Nonlinear wave-particle dynamics of energetic-particle driven instabilities in tokamak plasmas

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The success of the magnetic-confinement nuclear fusion research program critically depends on the ability of understanding the particle and heat transport in burning plasmas. Burning plasmas are characterized by the presence of energetic particles (EP) which are the product of fusion reactions as well as of auxiliary heating and current drive systems. As a consequence the system of plasma instabilities, turbulence and energetic particles in a tokamak is very complex and intrinsically nonlinear. Nevertheless, the comparison of multi-scale 3D kinetic simulations and lower-dimensionality models where reduced physical problems are considered, has proven to be surprisingly powerful in sheding light on some of the main nonlinear saturation mechanisms.

The nonlinear dynamics of energetic-particle (EP) driven geodesic acoustic modes (EGAM) [1–5] is investigated here. A numerical analysis with the global gyrokinetic particle-in-cell code ORB5 is performed. ORB5 is a nonlinear global particle-in-cell code, developed for turbulence studies [7] and extended to its electromagnetic multi-species version [8]. Only axisymmetric modes are considered, with a nonlinear dynamics determined by wave-particle interaction. The results are interpreted with the analytical theory, in close comparison with the theory of the beam-plasma instability [9–13].

Quadratic scalings of the saturated electric field with respect to the linear growth rate are found for the case of interest. As a main result, the formula for the nonlinear saturation level is provided [14]. The EP bounce frequency is calculated as a function of the EGAM frequency, and shown not to depend on the value of the bulk temperature. Near the saturation, we observe a transition from adiabatic to non-adiabatic dynamics, i.e., the frequency chirping rate becomes comparable to the resonant EP bounce frequency. The numerical analysis is performed here with electrostatic simulations with circular flux surfaces, while kinetic effects of the electrons are neglected.

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