Ionization by drift and ambipolar electric fields in electronegative capacitive radio frequency plasmas

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Unlike α- and γ-mode operation, electrons accelerated by strong drift and ambipolar electric fields in the plasma bulk and at the sheath edges are found to dominate the ionization in strongly electronegative capacitively coupled radio frequency (CCRF) discharges. These fields are caused by a low bulk conductivity and local maxima of the electron density at the sheath edges, respectively. This *Drift-Ambipolar mode* is investigated by kinetic particle simulations, experimental phase-resolved optical emission spectroscopy, and an analytical model in CF_4. Mode transitions induced by voltage and pressure variations and consequences on the Electrical Asymmetry Effect are studied.

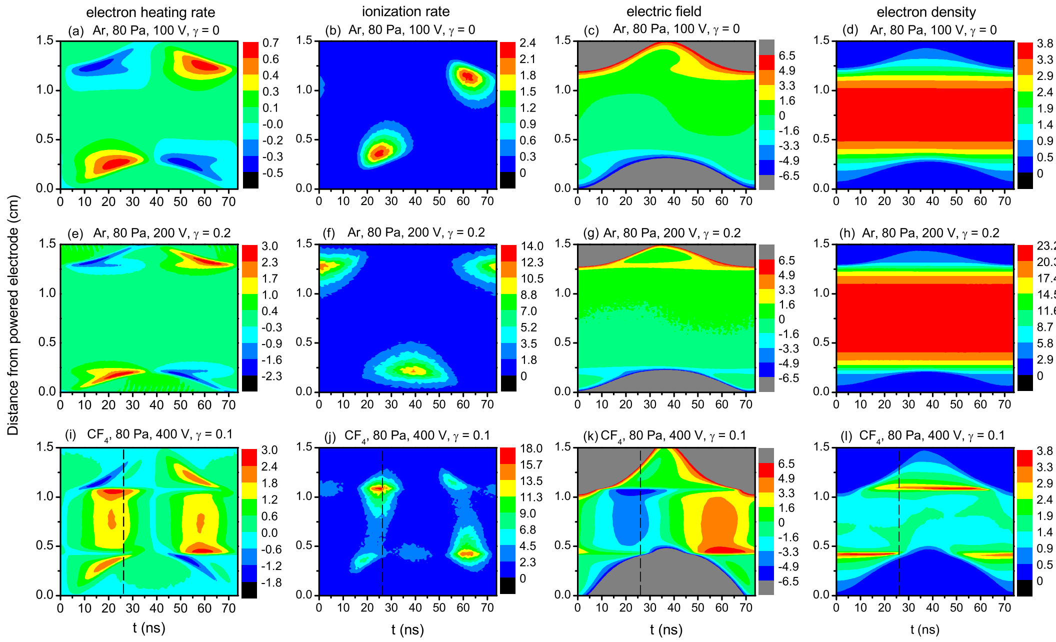

Fig. 1: PIC simulation results: spatio-temporal plots of the electron heating rate (first column), ionization rate (second column), electric field (third column), and electron density (fourth column) in Ar and CF_4 discharges driven at 13.56 MHz and 80 Pa with an electrode gap of 1.5 cm. First row: Ar, 100 V, $\gamma = 0$. Second row: Ar, 200 V, $\gamma = 0.2$. Third row: CF_4, 400 V, $\gamma = 0.1$ [1]. The color scales are given in units of 10^5 W m^{-3} (heating rate), 10^{21} m^{-3} s^{-1} (ionization rate), 10^3 V m^{-1} (electric field), and 10^{15} m^{-3} (electron density).

There are two well known operation modes of CCRF discharges [2]: (i) In α-mode, the ionization is dominated by electrons accelerated by the oscillating boundary sheaths via sheath expansion heating [3] and field reversals [4]. (ii) In γ-mode, the ionization is dominated by secondary electron avalanches inside the sheaths at times of high sheath voltage [2]. Transitions from α- to γ-mode are induced by increasing the voltage and/or pressure due to enhanced heating and multiplication of secondary electrons in the sheaths [2]. In both modes, the bulk conductivity is typically high, the bulk electric field is low, and ionization due to electrons heated inside the bulk is not observed (1st and 2nd rows in fig. 1). In electropositive plasmas, ambipolar electric fields accelerating electrons away from the adjacent electrode are observed at the sheath edges due to strong local gradients of the plasma density [4].

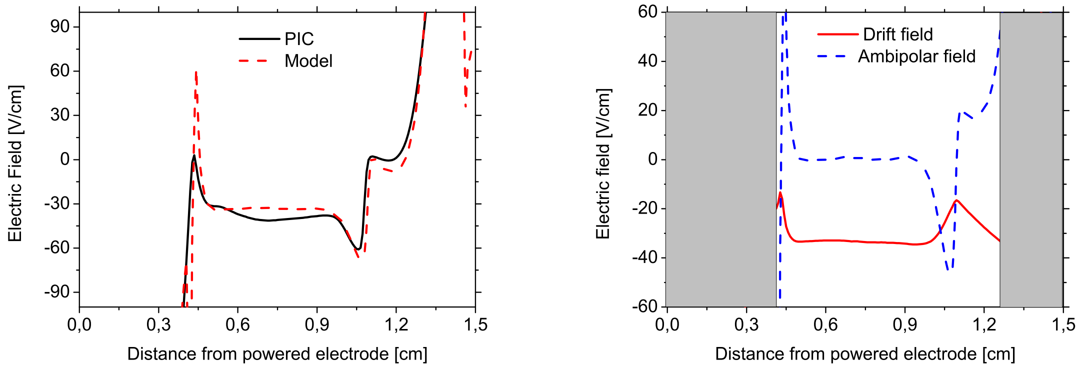

Fig. 2: Profiles of (a) the electric field obtained from the simulation and the model; (b) Drift and ambipolar component of the electric field in the bulk at $t \approx 26\,\mathrm{ns}$ [vertical dashed lines in Fig. 1 (i)-(l), model]. Discharge conditions: CF_4, 13.56 MHz, 400 V, 80 Pa, $\gamma = 0.1$ [1].

Here, we investigate the electron heating dynamics in electronegative CF_4 discharges [5] driven at 13.56 MHz with 1.5 cm electrode gap by Particle in Cell/Monte Carlo simulations, Phase Resolved Optical Emission Spectroscopy (PROES) [6], and analytical modeling. We find a novel *Drift-Ambipolar* (DA) heating mode, where electrons are accelerated to high energies by strong electric fields inside the bulk and at the sheath edges at distinct times within the RF period causing significant ionization inside the bulk (3rd row in fig. 1, [1]). Its physical origin is understood by an analytical model to calculate the electric field (fig. 2a) at the time of maximum ionization (vertical lines in fig. 1 (i)-(l)) [4]. The model results show, that the high electric field inside the bulk is a drift field caused by a low DC conductivity due to the depleted electron density in this electronegative discharge (fig. 2b). It predicts, that such high drift fields can also be caused by a high electron-neutral collision frequency at high pressures such as observed in Atmospheric Pressure Plasma Jets [7]. The strong electric fields at the sheath edges are found to be ambipolar fields caused by local maxima of the electron density in the electropositive edge region of the discharge (fig. 2b).
Mode transitions from the DA-mode into the α-mode are induced by voltage and pressure variations. Finally, the DA-mode affects the electrical generation of a DC self bias via the Electrical Asymmetry Effect in dual-frequency CF_4 discharges, where it limits the quality of the separate control of the average ion energy and flux at the electrodes [8].

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