Effect of ECH/ECCD on energetic-particle-driven MHD modes in helical plasmas

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Abstract

The effect of electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) on energetic-particle (EP)-driven magnetohydrodynamic (MHD) modes is studied in the helical devices LHD, TJ-II and Heliotron J. We demonstrate that EP-driven MHD modes, including Alfvén eigenmodes (AEs) and energetic particle modes (EPMs), can be controlled by ECH/ECCD. In the LHD device, which has a moderate rotational transform and a high magnetic shear, co-ECCD enhances toroidal AEs (TAEs) and global AEs (GAEs), while counter-ECCD stabilizes them, which improves the neutron rate compared with the co-ECCD case. Counter-ECCD decreases the core rotational transform and increases the magnetic shear, strengthening the continuum damping on the shear Alfvén continua (SAC). In the TJ-II device, which has a high rotational transform, moderate magnetic shear and low toroidal field period, helical AEs (HAEs) appear when the HAE frequency gap of the SAC is changed by counter-ECCD combined with a bootstrap current and neutral-beam-driven current. On the other hand, both co- and counter-ECCD are effective in stabilizing GAEs and EPMs in the Heliotron J device, which has a low rotational transform and low magnetic shear. The experimental results indicate that the magnetic shear has a stabilizing effect regardless of its sign. Modeling analysis using the FAR3d code shows that the growth rates are reduced by both co- and counter-ECCD in Heliotron J, reproducing the experimental results.
ECH only affects EP-driven MHD modes, and the experimental results show that the effect depends on the magnetic configuration. In Heliotron J, some modes are stabilized with an increase in ECH power in the low-bumpiness magnetic configuration, while some modes are destabilized in the high- and medium-bumpiness magnetic configurations.

**Keywords:** energetic-particle-driven MHD mode, ECH/ECCD, helical plasma

(Some figures may appear in colour only in the online journal)

1. **Introduction**

In magnetically confined fusion plasmas, energetic particles (EPs) generated by D–T fusion reactions and plasma heating interact resonantly with shear Alfvén waves through slowing-down processes when their velocity is comparable to the Alfvén velocity, resulting in the excitation of EP-driven magnetohydrodynamic (MHD) modes. The EP-driven MHD modes include Alfvén eigenmodes (AEs) and energetic particle modes (EPMs), and have been experimentally observed in tokamaks and helical devices (see the reviews [1–3]). Since these modes enhance the anomalous transport of EP and induce EP loss, which reduces heating efficiency and damages the first wall, it is important to stabilize and/or control the EP-driven MHD modes. Studies have been made on the physical properties of specific modes, and several external actuators have been proposed and demonstrated in tokamaks and helical devices for controlling and/or stabilizing EP-driven modes [4]. Promising control techniques are based on (i) varying the energetic-ion sources to modify the gradients in the energetic ion-distribution [5–10], (ii) localized electron cyclotron heating (ECH) to modify the energetic-ion slowing-down distribution [11–18], (iii) a localized electron cyclotron current drive (ECCD) for modifying the equilibrium [19, 20] and (iv) externally applied 3D perturbative magnetic fields for manipulating the energetic-ion distribution and thus the wave drive [21, 22].

ECH/ECCD is an ideal technique to control the EP-driven MHD modes, since it can provide highly localized EC waves with a known location and good controllability. According to linear MHD theory, the changes in electron density and temperature by ECH and in the plasma current by ECCD can affect both the growth and damping rates of the EP-driven MHD modes through changes in (i) the pressure gradient of the energetic ions, (ii) the structure of the shear Alfvén continua (SAC) through a change in the magnetic configuration and (iii) electron Landau damping. In the DIII-D tokamak, for example, reversed shear AEs (RSAEs) were stabilized by applying a localized ECH near the minimum of the magnetic safety factor in a neutral beam (NB) heated discharge with reversed magnetic shear [11, 12]. The effect of ECH on RSAEs is due to an increase in the frequency of a geodesic acoustic mode (GAM) through the increase in electron temperature. In helical devices, ECH/ECCD is also expected to be an effective technique to control EP-driven MHD modes. For instance, in the TJ-II helical device, the behavior of AEs was changed from a steady mode to a chirping mode when ECH power was applied to a neutral beam injection (NBI) plasma [16]. Further off-axis electron cyclotron resonance heating (ECRH) power resulted in a strong reduction of the chirping mode amplitude [17, 18]. In the Heliotron J helical device, it was demonstrated that EPMs and global AEs (GAEs) were stabilized by both co- and counter-ECCD [19, 20].

In this paper, we report recent progress in the control of EP-driven MHD modes with ECH/ECCD in the helical device LHD, TJ-II and Heliotron J. EP-driven MHD modes, including toroidal AEs (TAEs), GAEs, helical AEs (HAEs) and EPMs, are observed in tangential NBI-heated plasmas of the helical devices. Since the stability of the EP-driven MHD modes depends on the magnetic configuration, comparative studies among the three devices based on similarities and differences in the configuration are useful for a comprehensive understanding of the physics of EP-driven MHD modes in toroidal plasmas. We employ ECH and ECCD in order to mitigate and eventually suppress the observed EP-driven MHD modes. Although the EC-driven current in helical devices is not high, because there are a few 10 kA in LHD and a few kA in TJ-II and Heliotron J, due to a strong Ohkawa effect [23]. ECCD is effective for tailoring the rotational transform (inverse safety factor: l/q) profile, particularly at the core region, since the poloidal magnetic field generated by ECCD is comparable to the vacuum poloidal magnetic field. Localized ECH changes the local electron temperature and its gradient significantly, affecting the driving and damping terms of EP-driven MHD modes.

The paper is organized as follows. The EP-driven MHD modes in the helical plasmas are described in section 2. Experimental and theoretical results on the ECCD effect on the EP-driven modes are given in section 3 and experimental results on the ECH effect are given in section 4. A summary is presented in section 5.

2. **EP-driven MHD modes in helical plasmas**

The EP-driven MHD modes are commonly observed in tokamaks and helical devices. The modes excited by the poloidal mode coupling such as TAE in helical devices has no significant differences to those in tokamaks [3]. The difference between tokamaks and helical devices is related to the magnetic field structure, that is, tokamaks are two dimensional (2D) and axisymmetric in an ideal case while helical devices are three dimensional (3D). In helical devices, a spectral gap is generated by the toroidal mode coupling as well as the poloidal mode coupling, which can result in EP-driven MHD modes such as HAE being excited. However, it should be noted that
Table 1. Device and plasma parameters of the LHD, TJ-II and Heliotron J devices in the plasma experiments for EP-driven MHD modes reported in this paper.

|                     | LHD                  | TJ-II                | Heliotron J          |
|---------------------|----------------------|----------------------|----------------------|
| Major radius        | 3.9 m                | 1.5 m                | 1.2 m                |
| Minor radius        | 0.6 m                | ≤0.22 m              | <0.2 m               |
| Field period        | 10                   | 4                    | 4                    |
| Magnetic field on axis | 1.375 T          | 0.95 T               | 1.25 T               |
| Rotational transform| 0.4–1.2              | 1.5–1.7              | 0.57                 |
| Magnetic shear      | High                 | Moderate             | Low                  |
| Working gas         | D2                   | H2                   | D2                   |
| NBI system          | 18.8 MW D2 (co and counter) | 1.4 MW D2/H2 (co and counter) | 1.6 MW H2 (co and counter) |
| ECH/ECCD system     | 77 GHz 2nd X-mode 1.0 MW (0.5 MW × 2) | 53.2 GHz 2nd X-mode 0.5 MW (0.25 MW × 2) | 70 GHz 2nd X-mode 0.4 MW |
| n_e                 | 0.2–1.0 × 10^{19} m^{-3} | 0.3–0.8 × 10^{19} m^{-3} | 0.5–1.1 × 10^{19} m^{-3} |
| T_e(0)              | 2 keV                | 0.4–1.5 keV          | 0.5–0.8 keV          |
| v_{beam}/V_{A} (n_e ~ 0.5 × 10^{19} m^{-3}) | ~0.62               | ~0.25                | ~0.38                |

The 3D effect also appears in tokamaks due to toroidal field ripple, applied resonant magnetic perturbation and deformation caused by large-scale MHD instabilities. The LHD, TJ-II and Heliotron J devices are categorized as helical systems. Although the magnetic configuration is generated by external coils in each of these devices, their magnetic configurations are different. The main parameters of the three devices for our experiments are summarized in table 1. The toroidal mode coupling in helical devices depends on the number of toroidal field period. The rotational transform profile affects the mode structure and growth rate. The LHD device has a large toroidal field period and moderate rotational transform with high magnetic shear, the TJ-II device has a low toroidal field period and low rotational transform with moderate magnetic shear, and the Heliotron J device has a low toroidal field period and low magnetic shear. These differences allow us to observe a variety of EP-driven MHD modes, as described in this section. In this paper, tangential NBI and ECH/ECCD are used for the excitation and suppression of EP-driven MHD modes. The co-direction of the plasma current refers to the toroidal current direction that increases the rotational transform.

LHD is a large helical device whose magnetic configuration is produced by a set of helical winding coils and three sets of poloidal field coils, which all use superconducting magnets [24]. The magnetic configuration is characterized by a high magnetic shear and high toroidal field period, \( N_f = 10 \). The injection power of the tangential deuterium NBI is 18.8 MW, and negative-ion-based NBIs produce NBs with a beam energy of 180 keV. Two launcher systems for the second-harmonic 77-GHz X-mode of 0.5 MW each are used for ECH/ECCD. Since neither of the launching systems is allowed to be used for perpendicular injection due to safety of the divertor plates, balanced ECCD injection is used if no EC-driven current is desired.

TJ-II is a medium-sized heliac-type helical device [25, 26]. Its magnetic configuration is characterized by a high rotational transform and low toroidal field period, \( N_f = 4 \), a moderate magnetic shear and a magnetic well for good pressure-driven MHD stability. Plasmas are produced by 53.2 GHz second-harmonic X-mode ECH, and heated by both ECH and tangential NBI. The ECH/ECCD system consists of two 53.2 GHz gyrotrons of 0.25 MW power each. Two NBIs with beam energies of 30–32 keV, which deliver up to 0.7 MW port-through power per injector, provide co- and counter-sub-Alfvénic H\(_0\) beams (\( V_{\text{beam}}/V_A \approx 0.2 – 0.3 \)) for a line-averaged density of around \( 0.5 \times 10^{19} \text{ m}^{-3} \). Here \( V_{\text{beam}} \) and \( V_A \) are the beam velocity and the Alfvén velocity, respectively. The experiments described in this paper were carried out using only the co-direction injector in deuterium plasmas.

Heliotron J is a medium-sized helical device [27, 28]. Its coil system is composed of an \( L = 1 \), \( M = 4 \) helical coil, with two types of toroidal coils A and B, and three pairs of vertical field coils. Here, \( L \) and \( M \) are the pole number and field period corresponding to the toroidal field period \( N_f \),...
The magnetic configuration can be controlled by varying the current ratios in each coil, allowing us to investigate the role of the magnetic configuration on confinement and transport. Three configurations are chosen in this paper, the high-, medium- and low-bumpiness configurations with fixed toroidicity, helicity, rotational transform and plasma volume [29], where bumpiness means the toroidal variation of the magnetic field strength. The magnetic well is formed in the whole confinement region, as for TJ-II [30]. Plasmas are produced and heated by second-harmonic X-mode 70 GHz ECH and NBI. Two NBI tangential hydrogen beam lines, BL1 and BL2, are used, both of which have a maximum acceleration voltage of 30 kV and a maximum power of 0.8 MW. The injected ECH power is as high as 0.3 MW and the NBI power is as high as 1.3 MW in total in the experiment reported here.

Figure 1 shows rotational transform profiles in vacuum from LHD, TJ-II and Heliotron J. The LHD device has a rotational transform of $u/2\pi = 0.4-1.15$ and a relatively high magnetic shear. The TJ-II and Heliotron J devices have similar plasma/device parameters, namely a low toroidal field period and weak magnetic shear, but different rotational transform profiles. The rotational transform for TJ-II is high ($u/2\pi \approx 1.6$) while it is low ($u/2\pi \approx 0.6$) for Heliotron J. A variety of EP-driven MHD modes are often observed in helical devices, depending on the magnetic configuration parameters such as the rotational transform profile and toroidal field period.

It is worth comparing the typical frequencies of the Alfvén gap modes associated with the dominant coefficients $\epsilon^{\mu\nu}(\rho)$, of the magnetic field spectrum, where $\rho$ is the square root of the toroidal magnetic flux. The dependence of Alfvén gap mode frequency on the rotational transform can be estimated using a cylindrical approximation for the longitudinal wave vector of the $n$ (poloidal mode number) and $m$ (toroidal mode number) perturbation, given by $k_\parallel(\rho) = (m\rho/2\pi - n)/R$. Following [31], we may write the characteristic Alfvén gap ‘frequency’ as $\omega(\rho) = |k^{\mu\nu}(\rho)|v_A(\rho)$, where $k^{\mu\nu}(\rho) = (\mu(\rho)/2\pi - \nu N_\rho)/2R$ and $v_A(\rho) = B(\rho)/\sqrt{\mu_0 n_i(\rho)m_i}$ is the Alfvén velocity, which depends on the magnetic field ($B$), ion density ($n_i$) and ion mass ($m_i$). For the present purpose, we can use the rotational transform instead of $\rho$ as an independent variable, in a range appropriate for each device (see figure 1) and take constant values for the magnetic field and density in each case. Figure 2 shows the characteristic frequencies of the Alfvén gap modes, i.e. TAE ($\mu = 1, \nu = 0$), ellipticity AE (EAE) ($\mu = 2, \nu = 0$), non-circular AE (NAE) ($\mu = 3, \nu = 0$), HAE ($\mu = 1, \nu = 1$), HAE ($\mu = 2, \nu = 1$) and HAE ($\mu = 3, \nu = 1$). A range of ion densities ($n_i = 0.8 \times 10^{19} m^{-3}$) is taken to evaluate $v_A(B)$ as a function of the on-axis magnetic field for each device. For the magnetic field used in the experiments, moderate frequency TAEs ($\nu = 0$) are expected in the LHD plasmas because of its larger size and low iota values, while the TAE gap is located at a higher frequency in TJ-II and Heliotron J. In TJ-II, very faint activity is sometimes observed in the TAE frequency range [32]. HAE gaps in the frequency ranges studied in the experiments only appear for the TJ-II due to its larger rotational transform, while they occur at much higher frequencies for LHD and Heliotron J (above 1 MHz for $B_1 > 1 T$).

Besides the Alfvén gap modes, GAEs are observed for TJ-II and Heliotron J because of the low/moderate magnetic shear favoring the existence of extrema in the SAC. EPMs are also observed when the plasma density is less than a critical density for which the energetic ion beta is comparable to the bulk plasma beta and exceeds the strong continuum damping. The details of the mode characteristics can be found in [3, 20, 33-35]. An accurate calculation of the Alfvén continuum that considers the real magnetic configuration of each device may be obtained by means of the STELLGAP code [36], as shown in figure 3. The EP-driven MHD modes experimentally observed in the LHD, TJ-II and Heliotron J are summarized in table 2. The modes in the ECH/ECCD experiments reported in this paper are TAEs, GAEs and EPMs in LHD, HAEs and GAEs in TJ-II and GAEs and EPMs in Heliotron J.

3. ECCD effect on EP-driven modes

3.1. ECCD effect in LHD

ECCD drives the localized plasma current whose amplitude and location can be controlled by the parallel refractive index, $N_i$, of the launched EC waves. Co-ECCD injection increases the rotational transform, while counter-ECCD decreases it. Co-ECCD, balanced-ECCD (ECH only) and counter-ECCD have been applied to NBI plasmas in LHD to study the effect...
Figure 3. Typical vacuum SAC in (a) LHD, (b) TJ-II and (c) Heliotron J. LHD has strong magnetic shear and a high toroidal field period. TJ-II has a high rotational transform, low magnetic shear and low toroidal field period. Heliotron J has a low rotational transform, low magnetic shear and low toroidal field period.

Table 2. EP-driven MHD modes experimentally observed in the LHD, TJ-II and Heliotron J devices.

|                | LHD       | TJ-II     | Heliotron J |
|----------------|-----------|-----------|-------------|
| EP-driven MHD modes | TAE       | HAE       | GAE         |
|                 | GAE       | EPM       | GEM         |
|                 | GAM       | EPM       | GAE         |
|                 | EP-driven resistive interchange mode (EIC) | | |

*The observation of TAE in TJ-II still awaits confirmation.

Figure 4. Time evolution of magnetic spectrogram, electron density, plasma current and heating power in LHD: (a) co-ECCD, (b) ECH (balanced-ECCD) and (c) counter-ECCD.

of plasma current on EP-driven MHD modes. Figure 4 shows the time evolution of a magnetic spectrogram obtained from a Mirnov coil, plasma current and heating power. The plasma current is approximately –(20–30) kA for co-ECCD, 5 kA for balanced ECCD and 10–20 kA for counter-ECCD at a line-averaged electron density of \( n_e \approx 1.0 \times 10^{19} \) m\(^{-3}\). Here, a positive plasma current corresponds to the direction that decreases the rotational transform because of the reversed magnetic field. The contribution of the bootstrap current and NB-driven current to the total plasma current is weak in these discharges because of the balanced NB injection and relatively low density. A Thomson scattering diagnostic confirms that the electron density and temperature profiles are almost the same in this \( N_t \) scanning experiment, meaning that the contribution of ECH is the same in all three cases. For co-ECCD, TAEs and GAEs with \( f > 100 \) kHz and EPMs with an observed frequency of \( f < 100 \) kHz are excited, and frequency chirping is observed. The toroidal mode numbers are \( n = 1–5 \), depending on the observed modes, and the modes rotate in the ion diamagnetic direction. It can be seen that the modes are mitigated by the balanced-ECCD corresponding to ECH only and are suppressed completely with counter-ECCD. Figure 5 shows the rotational transform profiles experimentally measured with a motional Stark emission (MSE) diagnostic in LHD. The core rotational transform increases to about 0.55 and the magnetic shear is weakened for co-ECCD, while the core rotational transform decreases to about 0.25 and the magnetic shear is strengthened for
counter-ECCD. The same tendency of mode excitation and stabilization has been observed at a lower electron density of $<n_e> = 0.5 \times 10^{19} \text{ m}^{-3}$.

A change in plasma current can modify the SAC through a change in the rotational transform for the whole plasma region. Figure 6 shows the SAC together with discrete eigenmodes for co-, balanced and counter-ECCD in LHD, calculated by the STELLGAP and AE3D codes [37]. The TAE frequency gap in SAC is well aligned from the core towards the edge and many discrete eigenmodes corresponding to TAE and GAE can exist for co-ECCD. On the other hand, for counter-ECCD, discrete eigenmodes tend to intersect with the SAC, which suffers from continuum damping.

Mode suppression affects the core plasma performance in LHD. Figure 7 shows the measured neutron rate as a function of electron density for co- and counter-ECCD in LHD. The NB power is 3.2–3.3 MW and the EC power is 0.6 MW. It can be seen that the neutron rate for counter-ECCD is higher than that for co-ECCD, indicating that the mode suppression improves plasma performance. Suppression of the EP-driven MHD modes may reduce the direct loss of energetic ions. Further study is required to clarify the physical mechanism of the suppression effect of the EP-driven MHD mode on bulk plasma heating.

3.2. ECCD effect in TJ-II

In TJ-II, the targeted EP-driven MHD modes are mainly HAEs and GAEs, which are observed in NB-heated plasmas because of the high rotational transform, low magnetic shear and low toroidal field period (see figure 3). The contributions to the total plasma current are bootstrap current, NB-driven current and EC-driven current. In the NB-heated plasma without ECH/ECCD (see figure 8(a)), the core NB-driven current flows in the co-direction while the broad bootstrap current flows in the counter-direction [38]. As a result, the total plasma current increases the core rotational transform producing a negative magnetic shear. Adding on-axis ECH power during the NBI phase (from 1170 to 1230 ms) induces a strong pump-out effect that lowers the plasma density (see figure 8(b)). This affects the bootstrap current and degrades the NBI absorption efficiency as well as NB current drive (NBCD) performance. Consequently, the rotational transform profile changes and the SAC is modified. Finally, the same ECH power can be injected obliquely ($N_t = 0.2$) to induce counter-ECCD without modifying the plasma profiles. The effect of ECCD is clearly observed in the magnetic spectrogram (see figure 8(c)). In the discharges with ECH but no ECCD and ECH with ECCD, the line-averaged density is $0.5–0.6 \times 10^{19} \text{ m}^{-3}$, the electron density and temperature profiles barely change and only the plasma current measured in the ECCD case exhibits slight, but significant modification ($\Delta I_p \approx -0.7 \text{ kA}$) with respect to the non-ECCD case.

No rotational transform measurements are available for TJ-II. However, we may estimate the rotational transform profile and the changes in the different heating conditions by calculating the bootstrap current, NBI-driven current and EC current contributions and then recalculating the plasma equilibrium using the VMEC code [39] with the estimated current profiles. Then, using the STELLGAP code, we obtain the SAC for these experimental cases and the mode families typical of a four-period device. The results are shown in figure 9 for the $n = 1$ family. The details of the calculation conditions are described in [38]. Simulations for determining the growth rate of the main modes have been carried out using the FAR3D code [40–42], which solves the reduced linear resistive MHD equations and moment equations of the energetic ion density and parallel velocity [43, 44], including the linear wave-particle resonance effects required for Landau damping/growth and the parallel momentum response of the thermal plasma required for coupling to the geodesic acoustic waves [45]. The code variables evolve starting from the equilibrium calculated by the VMEC code. The FAR3D simulation shows that the observed steady mode around 250 kHz is consistent with an $n/m = 9/6$ HAE$_{21}$ mode [32].

A TAE gap is also predicted at higher frequencies, and very faint activity is observed at frequencies compatible with those predicted. For the structure of the SAC shown in figure 9, it appears that the HAE$_{21}$ gap becomes wider as the iota profile evolves from the NBI only to the NBI + counter-ECCD case, thus favoring the presence of the steady mode in the NBI + counter-ECCD case. Given the high sensitivity of the SAC to rotational transform variations, the uncertainties related to the current density calculations, which have not been included in the analysis, need to be assessed to check the robustness of the result.

3.3. ECCD effect in Heliotron J

Although suppression of the EP-driven MHD mode amplitude by ECCD has also been observed in Heliotron J plasmas, the dependence on the direction of the EC-driven current is
The GAE amplitude with $m/n = 4/2$ is one-third smaller than the EPM amplitude with $m/n = 2/1$ and completely disappears when the EC-driven plasma current reaches $|I_p| = 0.5$ kA. When the plasma current exceeds 0.5 kA, GAEs with $n = 0$ are observed and mitigated by further increases in the plasma current. It is hard to estimate the effect on global confinement in this experiment, since the stored energy measured with a diamagnetic loop does not have sufficient accuracy due to the low density. Since Heliotron J has a low magnetic shear, co- and counter-ECCD make the magnetic shear negative and positive, respectively. The SACs are not greatly modified even when the ECCD is applied [20]. These results indicate that the modes are suppressed by variations in the magnetic shear regardless of its sign.

A modelling analysis was performed for Heliotron J using the FAR3d code again. The EPM frequency with $n = 1$ is 89 kHz and the GAE frequency with $n = 2$ is 145 kHz, a similar frequency range to those observed in the experiment. Figure 12 shows the dependence of the mode growth rates on the central rotational transform. A counter-ECCD injection that leads to a central rotational transform located between $[0.4, 0.56]$ increases the EPM/GAE growth rate, because the rational surface of $\iota = 1/2$ appears in the plasma and the mode destabilizing effect is enhanced, overcoming the stabilizing effect of the magnetic shear. If 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, resulting in a decrease in EPM/GAE growth rate. On the other hand, the co-ECCD injection decreases the EPM/GAE growth rate because the destabilizing effect of the 1/2 rational surface is weakened and the negative magnetic shear is enhanced as the central rotational transform increases. The effect of magnetic shear enhancement decreases the EPM/GAE growth rate. The simulation result reproduces the suppression of the EPM/GAE as the EC-driven current increases, as well as the threshold with respect to the counter-ECCD intensity observed in the experiments. The details of the simulation results will be reported in a forthcoming paper.

It is concluded that the EC-driven plasma current affects both the damping rate of the modes and the SAC structure in the three devices. The appearance of TAEs and HAEs strongly depends on the structure of the SAC, especially around those gaps. On the other hand, the GAEs and EPMs, which are not
Figure 8. Magnetic fluctuations during the NBI phase in TJ-II. Reference shots without ECRH (#44257, (a)), with ECRH and no ECCD (#44272, (b)) and with ECCD (#44274, (c)) are shown.

a frequency gap mode, are stabilized by the enhancement of continuum damping through the change in magnetic shear.

4. ECH effect on EP-driven MHD modes

The effect of ECH on EP-driven MHD modes was previously studied for CHS [15] and TJ-II [16]. In TJ-II, a significant reduction of the EP-driven mode amplitude was observed when the ECH power was doubled. It was also observed that some continuous modes changed into chirping modes in association with a decrease in their amplitudes when ECH was applied. This may have been caused by a decrease in the growth rate of the observed mode because bursting behavior of the mode is sometimes observed around the threshold of destabilization of the EP-driven MHD modes.

The ECH effect on the modes has also been observed for Heliotron J. Figure 13 shows the magnetic spectrograms in the low-bumpiness configuration. The on-axis EC power was scanned from 109 to 308 kW with the electron density and NB power fixed at \( n_e = 0.6 \times 10^{19} \text{ m}^{-3} \) and \( P_{NB} = 650 \text{ kW} \). \( \rho \| \) was fixed at 0.0 to exclude the ECCD effect on the observed modes so that the plasma current is almost constant, \( I_p \sim 0.5 \text{ kA} \). The central electron temperature, measured with a Thomson scattering diagnostic, ranged from 0.4 to 0.9 keV. The EPM amplitude at 100 kHz reduces with an increase in EC power, and the GAE amplitude at 140 kHz also reduces, although the amplitude increases slightly at 308 kW.

Figure 9. Shear Alfvén spectra of the \( n = 1 \) family for (a) NBI, (b) NBI + ECRH and (c) NBI + ECCD, showing the strong effect of changes in the rotational transform profile in TJ-II. TAE and HAE gaps are indicated.
Figure 10. Dependence of EPM amplitude on EC-driven plasma current, which induces magnetic shear, in Heliotron J. EPM amplitude clearly decreases for increasing $I_p$ regardless of its sign.

Figure 11. Dependence of GAE amplitude on EC-driven plasma current, which induces magnetic shear, in Heliotron J. GAE amplitude clearly decreases for increasing $I_p$ regardless of its sign.

The above tendency is similar to the TJ-II result, but the behavior is different for other magnetic configurations. Figure 14 shows the amplitudes of the observed main modes for three kinds of magnetic configuration in Heliotron J. The mode amplitudes are estimated from the density fluctuations measured by beam emission spectroscopy. For the low-bumpiness configuration, the modes are mitigated with an increase in ECH power, while the mode behavior is not simple in the high- and medium-bumpiness configurations. In the high-bumpiness configuration, the GAE at 90 GHz is monotonically suppressed as the EC power increases, but the EPM at 100 kHz is destabilized. In the medium-bumpiness configuration, the GAE at 100 kHz is suppressed and the EPM at 120 kHz is not a monotonic function.

Since the local pressure gradient of energetic ions can contribute to destabilizing EP-driven MHD modes, we scanned the ECH deposition location in Heliotron J, as shown in figure 15. Here, the deposition location is controlled by changing the EC injection angle poloidally. The GAE amplitude decreases with increasing ECH power for on-axis ECH.
Figure 12. Simulation results on the growth rates of 2/4 GAE and 1/2 EPM in Heliotron J.

Figure 13. Magnetic spectrogram of NBI + ECH plasmas in Heliotron J. ECH power is scanned from 109308 kW. Electron density is $n_e = 0.6 \times 10^{19}$ m$^{-3}$ and the NB power is 650 kW. No EC current is driven.

When the ECH deposition is close to the GAE location, $r/a \approx 0.6$, the GAE amplitude is larger than that for on-axis ECH. These dependences indicate that both the change in energetic ion profile by ECH may affect mode stability through the change in electron density and temperature and/or the collisional damping due to trapped energetic electrons [46].

According to linear theory, the increase in electron temperature increases the mode growth rate due to the increasing energetic ion beta $\beta_{\text{fast}}$. Changes in the thermal plasma profiles induced by ECH may affect the AE stability through modifying the driving and damping terms. Such behavior is similar to the ECH effect in tokamaks [4]. The observed change in RSAE by ECH in DIII-D and ASDEX-Upgrade
is due to a combination of mode excitation, damping and eigenmode, which complicates the ECH effect. Further experimental and theoretical study is required to clarify the ECH effect.

5. Summary

We have studied the effect of ECH/ECCD on the EP-driven MHD modes including TAEs, HAEs, GAEs and EPMs in the helical devices, LHD, TJ-II and Heliotron J, based on their similarities and differences, that is, rotational transform, magnetic shear and toroidal field period. The experimental and theoretical results show that ECH/ECCD is an effective tool for controlling these modes and provides information for understanding the physical mechanism. The experimental results from applying ECCD show that the modes can be controlled by a change in SAC and the continuum damping due to the magnetic shear effect. Comparison of the results among three devices clarifies the two damping mechanisms. Although ECH (non-ECCD) can also influence EP-driven MHD modes, the response to ECH is complicated compared with that of ECCD, depending on the modes and configurations. In Heliotron J, some modes in the low-bumpiness configuration are stabilized with an increase in ECH power, while it depends on the modes in the high- and medium-bumpiness configurations. Further study is required to clarify the mechanism of the ECH effect.

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