Nonlinear saturation of toroidal Alfvén eigenmode via ion induced scattering in nonuniform plasmas

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In magnetically confined fusion plasmas, shear Alfvén waves (SAWs) can be resonantly excited by energetic particles (EPs), and in turn, induce EP anomalous transport loss across magnetic surfaces, resulting in plasma performance degradation and possibly damage of plasma facing components [1]. With the EP anomalous transport rate determined by the amplitude and spectrum of the SAW instabilities, it is thus, of particular interest to investigate the nonlinear evolution and saturation process of SAW instabilities in realistic reactor geometry, with plasma nonuniformities properly accounted for.

In this work, taking the well-known Toroidal Alfvén eigenmode [1] (TAE) as paradigm, the nonlinear saturation of TAE via ion induced scattering is investigated in the burning plasma relevant short wavelength ($k_\perp^2\rho_i^2 > \omega_0/\Omega_i$) regime [1,2,3], with particular attention to the role of plasma nonuniformities in determining both qualitatively and quantitatively the saturation level of TAE [4,5]. Here, $k_\perp$ is the perpendicular wavenumber, $\rho_i = v_i/\Omega_i$ is the ion gyroradius with v_i being the ion thermal velocity and Ω_i the ion cyclotron frequency. Specifically, our theory includes 1) nonlinear parametric decay of TAE via ion induced scattering, where the conditions for spontaneous decay is discussed [4]; and 2) nonlinear equation describing the resulting TAE spectral energy evolution is derived and solved, yielding the saturated spectrum of TAE in nonuniform plasmas. The nonlinear saturation levels of TAEs induced electromagnetic perturbation are derived from first-principle-based theory, allowing us to estimate the consequences on EP transport and potentially induced intrinsic rotation.

In the first part of this work, we investigate the parametric decay of TAE via nonlinear ion induced scattering in nonuniform plasmas. The nonlinear coupling process was originally investigated in Ref. [2] in the long wavelength MHD limit, and was extended to the burning plasma relevant short wavelength regime [3], with the new ingredients associated with plasma nonuniformity included here [4], which is shown to both qualitatively and quantitatively modify the scattering process. It is found that, the nonuniformity associated with bulk plasma density gradient will significantly enhance the ion induced scattering, and changing the condition for spontaneous decay from decaying into lower frequency TAE sideband, to decaying into TAE sidebands with higher-n.

In the second part, by summing up all the background TAEs within strong interaction region, the equation describing a test TAE nonlinear evolution due to the interaction with the bath of background TAEs is derived, which is then applied to deriving the equation for the TAE spectrum evolution in the continuum limit. The fluctuation amplitude evolution equation is solved to obtain the saturation spectrum of TAE, yielding an overall fluctuation level much lower than that predicted by Refs. [2,3] as a consequence of the further enhanced nonlinear couplings due to plasma nonuniformity. The associated EP transport coefficient is derived and estimated correspondingly, yielding a more realistic scaling law for fusion alpha particle transport in future reactors. The implication on plasma intrinsic rotation is also discussed [5].

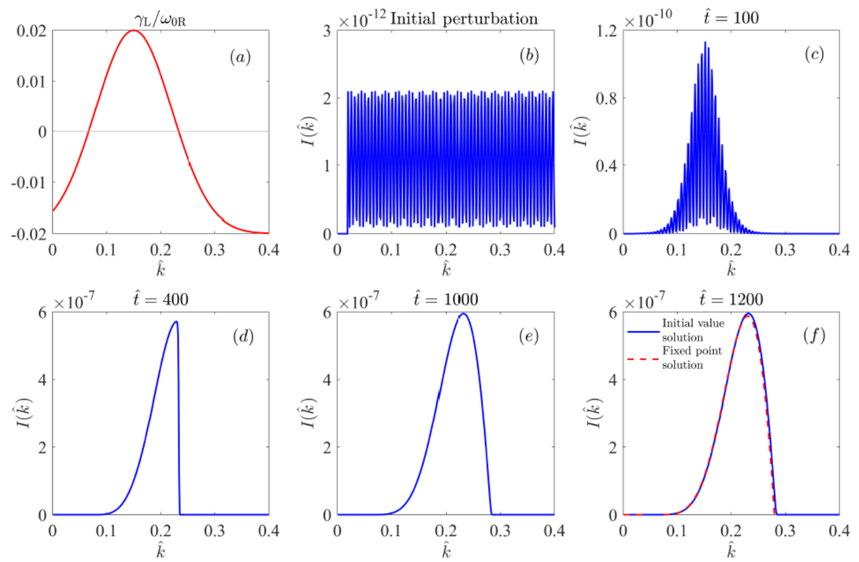

Fig. 1: TAE spectral evolution due to ion enhanced scattering, with the horizontal axis being the normalized toroidal mode number, Fig. (a) being a typical linear growth rate, and Figs (b-f) being the temporal evolution of the TAE spectrum.

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