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First Achievement of Free-Boundary Kinetic-Magnetohydrodynamic Hybrid Simulation of Energetic-Particle Driven Modes in Heliotron J

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The confinement of fusion-born energetic particles (EP) is essential for achieving the self-sustainable fusion plasma. However, the EP-driven MHD instability can be destabilized by the resonant interaction between EP and shear Alfvén wave (SAW) during the slowing-down process. The transported EPs by this instability reduce the EP heating efficiency and potentially cause damage to the plasma-facing component. The clarification of the interplay between EPs and SAW is necessary for the mitigation and the development of the suppression mechanism [1-2]. A computational simulation is an effective tool for the investigation of the linear and nonlinear interactions between the EP and the MHD wave in the 3-dimensional plasma. In this study, the EP-SAW interaction in Heliotron J (HJ) [1-2], a low magnetic shear helical-axis heliotron, was investigated with MEGA, a hybrid EP-MHD simulation code [3]. This code has been successfully validated in the planar-axis devices (tokamaks [4-5] and LHD [6]). This is the first time where MEGA is applied to the helical-axis configuration with low magnetic shear. In such a configuration, it is expected that the width of the EP-driven MHD mode can extend from the core region to the edge region. The EP can also interact with the SAW through multiple resonances due to the presence of the toroidally asymmetric magnetic field. The objectives of this study are to reproduce the experimental observations, to clarify the roles of these addition interactions, and to quantify the EP transport in HJ. Since HJ shares similar aspects with other advanced stellarator and heliotron devices, this study is potentially useful for the study of EP-driven MHD instabilities in other devices.

The commonly observed EP-driven MHD modes in the low beta currentless plasma of HJ are the n/m=1/2 energetic-particle mode (EPM) and the n/m=2/4 global Alfvén eigenmode (GAE). The n/m=1/2 EPM and the n/m=2/4 GAE are located at the edge and middle regions, respectively. The hybrid simulation is based on this equilibrium with the bump-on-tail velocity distribution for EP. This velocity distribution accounts for the finite charge-exchange loss observed in the HJ experiment. For the EP

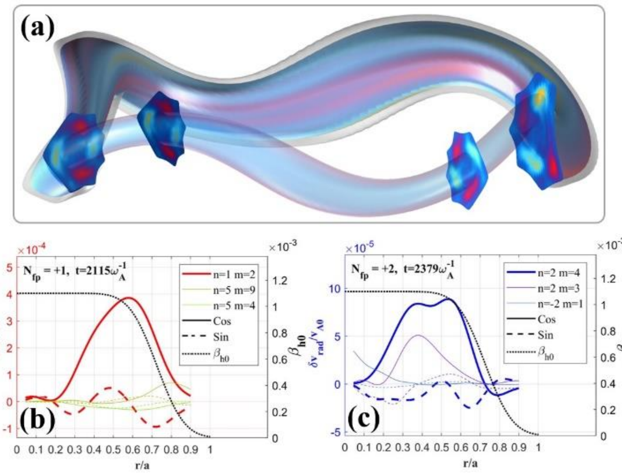

Fig. 1: Spatial structure of the n/m=1/2 EPM and the n/m=2/4 GAE in the low beta currentless discharge calculated with the free boundary MEGA. Panel (a) shows the 3D structure of the EP-driven MHD instabilities, while panels (b-c) show the radial MHD velocity profiles of the modes within the N_f=+1 and +2 toroidal mode families, respectively.

pressure profile, the EP pressure gradient (∇P_{h0}) is finite at the edge region.

From the simulation results [7-9], it was found that the low-n EP-driven MHD instabilities in HJ are sensitive to the boundary condition. Normally, the fixed boundary (non-slip) condition is used in the tokamak plasma to suppress external modes [6]. However, this assumption significantly underestimates the linear growth rate (γ/ω_A) of the low-n mode in HJ. Only the n/m=2/4 GAE was produced, while the edge-localized n/m=1/2 EPM was missing [7]. Instead, the weak core-localized n/m=1/2 EPM was observed.

To tackle this discrepancy, the free boundary simulation is introduced. The n/m=1/2 EPM and the n/m=2/4 GAE were successfully reproduced (fig.1) [9]. The linear growth rates of both modes increase significantly, but the increment is much higher for the n/m=1/2 EPM. The enhancement of the linear growth rate is attributed to the change in the perceived ∇P_{h0} by the outward shift of the mode position. In the fixed boundary simulation, the profile of n/m=1/2 and n/m=2/4 modes are restrained to the core region where ∇P_{h0} is weak. In contrast, the profiles of these modes are not restrained in the free boundary case; hence, they can exist at the edge region where ∇P_{h0} is stronger. The simulation with the core-localized ∇P_{h0} was also considered to clarify the dependency of the free boundary effect on the mode position. It was found that both the fixed and free boundary simulations produce similar results. This suggests that the free boundary effect is significant only for the mode within r/a>0.4 in HJ.

In terms of the EP-SAW interaction, the n/m=1/2 EPM and n/m=2/4 GAE are mainly destabilized by the high-velocity co-passing EPs that interact with the modes through the toroidicity-induced resonance (fig. 2a). This also explains the asymmetric downward frequency chirping of the n/m=1/2 EPM (fig.2b), where the upward branch chirps into the stabilizing region ($v_h > v_{inj}$). These resonant EPs transit the core region, and they have a sufficiently large orbit width such that they can effectively interact with the EP-driven MHD mode in the peripheral region. As a result, their transport results in the large reduction of the EP pressure in the core region (hollow EP pressure profile).

To minimize the contribution of these high-velocity EPs, the case with the slowing-down velocity distribution function is considered. The change in the linear growth rate is not significant because the EP drive is compensated by the toroidal asymmetric resonances in the low-velocity region.

This work may contribute to the clarification of the role of EP-SAW interaction on the particle and energy loss in fusion-grade toroidal devices, where the three-dimensional optimization of the magnetic field and boundary condition are crucial. It points out the importance of the boundary condition in HJ. The low magnetic shear of HJ is one of the possible candidates that may exacerbate the validity of the fixed boundary condition. Further investigation in other high shear and low shear devices is necessary.

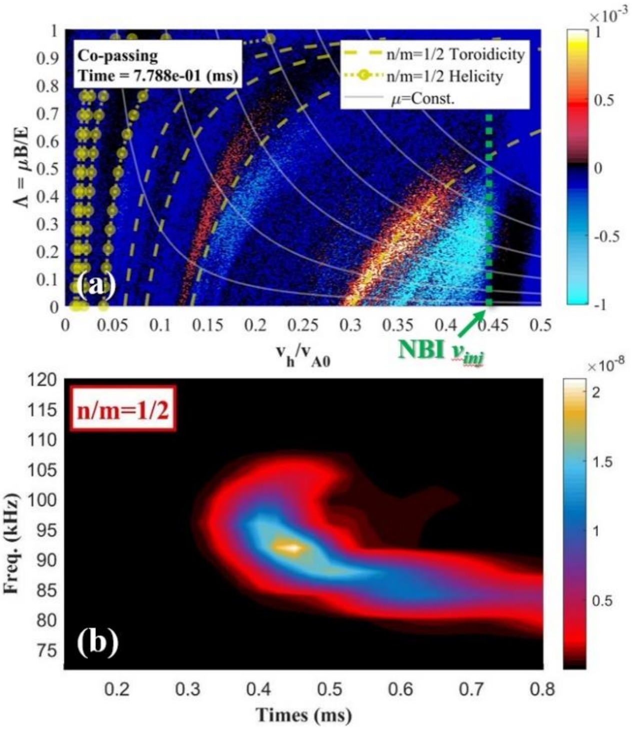

Fig. 2: (a) The EP redistribution (δf_{h0}) in velocity space by the n/m=1/2 EPM. The yellow dashed and dash-dotted lines represent the n/m=1/2 toroidicity and helicity-induced resonances, respectively. The green dashed line is the NBI injection velocity. Panel (b) shows the asymmetric downward frequency chirping of the n/m=1/2 EPM.

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