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Frequency chirping in the early stage of a near-threshold bump-on-tail instability

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The confinement of energetic particles (EPs) affects the operation of a fusion device. Their distribution function can be significantly modified by their interaction with Alfvén waves. A widely adapted paradigm is near-threshold bump-on-tail model, also known as the Berk-Breizman model [1]. Frequency chirping was found after the initial perturbation "blows up" and enters the hard nonlinear regime after phase space holes and clumps are created, with particles trapped inside moving adiabatically, in agreement with many simulations and experimental observations.

However, frequency chirping started well before the creation of holes and clumps, and the mechanism is clearly different from the "adiabatic chirping" regime above. In fact, the amplitude of the single-frequency wave alternates between positive and negative values shortly after entering the nonlinear stage: one can understand it as the beating of two waves [2]. Thanks to such beating, the phase space coherent island is destroyed each time when the amplitude changes the sign. The process repeats as the wave amplitude grows and the frequency further chirps before being overwhelmed by the strongly re-destabilized initial resonance.

The lack of coherent phase space island motivates the use of a quasi-linear method [3]. In this work, we examine the suitability of such a theory in the early stage chirping of the bump-on-tail problem. It happens that solving the linear dispersion relationship at each time step using the nonlinearly modified equilibrium distribution function reproduces the evolution of the mode amplitude, after a time delay is applied (Figure 1). However, the evolution of the equilibrium distribution function itself cannot be simplified to a diffusion equation since the dynamics is too fast. We also observe the direct conversion of the two chirping waves in the early stage into long-lived BGK modes carrying holes and clumps, if the initial resonance is stabilized.

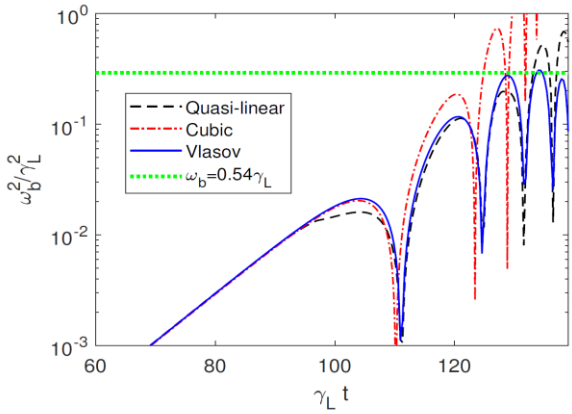

Figure 1: Time evolution of the wave amplitude computed by the quasi-linear method, the Berk-Breizman cubic equation, and a direct Vlasov solver, for $\frac{\gamma_l}{\gamma_d} = 0.9$.

References
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