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Energy balance for unstable ion Bernstein waves in 6D kinetic Vlasov simulations

We present a novel method for calculating particle and energy flows in the 6D kinetic Vlasov equation with adiabatic electrons. This approach enables the determination of energy and particle fluxes from lower-order moments of the distribution function, such as the kinetic energy density and the momentum transfer tensor. In addition to this decomposition, we derive the residual Poynting flux in the electrostatic limit and evaluate its contribution to the total energy flux.

The results indicate that energy fluxes are primarily dominated by the $E \times B$ heat flux, with additional contributions from the momentum transfer tensor and the Poynting flux. Our analysis reveals an additional contribution that is negligible for low-frequency gyrokinetic modes but may become significant for high-frequency modes, such as ion Bernstein waves (IBWs). This technique offers two major advantages. First, it allows for the identification of individual contributions to the energy flux, including the $E \times B$ heat flux known from gyrokinetics, thereby establishing a direct connection to established theory. Second, it reduces inherent gyro-oscillations in both energy and particle fluxes by decomposing the expressions into components with fewer gyrooscillations, allowing for more reliable diagnostics. [2].

The resulting expressions for the energy and particle fluxes are compared with simulation results of ion temperature gradient (ITG) turbulence, using both local and nonlinear treatments of the temperature gradient. By comparing the analytical expressions with the simulated fluxes and the decay of the initial temperature profile, we demonstrate good agreement with the sum of the individual contributions, thereby confirming the validity of the proposed method.

Previous research [1, 3] has shown that the fully kinetic system exhibits behaviors beyond the scope of gyrokinetics in scenarios with large density and temperature gradients, such as those found at the edge of a tokamak during transition phases. A comprehensive understanding of all energy transport channels is therefore essential—particularly when the model is extended to incorporate more detailed electron physics.

References

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