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Excitation of MHD modes by coupling between resistive wall mode and stable eigenmodes in rotating tokamaks

回転トカマクプラズマ中における抵抗性壁モードと安定なMHDモードの
共鳴によるMHDモードの不安定化

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A mechanism exciting magnetohydrodynamic (MHD) instabilities in rotating tokamak plasmas is found numerically. This mechanism is the interplay between a resistive wall mode and a stable MHD mode. When the plasma has a stable discrete eigenmode, a reversed shear Alfven eigenmode for example, a MHD mode is destabilized when plasma equilibrium rotation frequency is similar to the frequency of this stable eigenmode in a static equilibrium. This destabilization is also observed even when the eigenmode couples with Alfven continua. This result suggests that for steady state high beta tokamaks, it is necessary to shape the safety factor profile in such a way that no stable eigenmode exists in the band of rotation frequency.

1. Introduction

In high beta tokamak plasmas, a resistive wall mode (RWM) sometimes becomes unstable, and it is well known that this RWM can be stabilized by plasma toroidal rotation. However, it is still difficult to accurately predict the rotation frequency required for stabilizing RWM robustly, though many important results have been obtained to realize this prediction for 20 years. In particular, the most critical problem is that RWM can sometimes become unstable even when rotation frequency is much faster than the threshold rotation frequency predicted based on the latest model for RWM stability. To realize a tokamak reactor with high beta, it is necessary to resolve this problem by understanding the mechanism destabilizing RWM in rotating plasmas. In cylindrical plasmas, it was confirmed that the interplay between RWM and a stable kink mode can destabilize RWM[1,2], and from this viewpoint, we investigate numerically whether or not this destabilizing mechanism can play a role in tokamak plasmas.

2. MHD instabilities excited by interplay between RWM and stable modes

At first, we confirm whether $n = 1$ RWM can be destabilized by coupling with a stable discrete eigenmode in tokamak plasmas, where n is the toroidal mode number. The analyzed equilibrium, whose magnetic surface is circular, aspect ratio is 3 and poloidal beta $\beta_p = 0.3$, has a flat safety factor profile as shown in Fig.1 (a), and in this equilibrium, reversed shear Alfven eigenmode (RSAE) and global Alfven eigenmode (GAE) exist near $\omega/\omega_{A0} = \pm 0.06$ and ± 0.22 when plasma compression is neglected. Here ω is the mode frequency and ω_{A0} is the Alfven frequency on magnetic axis. In addition, one of the stable external kink modes has real frequency $\omega/\omega_{A0} = \pm 0.11$ when $d/a = 1.2$. The shear Alfven spectrum shown in Fig.1 (a) supports the existence of these modes. We apply rigid toroidal rotation to this equilibrium, and analyze the RWM stability with the MINERVA/RWMaC code[3,4]. The result shown in Fig.1 (b) clearly shows that RWM is once stabilized by increasing rotation frequency up to $\Omega_{\phi 0} = 0.05\omega_{A0}$, but becomes unstable near $\Omega_{\phi 0} \simeq 0.06\omega_{A0}$, where $\Omega_{\phi 0}$ is the toroidal rotation frequency on axis. Such local maximum of the dependence of growth rate on $\Omega_{\phi 0}$ exists not only $\Omega_{\phi 0} \simeq 0.06\omega_{A0}$ but also

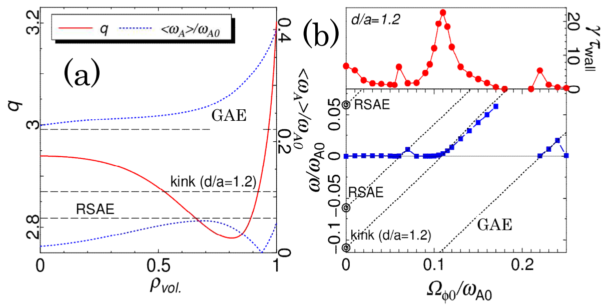

Fig.1 Circular equilibrium case. (a) Profiles of q and shear Alfven continua. (b) Dependence of growth rate γ and frequency ω on the rotation frequency $\Omega_{\phi 0}$.

$\simeq 0.11\omega_{A0}$ and $\simeq 0.22\omega_{A0}$, which are well identical to the frequencies of the RSA, the GAE and the external kink mode. In addition, the dependence of the mode frequency on $\Omega_{\phi 0}$ indicates that the destabilized mode is Doppler shifted when $\Omega_{\phi 0}$ increases and passes the eigenmode frequencies; the clearest result is obtained when $\Omega_{\phi 0}$ increases from $0.12\omega_{A0}$ to $0.16\omega_{A0}$. These features coincide with the MHD instability excited by interplay between RWM and a stable kink mode in cylindrical plasmas, and clarify for the first time that not only a kink mode but also Alfven eigenmodes can be the counterpart of this destabilizing mechanism in tokamak plasmas.

Based on this result, we analyze $n = 1$ RWM stability in the D-shaped high beta tokamak shown in Figs.2 (a) and (b). In this case, the rotation has shear and the profile is determined as $\Omega_\phi = \Omega_{\phi 0}(1-\psi^5)^2$ where ψ is the poloidal flux, and the impact of this rotation on RWM stability is analyzed in not only reversed shear plasma but also normal shear one. In both plasmas, $\beta_p = 1.2$ and the ideal kink ballooning mode is marginally stable when $d/a = 1.43$. The numerical result shown in Fig.3 clearly shows that RWM in the reversed shear plasma is once stabilized but is then destabilized when $\Omega_{\phi 0} \simeq 0.07\omega_{A0}$, though RWM in the normal shear plasma is smoothly stabilized when $\Omega_{\phi 0} \geq 0.04\omega_{A0}$ [5]. Note that the stability in this case is analyzed by taking into account plasma compression, and hence, the mode frequency of the destabilized mode in the reversed shear plasma is in shear Alfven and sound continuum spectra. The result of spectrum calculation shown in Fig.2 (b)

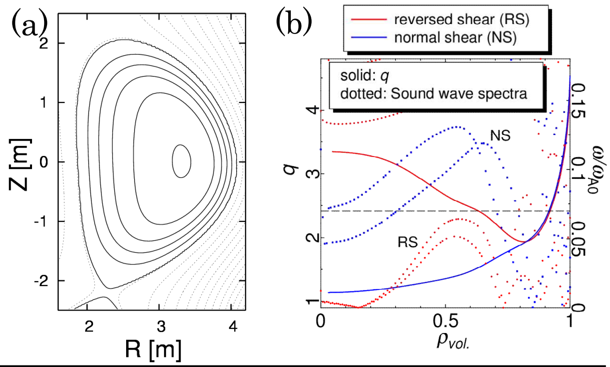

Fig.2 D-shaped equilibrium case with reversed shear (red) and normal shear (blue) safety factor profiles. (a)Contour of poloidal flux. (b) Profiles of q and spectra of MHD waves including plasma compression; the broken line shows $\omega/\omega_{A0} = 0.07$.

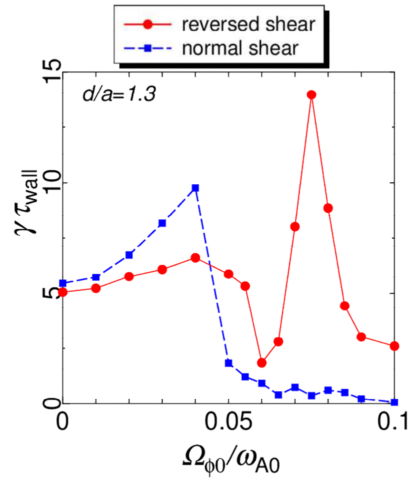

Fig.3 Dependence of the growth rate $\gamma\tau_w$ of RWM on rotation frequency on axis $\Omega_{\phi 0}/\omega_{A0}$ in D-shaped equilibrium.

implies that RSAE or a beta induced Alfven eigenmode can exist near $\omega = 0.07\omega_{A0}$. These results show that the eigenmode destabilized by the interplay between RWM and a stable MHD mode can be observed in a reactor-elevant tokamak plasma.

3. Summary

This study addresses numerically the mechanism exciting an MHD instability in tokamak plasmas which rotate toroidally enough fast to stabilize RWM, and finds for the first time that the interplay between RWM and a stable MHD mode plays a role for this destabilization. This progress of physics understanding suggests that the optimization of the safety factor profile that no stable eigenmodes exists in the band of rotation frequency is necessary to sustain high beta tokamak plasmas robustly stable in DEMO and future reactors.

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