THEORY OF FAST ION POPULATION EFFECT ON TURBULENCE SELF-REGULATION IN MAGNETIZED FUSION PLASMAS

[1]G.J. CHOI, [2]T.S. HAHM, [3]P.H. DIAMOND, [2]Y.-S. NA, [2]S.J. PARK, [2]Y.J. LEE AND [4]M.J. CHOI

[1]Department of Nuclear and Quantum Engineering, KAIST, Daejeon, Republic of Korea
[2]Department of Nuclear Engineering, Seoul National University, Seoul, Republic of Korea
[3]Department of Astronomy and Astrophysics, and Department of Physics, UC San Diego, CA, USA
[4]Korea Institute of Fusion Energy, Daejeon, Republic of Korea

Email: gyungjinc@kaist.ac.kr

ACKNOWLEDGEMENTS

Work supported by National R&D Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (NRF-2021M1A7A4091135, 2021M3F7A1084418, 2023R1A2C100773511), Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2022R1I1A1A01072713), and U.S. Department of Energy under Award Number DE-FG02-04ER54738.

We developed theory of fast ion population effect, namely thermal ion dilution by significant portion of fast ions, to drift wave turbulence-zonal flow system, which is probably the simplest self-consistent dynamical one that captures the favourable roles of fast ions to the tokamak confinement enhancement. We found that the fast ion population can lead to a drastic nonlinear suppression of transport in a core enhanced confinement state, due to its strong dependence $\sim(1-f)^3(L_{ne}/L_{ni})^2$ on the dilution factors $1-f$ and L_{ne}/L_{ni}.

Experimental findings of enhanced confinement modes from various tokamaks [1-5] with significant neutral beam injection (NBI) and/or ion cyclotron resonance heating (ICRH) have aroused interests in favourable roles of fast ions on confinement. Extensive studies [6-8] have revealed that self-generation of ExB shear flow, namely zonal flow, from drift wave turbulence triggers the transition to an enhanced confinement regime. In the presence of fast ions, the fast ion-driven Alfven eigenmodes (AEs) can also generate zonal flows by self-beating [9,10], which could nonlinearly interplay with microturbulence resulting in a confinement enhancement.

Meanwhile, there have been studies of direct fast ion effects on turbulent transport and confinement which does not rely on the AEs. Primarily, theories and simulations have shown that since fast ions raise the plasma beta significantly, they enhance finite-beta, in other word electromagnetic stabilization of microturbulence. More recently, a wave-particle interaction between ITG (ion temperature gradient) mode and fast ions has been addressed as a candidate which could stabilize the ITG turbulence in ICRH-like fast ion profiles [1]. However, there has been lack of theory of direct fast ion effect on the turbulence-zonal flow system, which is the minimal set to understand experimentally observed transition to an enhanced confinement regime with fast ions.

Motivated by this, we have developed a theory of coupled drift wave turbulence-turbulence system in the presence of fast ion population effect [11,12]. Careful consideration of the simplest fast ion responses to drift wave and zonal flow using modern gyrokinetics within the long-wavelength regime and the use of adiabatic electrons leads to a finding that the drift wave vorticity is reduced by the fast ion population, while the zonal flow vorticity is unchanged. Resultant Hasegawa-Mima equation with fast ions is then readily obtained. Linearizing it, we obtain the drift wave, of which eigenfrequency significantly downshifted by dilution. Here, notations are the typically used ones, of which definition can be found in Refs. [11,12]. As a next step, following standard procedure [6], we obtain the expression of modulational zonal flow growth rate from drift waves,

$$\Gamma^2 = \gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2, \tag{1}$$

where $\gamma_{\text{mod}}^2 = (1-f)\gamma_{\text{mod}(0)}^2$ is the zonal flow drive from the Hasegawa-Mima nonlinearity, the ExB advection of the vorticity, and $\Delta_{\text{mm}}^2 \simeq (1-f)^4(L_{ne}/L_{ni})^2\Delta_{\text{mm}(0)}^2$ is the frequency mismatch among drift waves involved in the process. We readily find that the frequency mismatch has much stronger reduction factor dependence than the drive, so that we have easier zonal flow generation with fast ions.

We extended our calculation from the case of a few drift waves to broadband drift wave turbulence using wave-kinetic equation, still recovering the same expression with Eq. (1) in the weak turbulence regime noticing that qv_{gx}, the zonal flow radial wavenumber multiplied by drift wave radial group velocity, is the continuum version of the frequency mismatch Δ_{mm}.

For a comprehensive understanding of the fast ion population effect on drift wave turbulence-zonal flow system, there are other important pieces in addition to the zonal flow generation. First, fast ion population can significantly reduce linear turbulence drive as shown in Refs. [13,14]. Second, turbulence self-damping can also be reduced. Finally, collisional zonal flow damping is also reduced due to negligible participation of fast ions. Combining all the pieces together, we constructed a predator-prey model of turbulence-zonal flow system with fast ions

$$\partial_t u^2 = \sqrt{\gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2}\, H(\gamma_{\text{mod}} - \Delta_{\text{mm}})u^2 - (1-f)\gamma_{d(0)}u^2, \tag{2a}$$

$$\partial_t \mathcal{E} = 2\gamma\mathcal{E} - \sqrt{\gamma_{\text{mod}}^2 - \Delta_{\text{mm}}^2}\, H(\gamma_{\text{mod}} - \Delta_{\text{mm}})u^2 - (1-f)B\mathcal{E}^2. \tag{2b}$$

From the nontrivial steady-state solution with finite zonal flows, we finally obtain the saturated turbulence level that is proportional to the turbulent transport coefficient. Its expression in the collisionless limit, relevant to core confinement enhancement, is

$$\mathcal{E} \approx (1-f)^3 (L_{ne}/L_{ni})^2 \mathcal{E}_{(0)}, \tag{3}$$

which has very strong reduction factor, indicating the significant impact of fast ion population on the suppression of turbulent transport and confinement enhancement.

The primary target of application of our analytic theory of fast ion population effects on the turbulence-zonal flow system is KSTAR FIRE mode having significant ion temperature internal transport barrier (ITB) [3,15] that is strongly correlated with fast ions, but usually having no change in Alfvenic activities during the transition phase. Indeed, for a typical KSTAR FIRE mode with $f\sim 1/3$, from Eq. (3) we expect roughly 1/3 decrease of transport level solely from the factor $(1-f)^3$, already significant enough. With additional reduction factor $(L_{ne}/L_{ni})^2$ in Eq. (3) due to thermal ion density profile moderation, our theory predicts a much more drastic suppression of transport after transition from L-mode to FIRE mode, consistent with experimental findings. Another good candidate to examine our theory would be recently found hot ion mode in ST40 with strong NBI [4].

Meanwhile, the confinement enhancement in the electron thermal channel is not clear in the FIRE mode as shown in Ref. [3]. Interestingly, we have found electron temperature profile corrugation in FIRE mode from recent analysis of ECEI data, which is the symptom of ExB staircase [16,17], the quasi-periodic radial structure consisting of mini transport barriers with avalanches in between [18]. Further analytic theory development in correlation with experimental data analysis is in progress on this non-local feature of the electron thermal channel observed in KSTAR FIRE mode.

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