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Validity of Gyrokinetic Theory in Magnetized Plasmas

Haotian Chen[1], Liu Chen[2,3], Fulvio Zonca[3,2] , Jiquan Li[1] and Min Xu[1]
[1] Southwestern Institute of Physics
[2] Institute for Fusion Theory and Simulation, Zhejiang University
[3] Center for Nonlinear Plasma Science and C. R. ENEA Frascati
e-mail (speaker): chenhaotian@swip.ac.cn

Magnetized plasmas are ionized gases in which the ambient magnetic field significantly alters particle trajectories. They are known to play crucial roles in various fields, including fusion research, solar-terrestrial and astrophysical environments, and plasma-based industries. Physically, the fundamental challenge in understanding magnetized plasmas is the vast disparity between the very fast gyromotion time scale of a charged particle and the much slower characteristic time scales for collective instabilities. Gyrokinetics provides a unified framework for describing the long-term spatiotemporal evolution of magnetized plasmas [1]. As one of the major achievements in modern plasma physics, this theory was established by an asymptotic construction of the magnetic moment adiabatic invariant, initially through the gyro-averaging method and later through the Lie-transform perturbation theory. The details of the charged particle's gyromotion are not of dynamical importance in the resulting gyrokinetic equation, which thereby reduces the kinetic problem from six dimensions to five. After half a century of intense pursuit, gyrokinetics now is the basis of numerous simulation codes and theoretical models used to study plasma instabilities, turbulence, and transport processes. A notable example in this regard is the recent launch of ambitious simulation projects that strive to deliver a high-fidelity whole-device model of magnetic fusion devices within the gyrokinetic framework (see, e.g., ref. 2).

Despite its practical success, the validity regime of gyrokinetic theory is typically stated by the nonlinear gyrokinetic ordering in terms of the formal expansion parameters and often assumed. The gyrokinetic theory is a reduced kinetic theory derived from adiabaticity. To ensure its generality, it is essential to establish the robustness of adiabatic invariant across a wide range of plasma conditions. Previous studies, however, mainly focus on the construction of adiabatic invariant, a clear physics picture of the destruction mechanism is still lacking. The aim of this study is to illuminate what kind of physics sets the validity limits of gyrokinetic theory. Below, we will perform a thorough analysis of the nonlinear particle dynamics to investigate (i) under which conditions the adiabaticity would be broken and, accordingly the gyrokinetic theory would become invalid; (ii) why the high-frequency gyrokinetic theory, which was developed in the early 1980s, has not gained much popularity in implementation; (iii) whether the superadiabaticity [3] could also be utilized to construct a reduced kinetic theory.

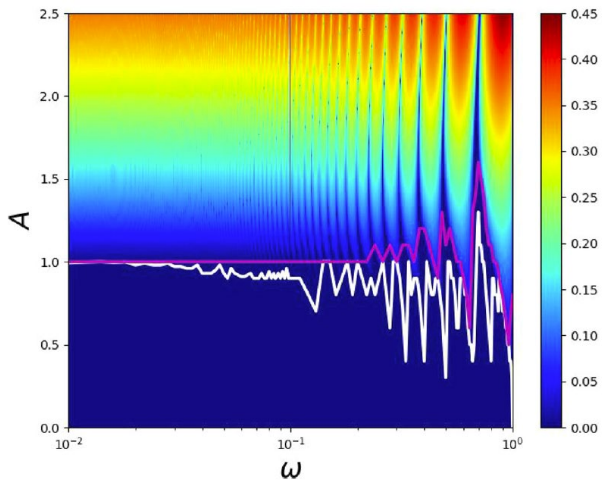

Figure 1 Stability diagram of the charged particle orbit.

In this work, we show the conventional ordering assumption is not precise enough for the strict validity of the gyrokinetic theory. The particle dynamics must constitute a boundary layer problem to guarantee the persistent existence of adiabatic invariant over a reasonably wide range of conditions. Consequently, in contrast to previous ordering arguments which are semi-quantitative in nature, we find a quantitative, frequency-independent threshold in the normalized amplitude below which the gyrokinetic theory is generally valid for low-frequency perturbations. Given the ordering of spatiotemporal scales and fluctuation strength in the standard low-frequency gyrokinetic theory, one could conclude that the corresponding normalized fluctuation level is considerably lower than the threshold. Therefore, the existence of such a threshold exhibits the robustness of the low-frequency gyrokinetic theory. The adiabaticity in high-frequency regimes, however, is sensitive to wave parameters, which raises concerns about the fundamental hypotheses of high-frequency gyrokinetic theory. Further analyses suggest that it is not possible to construct a reduced kinetic equation from superadiabaticity.

References

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