Energetic-particle-driven MHD Instabilities and Their Control by ECH/ECCD in Helical Plasmas

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1. Introduction

Energetic particles generated by D-T fusion reaction and plasma heating interact resonantly with shear Alfvén waves through damping/driving processes when their velocity is comparable with Alfvén velocity, resulting in excitation of energetic particle (EP)-driven MHD modes. A variety of the EP-driven MHD modes are often observed in helical systems, which basically depends on magnetic configuration parameters such as rotational transform and toroidal field period. Figure 1 illustrates the vacuum shear Alfvén continua in the Heliotron J, LHD and TJ-II devices. A high magnetic shear generates toroidicity-induced eigenmode (TAE) in LHD and TJ-II, and a low magnetic shear does global Alfvén eigenmodes (GAEs) in Heliotron J and TJ-II. Helicity-induced AEs (HAEs) are observed in TJ-II and LHD because of medium/high rotational transform. Energetic particle modes (EPMs) are observed when the energetic ion beta beats the continuum damping on shear Alfvén continua.

In order to control the EP-driven modes, several external actuators have been proposed and performed in tokamaks and helical systems [1][2]. Electron cyclotron heating (ECH) and current drive (ECCD) is an ideal method to control the EP-driven MHD modes since they can provide highly localized EC waves with a known location and good controllability. In this paper,

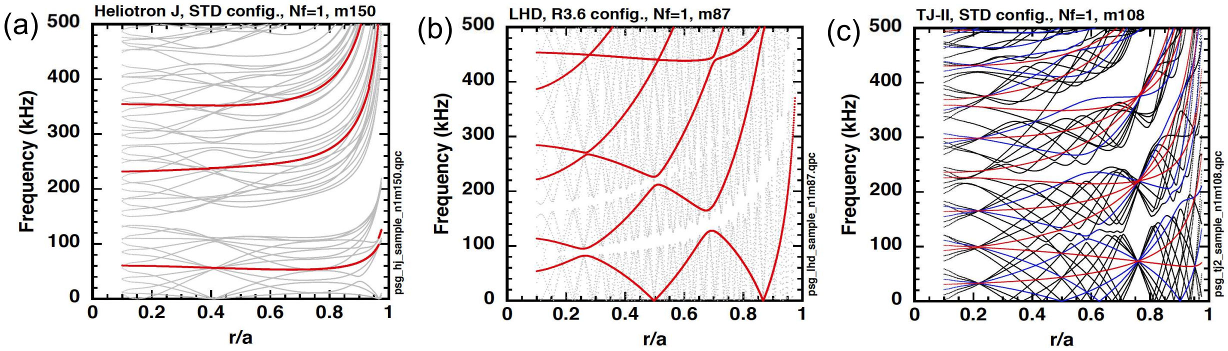

Fig. 1. Typical vacuum shear Alfvén continua in (a) Heliotron J, (b) LHD and (c) TJ-II. The Heliotron J has low rotational transform and low magnetic shear, The LHD has low rotational transform and high magnetic shear, and the TJ-II has high rotational transform and low magnetic shear.

we report recent progress of control of EP-driven MHD modes with ECH/ECCD in the helical devices. Since the stability of EP-driven MHD modes depends on the magnetic configuration, comparative studies among these devices based on similarities and differences in the configuration are useful for comprehensive understanding of AE physics in toroidal plasmas.

2. ECCD Effect on EP-Driven Modes

In Heliotron J, GAEs and EPMs have been successfully suppressed by co- and ctr-ECCD [3][4]. Here co-ECCD is defined as current drive increasing the rotational transform. Since Heliotron J has a low magnetic shear, co- and ctr-ECCD make the magnetic shear negative and positive, respectively. The shear Alfvén continua are not modified much. These results indicate that the modes are suppressed regardless of the sign of the magnetic shear. In high shear devices such as LHD, the modification of shear Alfvén continua is as important as the continuum damping due to magnetic shear. Figure 2 shows the time evolution of power spectrum density and plasma parameters for co-, balanced (ECH only) and ctr-ECCD in LHD. For co-ECCD, TAEs, GAEs with $f > 100$ kHz, and EPMs with $f < 100$ kHz are observed. They are mitigated with ECH (balanced ECCD), and are suppressed almost completely with ctr-ECCD. A mortional Stark emission diagnostic confirms that the core rotational transform increases to 0.5 and the magnetic shear is weakened for co-ECCD, while the core rotational transform decreases to 0.2 and the magnetic

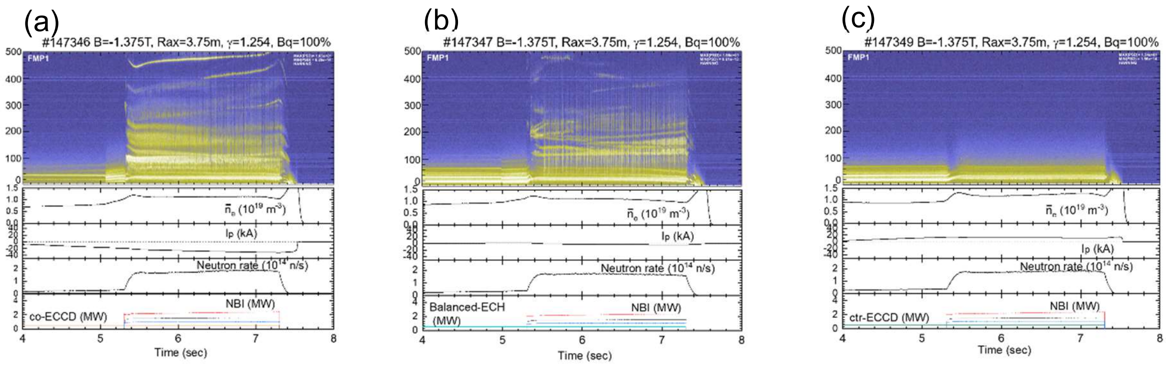

Fig. 2. Time evolution of shear Alfven spectra and plasma parameters in LHD, (a) co-ECCD, (b) ECH (balanced ECCD) and (c) ctr-ECCD in LHD.

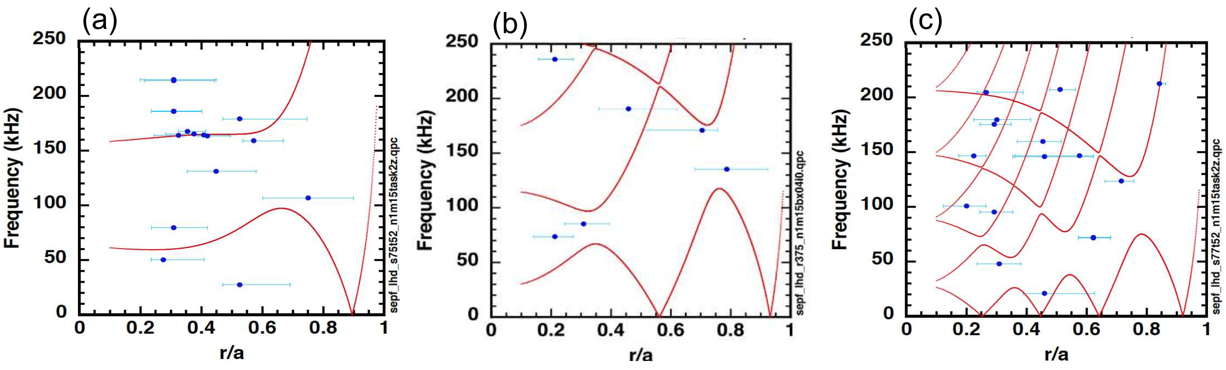

Fig. 3. Shear Alfvén continua in solid lines and eigenfunction corresponding to TAE or GAE in (a) co-ECCD and (b) ECH (balanced ECCD) and (c) ctr-ECCD plasmas in LHD. Blue dots shows the peak position of eigenfunction and FWHW is also shown in horizontal line.

shear is strengthened for ctr-ECCD. As shown in Fig 3, for co-ECCD, the TAE gap is shifted from the core to edge region, and many discreate eigenmodes appears corresponding to TAE and GAE. For ctr-ECCD, the discrete eigenmodes cross the shear Alfvén continua, subject to continuum damping. Figure 4 show the measured neutron rate as a function of electron density for co- and ctr-ECCD. The neutron rate for ctr-ECCD is higher than that for co-ECCD, indicating that the mode suppression improve plasma performance in LHD.

Modeling analysis is performed for Heliotron J and LHD using the FAR3d code [5]. The simulation results show that EPM/GAE in Heliotron J plasma can be stabilized by the effect of the magnetic shear (see Fig. 5). When the central rotational transform decreases below 0.4, the 1/2 rational surface is located at the plasma periphery where the magnetic shear is stronger, leading to a decrease in the EPM/GAE growth rate. When the rotational transform increases, the combined effect of the continuum damping and the magnetic shear enhancement leads to a decrease in the EPM/GAE growth rate. On the other hand, stabilization of the EPM/TAE with ctr-ECCD in LHD is caused by enhancement of the continuum damping in the core plasma region.

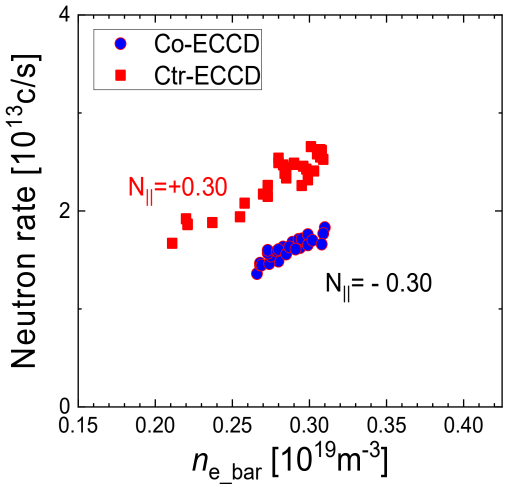

Fig. 4. n_e dpendence of neutraon rate for co- and ctr-ECCD in LHD.

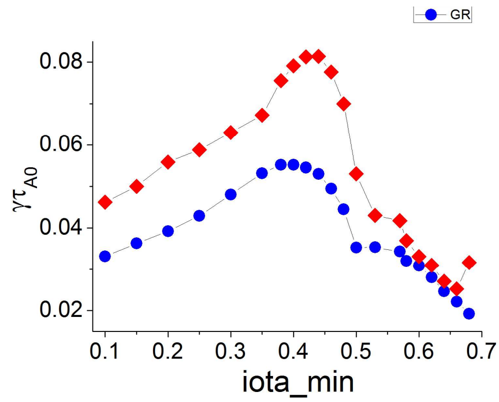

Fig. 5 Simulation results on growth rates of 2/4 GAE and 1/2 EPM in Heliotron J.

In the TJ-II experiment, on-axis ctr-ECCD compensates the core co-NBI current and the more distributed co-bootstrap current, inducing positive magnetic shear at HAE location. We observed a change in the HAE amplitude [6]. Calculation of shear Alfvén spectra shows that the structure of shear Alfvén continua around HAE gap is changed by the plasma current, affecting the stability rather than the continuum damping.

3. ECH Effect on EP-Driven Modes

Effect of ECH on EP-driven MHD modes was studied experimentally in CHS [7] and TJ-II [8][9]. In TJ-II, some continuous AEs were changed into chirping ones in association with the decrease in their amplitudes when ECH was applied to NBI plasmas. The modes are stabilized/destabilized by ECH depending on magnetic configuration, ECH power and deposition location in the Heliotron J and LHD plasmas. Figure 6 shows the mode amplitudes at three magnetic configurations in Heliotron J. The magnetic configuration can be changed by controlling the bumpiness. At low bumpiness configuration, the modes are mitigated with an increase in ECH power, while the mode amplitudes are not a monotonic function of ECH power in the other configurations. According to a linear theory, the increase in electron temperature leads to the increase in mode growth rate due to the increasing energetic ion beta. Changes in thermal plasma profiles induced by ECH may have impact on the AE stabiility through modification of the driving and damping terms. Such a behavior is similar to the ECH effect in tokamaks [10]. The observed change in reversed shear RSAE by ECH in DIII-D and ASDEX is due to combination of mode excitation, damping and eignenmode, which makes the ECH effect complicated.

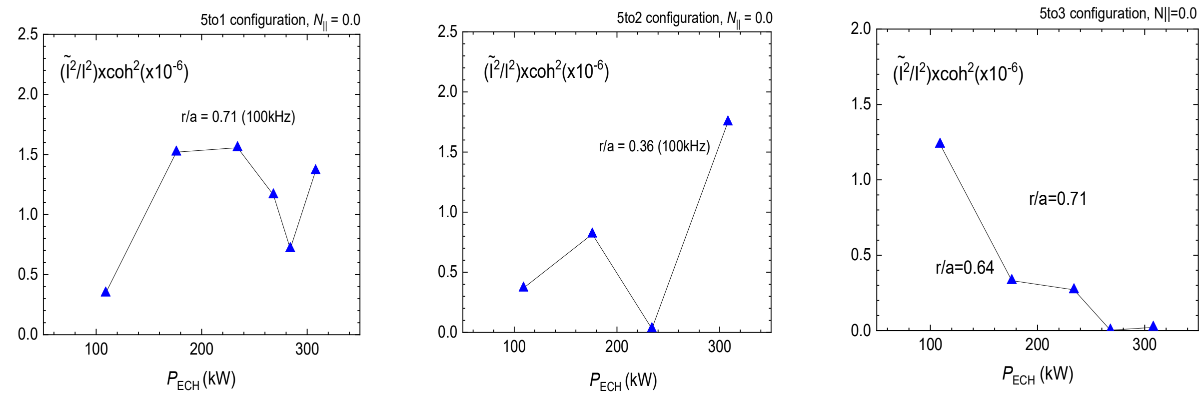

Fig. 6. Mode amplitudes at (a) high-bumpiness, (b) medium-bumpiness and (c) low-bumpiness configurations in Heliotron J.

4. Summary

We have demonstrated that ECH/ECCD is an effective tool to control the EP-driven MHD modes such as GAE, TAE, EPM and HAE in helical devices. The experimental results applying ECCD in the different magnetic configurations show that the modes can be controlled by the change in shear Alfvén continua and the continuum damping due to magnetic shear effect. Although ECH (balanced-ECCD) can also impact EP-driven MHD modes, the response to ECH is complicated compared with ECCD, depending on the modes and configurations. Further study is required to clarify the mechanism of ECH effect.

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