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Gyrokinetic theory of TAE saturation via nonlinear wave-wave coupling

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Nonlinear wave-wave coupling constitutes an important route for the turbulence spectrum evolution in both space and laboratory plasmas. E.g., in a reactor relevant fusion plasma, a rich spectrum of symmetry breaking shear Alfvén wave (SAW) instabilities are expected to be excited by energetic fusion alpha particles, and self-consistently determine the anomalous alpha particle transport rate by the saturated electromagnetic perturbations. In this talk, we will show that the nonlinear gyrokinetic theory is necessary in qualitatively and quantitatively investigating the nonlinear wave-wave coupling processes; in order to account for the breaking of the pure "Alfvénic state" in the short wavelength kinetic regime, due to the short wavelength structures associated with nonuniformity intrinsic to magnetically confined plasmas [1].

Using well-known toroidal Alfvén eigenmode (TAE) as a paradigm case, three nonlinear wave-wave coupling channels expected to significantly influence the TAE nonlinear dynamics will be presented to demonstrate the strength and necessity of nonlinear gyrokinetic theory in predicting crucial processes in a future reactor burning plasma. These are: 1. the nonlinear excitation of meso-scale zonal field structures via modulational instability and TAE scattering into short-wavelength stable domain [2]; 2. the TAE frequency cascading due to nonlinear ion induced scattering and the resulting saturated TAE spectrum [4]; and 3. the cross-scale coupling of TAE with micro-scale ambient drift wave turbulence and its effect on TAE regulation and anomalous electron heating [5].

Linearly stable zonal field structures can be spontaneously excited by finite amplitude TAE, and self-consistently regulate TAE via scattering into linearly stable short radial wavelength regime, providing a self-regulation mechanism of TAE. It is found that both electrostatic zonal flow and electromagnetic zonal current contribute significantly to the process, with the first being the result of breaking of the pure Alfvénic state by toroidal magnetic geometry that is also crucial for TAE excitation; while the latter is due to dynamo effects. We show that, to properly assess the condition for zonal field structure spontaneous excitation, realistic magnetic geometry and kinetic effects including trapped ion responses are mandatory.

The TAE spectral downward cascading via nonlinear ion induced scattering and saturation due to enhanced coupling to SAW continuum, originally investigated in Ref. [3] in the long wavelength MHD limit, is extended to the burning plasma relevant short wavelength regime [4]. The equation describing a test TAE nonlinear evolution due to interaction with the bath of background TAEs is derived, which is then applied and yields the wave-kinetic equation for the TAE spectral evolution in the continuum limit. The wave-kinetic equation is solved to obtain the saturated spectrum of TAE, yielding an overall fluctuation level much lower than that predicted by MHD [3] as a consequence of the enhanced nonlinear couplings in the short wavelength regime. The associated alpha particle transport coefficient is also derived and evaluated correspondingly.

In the last part of the talk, we show that, in the presence of ambient stationary drift wave turbulence, direct scattering by micro-scale drift wave turbulence could lead to appreciable damping of TAE via generation of short-wavelength electron Landau damped kinetic Alfvén waves. A corresponding analytic expression of the damping rate is derived, and found to be, typically, comparable to the linear drive by energetic particles. The implications of this novel mechanism on the transport and heating processes in burning plasmas are also discussed.

Our theory indicates that, for TAE saturation in the parameter regime of practical interest, several nonlinear wave-wave coupling processes could occur with comparable importance; and, thus, kinetic effects, plasma nonuniformity, and realistic magnetic geometry must be properly accounted for in order to accurately assess the nonlinear dynamics.

References

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