Topic number: 6

Charge dynamics in capacitively coupled radio frequency discharges

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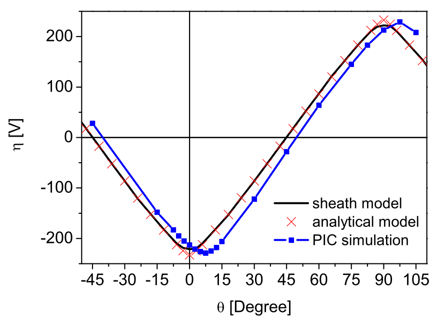
In a capacitively coupled radio frequency (CCRF) discharge the number of positive and negative charges lost to each electrode must balance within one RF period to ensure a constant total uncompensated charge in the discharge, Q_{tot}, on time average. This balance is the result of a compensation of electron and ion fluxes at each electrode within one RF period. Although Q_{tot} is constant on temporal average, it is time dependent on time scales shorter than one RF period, since it results from a balance of the typically constant ion flux and the strongly time dependent electron flux at each electrode. Nevertheless, Q_{tot} is assumed to be constant in various models of CCRF discharges [1–4].

In this work [5] we investigate a geometrically symmetric dual frequency CCRF discharge operated in argon at 13.56 MHz and 27.12 MHz with fixed, but variable phase shift θ between the driving frequencies, at a pressure of 2.66 Pa. The electrode gap is 6.7 cm. A voltage waveform $\tilde{\phi}(t) = \tilde{\phi}_0 (\cos(2\pi f t + \theta) + \cos(4\pi f t))$ is applied to one electrode with $f = 13.56\,\mathrm{MHz}$ and $\tilde{\phi}_0 = 315\,\mathrm{V}$. We address (i) the dynamics of Q_{tot} within the period $T_{RF} = 1/f$, (ii) the dynamics of the individual sheath charges (self-excitation of Plasma Series Resonance (PSR) oscillations of the RF current), and (iii) the dynamics of the electron conduction current to clarify why the ion flux remains approximately constant as a function of θ [7, 8].



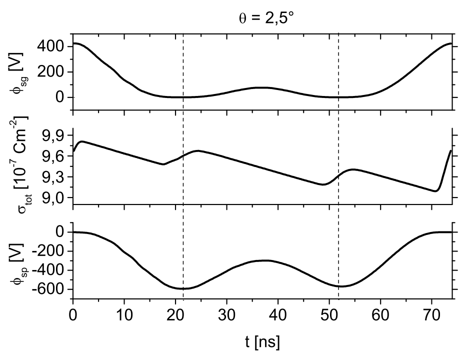


Fig. 1: Left: DC self bias η as a function of θ calculated by the Brinkmann sheath model (black line, [1–4]), the analytical model of the EAE (crosses, [1]), and a PIC simulation (squares). Right: Sheath voltages ϕ_{sg}, ϕ_{sp}, and σ_{tot} as a function of time within the period T_{RF} resulting from the PIC simulation at $\theta = 2.5°$. The vertical dashed lines indicate the phases of minimum sheath voltage at the grounded electrode.

Via the Electrical Asymmetry Effect (EAE) [1, 5–8] a variable DC self bias is generated as a function of θ (left plot of figure 1). This variable DC self bias allows to control the ion energy and flux at the electrodes separately, since the ion flux remains approximately constant as a function of θ [7, 8]. It is found that Q_{tot} is not temporally constant within the period T_{RF} such as assumed in previous models, but fluctuates by about 10 % around its time average value. The right plot of figure 1 shows the sheath voltages and $\sigma_{tot} = Q_{tot}/A$, where A is the electrode surface area, as a function of time within one period T_{RF}.

The modulation of σ_{tot} is understood by an analytical model. It is demonstrated that this charge dynamics leads to the phase shift between the DC self bias calculated by the analytical model of the EAE [1] and the Brinkmann sheath model [1–4] on one side and the PIC simulation on the other side (see figure 1). The charge dynamics is neglected in the model of the EAE and the sheath model, but not in the PIC simulation.
Splitting Q_{tot} into the uncompensated charges in each sheath reveals the sheath charge dynamics and illustrates the self-excitation of non-linear self excited PSR oscillations of the RF current by the EAE in geometrically symmetric CCRF discharges operated at low pressures of a few Pa [9].

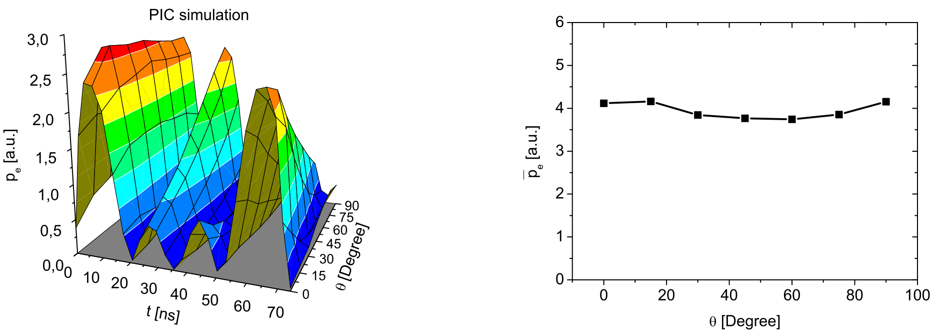


Fig. 2: Left: Power dissipated to electrons $p_e(t,\theta) \propto I^2$, where I is the electron conduction current in the discharge center. Right: Mean power dissipated to electrons calculated via equation 1 (PIC simulation).

Finally, the electron conduction current dynamics is studied by a PIC simulation, the analytical model of the EAE as well as experimentally to find out why the ion flux remains constant as a function of θ. The left plot of figure 2 shows the power dissipated to electrons $p_e(t,\theta) \propto I^2$, where I is the electron conduction current in the discharge center within the period T_{RF} (PIC simulation). Similar results are found experimentally and using the analytical model of the EAE. The mean power dissipated to electrons averaged over one period T_{RF}q, $\bar{p}_{\mathrm{e}}$, determines the ion flux:

$$\bar{p}_{\mathrm{e}} \propto \int_0^{T_{RF}} I^2 dt \tag{1}$$

This mean power is found to be constant as a function of θ due to the change of the applied voltage waveform with θ resulting in a constant ion flux.
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References

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