9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Kinetic effects of thermal ions on internal kink modes in tokamak plasmas

Jiangyue Han[1], Yasushi Todo[2], Hao Wang[2], Masahiko Sato[2] , Jialei Wang[2]
[1] The University of Tokyo, [2] National Institute for Fusion Science
e-mail :han.jiangyue@nifs.ac.jp
Toki, Gifu 509-5292, Japan

Internal kink mode is investigated using a kinetic-MHD hybrid simulation model under DIII-D tokamak conditions. By comparing purely fluid (single-fluid MHD) simulations with kinetic thermal ion (KTI) simulations, it is demonstrated that thermal-ion effects—including finite orbit width (FOW) and ion pressure anisotropy—can significantly stabilize the internal kink mode. The maximum perturbation of distribution function aligns with resonance regions and near the passing-trapped boundary, indicating outward transport and redistribution of thermal ions. The net positive energy transfer from the mode to thermal ions leads to a reduction in growth rate.

Thermal ions are modeled as kinetic particles, and their dynamics are computed using the Particle-in-Cell (PIC) δf method, while electrons are represented using a fluid model. The kinetic ion behavior is integrated with extended MHD equations through current coupling [1].

We use the whole tokamak plasma domain with the toroidal angle range $0 \leqslant \phi < 2\pi$. The simulation cross section is $R_0 - a \leqslant R \leqslant R_0 + a$, and $-1.8a \leqslant Z \leqslant 1.8a$, where R_0= 1.67 m and a = 0.67 m are the major radius and the minor radius, respectively. The number of grid points is 256× 64× 256 for cylindrical coordinates (R, ϕ, Z). For the KTI-MHD simulations, we set 64 particles per cell.

The We constructed MHD equilibria via the Grad–Shafranov equation with reference to DIII-D discharge #141216 [2]. Thermal ions are deuterium; on-axis toroidal field $B_0 = 2.0\text{T}$;central densities $n_{e0} = n_{i0} = 5 \times 10^{19} m^{-3}$;on-axis pressure$p_0 = 8 \times 10^4$Pa (yielding $\beta_{axis} = 5\%$; core temperatures $T_{e0} = T_{i0} \sim 5.0\text{keV}$; Alfvén velocity $v_A = B_0/\sqrt{\mu_0 n_e m_i} \sim 4 \times 10^6 \text{m/s}$.

The plasma resistivity is set to $\eta = 1 \times 10^{-6} \mu_0 v_A R_0$. Under these simulation conditions, the internal kink mode is resistive, as its growth rate depends strongly on the plasma resistivity. External sources are not included.

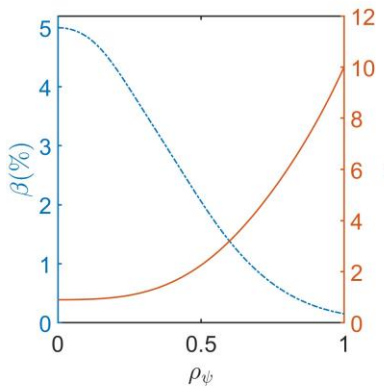

Figure 1. Initial equilibrium profiles: plasma beta (dash-dot curve) and safety factor (solid curve).

An obvious $\delta f > 0$ region appears along the resonance line (magenta) $\omega = \omega_\phi - \omega_\theta$. On the core side of the resonance line, $\delta f < 0$ dominates. This pattern suggests that thermal ions are transported outward from the plasma center due to resonant interactions with the mode.

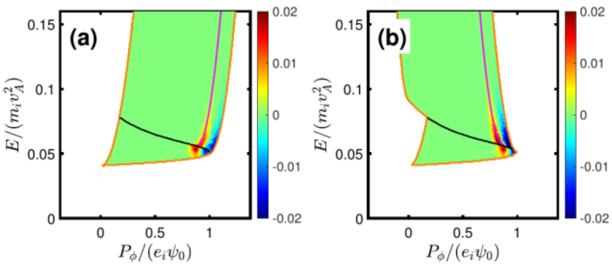

Figure 2. Variations of the thermal ion distribution function δf in (P_ϕ, E) space at $\mu = 0.05 m_i v_A^2/B_0$ (a) Co-going ions, (b) Counter-going ions.

For trapped thermal ions, most of them exhibit δf>0 and δf increases with μ, indicating that the number of trapped ions increases near the passing-trapped boundary. By calculating the change in ion energy, $\Delta E = \sum_i E_i \delta f_i$, we quantified the energy exchange between the particles and the mode. The trapped thermal ions gain energy from the mode, whereas the passing ions lose energy to the mode.

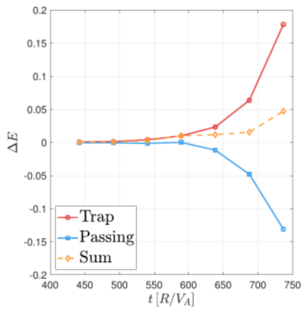

Figure 3. Energy change of thermal ions.

A key finding is that FOW effects from thermal ions reduce the growth rate relative to the pure MHD case. When FOW effects are artificially removed, Ion pressure anisotropy emerges as another important stabilizing factor. In our simulations, when anisotropy is included (as in the KTI and KTI-p(CGL) models), the growth rate of the internal kink mode is more strongly suppressed than in the models that assume isotropic ion pressure.

References

[1] Y Todo et al 2021 Plasma Phys. Control. Fusion 63 075018
[2] G. Brochard et al 2022 Nucl. Fusion 62 036021

Note: Abstract should be in (full) double-columned one page.