Effect of Trapped Energetic Particles on the Resistive Wall Mode

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A stability analysis for the resistive wall mode is studied in the presence of trapped energetic particles (EPs). When the EPs’ beta exceeds a critical value, a fishbonelike bursting mode (FLM) with an external kink eigenstructure can exist. This offers the first analytic interpretation of the experimental observations [Phys. Rev. Lett. 103, 045001 (2009)]. The mode-particle resonances for the FLM and the \( q = 1 \) fishbone occur in different regimes of the precession frequency of EPs. In certain ranges of the plasma rotation speed and the EPs’ beta, a mode conversion can occur between the resistive wall mode and FLM.

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It is well-known that future advanced tokamak devices (AT) need to steadily operate in a rather high-\( \beta \) (\( \beta = 2 \mu_0 P/B^2 \), the ratio of the plasma pressure to the magnetic field pressure) region. However, the achievable maximum \( \beta \) is often limited by macroscopic MHD instabilities such as the external kink mode. The latter can be completely stabilized by a perfectly conducting wall located close enough to the plasma surface. In a realistic device, the wall has finite conductivity, which only helps to convert the fast growing kink mode to a slowly growing, the so-called resistive wall mode (RWM). The growth time of the RWM is comparable to a slowly growing, the so-called resistive wall conductivity, which only helps to convert the fast growing external kink mode. The latter can be completely stabilized is often limited by macroscopic MHD instabilities such as the minor radius, plasma current, and toroidal magnetic field, respectively; \( r, I \), and \( B \) being the radial variable and major radius, plasma current, and toroidal magnetic field, respectively. Early theories [1–3] have shown that the combination of the plasma flow and certain energy dissipation mechanisms, such as Landau damping, shear Alfvén damping, and classical viscosity, can fully suppress the RWM instability. Further investigations [4–7] have shown that the RWM can be suppressed by a very slow plasma rotation, when the drift kinetic damping, resulting from the resonant interaction between the magnetic precession motion of trapped thermal particles and the mode, is considered. The stabilizing effect of the trapped energetic particles (EPs) on the mode has also been investigated numerically [8–10]. In recent experiments, a fishbonelike bursting mode (FLM) is observed when the neutral beam injection is perpendicularly injected into the high-\( \beta \) plasmas [11,12]. At the same time, a marginally stable RWM is also observed. We mention that various names for this bursting mode have been proposed in the literature, such as “energetic-particle-driven wall mode (EWM)” in JT-60U [11] and “off-axis fishbone” [12] in DIII-D, respectively.

In this Letter, we explain the above experimental observations, based on an analytic calculation. We use an extended RWM dispersion relation including the contribution of the trapped EPs. We demonstrate that when the perpendicular beta of EPs exceeds a critical value, a FLM instability can be excited, together with the slowly growing RWM.

In what follows, the extended dispersion relation [4,13] of the RWM, neglecting the inertial term but taking into account the contribution of the trapped EPs, is written as

\[
D = -i \omega \tau_w^* + \frac{\delta W^\infty + \delta W_k + \delta W_{\text{MHD},b}}{\delta W^b + \delta W_k + \delta W_{\text{MHD},b}} = 0,
\]

where \( \omega = \omega_r + i \gamma \) is the eigenvalue of the RWM instability, with \( \omega_r \) and \( \gamma \) being the real frequency and the growth rate of the mode, respectively. \( \delta W^\infty \) and \( \delta W^b \) refer to the perturbed fluid potential energy without and with an ideal wall, respectively. The fluid potential energy includes both the plasma and vacuum contributions. \( \delta W_k \) and \( \delta W_{\text{MHD},b} \) denote the kinetic and fluid components, respectively, of the perturbed kinetic energy induced by the trapped EPs. The factor \( \tau_w = \mu_0 \sigma_b d(1 - a_{2m}/b_{2m})/(2m) \) is defined as the typical wall eddy current decay time, with \( a, b, d, m, \sigma, \) and \( \mu_0 \) being the plasma minor radius, the wall minor radius, the poloidal mode number, the wall conductivity, and the permeability of free space, respectively. We note that the fluid energy term (the adiabatic term), associated with EPs, explicitly appears in Eq. (1), but it is implicitly included in the total fluid energy in Refs. [4,13].

According to Refs. [14–16], the forms of \( \delta W_k \) and \( \delta W_{\text{MHD},b} \), in the presence of the plasma flow, can be written as

\[
\delta W_k = -2^{9/2} \pi^3 R_m \int B dr \int d\alpha \int dE K_b \frac{Q}{\omega - \omega_0 - \omega_d} J, \quad (2)
\]

\[
\delta W_{\text{MHD},b} = - \int d^3 x (\xi_\perp \cdot \nabla P_{h,1})(\xi_\perp \cdot \kappa), \quad (3)
\]

where \( \xi_\perp, \kappa = (b \cdot \nabla) b, P_{h,1}, \) and \( m_i \) are the perpendicular component of the plasma displacement, magnetic curvature, perpendicular component of the EPs’ pressure, and EP mass, respectively; \( r \) and \( R \) are the radial variable and major radius.