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Wave-kinetic approach to zonal-flow dynamics: Recent advances

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ABSTRACT

The basic physics of drift-wave turbulence and zonal flows has long been studied within the framework of the wave-kinetic theory. Recently, this framework has been reexamined from first principles, which has led to more accurate yet still tractable "improved" wave-kinetic equations. In particular, these equations reveal an important effect of the zonal-flow "curvature" (the second radial derivative of the flow velocity) on the dynamics and stability of drift waves and zonal flows. We overview these recent findings and present a consolidated high-level picture of (mostly quasilinear) zonal-flow physics within reduced models of drift-wave turbulence.

I. INTRODUCTION

It is well known that sheared $\boldsymbol{E} \times \boldsymbol{B}$ flows, including equilibrium flows and spontaneously generated zonal flows (ZFs), can reduce the level of drift-wave (DW) turbulence in fusion plasmas and play a crucial role in the transition between regimes with low and high (L–H) confinement (for reviews, see, e.g., Refs. 1–4). Numerical simulations have also shown that ZFs can even completely suppress turbulence near the instability threshold, which effect is known as the Dimits shift.[5–11] Because of this, DW–ZF interactions have been attracting much attention over the last decades and studied extensively.

One of the theoretical frameworks used for studying DW–ZF interactions is the wave-kinetic theory of inhomogeneous DW turbulence.[1,12–24] Within this framework, which assumes ZFs to have scales much larger than the characteristic DW wavelength, DWs are described as effective classical particles, sometimes called "driftons."[16] The drifton phase-space density is described by the wave-kinetic equation (WKE). The ZF velocity enters the WKE through the drifton Hamiltonian and serves as a collective field through which driftons interact. This approach has been fairly successful; for example, it has yielded predator–prey models that explain some aspects of the L–H transition.[12,25,26] However, because the "traditional" WKE relies on *ad hoc* assumptions and is not entirely rigorous, the potential of the wave-kinetic approach in application to DW turbulence is yet to be fully appreciated.

Recently, the wave-kinetic description of inhomogeneous DW turbulence has been reexamined from first principles and applied to make quantitative predictions in a number of problems.[27–38] Although still limited to simplified DW models, those results indicate that important qualitative physics has been overlooked in the past but can be described transparently if the wave-kinetic formalism is properly amended. In particular, the "improved" WKE reveals an important effect of the ZF "curvature" (the second radial derivative of the zonal velocity) on the dynamics and stability of DWs and ZFs. Here, we overview these results and present a consolidated high-level picture of DW–ZF interactions and ZF stability. Our analysis is mostly based on the modified Hasegawa–Mima model[39–41] and on the quasilinear approximation (which neglects DW–DW interactions but keeps DW–ZF coupling), although more general models are also considered. A special focus is made on understanding drifton phase-space dynamics, associated solitary structures, merging and splitting of ZFs, as well as the Kelvin–Helmholtz instability (KHI) and the tertiary instability. Notably, while the KHI and the tertiary instability are often confused with each other, they have very different properties, as discussed below. We also briefly mention the connection between