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Nonlinear Dynamics of Frequency Oscillation of Alfvén Eigenmodes in Toroidal Plasmas

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Energetic particles, including energetic ions and electrons produced by the fusion reaction and auxiliary heating, can excite various Alfv\'en instabilities in magnetic confinement fusion plasma such as ITER, which may induce significant transport of energetic particles and degrade the overall plasma confinement. Increased energetic particle transport enhanced by Alfv\'en eigenmodes has been correlated with a fast frequency oscillation (chirping) with a sub-millisecond period, which has been observed in many experiments. In previous theoretical studies, Thomas O'Neil [T. M. O'Neil, J. Winfrey, and J. Malmberg, Phys. Fluids 14, 1204 (1971)] analytically solves an one-dimensional (1D) chirping case of the beam plasma. And an analytic model for the chirping based on the 1D nonlinear wave-particle with sources and sinks has been constructed by Berk and Breizman (BB) [H. L. Berk, B. N. Breizman, and H. Ye, Phy. Rev. Lett. 68, 3563 (1992)]. Some numerical computation results based on the BB model show the directional frequency chirping. Some simulations based on simple reduced models with fixed mode structure are carried on to investigate the chirping phenomenon. A single burst of chirping has been observed in hybrid magnetohydrodynamic simulations with sources and sinks. Repetitive frequency chirping has been observed by first-principle kinetic simulations without source and sinks. Furthermore, the interaction of energetic particles such as cosmic rays with Alfv\'en turbulence is an important issue in space and astrophysical plasmas.

Here we demonstrate a novel model to reveal the physics for the dynamics of fast and repetitive frequency chirping of Alfv\'en eigenmodes excited by energetic particles without sources and sinks in the toroidal geometry, which is verified and validated by the massively parallel, first-principle kinetic simulations.

In this work, fast and repetitive frequency chirping of beta-induced Alfv\'en eigenmodes (BAE) excited by energetic electrons in the fusion plasmas was observed and analyzed by massively parallel gyrokinetic particles simulations, where the energetic particles are found responsible for such chirpings. It is further discovered that the evolution of the phase-space structure of energetic electrons are consistent with the excitation and suppression processes accompanied by repetitive down-chirping of the BAE frequency. A model was proposed to explain the evolution of particle trajectories, which are essentially determined by a clockwise modified Lissajous rotation and a distortion provided by the equilibrium shear flow along the toroidal direction. The dynamic leads to a phase-space twisting structure, which excites and suppresses the BAE, within one chirping period and superposed folding between successive chirping. The nonlinear dynamics mechanism in the present studies can be easily extended, enriched and applied to various Alfv\'en eigenmodes in toroidal plasmas, which provides a conceptual framework for understanding the nonlinear wave-particle interaction underlying the transport processes in collisionless plasmas.

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Affiliation

Institute of Physics, Chinese Academy of Sciences

Country or International Organization

China

Primary authors: Dr ZHANG, Wenlu (Institute of Physics, Chinese Academy of Sciences); Dr CHENG, Junyi (Institute of Physics, Chinese Academy of Sciences); Prof. LIN, Zhihong (University of California, Irvine); Prof. LI, Ding (Institute of Physics, Chinese Academy of Sciences)

Presenter: Dr ZHANG, Wenlu (Institute of Physics, Chinese Academy of Sciences)

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