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Zonal Flow Generation in the Presence of Fast Ions

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Fast ions' effects on turbulence-driven zonal flow generation are investigated in the context of a simple reduced model based on the Hasegawa–Mima equation.[1] Fast ions' much higher characteristic frequency of parallel motion in comparison to the drift wave's phase velocity along the magnetic field facilitates a derivation of the reduced model equations. Nonlinear mode coupling analyses show that the threshold amplitude of drift wave required for the zonal flow modulational instability is significantly reduced, making its generation easier. This occurs as both a down-shift of the drift wave's frequency and a reduction of dispersion in the presence of the fast ions cause a decrease in the mismatch between the primary drift wave frequency and the zonal flow modulated sideband drift wave's characteristic frequency.

Specifically, in the long wavelength regime, satisfying $k_\perp q_s \sim q_x \rho_s \ll k_\perp \rho_{Tf} \sim q_x \rho_{Tf} \ll 1$ ($k_\perp$ and q_x are wavenumbers of drift wave and zonal flow, and q_s and q_{Tf} are the Larmor radius of main ion at electron temperature and of fast ions), fast ions do not contribute to the vorticity of drift waves, while they do for the vorticity of zonal flows. Consequently, the reductions of the drift wave frequency and its dispersion due to the dilution of main ion density lead to the reduction of frequency mismatch from the sideband induced drift wave's characteristic frequency. As a result, the threshold of drift wave amplitude is reduced, making the zonal flow generation easier as shown in the below equation and Figure 1-a.[2] for zonal flow growth rate.

$$\Gamma \approx \sqrt{1-f_h}\, k_y q_x \sqrt{2|\phi_{\mathrm{DW0}}|^2 - (1-f_h)^3 \left(\frac{L_{ne}}{L_{ni}}\right)^2 q_x^2}$$

Here, Γ is a growth rate of zonal flow, $f_h \equiv Z_f n_{f0}/n_{e0}$, $\phi_{\mathrm{DW0}} = (L_{ne}/\rho_s)(|e|\delta\phi_{\mathrm{DW0}}/T_e)$ where $\delta\phi_{\mathrm{DW0}}$ is an primary electrostatic potential fluctuation, and the length and time are normalized to ρ_s and L_{ne}/c_s.

In the intermediate wavelength regime, $k_\perp q_s \sim q_x \rho_s \ll 1 \ll k_\perp \rho_{Tf} \sim q_x \rho_{Tf}$, the fast ions' contribution to vorticity is negligible for both drift waves and zonal flows due to unmagnetized fast ion density response to potential fluctuation. Therefore, the zonal vorticity equation is not affected. However, the dilution of main ion density and the reduction of its gradient decrease the threshold value of the primary drift wave amplitude required for the zonal flow generation via the reductions of the drift wave frequency and its dispersion. Its dependence on the main ion dilution factor is stronger compared to the long wavelength case as shown in the below equation and Figure 1-b.[2] for zonal flow growth rate.

$$\Gamma \approx k_y q_x \sqrt{2|\phi_{\mathrm{DW0}}|^2 - (1-f_h)^4 \left(\frac{L_{ne}}{L_{ni}}\right)^2 q_x^2}$$

This finding could be a common nonlinear physics mechanism behind numerous recent results on tokamak plasma confinement enhancement caused by the fast ions.[3,4] Our long wavelength approximation for zonal flows are reasonable for the case with 100 keV range fast ion temperature with $T_f/T_e \sim 10$ as shown in an example in Ref [3]. Regarding the ITER parameters with $T_\alpha/T_e \sim 10$ [5] and an example dealing with 1 MeV range fast ions with $T_f/T_e \sim 30$,[4] our results for the moderate wavelength regime can be tested.

References
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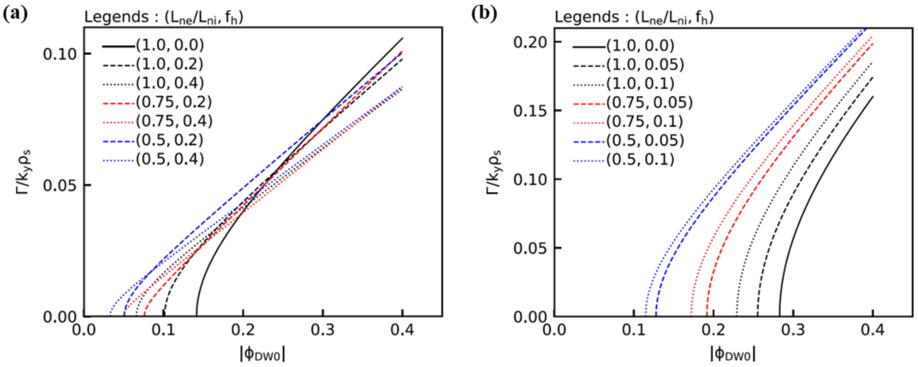

Figure 1. Normalized zonal flow growth rate $\Gamma/\mathrm{k_y}\rho_{s_s}$ in the unit of $\mathrm{c_s}/L_{ne}$ (a) for $\mathrm{q_x}\rho_s = 0.2$ in the long wavelength regime and (b) for $\mathrm{q_x}\rho_s = 0.4$ in the intermediate wavelength regime.