On surface effects in capacitive argon discharges

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Abstract

One-dimensional particle-in-cell/Monte Carlo collisional simulations were performed on capacitive argon discharges in order to explore the role of excited argon species and surface processes over a wide pressure range. In the intermediate pressure regime (133 Pa) when secondary electron emission from the electrode surfaces is included in the discharge model, the discharge operation transitions from α-mode to γ-mode, and nearly all the ionization is due to secondary electrons. Simulation results compared to experimental measurements in the pressure range 1 – 20 Pa show good agreement when all surface processes are included in the discharge model.

Introduction

One of the most widely used types of low-pressure discharges is sustained by radio-frequency (rf) currents and voltages, introduced through capacitive sheaths.

Here, we explore how the addition of excited argon atoms and various surface processes to the discharge model influences the discharge properties of a capacitive argon discharge.

Pressure dependence – no surface effects

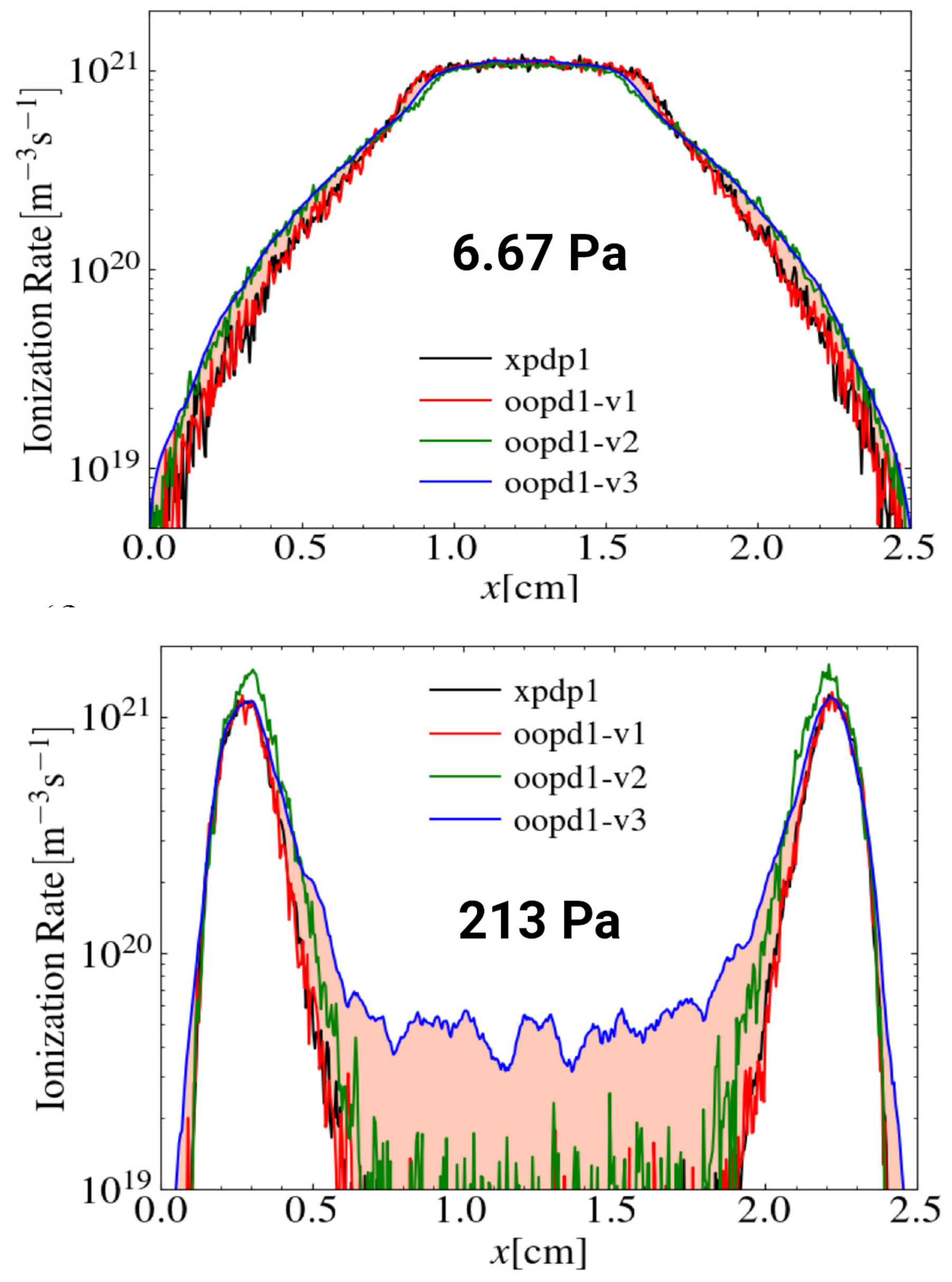

Figure 1: The total ionization rate profile at (a) 6.67 Pa and (b) 213 Pa for a capacitive argon discharge in a 2.5 cm gap driven by a rf current source at $50\,\mathrm{A/m^2}$ and 13.56 MHz [1].

Figure 1 shows the ionization rate profiles at 6.67 Pa and 213 Pa for capacitive argon discharge driven by rf current source at $50\,\mathrm{A/m^2}$ and 13.56 MHz, while varying the completeness of the discharge model.

The blue solid line indicates simulations where the metastable $\mathrm{Ar^m}$, the radiative $\mathrm{Ar^r}$, and the Ar(4p) manifold are included and modeled as time- and space-evolving fluid species.

At low pressure nonlocal effects are important and the electron-neutral ionization/excitation frequency is typically fairly uniform across the discharge gap.

In the higher (intermediate pressure) regime, the mean free path for both ions and electrons is comparable to or smaller than the electrode spacing.

Hence the plasma characteristics are significantly different from that in a low pressure capacitive discharge – the electron-neutral ionization and excitation are localized at the sheath edges.

Without excited species there is no ionization in the bulk at the higher pressure.

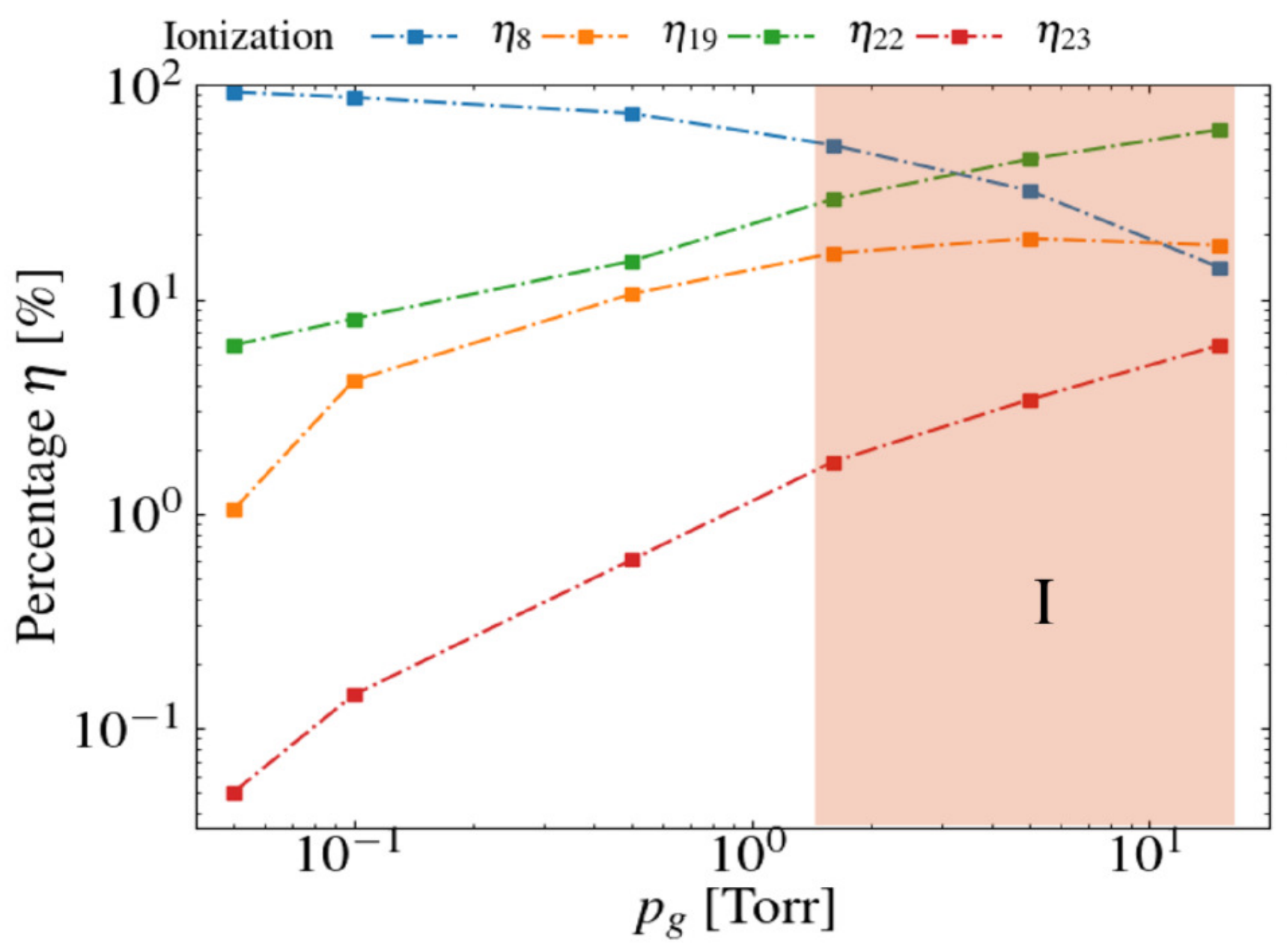

Figure 2: Percentage (η_j) of the total reaction rate of each reaction j that contributes to ionization of the argon atom in a capacitive argon discharge in a 2.5 cm gap driven by a rf current source at $50\,\mathrm{A/m^2}$ and 13.56 MHz [1].

Figure 2 shows the relative contrubutions of various processes to the ionization of argon in a capacitive argon discharge versus pressure.

The most important ionization reactions

- R8: $\mathrm{e^- + Ar \rightarrow 2e^- + Ar^+}$ electron impact ionization
- R22: $\mathrm{Ar^m + Ar^m \rightarrow e^- + Ar^+ + Ar}$ – Penning ionization
- R19: $\mathrm{e^- + Ar^m \rightarrow e^- + Ar^+ + Ar}$ – step wise ionization

There is a transition at pressure around 200 Pa where the contributions of metastable pooling and step-wise ionization exceed electron imapct ionization of the ground state argon atom.

Intermediate pressure – including surface effects

One-dimensional particle-in-cell/Monte Carlo collisional (PIC/MCC) simulations were performed on a capacitive argon discharge in the intermediate pressure regime (213 Pa) for a 2.54 cm gap, driven by a sinusoidal rf current density of 50 A/m^2 at 13.56 MHz.

The excited argon states (metastable levels, resonance levels, and the 4p manifold) are modeled self-consistently with the particle dynamics as space- and time-varying fluids.

When the excited states, and secondary electron emission due to neutral and ion impact on the electrodes are included in the discharge model, the discharge operation transitions from α-mode to γ-mode, in which nearly all the ionization is due to secondary electrons.

Secondary electron production due to the bombardment of excited argon atoms is roughly 14.7 times greater than that due to ion bombardment.

Electron impact of ground state argon atoms by secondary electrons contributes about 76 % of the total ionization; primary electrons, about 11 %. Penning ionization, about 13 %; and multi-step ionization, about 0.3 % [3].

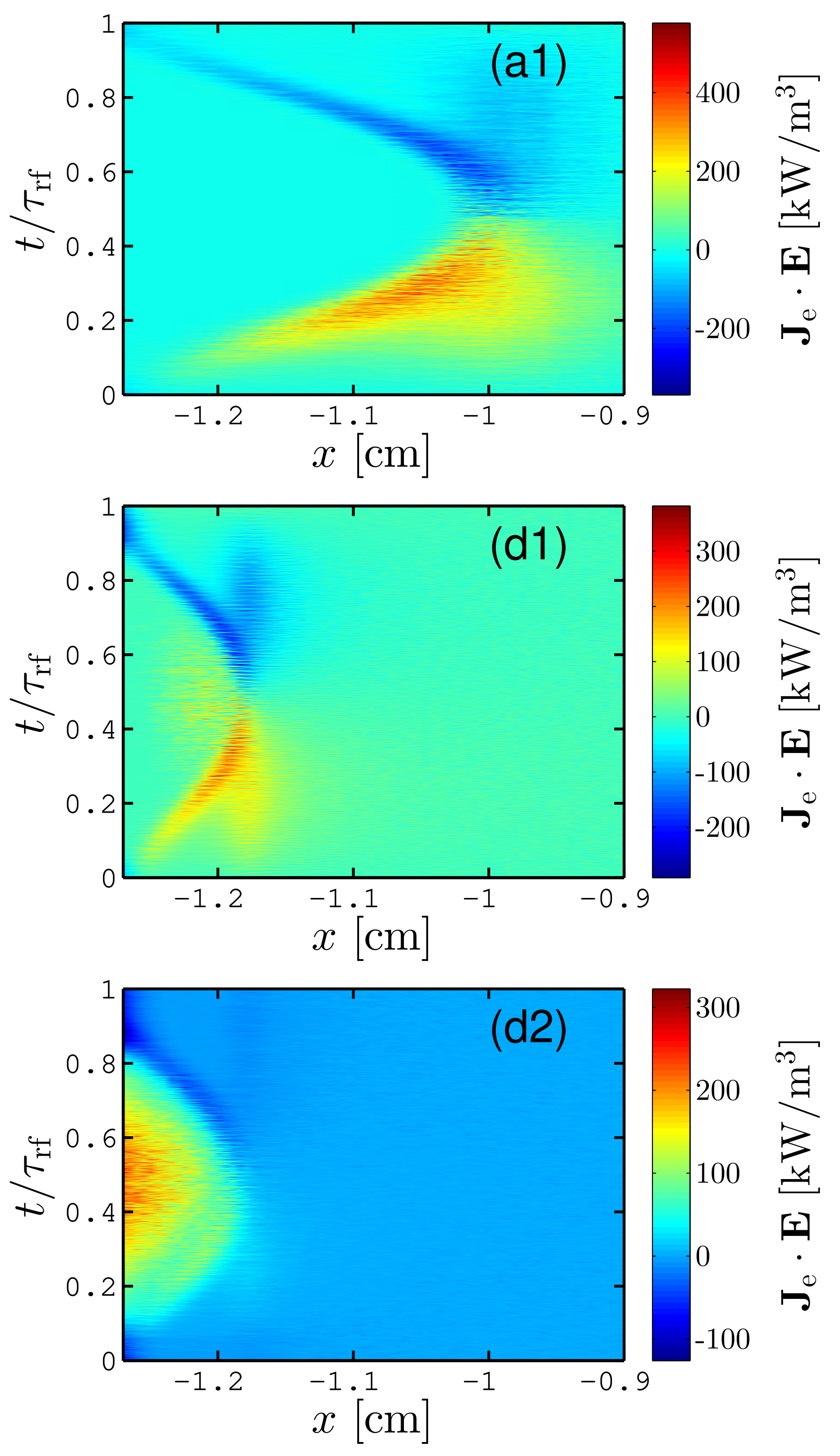

Figure 3: The spatio-temporal behavior of the electron power absorption (a) neglecting excited state kinetics and secondary electron emission and (d) including excited state kinetics, energy dependent secondary electron emission due to ion and atom bombardment of the electrodes, and electron reflection. Primary electrons (1) and secondary electrons (2). For a parallel plate capacitive argon discharge at 213 Pa with a gap separation of 2.54 cm driven by a 50 A m^2 sinusoidal current source at 13.56 MHz [3].

The spatio-temporal behavior of the electron power absorption in the sheath region is shown in figure 3 for both primary and secondary electrons.

For the case when only primary electrons are present (figure 3 (a1)), the electron power absorption is highest near each sheath edge and at phases corresponding to when the sheath is most rapidly expanding into the bulk, and the discharge operates in pure α-mode.

For the case including excited state kinetics and energy dependent secondary electron emission there is apparent power absorption by the primary electrons due to the expanding and contracting sheath, as well as near the maximum of the sheath width (yellow shading) (figure 3 (d1)).

For the secondary electrons there is power absorption within the sheaths at phases corresponding to maximum sheath width, maximum sheath voltage, and minimum rf current – the discharge is operated in pure γ-mode (figure 3 (d2)).

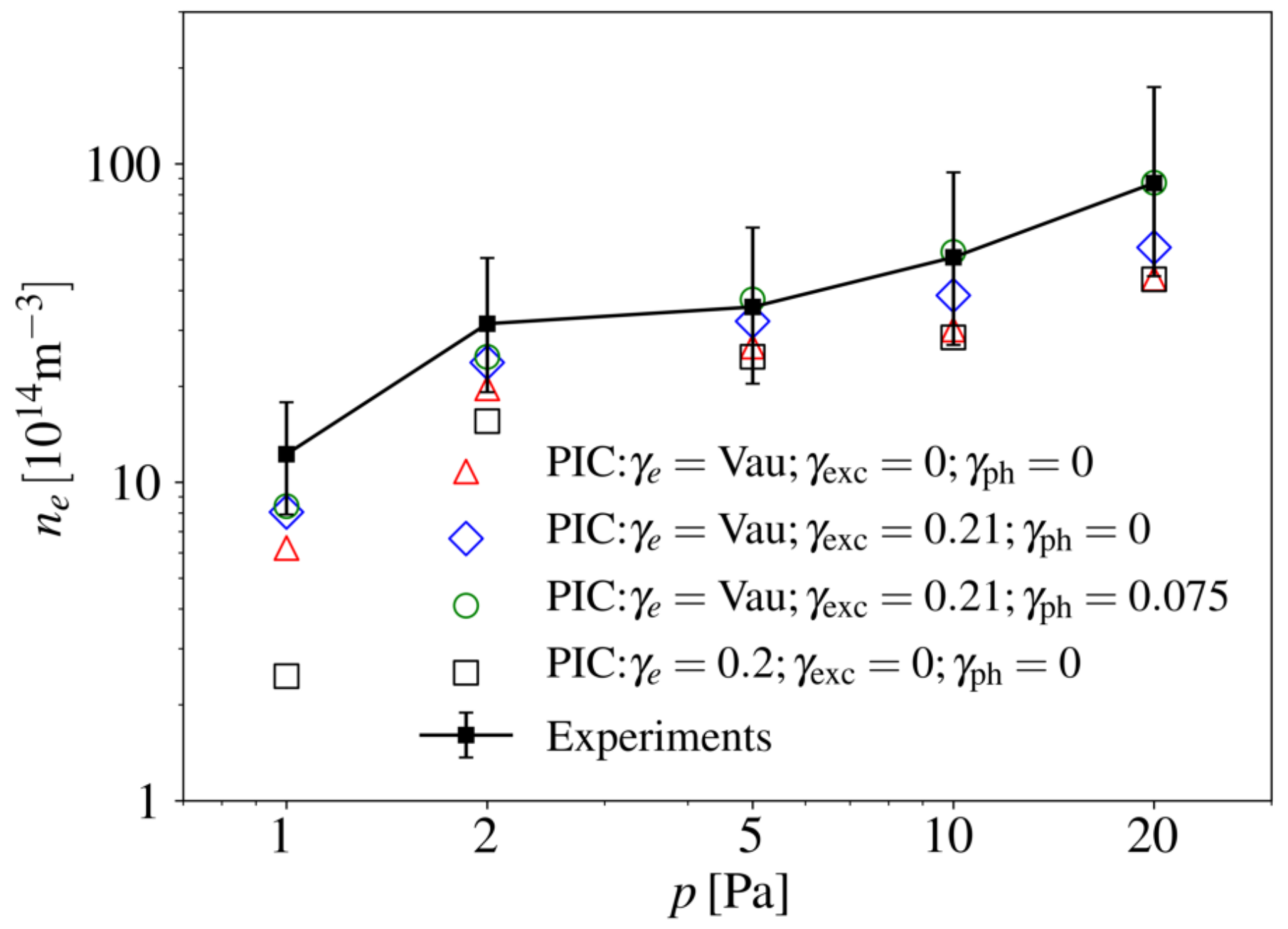

Figure 4: The time-averaged plasma density at the discharge center from kinetic particle-in-cell simulations and experimental measurements, versus the argon gas pressure at a driving voltage of 150 V, driving frequency of 13.56 MHz, and electrode spacing 4 cm, including various surface processes: electron reflection coefficient γ_e, excited state species-induced secondary electron emission yield γ_{exc} and resonant photon-induced secondary electron yield γ_{ph}. The experimental results for the plasma density are from Schulenberg et al. [5]. From Wen *et al.* [4].

In figure 4 we compare experimental measurements of the electron density by Schulenberg *et al.* [5] and the effects of different surface processes.

The surface processes that we explore focus on the electron reflection (constant coefficient), electron-induced real secondary electron emission, excited state species-induced secondary electron emission, and resonant photon-induced electron emission.

The addition of excited state species, that produces excited state neutral and resonant photon impact on the surface and creates secondary electrons, enhances the plasma density by 35 % in total and the results of the simulation agree with the measured values.

Conclusions

We have simulated capacitive argon discharges where we include excited atoms modeled as time- and space-evolving fluid species and studied the role of various surface processes inducing secondary electron emission on the discharge properties.

The presence of excited state species enhances the plasma density via excited state neutral and resonant state photon-induced secondary electron emission from the electrode surface.

The simulation results show good agreement with the recent experimental measurements in the low pressure range (1 – 20 Pa).

References

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