An improved analytical theory of ion temperature gradient instability in tokamak plasmas

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Ion Temperature Gradient (ITG) instability has long been known to be one of the important mechanisms for energy transport[1,2] in magnetically confined fusion plasmas such as tokamaks. Therefore, it is desirable to have an accurate analytical model for the ITG instability in order to develop reliable theoretical understanding and prediction for thermal confinement in fusion plasmas.

Previous ITG analytical theories have typically adopted fluid ion approximation[3,4,5] by assuming $|\omega| \gg |\omega_{di}|$ and employing gyrokinetic equation. Hence, ω is the mode frequency and $\omega_{di} = \vec{k}_\perp \cdot \vec{v}_{di}$ with $\vec{k}_\perp$ being the perpendicular wave vector and $\vec{v}_{di}$ being the ion guiding-center drift velocity due to magnetic gradient and curvature. Furthermore, assumptions such as the strong coupling[3] or the two-scale length[4,5] approximations are often made in order to solve the ITG eigenmode equation analytically.

However, recent advances in computational methods, including Particle-In-Cell (PIC) simulations (e.g. GTC and GT3D) and eigenvalue solvers (e.g. FULL)[6], have revealed that the ITG mode frequency ω is comparable to ω_{di}. This result invalidates the fluid ion assumption, leading to discrepancies between analytical and numerical results and highlighting the need for an improved analytical theory.

In the present work, we have developed a new analytical theory of ITG instability including trapped electron effects, which are known to further destabilize the ITG mode[6]. Using the linear electrostatic gyrokinetic equation and quasi-neutrality condition in ballooning mode representation[7] for a tokamak with circular magnetic surface and normal shear, we have derived a new analytical solution for the dispersion relation and eigenfunction. Figure (1.a) shows our new analytical theory benchmarked against numerical results from GTC, GT3D, and FULL codes[6], based on cyclone parameters [8] derived from DIII-D experiments.

First, we have developed an analytical theory without trapped electrons (i.e., electrons are taken to be adiabatic), which is found to be in good agreement with the numerical results. We then include the effects of trapped electrons via a perturbation theory. As shown in Figure (1.b), our analytical predictions again agree very well with the numerical results given by simulation code and eigenvalue solver[6]. Our improved ITG analytical theory thus provides further detailed theoretical insights on ITG instability in tokamak plasmas and thereby helps future development of ITG-related nonlinear theories and models.

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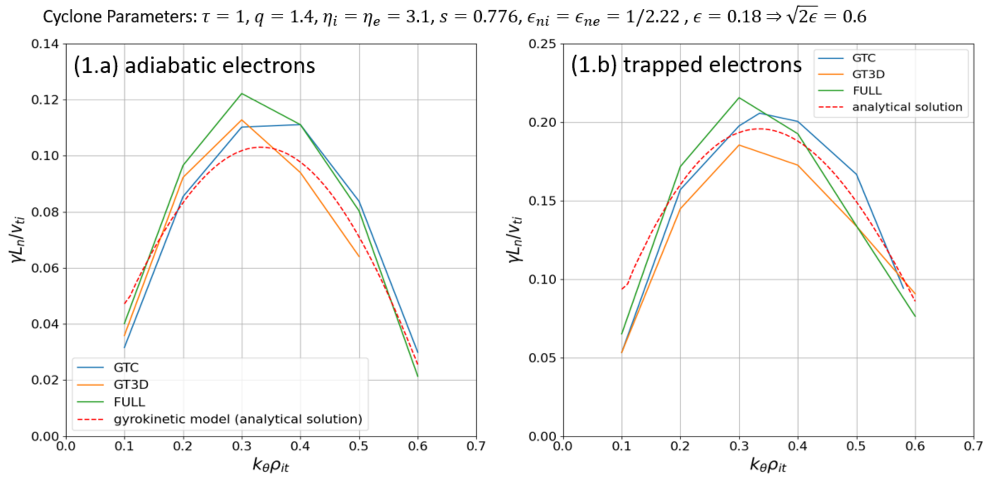

Figure 1 Comparison of the analytical and simulated[6] growth rate γ of ITG (1.a) without and (1.b) with consideration of trapped electrons.