Response of Energetic-Particle-Driven Magnetohydrodynamics (MHD) Instability to Modulated ECH in Heliotron J

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The response of energetic particle (EP)-driven magnetohydrodynamic instability to electron cyclotron heating (ECH) was experimentally studied in Heliotron J. The neutral beam injection power remained constant throughout the experiment, and the ECH power was systematically modulated. When the ECH power was gradually decreased to a certain threshold, the excitation of an EP mode with a frequency of approximately 100 kHz was observed. The response to ECH showed a close linkage with variations in electron density and temperature. In addition, a distinct delay response effect concerning plasma pressure suggests a complex delay response of mode excitation and suppression.

Keywords: MHD instability, energetic-particle-driven mode, ECH

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Energetic particles (EPs) are generated in magnetically confined plasmas through processes, such as the D–T fusion reaction or auxiliary heating methods that include neutral beam injection (NBI). These EPs can excite certain types of magnetohydrodynamic (MHD) waves, including Alfven eigenmode and EP mode (EPM) [1], through the gradient of EP distribution function in the resonance region. These MHD waves can lead to the transport and loss of EPs, which in turn reduces the heating efficiency and confinement performance. In addition, these lost EPs can affect the walls of devices, causing 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 [2]. Electron cyclotron heating (ECH) and electron cyclotron current drive effectively stabilize these MHD instabilities [3–5]. In this study, we analyzed the effect of ECH on the suppression of EP-driven MHD modes in Heliotron J. ECH exerted a complicated effect on EP-driven modes. Almost all factors related to MHD stability can be affected by ECH, including the driving and dissipative terms. The ECH can change ion, electron Landau damping, radiation damping, and continuous spectrum damping (by changing the pressure) by changing the electron temperature (Te). Conversely, the change in Te also affects the electron drag collision, which affects the slowing down period of the local energy.

Heliotron J is a medium-sized helical-axis heliotron device. It has a major radius of R = 1.2 m, a minor radius of a = 0.17 m, and operates at a magnetic field strength of B = 1.25 T [6, 7]. In this experiment, the NBI power was fixed at 90 kW for coinjection, and the ECH was operated with modulation. The maximum power of modulation was 192 kW, and the minimum power varied from 158 kW to 113 kW. The ECH modulation frequency was set at 50 Hz, with a duration of 10 ms for the maximum and minimum power levels.

Figure 1 illustrates the temporal evolution of plasma discharge. An EP-driven mode was observed in the frequency range of 95 - 103 kHz, with some delays after the modulated ECH power reached its minimum amplitude. The electron cyclotron emission (ECE), which reflects the core Te, was plotted; the optical thickness at the core region was approximately 2. The ECE signal increased with an increase in the ECH power, whereas the average electron density measured using a microwave interferometer decreased. Furthermore, after reducing the ECH power, the mode was excited with a delay of 6.0 ms. Subsequently,

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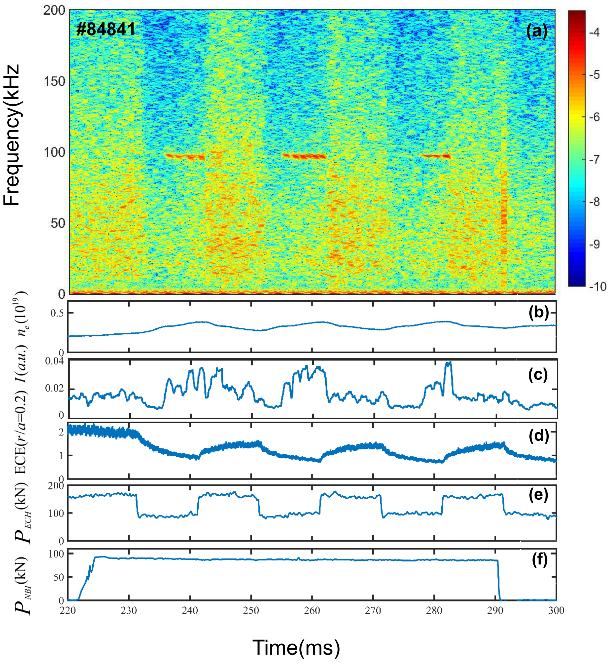

Fig. 1 Time evolution of (a) the power spectrum density of a magnetic probe, (b) line-averaged density (ne), (c) mode intensity (I), (d) ECE, (e) ECH signal, and (f) NBI signal.

after a short delay of 1.5 ms, the mode disappeared and was effectively suppressed after an increase in the ECH power. According to the hybrid EP-MHD simulation results calculated using MEGA [8] and the shear Alfven continua calculated using STELLGAP [9] and previous experimental results obtained under the same magnetic configuration [4], the observed mode was likely an EPM with m/n = 1/2, where m and n refer to the poloidal and toroidal mode numbers, respectively.

The amplitude of the observed mode exhibited a distinct correlation with the ECH injection power. As the ECH power was increased, mode suppression became evident. When the minimum ECH amplitude was set at 100 kW, a distinct mode was observed. Once the ECH power surpassed the threshold, effective mode suppression occurred (Fig. 2). The threshold was between 110 and 138 kW. These results highlight the critical role of ECH power in the control and mitigation of the observed mode. The establishment of the threshold range for mode suppression provides valuable insights into the optimized operation of the Heliotron J device and management of the associated MHD instabilities driven by EPs.

A delay response effect was observed in the response of the mode amplitude to ECH modulation. This behavior is illustrated in Fig. 3, which also displays the evolution of mode intensity ⟨I⟩ as a function of the product of line-averaged electron density ⟨ne⟩ and ECE intensity, which serves as an indicator of the core plasma pressure. At high amplitudes of ECH modulation, the mode intensity remained low. However, as the ECH power decreased, the mode strength rapidly increased, as indicated by the red circle in Fig. 3.

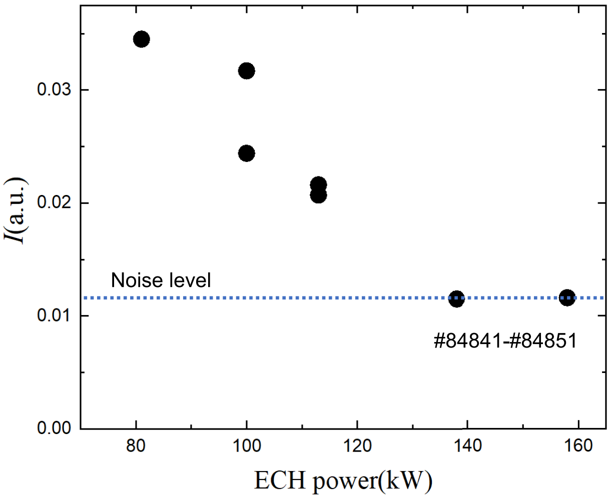

Fig. 2 Dependence of mode amplitude on ECH power.

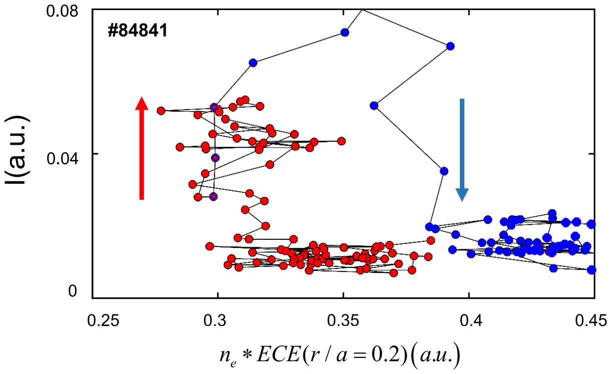

Fig. 3 Evolution of normalized intensity (I) with the product of ⟨ne⟩ and ECE intensity.

The mode intensity remained high as the plasma pressure began to rise, and mode suppression eventually occurred at high pressure levels. To understand the dominant factors influencing this response, we investigated mode intensity as a function of either the electron density ⟨ne⟩ or ECE intensity. The analysis reveals that compared with the electron density, Te plays a more important role in determining mode strength. This result suggests that the delay response effect is closely correlated with variations in Te. The difference in the product of ⟨ne⟩ and ECE intensity indicates that mode excitation suppression is related not only to bulk plasma pressure but also fast ion confinement.

In addition to the EP mode, the intervals of elevated ECH power were characterized through broadband fluctuations. The increase in broadband fluctuation may be related to mode suppression. EP-driven modes suppress turbulence [10]. In future work, we will conduct relevant experiments to further study the relationship between mode suppression and broadband fluctuation.

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