The dynamics of Alfvén eigenmodes excited by energetic ions in toroidal plasmas

EMMI THOLERUS

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Abstract

The future fusion power plants that are based on magnetic confinement will deal with plasmas that inevitably contain energetic (non-thermal) particles. These particles come, for instance, from fusion reactions or from external heating of the plasma. Ensembles of energetic ions can excite eigenmodes in the Alfvén frequency range to such an extent that the resulting wave fields redistribute the energetic ions, and potentially eject them from the plasma. The redistribution of ions may cause a substantial reduction of heating efficiency. Understanding the dynamics of such instabilities is necessary to optimise the operation of fusion experiments and of future fusion power plants.

Two models have been developed to simulate the interaction between energetic ions and Alfvén eigenmodes. One is a bump-on-tail model, of which two versions have been developed: one fully nonlinear and one quasilinear. The quasilinear version has a lower dimensionality of particle phase space than the nonlinear one. Unlike previous similar studies, the bump-on-tail model contains a decorrelation of the wave–particle phase in order to model stochasticity of the system. When the characteristic time scale for macroscopic phase decorrelation is similar to or shorter than the time scale of nonlinear wave–particle dynamics, the nonlinear and the quasilinear descriptions quantitatively agree. A finite phase decorrelation changes the growth rate and the saturation amplitude of the wave mode in systems with an inverted energy distribution around the wave–particle resonance. Analytical expressions for the correction of the growth rate and the saturation amplitude have been derived, which agree well with numerical simulations. A relatively weak phase decorrelation also diminishes frequency chirping events of the eigenmode.

The second model is called FOXTAIL, and it has a wider regime of validity than the bump-on-tail model. FOXTAIL is able to simulate systems with multiple eigenmodes, and it includes effects of different individual particle orbits relative to the wave fields. Simulations with FOXTAIL and the nonlinear bump-on-tail model have been compared in order to determine the regimes of validity of the bump-on-tail model quantitatively. Studies of two-mode scenarios confirmed the expected consequences of a fulfillment of the Chirikov criterion for resonance overlap. The influence of ICRH on the eigenmode–energetic ion system has also been studied, showing qualitatively similar effects as seen by the presence of phase decorrelation.

Another model, describing the efficiency of fast wave current drive, has been developed in order to study the influence of passive components close to the antenna, in which currents can be induced by the antenna generated wave field. It was found that the directivity of the launched wave, averaged over model parameters, was lowered by the presence of passive components in general, except for low values of the single pass damping of the wave, where the directivity was slightly increased, but reversed in the toroidal direction.

Descriptors
Fusion plasma physics, tokamak, wave–particle interactions, TAEs, bump-on-tail instabilities, magnetohydrodynamics, nonlinear dynamics, quasilinear dynamics, Hamiltonian mechanics, Monte Carlo method, ICRH, FWCD.

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