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Electron heating in capacitively coupled plasmas revisited: single and multi-frequency discharges

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Using particle-in-cell (PIC) simulations, we re-analyse the mechanism of electron heating in low pressure capacitively coupled plasmas (CCPs). After equilibrium has been reached in the simulations, spatio-temporal moments of the electron distribution function are taken within the rf cycle, and from this the density, current, pressure, and momentum loss due to collisions, of the electrons is found in the discharge. With these moments we then reconstruct each term in the electron fluid mechanical energy conservation equation, so as to explicitly analyse the power deposition process. We perform simulations for both single frequency sinusoidal discharges, and also for more recent multi-frequency, or "tailored voltage waveform" driven discharges. The single frequency (13.56 MHz) simulations are modelled on the original experiments in Argon performed by Godyak, showing the transition from a bi-Maxwellian distribution function at low pressure (below 200 mTorr) to a Druyvestyen-type distribution at high pressures (above 400 mTorr). The results of the PIC moment analysis shows that only two terms in the fluid conservation equation contribute a net power deposition: a term accounting for collisional power absorption, and a term accounting for pressure heating. The latter term is dominant at low pressures, while the former is dominant at higher pressures. We find however that the collisional heating is almost always significant, and even at the lowest pressure, accounts for about 40% of the total power absorption. By comparing the electron momentum loss due to collisions with that usually used in analytical sheath models, we find a significant difference at low pressures, which cannot be explained by conventional local kinetic theories based on the two-term expansion of the Boltzmann equation. The moment analysis is repeated for the multi-frequency discharges, where we obtain similar results: collisional power absorption is always observed to be significant, even at the lowest pressures simulated (20 mTorr). However the generation of a bias voltage due to the electrical asymmetry effect, and consequently the unequal division of the sheath voltages, causes high frequency oscillations to develop in the plasma at frequencies more than an order of magnitude higher than the applied rf frequencies. These so-called nonlinear plasma series resonance oscillations are found to enhance both the collisional and pressure heating, and for sufficiently large applied voltages, an additional heating mechanism is identified associated with the electron inertial terms in the conservation equation.