Stabilization of the resistive wall mode instability by trapped energetic particles

G. Z. Hao,1,a) Y. Q. Liu,2 A. K. Wang,1 H. B. Jiang,1 Gaimin Lu,1 H. D. He,1 and X. M. Qiu1

1Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China
2Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, United Kingdom

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A theoretical model for investigating the effect of the trapped energetic particles (EPs) on the resistive wall mode (RWM) instability is proposed. The results demonstrate that the trapped EPs have a dramatic stabilizing effect on the RWM because of resonant interaction between the mode and the magnetic precession drift motion of the trapped EPs. The results also show that the effect of the trapped EPs depends on the wall position. In addition, the stabilizing effect becomes stronger when the plasma rotation is taken into account. For sufficiently fast plasma rotation, the trapped EPs can lead to the complete stabilization of the RWM. Furthermore, the trapped EPs can induce a finite real frequency of the RWM in the absence of plasma rotation. © 2011 American Institute of Physics. [doi:10.1063/1.3569854]

I. INTRODUCTION

One of the major goals of the magnetic confinement devices is to produce high-$\beta$ (ratio of plasma to magnetic pressures) plasma at steady state. However, the maximum achievable $\beta$ is often restricted by macroscopic magnetohydrodynamic (MHD) instabilities, such as the external kink mode. The latter can be completely stabilized by a perfectly conducting wall placed close enough to the plasma edge. However, in reality, the wall with finite conductivity will convert the fast-growing kink mode to the slowly growing resistive wall mode (RWM) at the time scale of the wall eddy current decay time. The RWM is unstable in the high $\beta$ regime $\beta_{\text{wall}} < \beta_N < \beta_{\text{ideal}}$, where $\beta_{\text{wall}}$ and $\beta_{\text{ideal}}$ are the so-called normalized $\beta$ limits without and with an ideal wall, respectively, where $\beta_N$ is defined as $\beta_N = \beta[\%]a[\text{m}]B[\text{T}]/I[\text{MA}]$ with $a$, $I$, and $B$ being a plasma minor radius, current, and toroidal magnetic field, respectively.

Earlier theories1–4 have shown that the unstable RWM can be fully suppressed by a combination of the plasma toroidal rotation and an energy dissipation mechanism. The critical plasma rotation needed for full stabilization of the mode depends on the choice of the damping mechanism.5 It has been suggested that the critical plasma rotation frequency is a few percent of the Alfvén frequency at the $q=2$ rational surface.6,7 A strong viscous term modeling the Landau damping (sound wave resonance) was introduced into the MHD description,4 and possibly this term resulted in the critical rotation frequency comparable to the value of experimental observations.6–8

A damping model,9 including the kinetic contributions resulting from resonance of the mode with the bounce motion of thermal particles, has also been suggested. It was found that in some cases the predicted threshold value can be comparable to the experimental values.7,10–12 Recently, a kinetic damping model, including resonance between the mode with the magnetic precession drifts of the trapped thermal particles, for the RWM instability was suggested.13,14 This kinetic damping can lead to full stabilization of the RWM in the plasmas with very slow rotation or even without one. Ref. 15 found that the kinetic contribution of fusion born $\alpha$ particles generally led to better stabilization compared with the thermal particle kinetic contribution alone. Ref. 16 suggested that the stabilization of the EPs on the RWM is roughly proportional to the ratio of the trapped EPs beta to the plasma pressure, but nearly independent on the plasma rotation. Ref. 17 showed that a new instability with small growth rate can be excited when the trapped EPs were taken into account in the RWM dispersion relation. However, the effect of the trapped EPs on the RWM has not been fully resolved, and could be crucial for the future tokamak devices.18

The present paper focuses on the stabilization of the trapped EPs on the RWM instability. In Refs. 15 and 16, the kinetic contribution from the mode-particle resonance to the RWM dispersion relation was evaluated numerically. In contrast, this work presents the analytic formulation to express the perturbed energies terms in the extended RWM dispersion relation. It should be pointed out that this work neglects the finite orbit width (FOW) of the EPs. Normally the FOW effect tends to reduce the stabilizing effect.14 Therefore, in reality, we expect that the stabilizing effect on the RWM might be weaker than this theory prediction.

The dispersion relation of the RWM taking the trapped EPs into account are carried out in Sec. II. In Sec. III, the numerical results of the dispersion relation are presented and discussed in detail. Finally, Sec. IV is the conclusions and discussion.

II. DISPERSION RELATION

The extended dispersion relation of the RWM with the contribution of the trapped EPs, is obtained as

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*a)Electronic mail: haogz@swip.ac.cn.*