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Gyrokinetic theory of toroidal Alfven eigenmodes nonlinear saturation via ion induced scattering

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Shear Alfven wave (SAW) instabilities and energetic particle (EP) related physics are expected to play important roles in magnetic confined fusion devices as EP contribute significantly to the total power density [1,2]. SAWs are often excited as Alfven eigenmodes due to periodicity of the device, such as toroidal Alfven eigenmodes (TAEs), and their kinetic counter-parts, e.g., kinetic TAEs (kTAE).

In burning plasmas of future reactors with EP characteristic orbit width much smaller than the minor radius, TAEs are characterized by toroidal mode numbers $n \sim 10$. As a result, many TAEs coexist and nonlinear mode couplings such as ion induced scattering, are expected to play important role in TAE nonlinear saturation and thus, qualitative and quantitative understanding of EP confinement in future reactors. The condition for TAE saturation via ion induced scattering is favored in burning plasmas, since 1. there are many ($\sim O(n^2 q)$) TAEs with radially overlapping mode structures, 2. TAE frequency is weakly dependent of toroidal mode number and can be roughly estimated by $\omega \sim V_A/(2qR_0)$ with the frequency deviation being $\sim O(\epsilon_0 \omega)$, and 3. TAEs are characterized by finite parallel wavenumber $|k_\parallel| \simeq 1/(2qR_0)$ in the radially fast varying inertial layer where nonlinear coupling dominates [2,3]. The scattering process is sensitively dependent on plasma beta, as addressed in Ref. [4], and we focus on the high beta limit, which is relatively less explored in literatures.

In the high beta limit with $\beta \gg \epsilon_0^2$, a pump TAE decays into a propagating lower kTAE (LKTAE) in the SAW continuum and an ion sound wave (ISW) daughter wave, which are then dissipated due to electron and ion Landau damping, leading to thermal electron and fuel ion heating, respectively. The stability of the nonlinear decay process is investigated, which is shown to be competitive in saturating TAE. The parameter regime for the process to occur is analyzed, and the saturation level of TAE and the secondary waves are derived, which are used to quantitatively estimate the corresponding TAE induced EP transport level as well as thermal plasma heating rates.

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