Nonlinear evolutions of energetic particle modes in tokamak plasmas with reversed magnetic shear configuration

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In this paper, the effects of energetic particles (EPs) on MHD instabilities has been investigated using CLT-K code [1]. So far, the investigation of energetic particles modes (EPMs) has been limited to the theoretical analysis and linear simulation [2-3]. The role of nonlinear evolution of EPMs has not been considered. Once the EP beta is larger than a critical value, a global EPM can be excited with high mode frequencies [4-5]. In this work, the linear and nonlinear results of EPMs are shown in tokamak plasmas with reversed magnetic shear configuration.

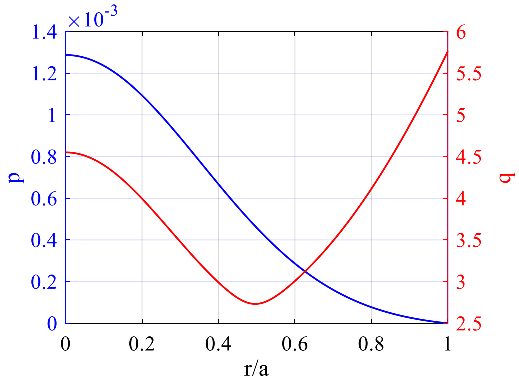

Figure 1. The profiles of safety factor(q) and plasma pressure (p) .

To study the effect of EPs on the mode, we employ an equilibrium without flows and the function of the safety factor is $q(r) = q_0 + q_c \left\{1+(\frac{r}{r_0})^{2\lambda}\right\}^{1/\lambda}\left[1+A\cdot\exp\left\{-\left(\frac{r-r_d}{\delta}\right)^2\right\}\right]$, where q_c=1.2 is the safety factor at the magnetic axis, constant values of q_0=0.95, λ=10, r_0=0.5, δ=0.39, r_d=0, and A=2. The safety factor profile q and plasma pressure profile p are shown in figure 1.

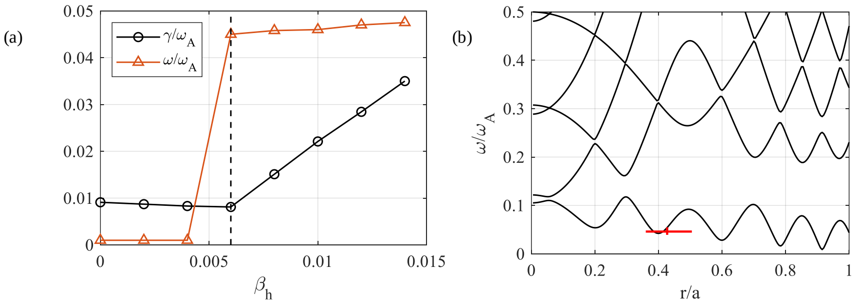

Figure 2. (a) The growth rate and mode frequency against β_h and *(b) Alfvén continuum spectra of n = 1.*

The growth rates as a function of β_h are shown in Figure 2(a). In the low β_h cases, the growth rate of DTMs decreases with increasing β_h. This indicates that EPs have a stabilizing effect on DTM, which is similar to the result of resistive tearing modes. When β_h is large enough than the threshold value, the growth rate increases with increasing β_h, meanwhile, the mode frequency increases rapidly. Then a new mode could be driven by EPs, the mode structure should be different from that of DTMs. In order to examine the type of mode in the high β_h, we show the Alfvén continuum spectrum of toroidal mode number n = 1 in figure 2(b), which is calculated by the NOVA code. Here, it can be found that the mode with its normalized frequency ω=0.046 marked by the red cross line can lie in the Alfvén continuum and the location of the largest mode amplitude of radial perturbed velocity v_r with β_h =0.01 is almost at r~0.43, which is consistent with that in figure3(d). And the location of the unstable mode is defined by the region where the intensity of the cosine part of the m/n = 3/1 harmonic is larger than 90% of the peak value. We can find the EPM is excited by the strong EP drive with lying into the Alfvén continuum.

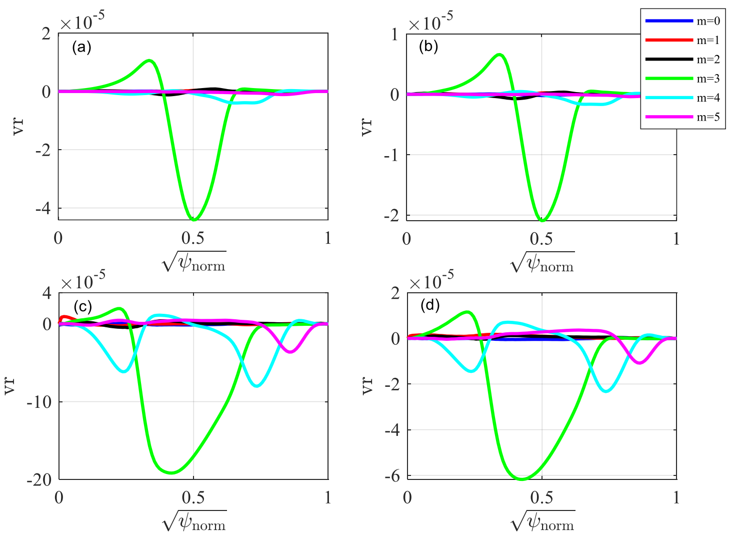

Figure 3. The mode structure with (a) β_h =0, (b) β_h =0.004, (c) β_h =0.008 and (d) β_h =0.01.

To show the mode structure changed by EPs, we plot the radial perturbed velocity in figure 3. In theory, the radial displacement of DTMs, ξ, is usually assumed to be a "top-hat" shape as similar to figure 3(a) and figure 3(b) due to the singularity of $d\xi/dr$ near dual 3/1 rational surfaces. In the presence of strong EPs, however, the mode structure is modified near the rational surfaces. A possible reason is that the finite mode frequency changes the local resonance condition. For β_h =0.008 and β_h =0.01, the EPMs, with wider mode structure, are different from the DTMs. When β_h is large enough, high-*m* modes can be driven, such as m=4 and 5, and lead to an enhancement of the mode coupling.

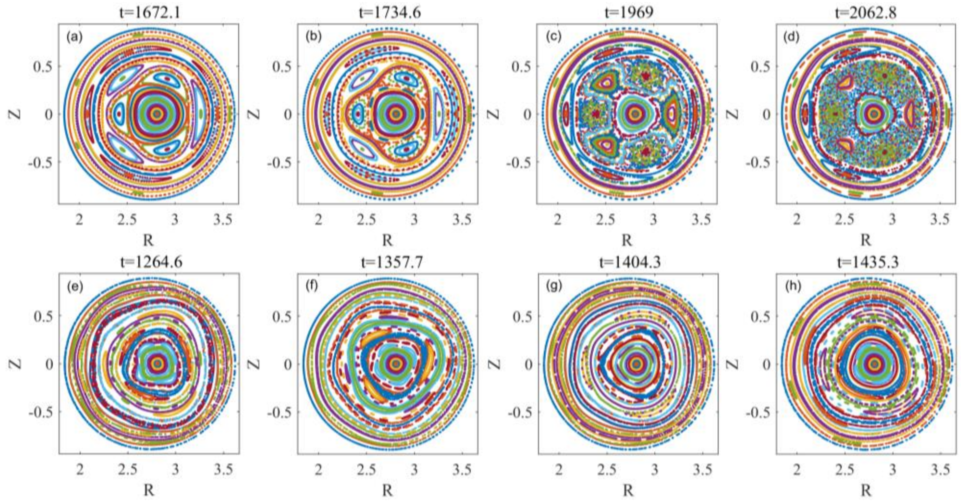

Figure 4. Poincaré plot of magnetic field lines with β_h =0 *(Top) and with* β_h =0.01 *(Bottom).*

Poincaré plot is usually method to describe the nonlinear evolution of magnetic islands and show a mode coupling directly. As we can see in figure 4, the DTM without EPs undergoes an overlap of dual 3/1 rational surfaces due to strong nonlinear coupling. As a comparison, when the value of β_h is high, β_h =0.01, good magnetic flux surfaces are kept even in the nonlinear stage. It means that the EPMs appear like an ideal MHD mode rather than a resistive mode.

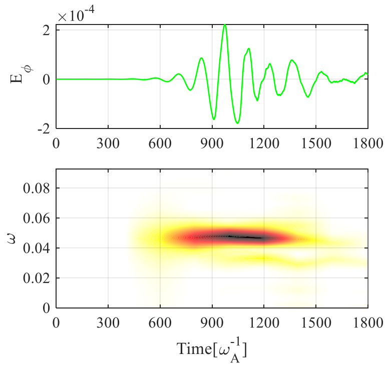

Figure 5. Time evolution of frequency spectrum of the toroidal electric field for β_h =0.01.

In order to further clarify the type of mode with the high EP driven, we performed nonlinear simulations of the toroidal perturbed electric field E_ϕ and show the time evolution of mode frequency for β_h =0.01 in figure 5. It is interesting to note that frequency is basically constant and ω~0.046 normalized by Alfvén frequency.

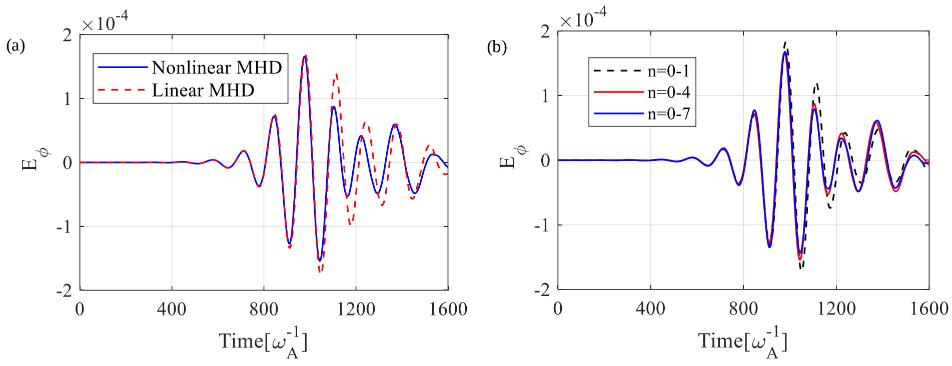

Figure 6. Comparison of toroidal electric field evolution for β_h =0.01 .

To understand dynamic process during the period of existence of high β_h , we further examine the β_h =0.01 case in detail. The evolution of the m/n=3/1 harmonics of the E_ϕ is compared in figure 6(a) for linear and nonlinear MHD simulation. A significant reduction in the saturation level can be seen for the nonlinear MHD run here. The MHD nonlinearity effects reduce the EPM saturation level by ~40% of the linear case when it reaches E_ϕ~1.4× 10^{-4} . For cases where the instability growth is lower (not shown here), the MHD nonlinearity does not play any important role. Then the saturation mechanism is dominated by the particle nonlinear dynamics, i.e. the particle trapping by the EP mode causes the saturation. In the time evolution of the EPM, the nonlinear terms in the MHD equations generate the fluctuations with toroidal mode numbers multiples of n(n=0,1,2...). It is interesting to investigate which toroidal mode number is important for the EPM saturation level reduction. We conducted three types of nonlinear MHD simulations in figure 6(b). In the first type, only the n=0-1 modes are retained while the high-*n*(n=2-7) modes are removed artificially. In the second type, the n=0-4 modes are retained while the high-*n*(n=5-7) modes are removed artificially. In the last type, all toroidal modes(n=0-7) are retained. With our spatial resolution in the toroidal direction, the maximal toroidal mode number n=7 is chosen, the mode numbers in the multiple mode simulation is n=0, 1, ..., 7. We can see that coupling between n=0 and n=1 dominates the saturation level of the EPM, while high-*n* harmonics have weak effects.

Acknowledgments

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