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# Effects of low-frequency voltage on nonlinear standing wave excitation and ion dynamics in dual-frequency asymmetric capacitive discharges

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It is known that in very-high-frequency capacitively coupled plasmas (VHF CCPs), the higher harmonics generated by nonlinear sheath motion can enhance the standing wave effect (SWE), which leads to center-peaked plasma density profiles.[1-3] In this work, an improved nonlinear electromagnetic transmission line model incorporating a bulk plasma model, a numerical ion sheath model, and an ion Monte-Carlo collision (MCC) model is developed to study the effects of low-frequency (LF) voltage $V_L$ on the nonlinear standing wave excitation, plasma uniformity, and ion energy and angular distribution functions (IEDF and IADF) in dual-frequency (DF) asymmetric capacitive argon discharges at relatively low pressure of 3 Pa. The plasma diffusion in the radial direction and ion dynamics within the LF oscillating sheath are self-consistently considered. The LF voltage $V_L$ at 2 MHz varies from 0 to 700 V while the high-frequency (HF) voltage $V_H$ at 60 MHz is fixed at 100 V.

Simulation results indicate that without the addition of LF source (i.e. $V_L = 0$ V), there are a considerable number of high-order harmonics with short wavelengths, leading to significant SWE and central peak in the radial plasma density profile. Nevertheless, the high-order harmonic excitations tend to be weakened and merely occur around the phase of the full LF sheath collapse due to a shorter characteristic damping time of the surface waves as $V_L$ increases (figure 1). This, combined with increased surface wavelengths of both the driving frequency and the higher harmonics at a higher $V_L$, leads to suppressed standing waves and improved plasma uniformity. Meanwhile, the simulations show that both the low and the high energy peaks of IEDF move towards higher energies, and the energy peak separation width $\Delta E$ becomes wider with the increase of $V_L$. The IEDF at the radial center of the powered electrode exhibits a broader $\Delta E$ than that at the edge. For the IADF, an increased $V_L$ results in more ions incident on the electrode with a smaller deflection angle. Because of a thinner sheath and a higher sheath voltage at the electrode center, the peak value of IADF at the electrode center is greater than that at the edge. This work has been financially supported by the National Natural Science Foundation of China (NSFC) (Grants No. 11935005, No. 12005035, and No. 12275041), and the Fundamental Research Funds for the Central Universities (Grant No. DUT21TD104).

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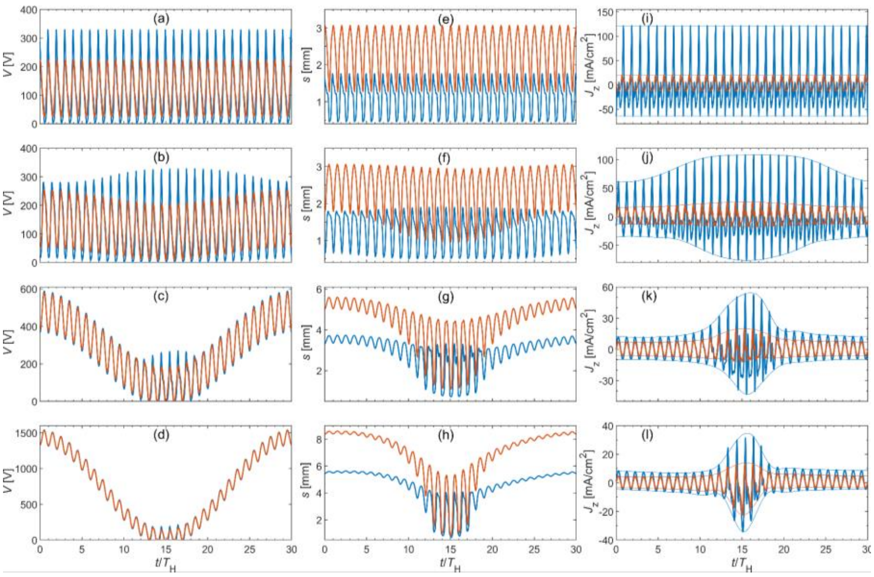


**Figure 1**. Simulation results of the temporal evolution of the total discharge voltage $V$ (left column), the sheath thickness $s$ (middle column), and the current density $J_z$ (right column) over one LF period at the radial center $r = 0$ (blue lines) and the edge $r = R_1$ (red lines) for different $V_L$: 0 V (first row), 25 V (second row), 200 V (third row), and 700 V (fourth row).