EFFECTS OF ZONAL FIELDS ON ENERGETIC-PARTICLE EXCITATIONS OF REVERSED-SHEAR ALFVÉN EIGENMODES

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1. BACKGROUND

The interaction between energetic particles (EPs) and Alfvén eigenmodes (AEs) is crucial for understanding the stability and transport properties of fusion plasmas in magnetic confinement devices like tokamaks. Among the various types of AEs, reversed-shear Alfvén eigenmodes (RSAEs) [1, 2] have attracted significant attention due to their complex interaction with EPs in reversed-shear configurations, which are essential for achieving self-sustained, steady-state operations necessary for continuous fusion reactions. Extensive previous simulations exploring the nonlinear behaviour of RSAEs [3–5] have demonstrated that zonal electromagnetic fields (ZFs) can be excited by RSAEs through beat-driven mechanisms, leading to a significant reduction in the RSAE saturation level. The suppression of RSAEs by ZFs can occur through two primary routes. The first route involves the nonlinear dynamics of thermal plasmas, such as shifts in the mode frequency or modifications to the local current and safety factor profiles, which enhance continuum damping [4, 6]. The second route involves the influence of ZFs on the dynamics and driving mechanisms of EPs, altering their interaction with RSAEs. While both routes have been explored, the underlying physical mechanisms remain poorly understood. This work focuses on elucidating the physics of second route, particularly in the context of the initial saturation phase of RSAEs, to provide a clearer understanding of how ZFs affect EP-driven RSAE saturation.

2. SIMULATION MODEL

We employ the gyrokinetic toroidal code (GTC) to simulate RSAE dynamics with the equilibrium and plasma profiles are selected from DIII-D discharge #159243 [7] at 805 ms, reproduced using the kinetic EFIT code [8]. The simulations are based on a reversed magnetic shear configuration with a minimal safety factor $q_{min} = 2.94$ near the major radius $R = 1.98$ m on the mid-plane for the low-field side, where RSAEs are typically observed. The GTC model includes gyrokinetic descriptions for both EPs and thermal ions, while electrons are treated using a drift kinetic model. The simulations are performed using a low-noise δf scheme to minimize numerical noise, with a radial domain spanning $R = [1.81, 2.23]$m and a global field-aligned mesh to resolve the long parallel wavelengths of RSAEs. In the GTC simulations, the gyro-center distribution function is given by

$$f = \frac{q}{m}\frac{\partial \mathrm{F}_0}{\partial \varepsilon}\left(1 - \mathrm{e}^{-\boldsymbol{\rho}\cdot\boldsymbol{\nabla}}\mathrm{J}_0\right)\delta\phi + \mathrm{e}^{-\boldsymbol{\rho}\cdot\boldsymbol{\nabla}} f_{\mathrm{g}}, \qquad (1)$$

where f_{g} satisfies the nonlinear gyro-center gyrokinetic equation [9]:

$$\left(\mathcal{L}_{\mathrm{g}0} + \delta\mathcal{L}_{\mathrm{x}} + \delta\mathcal{L}_{\varepsilon}\right) f_{\mathrm{g}}(\varepsilon, \mu, \mathrm{x}, t) = 0 \qquad (2)$$

Here, $\mathcal{L}_{\mathrm{g}0} = \partial_t + v_\parallel \mathbf{b_0}\cdot\boldsymbol{\nabla} + \boldsymbol{v_d}\cdot\boldsymbol{\nabla}$, $\delta\mathcal{L}_{\mathrm{x}} = \left\langle \delta\boldsymbol{U}_g \right\rangle\cdot\boldsymbol{\nabla}$, $\left\langle \delta\boldsymbol{U}_g \right\rangle = \frac{c}{B_0}\mathbf{b_0}\times\left\langle\left(\delta\phi - \frac{v_\parallel \delta A_\parallel}{c}\right)_g\right\rangle = \langle\delta\mathbf{U}_E\rangle + \frac{v_\parallel\langle\delta\mathbf{B_0}\rangle}{\mathrm{B}_0}$, $\delta\mathcal{L}_\varepsilon = \delta\dot{\varepsilon}\frac{\partial}{\partial\varepsilon}$, $\delta\dot{\varepsilon} = \frac{q}{m}\left[v_\parallel\left(b_0 + \frac{\langle\delta\mathbf{B}_\perp\rangle}{\mathrm{B}_0}\right)\cdot\langle\delta\boldsymbol{E}\rangle + \boldsymbol{v}_d\cdot\langle\delta\boldsymbol{E}\rangle\right]$. Besides, we consider only a single-n RSAE. To investigate the effects of ZFs on EP-driven RSAEs, we conduct three simulation cases: 1) Case A (No-ZFs): ZFs are excluded from the EP dynamics, while fully nonlinear thermal plasma dynamics are retained. 2) Case B (Full-ZFs): Both thermal plasma and EP dynamics include ZFs. Case C (Partial-ZFs): ZFs are included in the thermal plasma dynamics, but zonal shearing effects are removed from the EP dynamics.

3. RESULTS AND DISCUSSION

The simulations results, shown in figure 1, reveal that the inclusion of ZFs in the EP dynamics (Case B) leads to an unexpected increase in the RSAE saturation level, contrary to the conventional expectation that ZFs suppress instabilities. Case C, where zonal shearing effects are removed, shows a weak stabilizing effect, with results similar to Case A. These findings suggest that ZFs enhance the EP drive of RSAEs, leading to higher saturation levels.

To understand these simulation results theoretically, two key steps are required. First, it is necessary to establish theory-based for ZFs generation by RSAEs via beat-driven mechanisms. Second, using the gyrokinetic equation and the derived beat-driven ZFs to calculate the instability response. During the derivations, the framework of the general fishbone-like dispersion relation [10,11] and the concept of phase-space zonal structure [12] are adopted. The theoretical expressions for the beat-driven ZFs are given by [13]

$$\phi_z \simeq \frac{c}{B_0\omega_{0r}^2}(1+c_0\eta_i)\partial_r[k_{\theta0}\omega_{*in}|\delta\phi_0|^2] \quad (3)$$

$$\frac{A_{\|z}}{c} \simeq \frac{c}{B_0\omega_{0r}^2}\partial_r[k_{\theta0}k_{\|0}|\delta\psi_0|^2] \quad (4)$$

where c_0 is related to the Rosenbluth-Hinton neoclassical polarization due to the trapped ions and $c_0 = 1$ for $|k_\perp\rho_{bi}|^2 \ll 1$. To compare the analytical expressions with the simulation results, figure 2(a) shows the radial profile of the normalized $\delta\phi_z$ from the Full-ZFs Case B simulation at $t = 0.42$ ms (linear phase). The black dashed line represents the corresponding analytical curve according to equation (3) with $c_0 = 1$. Similar curves for $\delta A_{\|z}$ with equation (4) along with $\delta\psi_0$ are plotted in figure 2(b). The analytical and simulation results are in excellent agreement for both zonal fields.

The simulation results indicate that ZFs, which are beat-driven by RSAEs, play a significant role in modifying the EP phase-space structures (PSZS). In Case B (Full-ZFs), the RSAE saturation level is higher than in Case A (No-ZFs), indicating that ZFs enhance the EP drive. Analytical theory supports this observation by showing that ZFs induce different EP PSZS in each case, which either enhance or reduce the EP drive. The derived analytical expressions for ZFs beat-driven by RSAEs are in good agreement with the simulation results, validating the theoretical and simulation model. However, the current results indicate that the suppression of RSAE is not primarily due to the effects of ZFs on EPs, i.e. not via the second route. Instead, ZFs suppress RSAE mainly through the nonlinear physics of thermal plasma, i.e. the first route. This topic is currently under investigation.

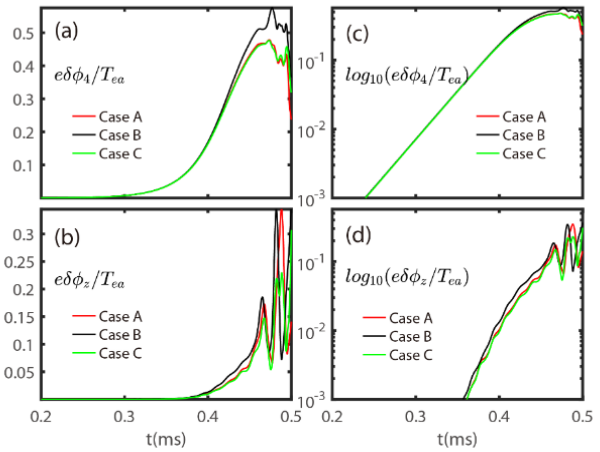

Figure 1 Time history of the RSAE scalar potential $\delta\phi_4$ and zonal scalar potential $\delta\phi_z$ for Cases A, B, and C. The plots show the evolution of the mode amplitude and the growth of ZFs during the linear and nonlinear phases of the simulation.

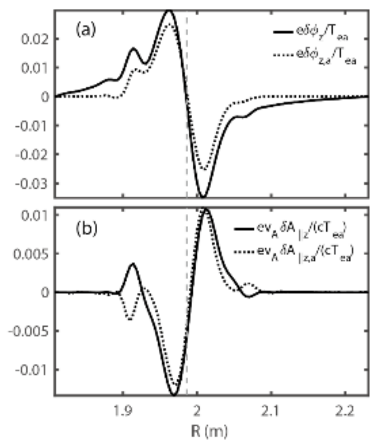

Figure 2 Radial profiles of the normalized zonal scalar potential $\delta\phi_z$ and zonal parallel vector potential $\delta A_{\|z}$ from simulations and analytical theory.

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