FINAL TECHNICAL REPORT

Grant Title: Theoretical Studies of Alfven Waves and Energetic Particle Physics in Fusion Plasmas

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The followings summarize major research accomplishments.

Part A: Linear Physics

1.Theory on excitations of drift Alfven waves by energetic particles. I. Variational formulation

DOI: 10.1063/1.4889019

A unified theoretical framework is presented for analyzing various branches of drift Alfven waves and describing their linear and nonlinear behaviors, covering a wide range of spatial and temporal scales. Nonlinear gyrokinetic quasineutrality condition and vorticity equation, derived for drift Alfven waves excited by energetic particles in fusion plasmas, are cast in integral form, which is generally variational in the linear limit; and the corresponding gyrokinetic energy principle is obtained. Well known forms of the kinetic energy principle are readily recovered from this general formulation. Furthermore, it is possible to demonstrate that the general fishbone like dispersion relation, obtained within the present theoretical framework, provides a unified description of drift Alfven waves excited by energetic particles as either Alfven eigenmodes or energetic particle modes. The advantage of the present approach stands in its capability of extracting underlying linear and nonlinear physics as well as spatial and temporal scales of the considered fluctuation spectrum. For these reasons, this unified theoretical framework can help understanding experimental observations as well as numerical simulation and analytic results with different levels of approximation. Examples and applications are given in the following paper.

2.Theory on excitations of drift Alfven waves by energetic particles. II. The general fishbone-like dispersion relation

DOI: 10.1063/1.4889077

The theoretical framework of the general fishbone-like dispersion relation (GFLDR), presented and discussed in the preceding paper is applied to cases of practical interest of shear/drift Alfven waves (SAWs/DAWs) excited by energetic particles (EPs) in toroidal fusion plasmas. These applications demonstrate that the GFLDR provides a unified approach that allows analytical and numerical calculations of stability properties, as well as mode structures and, in general, nonlinear evolutions, based on different models and with different levels of approximation. They also show the crucial importance of kinetic descriptions, accurate geometries and boundary conditions for predicting linear as well as nonlinear SAW/DAW and EP behaviors in burning plasmas. Thus, the GFLDR unified theoretical framework elevates the interpretative capability for both experimental and numerical simulation results.

3.Global theory of beta-induced Alfven eigenmode excited by energetic ions

DOI: 10.1063/1.4929849

The two-dimensional global stability and mode structures of high-n beta-induced Alfven eigenmodes excited by energetic ions in tokamaks are examined both analytically and numerically, employing the WKB-ballooning mode representation along with the generalized fishbone like dispersion relation. Here, $n \gg 1$ is the toroidal mode number. Our results indicate that (i) the lowest radial bound state corresponds to the most unstable eigenmode, and (ii) the anti-Hermitian contributions due to wave-energetic particle resonance give rise to the twisting radial mode structures.

4.On energetic-particle excitations of low-frequency Alfven eigenmodes in toroidal plasma

DOI: 10.1063/1.4993056

It is well-known that, within the ideal magnetohydrodynamic (MHD) description, there exist two low-frequency Alfven continuous spectra in toroidal plasma devices, such as tokamaks. The corresponding three accumulation frequencies are the beta-induced Alfven eigenmode (BAE) frequency, the ion-sound wave (ISW) frequency, and the zero frequency accumulation point at vanishing parallel wave number, k(parallel to) = 0. To form localized discrete eigenmodes, the plasma with a normal magnetic shear must be ideal MHD unstable. The zero-frequency branch then corresponds to the ideal MHD unstable discrete mode, while the BAE and ISW discrete eigenmode frequencies could be significantly shifted away from the respective accumulation frequencies. Energetic-particle (EP) effects can be analyzed and understood as an effective potential well via the generalized fishbone linear dispersion relation. In particular, it is demonstrated that, for an ideal MHD stable plasma, EPs could play the roles of both discretization and destabilization, and their effect is generally non-perturbative. The theoretical results further predict that EPs preferentially excite the BAE branch over the ISW branch. The zero-frequency branch, meanwhile, becomes the well-known fishbone dispersion relation, giving rise to energetic-particle modes. Extensions to the case of reversed magnetic shear as well as the kinetic effects will also be discussed.

Part B. Nonlinear Physics

1.Spontaneous excitation of convective cells by kinetic Alfven waves

DOI: 10.1209/0295-5075/112/65001

Spontaneous excitation of convective cells by kinetic Alfven waves in a uniform plasma is investigated analytically employing the nonlinear gyrokinetic equations. Self-consistent theoretical analysis demonstrates the novel results that excitation via modulational instability can only occur when the finite ion Larmor radius effects are properly included, and, furthermore, both the electrostatic and magnetostatic convective cells are excited simultaneously. Theoretical predictions are verified with direct numerical simulations; showing excellent agreement in the modulational growth rate and field structures. Significant implications of the present results to the cross-field transport in space and fusion plasmas are also briefly discussed.

2.Effects of energetic particles on zonal flow generation by toroidal Alfven eigenmode

DOI: 10.1063/1.4962997

Generation of zonal flow (ZF) by energetic particle (EP) driven toroidal Alfven eigenmode (TAE) is investigated using nonlinear gyrokinetic theory. It is found that nonlinear resonant EP contribution dominates over the usual Reynolds and Maxwell stresses due to thermal plasma nonlinear response. ZF can be forced driven in the linear growth stage of TAE, with the growth rate being twice the TAE growth rate. The ZF generation mechanism is shown to be related to polarization induced by resonant

EP nonlinearity. The generated ZF has both the usual meso-scale and micro-scale radial structures. Possible consequences of this forced driven ZF on the nonlinear dynamics of TAE are also discussed.

3.Fine structure zonal flow excitation by beta-induced Alfven eigenmode

DOI: 10.1088/0029-5515/56/10/106013

Nonlinear excitation of low frequency zonal structure (LFZS) by beta-induced Alfven eigenmode (BAE) is investigated using nonlinear gyrokinetic theory. It is found that electrostatic zonal flow (ZF), rather than zonal current, is preferentially excited by finite amplitude BAE. In addition to the well-known meso-scale radial envelope structure, ZF is also found to exhibit fine radial structure due to the localization of BAE with respect to mode rational surfaces. Specifically, the zonal electric field has an even mode structure at the rational surface where radial envelope peaks.

4.Physics of Alfven waves and energetic particles in burning plasmas

DOI: 10.1103/RevModPhys.88.015008

Dynamics of shear Alfven waves and energetic particles are crucial to the performance of burning fusion plasmas. This article reviews linear as well as nonlinear physics of shear Alfven waves and their self-consistent interaction with energetic particles in tokamak fusion devices. More specifically, the review on the linear physics deals with wave spectral properties and collective excitations by energetic particles via wave-particle resonances. The nonlinear physics deals with nonlinear wave-wave interactions as well as nonlinear wave-energetic particle interactions. Both linear as well as nonlinear physics demonstrate the qualitatively important roles played by realistic equilibrium nonuniformities, magnetic field geometries, and the specific radial mode structures in determining the instability evolution, saturation, and, ultimately, energetic-particle transport. These topics are presented within a single unified theoretical framework, where experimental observations and numerical simulation results are referred to elucidate concepts and physics processes.

5.Nonlinear excitation of finite-radial-scale zonal structures by toroidal Alfven eigenmode

DOI: 10.1088/1741-4326/aa6413

The set of equations describing nonlinear evolution of a single toroidal Alfven eigenmode are derived, including both zero frequency zonal structure (ZFZS) generation and wave-particle phase space nonlinearities. The simplified case of neglecting wave-particle phase space nonlinearity is then investigated to focus on different roles of energetic particles and bulk plasmas on ZFZS generation. It is shown that energetic particles and bulk plasma play dominant roles in ZFZS generation in different nonlinear stages, and the corresponding processes are qualitatively different. Several properties of ZFZS generation, e.g. fine-versus meso-scale, forced driven versus spontaneous excitation, are clarified by the present analysis.