9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Full-f 6D particle-in-cell simulations of quasi-kinetic equilibrium and drift-wave instability under spatial inhomogeneity

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We have studied the quasi-kinetic equilibrium with spatial inhomogeneity and instability driven by ion temperature gradient by six-dimensional (6D) full-f particle-in-cell (PIC) simulations. In a system with spatial inhomogeneity, fluid equilibrium can be established straightforwardly, but there is no known suitable analytical equilibrium that satisfies the time-independent Vlasov-Maxwell system exactly. Full-f simulations with 6D ions and adiabatic electrons are carried out by a geometric structure-preserving PIC algorithm [1] on unstructured mesh to search for a quasi-kinetic equilibrium with spatial inhomogeneity. The time evolution of density, ion-temperature and ion-velocity profiles are obtained, and the time-dependent ion distribution function is also numerically constructed. The frequency spectrum of the density, ion-temperature, ion-velocity, ion distribution function from the PIC simulation is compared to the timescale analysis of the dynamics of the Vlasov equation.

The simulation is carried out in a system with a constant ion density and the spatial-inhomogeneous ion temperature. Under an external electric field, the system is in a fluid equilibrium instead of a kinetic equilibrium. The PIC simulation starting from a fluid system is expected to numerically construct a kinetic equilibrium. In the full-f simulation, we find that the 6D ion gyromotions combining with the particle ExB drift and diamagnetic drift, have formed an equilibrium velocity-shear in the poloidal direction. An instability appears on the top of this velocity-shear in the region of the strong temperature gradient with the inhomogeneity scale length of only a few ion gyroradii. By comparing to the five-dimensional (5D) gyrokinetic (GK) theory [2], the real frequency of the instability, which is in the drift frequency region, agrees well with the full-f 6D PIC simulation in the growth stage. The growth rate obtained from the full-f simulation is consistent with the GK theory.

The simulation results, especially the role of 6D physics in driving the drift instability, demonstrates that the 5D gyrokinetic theory can predict the instability qualitatively consistent with the 6D full-f simulation, but the quantitative comparison shows the obvious divergence between the 5D gyrokinetic and the 6D full-f fully-kinetic results. Our study suggests the necessity to carry out fully kinetic 6D studies for drift instability and turbulence in strong gradient region like steep edge pedestal.

References
[1] Z. Wang et al, Journal of Plasma Physics, 2021.
[2] Z. Wang, B. Sturdevant, C.S. Chang et al. Paper in perp.

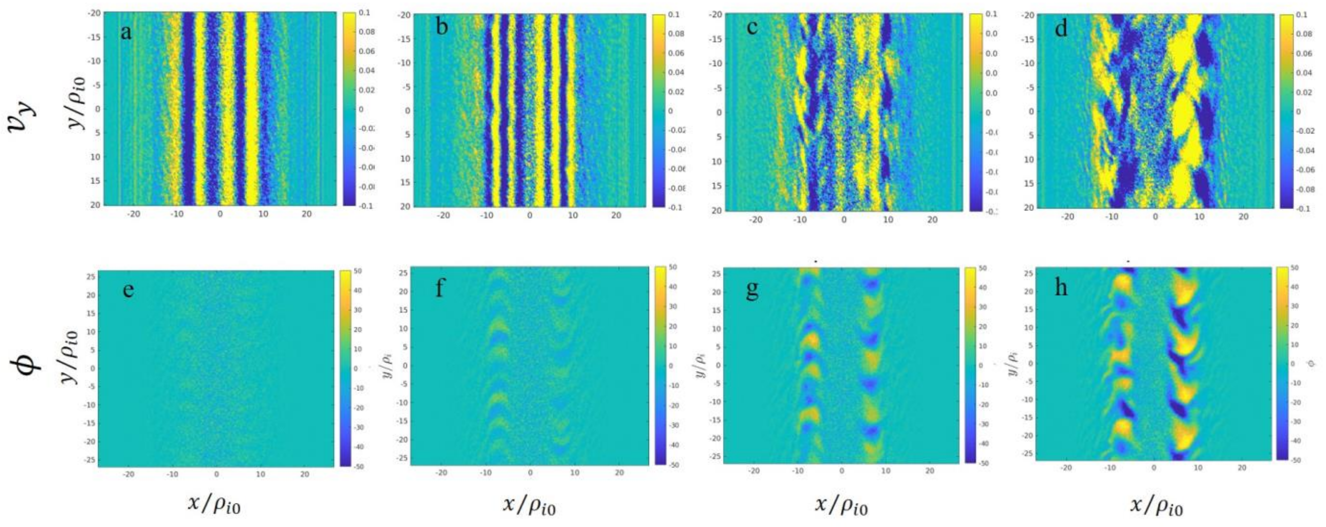

Figure 1: correlation of electric potential ϕ and poloidal velocity v_y. (a)-(d) are poloidal velocity at $\Omega_i t = 500, 1000, 1500, 2000$, respectively, Ω_i is ion gyrofrequency and the velocity is normalized by ion thermal speed. Clear velocity shear appears in (a) and (b). (e)-(f) are electric potentials in the unit of eV. The instability appears in (f) correlating to the strong velocity-shear in (b).