Direct kinetic simulation of nonlinear plasma waves and Hall thruster discharge plasmas

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Plasma instabilities and oscillations play an important role in many plasma applications ranging from wave- and beam-plasma interactions to plasma propulsion. In order to investigate such nonlinear plasma phenomena, we have developed a direct kinetic (DK) simulation, in which the velocity distribution functions are directly obtained by solving kinetic equations such as the Vlasov equation in a discretized phase space, i.e., physical and velocity space. One advantage of a DK method is that the numerical noise inherent in particle methods is essentially eliminated. We employed the DK simulation to investigate plasma-wave interactions, including electron plasma waves, ion acoustic waves, and trapped particle instabilities, and the low-frequency ionization oscillations in the discharge plasmas of Hall effect thrusters.

1. Background and Motivation

Two main plasma simulation techniques that have been developed include fluid and kinetic models. Fluid models solve the conservation equations for macroscopic quantities, including the density, bulk velocity, and energy. On the other hand, the first-principles gas kinetic equations, such as the Vlasov and Boltzmann equations, are solved to obtain the distribution functions in kinetic models. One of the most popular is particle methods, in which computational “macroparticles” are used. However, the statistical noise inherent in the particle methods may alter the physical oscillation signals if the number of macroparticles is not sufficient.

We have developed a grid-based kinetic simulation, called the direct kinetic (DK) method, which is an alternative to particle-based kinetic models such as particle-in-cell (PIC) method. As the kinetic equations are hyperbolic partial differential equation, we employ a finite-volume method using Monotonic Upwind Scheme for Conservation Laws (MUSCL) framework with the Arora-Roe limiter, which preserves conservation and positivity of the distribution functions.

The DK method has been tested against plasma-sheath theory with and without secondary electron emission, Landau damping, and nonlinear plasma wave theories for Langmuir and ion acoustic waves. It is also benchmarked with a PIC simulation in the Hall thruster discharge plasma. [1] We developed a hybrid-kinetic simulation, in which ions are solved using a kinetic (DK or PIC) simulation while a fluid model is used for electrons, and showed that DK simulation is useful for ionization oscillations.

2. Key Results

I will focus on the two nonlinear phenomena that we investigated using a DK method.

First, we performed kinetic simulations of the trapped particle bunching instability in nonlinear plasma waves. [2] We have shown that the trapped particles in traveling potential wells experience a bunching instability and form a bunch in the phase space depending on the initial trapped particle distribution. The growth rates obtained from the numerical simulation are in good agreement with the theoretical predictions.

Second, low-frequency (10-30 kHz) ionization oscillation, also called the breathing mode, in Hall effect thrusters is investigated. Although this phenomenon has been often observed in experiments and numerical simulations, the mechanism of excitation and damping of the breathing mode was not fully understood. We have employed a hybrid-DK method and showed a qualitative agreement of the discharge current oscillations between experiments and numerical simulations. [3] Furthermore, we developed a perturbation theory of ionization oscillations by accounting for the perturbation of electron energy, which was neglected in the conventional predator-prey type formulation. [4] From the numerical results and the perturbation theory, we have concluded that the electron heat transfer mechanism plays a significant role in the mode transition of the ionization oscillations.

3. References

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