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Excitation dynamics in electrically asymmetric capacitively coupled radio frequency discharges - Experiment, simulation, and model

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The symmetry of capacitively coupled radio frequency (CCRF) discharges can be controlled electrically by applying a fundamental frequency and its second harmonic with fixed but adjustable phase shift θ between the driving voltages to one electrode [1–9]. The applied voltage waveform is then:

$$\tilde{\phi}(t) = \tilde{\phi}_0 \left(\cos\left(2\pi f t + \theta\right) + \cos\left(4\pi f t\right)\right) \tag{1}$$

Here $f = 13.56\,\mathrm{MHz}$. In such a discharge a variable DC self bias η is generated as an almost linear function of θ for $0^\circ \leq \theta \leq 90^\circ$ via the Electrical Asymmetry Effect (EAE) [1–9]. The control parameter for η and the discharge symmetry is θ. The normalized DC self bias, $\bar{\eta} = \eta/2\tilde{\phi}_0$, and the symmetry parameter ε as a function of θ are shown in figure 1 for high pressure conditions (100 Pa). In a geometrically symmetric discharge ε is defined as:

$$\varepsilon = |\hat{\phi}_{s,g}|/|\hat{\phi}_{s,p}| \approx \bar{n}_{s,p}/\bar{n}_{s,g} \tag{2}$$

Here $\hat{\phi}_{s,g}$, $\hat{\phi}_{s,p}$ are the maximum sheath voltages, that drop across the sheaths at the grounded and powered electrode, respectively. $\bar{n}_{s,p}$, $\bar{n}_{s,g}$ are the mean ion densities in the respective sheath.

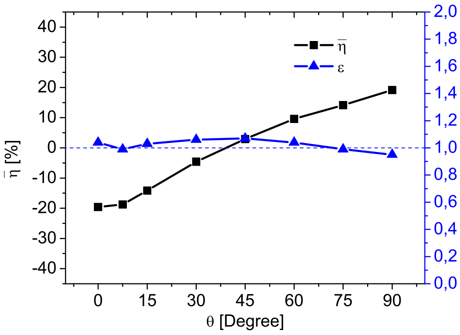

Fig. 1: DC self bias normalized by the amplitude of the applied voltage waveform, $\bar{\eta}$, and symmetry parameter ε as a function of the phase shift between the driving frequencies, θ, in a geometrically symmetric dual frequency discharge operated at 13.56 MHz and 27.12 MHz (100 Pa, $\tilde{\phi}_0 = 120\,\mathrm{V}$, and $d = 2\,\mathrm{cm}$) resulting from the PIC simulation.

In this work electron dynamics in such electrically asymmetric geometrically symmetric dual frequency discharges operated in argon is investigated experimentally, by a Particle in Cell simulation, and by an analytical model [9]. The electron dynamics is probed by the electron impact excitation rate of energetic electrons from the ground state into highly excited levels. Exemplary spatio-temporal plots of the total excitation rate of argon atoms at 100 Pa are shown in figure 2 for different phase angles θ. At high pressures of 100 Pa (collisional sheaths, see figure 2) the excitation dynamics is found to work differently compared to CCRF discharges without EAE (termed

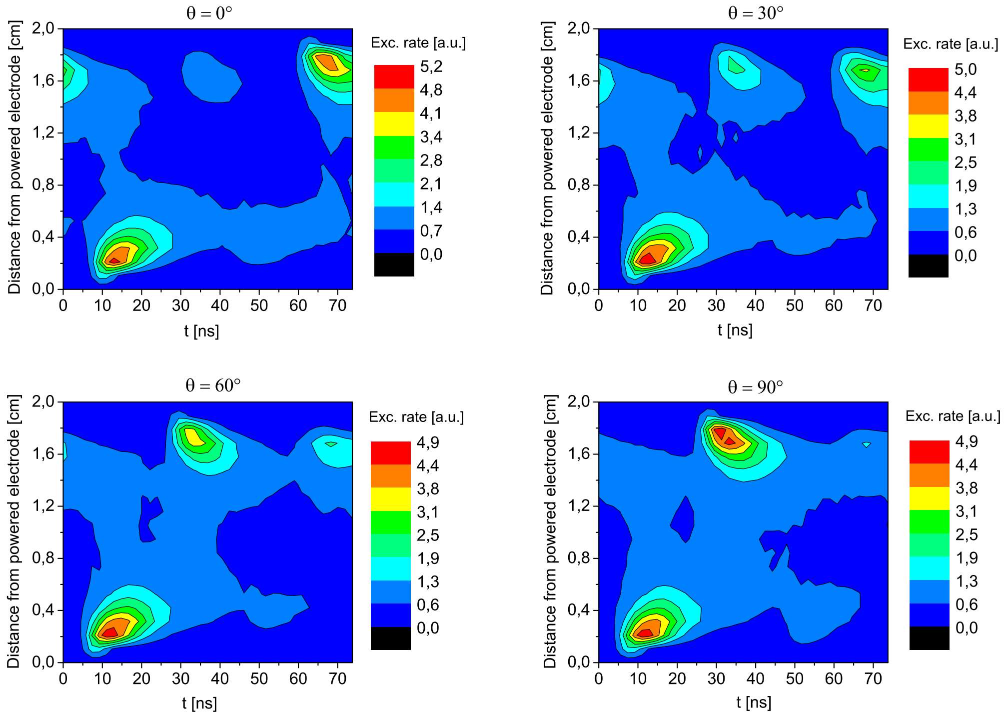

Fig. 2: Spatio-temporal plots of the total excitation rate of argon atoms at 100 Pa, $\tilde{\phi}_0 = 120\,\mathrm{V}$, and $d = 2\,\mathrm{cm}$ at different phase angles θ calculated by the PIC simulation.

here as "classical" discharges). Unlike classical discharges the maxima of the time modulated excitation at the powered and grounded electrode within one low frequency period will be similar (symmetric excitation) at a strong η ($\theta \approx 0°$ and $90°$, see figure 1), and significantly different (asymmetric excitation) at $\eta \approx 0\,\mathrm{V}$ ($\theta \approx 45°$, see figure 1). At low pressures (collisionless sheaths) the excitation dynamics works similar to classical discharges, i.e. the excitation will be asymmetric at strong η and symmetric at $\eta \approx 0\,\mathrm{V}$. This dynamics is understood in the frame of an analytical model, which provides a more detailed insight into electron heating in CCRF discharges and could be applied to other types of capacitive RF discharges as well.

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