Resonant and non-resonant particle dynamics in Alfvén Mode excitations

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The resonant excitations of Alfvén Modes in toroidal plasmas by fast ions is considered in the present work, revisiting previous analyses that demonstrated in general the existence of two types of modes; *i.e.*, a discrete shear Alfvén gap mode, or Alfvén Eigenmode (AE), and an Energetic Particle continuum Mode (EPM) [1]. For AE, the non-resonant fast ion response provides a real frequency shift, while the resonant wave-particle interaction gives the mode drive. In the case of EPM, ω is set by the relevant energetic ion characteristic frequency and mode excitation requires the drive exceeding a threshold due to continuum damping [2, 3]. However, the non-resonant fast ion response is crucially important for EPM excitation as well, since it provides the compression effect that is necessary for balancing the positive MHD potential energy of the wave, as explicitly shown in the *fishbone*-like general dispersion relation [1, 4, 5]. Here, we demonstrate that the resonant fast ion dynamics in toroidal plasmas is dominated by the magnetic drift curvature coupling in the vorticity equation, while the non-resonant response has various contributions, whose relative weight depends on the ratio of the characteristic fast ion orbit width to the perpendicular mode wavelength, $\lambda_\perp$. At very short wavelength, shorter than the fast ion Larmor radius ρ_{LE}, the resonant wave-particle interaction becomes small due to the quasi-adiabatic energetic ion behavior. In these conditions, the non-resonant fast ion dynamics is due to the *charge uncovering* effect [6, 7, 8] and it may be derived ignoring toroidicity [9]. However, the small but finite drive is still due to resonant particles via the magnetic drift curvature coupling and is necessary for the mode excitation. Besides, only resonant particles interacting with the mode can be affected by fluctuation enhanced transport and, thus, are crucially important for understanding alpha particle confinement and collective behaviors in burning plasmas. In the present work, we demonstrate that the optimal wavelength ordering for analyzing energetic ion transport in burning plasmas is $\lambda_\perp \gtrsim \rho_{LE}$, considered in [1], for which both resonant and non-resonant fast ion behaviors are dominated by the magnetic drift curvature coupling, that fully accounts for the energetic ion dynamics [10, 11], including the *charge uncovering* effect [6, 7, 8].

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