Two-stream instability and Bernstein–Greene–Kruskal mode formation in coulomb one component plasma

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ABSTRACT

We investigate the two-stream instability in a strongly coupled plasma using classical molecular dynamics simulations with long-range Coulomb interactions between particles. The nonlinear evolution of the instability is identified by the emergence of a Bernstein–Greene–Kruskal (BGK) mode. Our simulations capture key microscopic effects, such as inter-particle correlations, collisional dynamics, and coherent wave-particle interactions—features often absent in traditional fluid and kinetic models, including particle-in-cell and Vlasov approaches. In the linear regime, the instability grows rapidly and saturates within a few tens of plasma periods. As the system transitions into the nonlinear saturation phase, a single BGK mode emerges. This mode (or phase-space hole) becomes dynamically unstable in the nonlinear regime, characterized by a continuous decay of electrostatic energy over time. An energy budget analysis reveals a bump in an otherwise thermal spectrum, indicating the excitation of a coherent mode, further confirmed through a numerical rendering of the dispersion relation. The pairwise interaction plays a crucial role: pronounced instability and BGK mode formation occur with long-range Coulomb forces, while such structures are suppressed under shielded Coulomb interactions. We observe the emergence of a single BGK mode across all coupling strengths in the fluid regime, provided the streaming velocity exceeds a critical threshold.

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I. INTRODUCTION

The two-stream instability (TSI) arises in a plasma system with two interpenetrating beams with velocity distribution departing from the Maxwellian.[1] This electrostatic instability grows rapidly due to bunching and charge separation in real space. It is a mechanism that transfers energy from particles to waves, an inverse Landau damping problem.[1,2] For a typical plasma with the kinetic energy dominating the average interaction energy, fluid, and kinetic models, such as particle-in-cell (PIC) and Vlasov simulations are appropriate to study the TSI.[1,4–8] In this paper, we focus on a class of plasmas whose average interaction energy is comparable to or higher than the kinetic energy of particles—the so-called strongly coupled plasmas (SCPs). For such systems, the correlations are important, and large-angle collisions significantly contribute to the collective dynamics. To capture these effects, we employ classical molecular dynamics (MD) simulations to investigate the evolution of the two-stream instability in a one-component plasma (OCP) system, with particular emphasis on the formation and stability of a single Bernstein–Greene–Kruskal (BGK) mode. Unlike the conventional kinetic approaches, the MD framework inherently incorporates correlations, collisional dynamics, viscosity, and wave-particle interactions.

The electrostatic wave associated with the two-stream instability extracts energy from the kinetic motion of drifting particles in the two beams, analogous to the mechanism of the Buneman instability.[9] During the nonlinear evolution of the TSI, a coherent phase-space vortex—commonly referred to as a BGK mode—emerges, signaling localized depletion or trapping of charged particles.[10–13] The formation of such structures offers critical insights into the nonlinear saturation

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