6th Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Self-consistent Simulations of ICRF-induced Alfvén Eigenmodes in Helical Plasmas

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Ion cyclotron resonance frequency (ICRF) heating has been chosen as one of the fundamental auxiliary heating systems in many present-day fusion devices. Minority ions accelerated by the ICRF wave will heat the bulk plasma via Coulomb collisions. Meanwhile, the high-energy minority ion tail developed during ICRF heating can drive a variety of Alfvén eigenmodes (AEs). The destabilized AEs, in turn, will significantly affect the ICRF heating efficiency by minority ion transport and losses. It is therefore necessary to consider AE effects during ICRF heating processes. Besides, in experiments, AEs excited by ICRF heating usually have a steady amplitude [1] while those excited by neutral beam injection (NBI) show sometimes bursting behavior [2]. Those different nonlinear states are determined by energetic particle phase-space dynamics according to the Berk-Breizman theory [3]. One of the key elements to performing the simulations of different AE nonlinear states is including the ICRF source term in the simulation model.

In this work, we extended a kinetic-MHD hybrid code: MEGA [4] by implementing the ICRH acceleration, source, sink, and collisions. In the extended MEGA code, the bulk plasma is described by nonlinear MHD equations, while drift-kinetic description and full-f PIC method are applied to energetic particles. Coulomb collisions between minority ions and the bulk plasma and the ICRF kick process are described by the Monte Carlo method. The extended MEGA code is applied to an ICRF minority heating scenario in the Large Helical Device (LHD). A three-dimensional equilibrium is constructed with the HINT code [5]. We assume proton minority ions in deuterium majority ions and the ICRF wave frequency is 38.47MHz. The ICRF power is 3MW which is the maximum accessible value in present LHD experiments.

Although a minority ion tail energy of up to a hundred kilo-electron volts can be formed in LHD during a high-power ICRF heating, AE induced by the minority ion tail has never been reported. To analyze the AE stability during ICRF heating, a combination of a classical simulation and a hybrid simulation is performed, where the MHD perturbation is turned off (on) in the classical (hybrid) simulation. As a first step, a hundred-millisecond classical simulation is performed to obtain the minority ion distribution function in the steady state. Then, AE stability is checked for the first time based on the realistic phase-space distribution of ICRF minority ions via a hybrid simulation. Both off-axis and on-axis ICRF heating are studied by varying the magnetic field strength at the magnetic axis. The steady-state minority ion pressure profiles for off-axis and on-axis cases are shown in Figure 1. The minority ion pressure is highly anisotropic and spatially localized around resonance layers. Hybrid simulation results show that an energetic particle mode (EPM) is destabilized in the on-axis heating case, while no unstable mode is found in the off-axis heating case even for a larger ICRF heating power with 4.6MW. Spatial profiles of the EPM are shown in Figure 2. The EPM shows a fast-chirping behavior with a frequency between 80~100kHz. A significant confinement degradation of minority ions is observed after the mode destabilization.

References:

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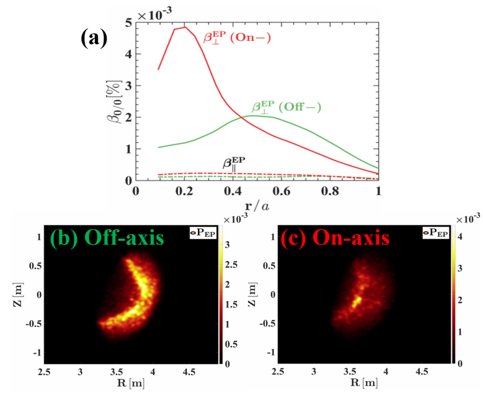

Figure 1. (a) m/n=0/0 component of steady-state minority ion radial beta profiles. Minority ion pressure profiles in a poloidal plane for (b) off-axis and (c) on-axis heating cases.

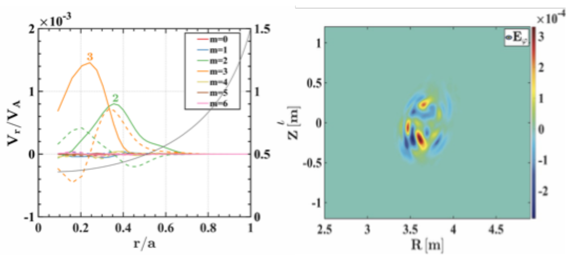

Figure 2. Mode structures of the EPM (n=1) driven by minority ions during on-axis heating.