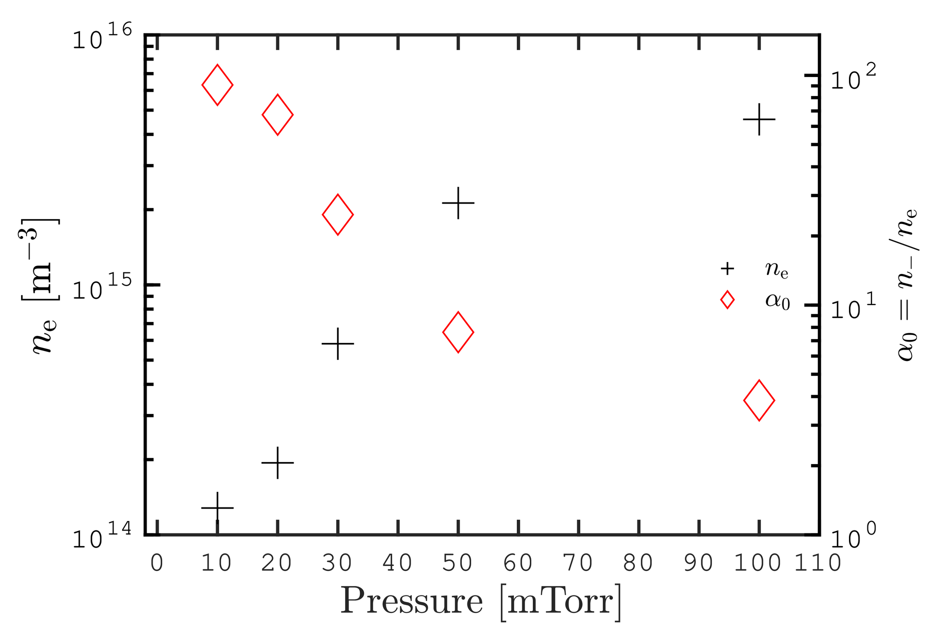

Figure 5: The electron density in the discharge center (left y axis) and the electronegativity in the discharge center (right y axis) as a function of pressure for a parallel plate capacitively coupled oxygen discharge at 45 mm of gap distance driven by a 400 V voltage source at driving frequency of 13.56 MHz.

Summary

For pressure of 50 mTorr for electrode seperation of 25 mm the electron power absorption occurs within the plasma bulk. At 30 mm the electron heating in the sheath region dominates over the bulk. For larger separation (35, 45 and 60 mm) no electron power absorption is observed within the plasma bulk and pure α-mode is observed.

Keeping the electrode separation fixed at 45 mm and varying the pressure we find that at low pressure (10 mTorr) electron heating occurs both within the bulk and in the sheath regions, and a hybrid DA- and α-mode heating was observed.

These findings are related to higher electronegativity and generation of electric field when operating at low pressure.

References

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