IMPACT OF ECH/ECCD ON FAST-ION-DRIVEN MHD INSTABILITIES IN HELICAL PLASMAS

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Abstract

In this article, the effect of electron cyclotron heating (ECH) and current drive (ECCD) on fast particle (FP)-driven MHD instabilities in stellarator/heliotron (S/H) plasmas obtained in LHD, Heliotron J and TJ-II, is discussed. It is demonstrated that FP-driven MHD instabilities including energetic particle modes (EPMs) and Alfén eigenmodes (AEs) can be controlled by means of magnetic shear \(s\) modified by EC-driven plasma current. EPMs can be controlled by changing continuum damping rate, which is the main damping mechanism of the EPM and depends on \(s\). AEs are significantly affected by the change of structure of the shear Alfén continuum which can be modified by \(s\). ECCD can also impact FP-driven MHD instabilities. Candidates to explain the ECH effect on FP-driven MHD instabilities are the variation in the fast ion profile and/or the trapped electron collisional damping.

1. INTRODUCTION

Fast particle (FP)-driven magnetohydrodynamics (MHD) instabilities enhance anomalous transport and/or induce the loss of fast particle including alpha particles in a D-T fusion reactor. Since redistribution and exhaust of alpha particles lead to reduction of fusion gain \(Q\) and damage of first wall, to establish methods of stabilization and/or control of FP-driven MHD instabilities is required for the D-T fusion reactor, but they have not been established yet. While several methods are proposed to control the FP-driven MHD instabilities, e.g. modification of the fast ion distribution in velocity space by additional neutral beam injection (NBI) \([1]\) and the changing of shear Alfén continua by resonant magnetic perturbation (RMP) which will induce toroidal mode coupling of shear Alfvén continua because of breaking axisymmetry of magnetic configuration \([2]\). The electron cyclotron heating (ECH) / electron cyclotron current drive (ECCD) are candidate method to control the FP-driven MHD instabilities because ECH/ECCD may be an ideal tool to control the modes since they can provide highly localized EC waves with a known location and good controllability. For example, neoclassical tearing mode (NTM) stabilization by ECCD utilizing local current drive is a good application example concerning the effect of ECCD on the MHD instabilities although the stabilization/destabilization mechanisms of NTM are completely different from that of FP-driven MHD instabilities. The effect of ECCD on the FP-driven MHD instabilities is being investigated in tokamaks and stellarator/heliotron (S/H) such as CHS \([3]\), Heliotron J \([4,5]\), DIII-D\([6,7]\), LHD and TJ-II \([8]\). In the tokamak plasma with non-monotonical reversed magnetic shear, they experimentally found some effects of ECH/ECCD on the observed FP-driven reversed shear AEs (RSAEs), the effect of ECH on RSAEs can be explained by the increasing the frequency of geodesic acoustic mode (GAM) by the increase of electron temperature by ECH. It may be difficult to apply this method into other AEs and EPMs in other magnetic configurations without non-monotonical reversed magnetic shear. According to a linear MHD theory, the changes in electron density and temperature by ECH and in plasma current by ECCD can affect both the growth and damping rates of the FP-driven MHD instabilities through the changes in (i) pressure gradient of fast ions, (ii) structure of shear Alfvén continuum through the change of magnetic configuration including magnetic shear, and (iii) electron Landau damping. In this paper, we discuss generalized effect of ECCD/ECH on FP-driven MHD instabilities by using the three S/H plasmas that have different and similar characteristics of magnetic configurations. FP-driven MHD instabilities including energetic particle modes (EPMs), global Alfvén eigenmodes (GAEs), helicity-induced AEs (HAEs), and toroidicity-induced AEs (TAEs) are observed in tangential NBI-heated plasmas of S/H devices, Heliotron J, TJ-II and LHD. We utilize the ECH and ECCD in order to mitigate and eventually suppress the observed FP-driven MHD instabilities in three devices.

Since the stability of FP-driven MHD instabilities depend upon the magnetic configuration, comparative studies among these devices based on similarities and differences in the configuration are useful to investigate...
the impact of ECH/ECCD on FP-driven MHD instabilities and finally to have a comprehensive understanding of AE physics in S/H. Figure 1 shows the profile of rotational transform, which characterizes the AE properties through the shear Alfvén continua, of these devices. Heliotron J and TJ-II, as shown in Green solid and Black dotted line, have similar plasma/device parameters, e.g. low toroidal field period ($N_{f}=4$) and low magnetic shear but different rotational transform. On the other hand, LHD (Red broken line) has high $N_{f}=10$ and high magnetic shear. Existence of stable AEs, which can be destabilized by fast particles, basically depends upon parameters of a magnetic configuration such as profile of rotational transform and toroidal field period in S/H devices. TAEs are observed in the LHD plasmas because of high magnetic shear which can induce the generation of TAE gap caused by the crossing of each shear Alfvén continua with $m$ and $m=\pm1$. Here $m$ being poloidal mode number. On the other hands, GAEs are observed in Heliotron J and TJ-II with low/middle magnetic shear because a shear Alfvén continuum does not intersect with others in almost magnetic configuration. HAEs are also observed in TJ-II as well as LHD because of high rotational transform. A variety of magnetic configurations in S/H induce the observation of a variety of FP-driven MHD instabilities. EPMs are usually observed in these plasmas, when the plasma density is less than $2 \times 10^{19}$ m$^{-3}$ where fast ion beta would be comparable to bulk plasma beta and beats the strong continuum damping on shear Alfvén continua.

2. ECCD EFFECT ON THE FP-DRIVEN MODES

ECCD can drive localized plasma current whose amplitude and location can basically be changed by the change of the parallel refractive index $N_{f}$ and the injection angle along resonance layer. When magnetic shear is increased by EC-driven plasma current, the observed FP-driven MHD instabilities are suppressed or mitigated in Heliotron J [5], LHD and TJ-II. The decrease of the observed FP-driven EPM and GAE amplitude are observed in NBI-heated Heliotron J plasma with low magnetic shear in vacuum, when we apply co-ECCD leading to the decrease of the rotational transform and the increase magnetic shear [5]. In addition to co-ECCD experiment, counter-ECCD is applied into NBI-heated Heliotron J plasma whose experimental conditions with regard to FP-driven MHD instabilities are almost same as co-ECCD experiments. The direction of $N_{f}$ can be changed by the change of magnetic field direction in Heliotron J. Counter EC-driven plasma current can increase the rotational transform and increase magnetic shear. Since Heliotron J has almost zero magnetic shear, EC-driven current having $N_{f}$ with same value but different sign can induce same magnetic shear with different sign. Both negative and positive magnetic shear, which is induced by co- and counter-EC-driven plasma current, suppress the observed EPMs and GAEs, as shown in Fig. 2 and Fig. 3, respectively. EPM amplitude has a maximum around plasma current of $I_{p}=0.2$ kA and decreases with the increase of the plasma current regardless of sign of plasma current. The maximum amplitude of EPM is observed at not $I_{p}=0.0$ kA but $I_{p}=0.2$ kA. This result can be explained by the increase of

![Fig. 1](image1.png) FIG. 1. Radial profile of rotational transform, which characterizes AEs, of LHD (red, broken line), Heliotron J (green, solid line) and TJ-II (black, dotted line).

![Fig. 2](image2.png) FIG. 2. Dependence of EPM amplitude on EC-driven plasma current, which induces magnetic shear, in Heliotron J. The EPM amplitude obviously decreases by increasing $I_{p}$ regardless of its sign.
negative magnetic shear around EPM location due to the finite beta effect. When the plasma current overcomes \( I_p = 0.4 \text{ kA} \), EPMs with \( |m|/n=2/1 \) suppressed and another EPMs with \( |m|/n=0/1 \) are additionally observed. This EPM finally suppressed by the further increase of the plasma current, as shown in Fig. 2. Figure 3 shows the stabilization of GAEs by EC-driven plasma current. The \( |m|/n=4/2 \) GAE amplitude is one third times smaller than EPM amplitude and is completely disappeared when EC-driven plasma current reaches to \( |I_p| = 0.5 \). When plasma current overcomes 0.5 kA, \( |m|=0 \) GAEs also are observed and mitigated by further increase of plasma current.

The plasma current can change the rotational transform and shear Alfvén continuum. This effect causes the destabilization of another GAE.

We estimate that the continuum damping whose damping rate is changed by the plasma current is a key mechanism to suppress the observed FP-driven MHD instabilities in previous work. The new result including counter-ECCD experiment supports our previous estimation because the damping rate of continuum damping does not relate to the sign of magnetic shear, depends upon the absolute value of magnetic shear. Different EPMs and GAEs are observed when further EC-driven plasma current is driven. EC-driven plasma current also affect MHD equilibrium and may degrade transport. We conclude that moderate change of magnetic shear is better in low magnetic shear magnetic configuration like a Heliotron J.

The effect of ECCD on FP-driven MHD instabilities is also investigated in TJ-II which has also low magnetic shear and high rotational transform \( \tau/2\pi >1.0 \). The targeted FP-driven MHD instabilities is mainly HAE which is basically observed in the NBI-heated TJ-II plasma because of high rotational transform. In the TJ-II experiment, plasma current is consisted of bootstrap current, neutral beam current driven current which flows in the co. direction and EC-driven current which flows in the counter direction. In the NBI-heated plasma of TJ-II without both ECH and ECCD, plasma current flows in the co. direction and increases rotational transform which produces negative magnetic shear. The EC-driven counter plasma current prevents co-plasma current to produce positive magnetic shear at HAE location. We observed the change of amplitude of the observed HAE. The calculation of shear Alfvén spectra shows that the structure of shear Alfvén continua around HAE gap is changed by the change of plasma current.

This effect is also observed in LHD with high magnetic shear. Figure 4 shows clear destabilization and stabilization of GAEs and TAEs with frequency \( f_{obs} > 100 \text{ kHz} \), and EPMs with \( f_{obs} < 100 \text{ kHz} \) in the LHD plasma with high magnetic shear \( s \) when magnetic shear at plasma core is decreased and increased by co- and counter-EC driven plasma current, respectively. The main differences in plasma parameters between both cases are plasma current and magnetic fluctuations. The difference in the amplitude of plasma current can lead the difference of shear Alfvén continua in whole plasma region. According to reconstructed MHD equilibrium, which qualitatively agrees with the measurement of rotational transform profile by motional stark effect (MSE) diagnostics, co-ECCD and counter-ECCD induced the co and counter plasma current whose profile peaked at plasma core. This increases and

Fig. 3. Dependence of GAE amplitude on EC-driven plasma current, which induces magnetic shear, in Heliotron J. The GAE amplitude obviously decreases by increasing \( I_p \) regardless of its sign.

Fig.4. (a) Destabilization and (b) stabilization of TAEs, GAEs and EPMs due to co- and counter-ECCD in the NBI-heated LHD plasmas. Plasma current is ~20kA which decreases \( s \) in (a) and ~30kA which increases \( s \) in (b).
decreases the rotational transform, and then magnetic shear will be decreased and increased by co- and counter-ECCD plasma current. Figure 5 shows the shear Alfvén continua together with discrete eigenmode in co- and counter ECCD case. In the case of co-ECCD, TAE gap in shear Alfvén continua will be aligned from the core toward the edge and many discrete eigenmodes corresponding to TAE and GAE can exist. On the other hands, counter-ECCD, discrete eigenmodes tend to cross the shear Alfvén continua leading to continuum damping.

It is concluded that EC-driven plasma current affect both damping rate of the modes and structure of shear Alfvén continuum in these devises. Concerning GAE which is not frequency gap mode is affected by the change of continuum damping though the change of plasma current. On the other hands, TAE and HAE existence is strongly depended on structure of shear Alfvén continuum especially for around those gap.

3. EFFECT OF ECH ON FP-DRIVEN MHD INSTABILITIES

The FP-driven MHD instabilities are also suppressed by both on- and off-axis ECH in the TJ-II plasmas [8]. On the other hand, some FP-driven MHD instabilities are stabilized and the others are destabilized by ECH depending on ECH power and deposition location in the Heliotron J and LHD plasmas.

TJ-II has two ECH systems whose power and $N_e$ can be independently changed. We applied ECH one after another to increase ECH power, we observed decrease of amplitude of fluctuation of the observed FP-driven MHD instabilities and also observed the change of mode behaviour in time from continuous mode to bursting mode. This may be caused by the decrease of growth rate of the observed mode because bursting behaviour of the mode sometimes observed around near the threshold of destabilization of FP-driven MHD instabilities.

Effect of ECH on FP-driven MHD instabilities has been also studied experimentally in Heliotron J and LHD. In the Heliotron J experiment, we have single ECH to shear the plasma production and heating. We can scan (i) heating power position and power. We observed both stabilization and destabilization of FP-driven MHD instabilities in the ECH power, deposition and magnetic configuration scan experiment in Heliotron J. Figure 6 shows the typical time evolution of power spectrum density of magnetic fluctuation, diamagnetic plasma stored energy, line averaged electron density, plasma current and $H_a$ signal in the case of (a) the lowest ECH power $P=114$ kW and (b) the highest ECH power $P=282$ kW. ECH injection power is changed from 114 kW to 282 kW and deposition is adjusted to magnetic axis (on-axis), and $N_e$ is fixed to 0.0 for reduction of ECCD effect on the observed modes. We fixed the time evolution of line averaged density in each ECH power as much as possible by adjustment of gas puffing. The diamagnetic stored energy of higher ECH power is higher than that of lower ECH power because of increasing electron temperature. Electron density and temperature profile measured by Thomson scattering data support diamagnetic stored plasma energy. It seems that...
mode amplitudes of the observed mode decreased by the increasing ECH power as shown in Figs. 6. Figure 7 shows the dependence of EPM and GAE amplitude on ECH injection power in Heliotron J. The EPM and GAE amplitude is slightly decreased and clearly decreased with increasing ECH power when on-axis ECH condition. According to linear theory of growth rate of mode, increasing electron temperature leads the increasing growth rate of mode due to the increasing fast ion beta $<\beta_f>$. Since the local pressure gradient of fast ion can contribute the destabilization of FP-driven MHD instabilities, we scanned the ECH deposition location in Heliotron J, as shown in Fig. 8. Here, the deposition location is controlled by changing the injection angle of EC wave. The GAE amplitude decreases with increasing ECH power for on-axis ECH. When ECH deposition is close to the GAE location $r/a \sim 0.6$, the GAE amplitude is larger than that for on-axis ECH. These dependences indicate that both the change of fast ion profile by ECH through the change of electron density and temperature, and/or the collisional damping due to trapped fast electrons may affect the AE stability.

4. CONCLUSION

In order to develop the method to control the observed EPMs and AEs in Stellarator/Heliotron, we investigate the effect of ECH/ECCD on EPMs/AEs in three devices, LHD, TJ-II and Heliotron J based on the similarities and differences, e.g. magnetic shear, toroidal field period. In a low shear device, the increasing continuum damping of the modes by increase in magnetic shear due to EC-driven plasma current is effective. In a high shear device, the modification of shear Alfvén spectrum is more important effect than continuum damping. ECH (non-ECCD) also impact on EP-driven EPMs/AEs. A candidate to explain this phenomenon is modification of $<\beta_{fast}>$ and/or collisional damping by trapped electrons.

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