Effect of ECH on Energetic-Particle-Driven MHD Modes in Heliotron J

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Energetic-particle (EP) -driven MHD modes have been experimentally studied in the Heliotron J helical device. Experiments scanning the magnetic configuration and electron cyclotron heating (ECH) power show that the excitation and suppression of Global Alfven Eigenmodes (GAEs) and Energetic Particle Modes (EPMs) depend on the magnetic configuration and that the optimal ECH power for mode suppression exists for some modes. The mode profiles measured with beam emission spectroscopy (BES) have a radial mode structure with multiple peaks, and the mode intensity is modified by the applied ECH. A distinct delay response effect concerning plasma pressure in ECH power modulation suggests a complex delay response of mode excitation and suppression.

Energetic particles (EPs) generated by the D-T fusion reaction or auxiliary heating methods such as neutral beam injection (NBI) can excite Alfvén eigenmodes and energetic particle modes (EPMs) through the gradient of EP distribution function in the resonance region. These MHD waves can give rise to a reduction in the heating efficiency and confinement performance. In addition, these lost EPs can cause serious wall damage. Therefore, understanding and controlling the interactions between EP and MHD waves are crucial in magnetically confined fusion plasmas. Various methods have been developed to suppress or mitigate EP-driven MHD instabilities such as NBI, ICRF and RMP, and ECH/ECCD. Since ECH exerts a complicated effect on EP-driven modes, further studies are required for application to ITER and DEMO reactors. In this paper, we have studied the ECH effect on the EP modes under several magnetic configurations in Heliotron J.

The Heliotron J device is a medium-sized helical device with R = 1.2 m, a ~ 0.2 m, and B = 1.25 T. The independent control of a helical coil, two types of toroidal coils, and vertical coils enables us to change the magnetic configurations to study the ECH effect on the EP modes. While no gap modes, such as toroidally induced Alfvén eigenmodes (TAE) are excited due to low magnetic shear in the rotational transform profile, global Alfvén eigenmodes (GAEs) and EPMs are excited according to the MEGA and STELLGAP code calculations. Figure 1 shows the radial profiles of an EP-driven mode measured with a BES diagnostic under several ECH power conditions in the low-bumpiness configuration. The on-axis EC power is scanned from 109 to 308 kW with the electron density and NB power fixed at n_e = 0.6×10^{19} m^{-3} and P_{NB} = 650 kW. The central electron temperature, measured with a Thomson scattering diagnostic, ranged from 0.4 to 0.9 keV. The mode frequency ranges from 85 to 95 kHz, and the mode number is m/n = 1/2 according to a magnetic probe measurement. It can be seen that the mode has a radial structure with two peaks around r/a = 0.35 and 0.65 when the ECH power is less than 176 kW. A linear simulation using the FAR3d code shows that an eigenfunction has a similar profile at 81 kHz with the same mode number [1]. In this configuration, most observed modes' intensity is decreased with an increase in the ECH power, as similarly observed in magnetic probe measurements.

The mode behavior is not simple in the high- and medium-bumpiness (MB) configurations. Figure 2 shows the mode intensities as a function of ECH power in the medium-bumpiness configuration. The EP modes of 60 kHz and 140 kHz are weakened with an increase in ECH power. On the other hand, the EP modes of 90 and 115 kHz are mitigated with an increase in ECH power when the ECH power is less than 240 kW, and they are enhanced again when the ECH power is 305 kW. Such dependence is also observed in the high-bumpiness configuration. Degradation of the bulk plasma confinement is observed at high ECH in the MB configurations. The measurement of EP loss is not available yet. Non-monotonic behavior of the EP modes may be related to the balance between driving and damping effects induced by ECH. The ECH can change Landau damping, radiation damping, and continuum damping through the T_e change. Conversely, the change in T_e also affects the electron drag collision, which affects the slowing-down time. According to a linear theory, the increase in T_e increases the mode growth rate due to energetic ion pressure. Further experimental and simulation study is required to determine the dominant effect on the mode excitation/damping.

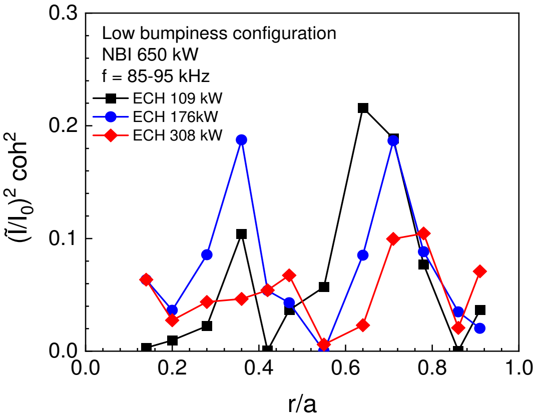

Fig. 1 Radial profiles of EPM in low-bumpiness configuration. The ECH power is scanned from 109 to 308 kW

The ECH power has been modulated in time to investigate the response of the EP modes to the bulk electron pressure [2]. The modulation frequency is set at 50 Hz, with a duration of 10 ms for the maximum and minimum power levels. Figure 3 shows the time evolution of a mode intensity as a function of the product of line-averaged electron density $\langle n_e \rangle$ and ECE intensity, which is an indicator of the bulk plasma pressure. The EP-driven mode of 95-103 kHz is excited with a delay of 6.0 ms after reducing the ECH power. Subsequently, after a short delay of 1.5 ms, the mode disappeared and is effectively suppressed after an increase in the ECH power. The mode intensity remains high as the plasma pressure begins to rise, and mode suppression eventually occurs at high-pressure levels. The difference in the bulk electron pressure at the ECH rise-up and fall-down indicates that mode excitation suppression is related not only to the bulk plasma pressure but also to the energetic ion confinement.

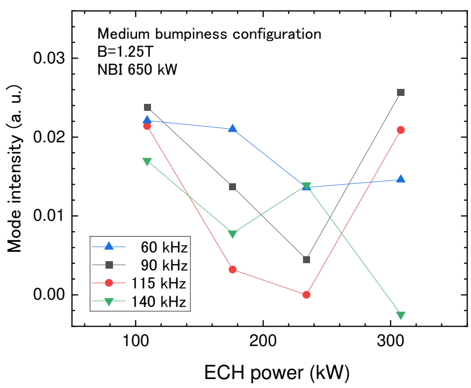

Fig. 2 ECH power dependence of mode intensities in MB configuration.

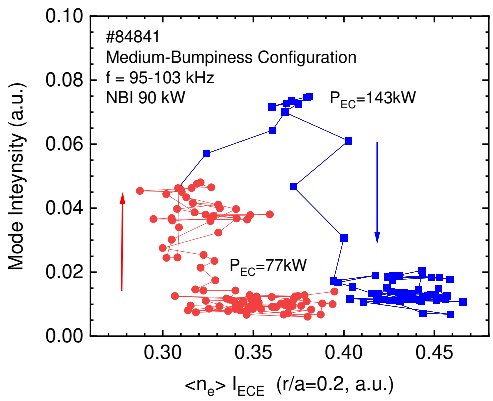

Fig. 3 Response of mode intensity to bulk pressure in ECH modulation experiment.

[1] J. Varela, K. Nagasaki, et al., Nucl. Fusion 63 (2023) 026009
[2] Y. Zhong, K. Nagasaki, et al., Plasma Fus. Res. 19 (2024) 1202008