Transport analysis in capacitively coupled plasmas

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The balance of particle and energy transport is fundamental to understanding low-temperature plasma discharges. While extensive studies have examined how low-pressure plasmas absorb energy from external electromagnetic fields, considerably less attention has been given to internal energy transport and dissipation mechanisms, which are equally important [1]. Due to significant deviations from thermodynamic equilibrium, low-pressure plasmas undergo intrinsically driven transitions from high- to low-energy states across both microscopic and macroscopic scales. This evolution can be characterized as a transport phenomenon—an irreversible progression from a perturbed state toward equilibrium.

In capacitively coupled plasmas (CCPs), periodic external fields drive the cyclic transport of conserved quantities, involving complex, synergistic transport of mass, momentum, and energy. In this study, PIC/MCC (particle-in-cell / Monte Carlo collision) simulations are employed in conjunction with the first three velocity moment equations of the Boltzmann equation to kinetically resolve the spatiotemporal evolution and transport characteristics of mass, momentum, and energy for electrons and ions. In steady-state CCPs, plasma density and temperature remain periodically stable, with all energy acquired from the electromagnetic field ultimately dissipated through collisions with neutrals or boundary outflows. It is found that electrons primarily gain energy near the sheath edge, and the spatial extent of the dissipation process is determined by their mean free path [2].

By decoupling mechanical and internal energy from the energy transport equation, we delineate the complete transport pathway following energy absorption from the external field—encompassing the conversion from electromagnetic energy to particle kinetic energy, then to internal energy, and ultimately to energy dissipation. Under the low-pressure conditions investigated in this study, the electric field energy absorbed by electrons in the sheath region is first converted into mechanical energy, which is then locally transformed into internal energy through the work done by pressure and frictional forces. This internal energy is subsequently transported into the bulk region, where it is dissipated through collisions with neutral particles. Notably, in addition to collision heating, the pressure–strain interaction term, $\mathcal{P}\cdot(\boldsymbol{\nabla}\cdot\boldsymbol{u})$, plays a central role in the conversion of kinetic energy into internal energy. This term can be further decomposed into pressure dilatation, $p\boldsymbol{\nabla}\cdot\boldsymbol{u}$, and viscous dissipation, $\Pi : D$, which correspond to energy conversion due to volumetric compression/expansion and shear deformation, respectively [3]. Furthermore, the transport of kinetic energy is spatially confined to the sheath region and is governed by kinetic energy flux driven by pressure gradients. In contrast, the transport of internal energy extends across both the energy absorption (sheath) and dissipation (bulk) regions and is primarily mediated by the divergence of the heat flux vector, which regulates the spatial redistribution of energy. Unlike electrons, ions exhibit strong anisotropy and largely remain in a non-thermalized state, with their energy absorption and dissipation processes concentrated mainly in the sheath region.

Each transport term is independently diagnosed and found to self-consistently satisfy the corresponding moment equations, verifying the accuracy and completeness of the results. This approach provides a useful framework for investigating energy deposition–redistribution–dissipation processes in CCPs and can be extended to the study of other plasma generation systems.

References

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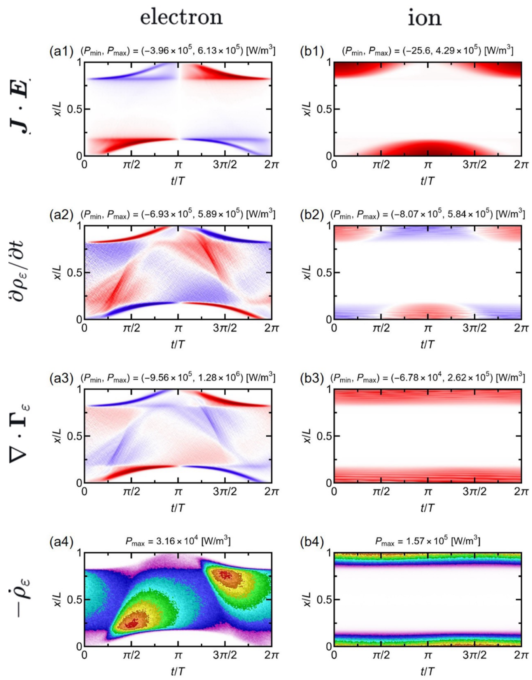

Figure 1 Spatiotemporal profiles of each transport term corresponding to energy transport equation for electrons (first column) and ions (second column).