Two-dimensional PIC/MCC modeling of inductively coupled plasma: a benchmark study in the GEC configuration

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While the particle-in-cell/Monte Carlo collision (PIC/MCC) method enables accurate modeling of low-pressure plasmas by resolving non-local and kinetic effects, its high computational cost often limits the scope of detailed investigations, leading to the use of relatively small computational domains. Due to the reduced domain size, the overall simulation time is also significantly shortened. This constraint becomes particularly critical when attempting to capture subtle non-linear phenomena.

To address the limitations of previous models that neglect higher-order harmonics, this work develops a two-dimensional axisymmetric implicit PIC/MCC framework capable of resolving harmonic-resolved electromagnetic fields and self-consistently capturing the kinetic behavior of charged particles. The simulation is conducted in the Gaseous Electronics Conference (GEC) reference cell. The solution for the inductive electric field in the θ direction was based on the work of Nanbu. To account for both metal and dielectric materials, the electrostatic field generated by space charges, the heterogeneous system under an implicit scheme is given by the Poisson equation. Our implicit PIC/MCC model is computationally intensive and remain relatively immature for certain complex configurations.

An overview of the plasma characteristics at 10 mTorr is presented in Figure 1, including the spatial distributions of the electron density, electron energy, and plasma potential. The electron density peaks at 5.22 × 10^{16} m^{-3}, while the electron energy reaches approximately 5.8 eV near the dielectric window. Notably, this localized temperature enhancement spatially correlates with the region of maximum power deposition, indicating efficient electron heating in that area. The elevated electron temperature at low pressure is attributed to a lower collision frequency and longer mean free paths, which require higher energy input to maintain sufficient ionization rates in the presence of diffusion losses. The inductive electric field is essentially a toroidal electric field, driving electrons to move azimuthally within the chamber, thus enabling efficient energy coupling. On the dielectric surfaces, the potential turns negative due to the development of ambipolar fields needed to maintain charge neutrality and suppress electron losses. The plasma potential within the bulk region is primarily governed by ion kinetics. The density, tempeture and potential all agree well with experiments and fluid simulations.

This work provides new insight into the role of harmonic fields in ICP discharges and highlights the importance of kinetic and nonlocal effects in plasma source optimization.

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References

[1] Wen H, Schulze J, Fu Y, et al. Similarity laws of low pressure inductively coupled discharges based on PIC/MCC simulations[J]. Plasma Sources Science and Technology, 2025, 34(3): 03LT01.
[2] Takekida H, Nanbu K. Journal of Physics D: Applied Physics, 2005, 38(18): 3461.
[3] Tsankov T V, Chabert P, Czarnetzki U. Plasma Sources Science and Technology, 2022, 31(8): 084007.
[4] Takao Y, Kusaba N, Eriguchi K, et al. Journal of Applied Physics, 2010, 108(9).

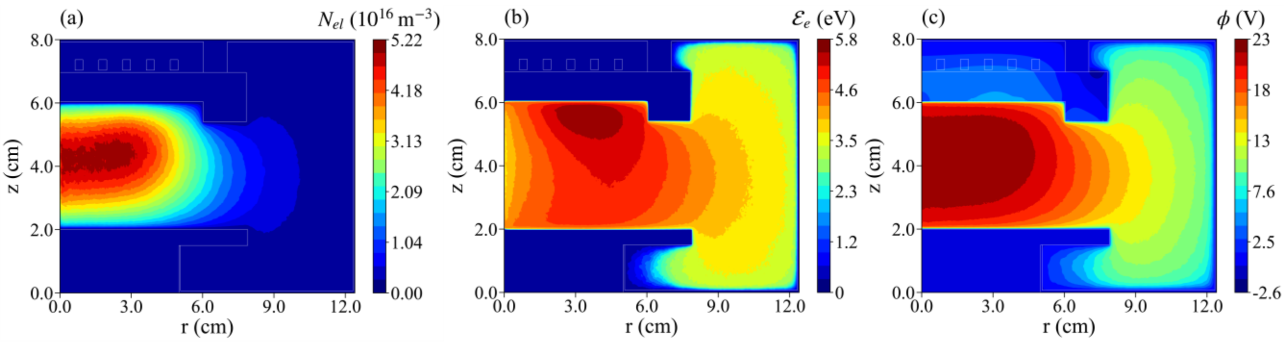

Figure 1. Two-dimensional distributions of the time-averaged. (a) electron density; (b) electron energy; (c) plasma potential. The RF of generator is 13.56MHz. The background gas is pure argon and maintained at 10mTorr.