Contribution ID: **634** Type: **Regular Poster**

Nonlinear saturation and energetic particle transport by toroidal Alfvén eigenmodes

Tuesday 11 May 2021 12:10 (20 minutes)

Energetic particles (EPs) including fusion-alpha particles related physics are expected to play important roles in magnetic confinement fusion devices as EPs contribute significantly to the total power density [1,2]. In particular, two important aspects are heating of thermal plasmas and excitation of symmetry breaking collective modes, e.g., shear Alfvén wave (SAW) instabilities. SAWs could be excited by EPs via resonant wave-particle interactions; and in turn, induce EP transport and degrade overall plasma confinement. Toroidal Alfvén eigenmode (TAE) can be excited inside the toroidicity induced SAW continuum frequency gap to minimize continuum damping [3-5], and is considered to be one of the most dangerous candidates for effectively scattering EPs and limit their good confinement. In this work, we present the theory for TAE nonlinear saturation in the burning plasma relevant short wavelength ($k_{\perp}^2 {}_i^2 > \omega_0/{}_i$) regime [6,7]. Here, $k_{\perp}$ is the perpendicular wavenumber, ${}_i = v_i/{}_i$ is the ion gyroradius with v_i being the ion thermal velocity and ${}_i$ the ion cyclotron frequency. Specifically, two individual processes are presented, including 1) parametric decay of pump TAE into geodesic acoustic mode (GAM) and lower frequency sideband with the same toroidal/poloidal mode numbers as the pump TAE [8,9], and 2) TAE spectral cascading and enhanced coupling to SAW continuum via ion induced scattering [10,11]. The nonlinear saturation levels of TAEs are derived from first principle-based theory. The consequent plasma heating and EP transport rates are quantitatively estimated, as well as their scaling law dependence of the individual saturation processes. The parameter regimes for the two processes to occur and dominate are also discussed.

TAE decaying into a GAM and a lower frequency daughter wave with the same toroidal/poloidal mode number as the pump TAE is investigated as a possible channel for TAE nonlinear saturation, which also contributes to the channeling of EP/fusion-α power density to bulk thermal plasma heating [8,9]. It is found that the nonlinear decay process depends on the thermal ion ${}_i$ value. Here, ${}_i$ is the plasma thermal to magnetic pressure ratio. In the low-${}_i$ limit, a TAE decays into a GAM and a lower TAE sideband in the toroidicity induced SAW continuous spectrum gap; while in the high-${}_i$ limit, a TAE decays into a GAM and a propagating lower kinetic TAE (LKTAE) in the continuum. The generated LKTAE and GAM would be dissipated by electron and ion Landau damping, respectively, contributing to anomalous α-particle slowing down and channeling of α-particle energy to thermal ions. In both low- and high-${}_i$ limits, the estimates of saturation levels of pump TAE, lower frequency daughter wave and GAM amplitudes are obtained from the fixed-point solution of the coupled nonlinear equations, and the power transfers to ion and electron heating are derived. The possibility of more complicated, perhaps, more realistic nonlinear behaviors will be addressed. The nonlinearly generated GAM, as the finite frequency zonal flow, also contributes to regulating DW turbulence and consequently, improved confinement.

The TAE spectral downward cascading via nonlinear ion induced scattering and saturation due to enhanced coupling to SAW continuum, originally investigated in Ref. [10] in the long wavelength MHD limit, is extended to the burning plasma relevant short wavelength regime [11]. The equation describing a test TAE nonlinear evolution due to interacting with the bath of background TAEs, is derived using gyrokinetic theory, which is then applied to deriving the wave-kinetic equation for the TAE spectral evolution in the continuum limit. The wave-kinetic equation is solved to obtain the saturated spectrum of TAE, yielding an overall fluctuation level much lower than that predicted by Ref. [8], as a consequence of the enhanced nonlinear couplings in the short wavelength regime. The associated EP transport coefficient is also derived and evaluated correspondingly.

Our theory shows that, for TAE saturation in the parameter regime of practical interest, several processes with comparable scattering cross sections can be equally important. The self-consistent theory for the nonlinear envelope evolution, simultaneously accounting for the dominant processes, is thus needed for the quantitative prediction of EP confinement and reactor performance.

This work is supported by the National Key R&D Program of China under Grant No. 2017YFE0301900, and the EUROfusion Consortium under grant agreement No.633053.

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Country or International Organization

China

Affiliation

Zhejiang University

Author: QIU, Zhiyong (Zhejiang University)

Co-authors: CHEN, LIU (ZHEJIANG UNIVERSITY); ZONCA, Fulvio (Associazione EURATOM-ENEA sulla Fusione)

Presenter: QIU, Zhiyong (Zhejiang University)

Session Classification: P1 Posters 1

Track Classification: Magnetic Fusion Theory and Modelling