

§22. Stabilization of the Kinetic Internal Kink Mode by the Sheared Poloidal Flow

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The physics of sawteeth oscillation in tokamaks is still far from complete understanding. The suppression of the sawtooth crash, the sawtooth crash on the rapid time scale, and the physics of q_0 (safety factor at the magnetic axis) < 1 after the sawtooth crash are some examples. It is believed that the nonlinear development of $m = 1$ (poloidal mode number) and $n = 1$ (toroidal mode number) (collisionless) kinetic internal kink modes is closely related to the sawteeth phenomena. For the numerical study of these phenomena, it is inevitable to develop the extended MHD simulation model, which is the kinetic extension of the conventional MHD model. We have developed gyrokinetic particle code, GYR3D^{1,2)}, gyro-reduced MHD code, GRM3D-2F³⁾, and particle-fluid hybrid code, Hybrid3D⁴⁾. These three codes, which have the exact energy invariances, are based on the nonlinear gyrokinetic Vlasov-Poisson-Ampère system and/or the moment equations of it. It is important to make several codes with different order of physical accuracy and to benchmark those codes for the same physical phenomena. The nonlinear phenomena of the kinetic $m = 1$ and $n = 1$ internal kink mode have been studied by GYR3D, GRM3D-2F, and Hybrid3D. The fast full reconnection (collisionless magnetic reconnection) followed by the second phase reforming the configuration of $q_0 < 1$ has been observed by these three codes. (The two step model predicted by Biskamp et al.)

Although previous studies have been concentrated on the unstable internal kink mode, the mode can be linearly or nonlinearly stabilized. The stabilization of the internal kink mode is related to the suppression of the sawteeth and the partial reconnection model in which the unstable internal kink mode is saturated at low amplitude; the shifted core plasma coexists with the $m = 1$ island (quasi)stationarily. The partial reconnection model is possible to explain the experimental results of $q_0 < 1$ after the sawtooth collapse if some physical model to explain the fast flattening of the density and temperature is introduced. So it is important to investigate the stabilization mechanism of the internal kink mode. There are many candidates for the stabilization of the internal kink mode such as the effects of the pressure gradients, energetic trapped ions, the flat current profile around the $q = 1$ magnetic surface, the sheared poloidal flow. Stabilization of the collisional internal kink mode by the sheared poloidal flow was studied by Kleva⁵⁾. Here we treat the collisionless case in which kinetic effects of electrons is responsible for the

destabilizing mechanism.

The linear stability analysis of the $m = 1$ and $n = 1$ kinetic internal kink mode with the sheared poloidal flow is performed by using the linearized version of GRM3D-2F based on the two-field and two-fluid gyro-reduced MHD code including the kinetic effects of electron inertia and the perturbed electron pressure gradients along the magnetic field⁶⁾. The numerical results verify that the unstable kinetic internal kink mode is stabilized by the sheared poloidal flow with the typical velocity being less than the poloidal Alfvén velocity. The stress due to the differential angular velocity of the flow, deforms the typical mode structure of the pure internal kink mode and hence has the stabilizing effect.

The parameter study for the different values of d_e (collisionless electron skin depth) with the fixed value of $\rho_s = 0$ (ion Larmor radius estimated by the electron temperature) shows that the smaller d_e case, which has the smaller growth rate, is stabilized by the smaller sheared poloidal flow. Note that the growth rate without the flow is proportional to d_e/L_x or d_e/a (a is a minor radius) for $d_e > \rho_s$. We recognize that the parameter study executed in the article is rather limited to the relatively large value of d_e/a because of the limitation of the computer resources, although $d_e/a \ll 1$. So further parameter study is needed to know whether this tendency can be extrapolated to the case of much smaller d_e/a corresponding to the tokamak experiment. When ρ_s is raised to be $\rho_s > d_e$ for the fixed value of d_e , the instability was stabilized by the smaller shear flow compared with the case of $\rho_s < d_e$, although the growth rate without the poloidal shear flow is larger for the case of $\rho_s > d_e$. Since d_e/a is extremely less than unity and $\rho_s > d_e$ for the existing and future experiments, it is possible that even the small sheared poloidal flow (i.e., the small radial electric field) may have dominant influences on the kinetic internal kink mode.

The study in the paper is limited to the linear mode analysis. The nonlinear simulation of the $m = 1$ and $n = 1$ kinetic internal kink mode with the sheared poloidal flow by using the nonlinear version of the GRM3D-2F is our forthcoming subject. Also, the comparison of the simulation results by the GRM3D-2F, GYR3D, and Hybrid3D codes will be reported in the near future.

Reference

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