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Impacts of self-organized zonal fields on BAE nonlinear dynamics in phase space

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It has been shown by early global gyrokinetic simulation[1] that, the energetic particle (EP) phase space island formation and destruction accompanied by resonant particle trapping and detrapping, are responsible for the nonlinear frequency and amplitude oscillations of beta-induced Alfvén eigenmode (BAE), which is essentially a nonlocal physics issue that closely related to the radial variation of EP resonance frequency and BAE mode structure.

In this work, we further incorporate the self-organized zonal fields (include zonal flow $\delta\phi_{00}$ and zonal current $\delta A_{\parallel 00}$ perturbations) and investigate their peculiar roles on BAE nonlinear dynamics in phase space. It is found that in the unstable BAE regime away from marginal stability with strong EP drive, zonal flow significantly suppresses the BAE non-adiabatic frequency chirping process, preserves the BAE radially broad mode structure during nonlinear evolution and increases the saturation amplitude, while zonal current effect is negligible on BAE nonlinear dynamics. Figure 1 shows the time evolution of BAE.

The primary reason is due to the resonant EP characteristic frequency change by zonal flow-induced Doppler shift based on the modified wave-particle resonance condition, which effectively prevents the detrapping process of EPs with large characteristic frequency and enhances the nonlinear particle trapping of EPs by BAE wave fields, and thus maintains the EP phase space island and BAE mode structure with maximal radial widths that ensures a large area for wave-particle energy transfer.

In summary, the self-organized zonal flow dramatically weakens the EP non-perturbative effect on BAE nonlinear dynamics, leading to the paradigm change from fishbone[2] to bump-on-tail[3] with the identical EP drive strength.

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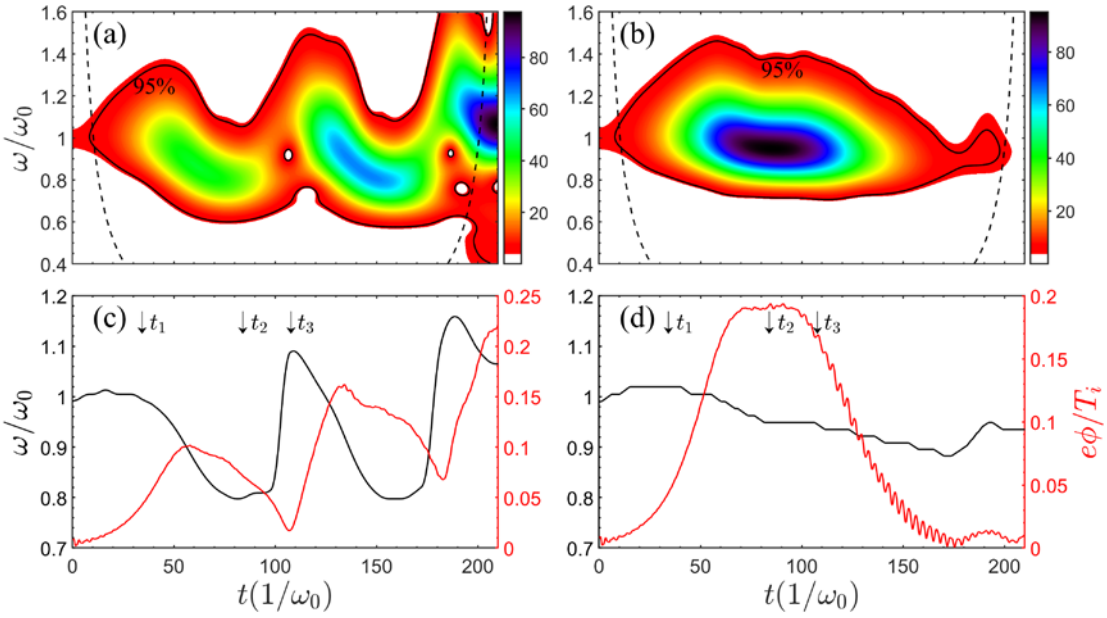

Figure 1. Time history of BAE amplitude $e\phi/T_i$ (red) and frequency ω (black) with (c) zonal fields artificially suppressed and (d) self-consistent generation of zonal fields. Three characteristic time steps (t_1,t_2,t_3) are identified for subsequent analysis. The frequencies with the maximum power intensity are selected through wavelet transform of the real part of $\delta\phi$, as shown in the frequency power spectrum (a) and (b), respectively. In panel (a) and (b), the dashed lines indicate cone of influence while the solid curves denote the significance level.