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ECH Launching Conditions in Helical System

NAGASAKI Kazunobu*, EJIRI Akira[1], MIZUUCHI Tohru, BESSHOU Sakae[2], FUNABA Hisamichi[1], IDA Katsumi[1], KONDO Katsumi[2], MORIOKA Hiroshi[2], OBIKI Tokuhiro, OKADA Hiroyuki, SANO Fumimichi and ZUSHI Hideki[2]

Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan
[1]National Institute for Fusion Science, Toki 509-5292, Japan
[2]Graduate School of Energy Science, Kyoto University, Uji 611-0011, Japan

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Abstract

Launching conditions for electron cyclotron heating (ECH) are studied on Heliotron E. In heliotron/torsatron configurations, the polarization of the launched wave should be determined by taking into account the effect of magnetic shear. The best-localized heating is obtained when the electric field of the launched wave is off-normal to the resonant magnetic field even for perpendicular beam injection. The experimental results are in good agreement with the numerical calculation results including the magnetic shear terms.

Keywords:

heliotron/torsatron, electron cyclotron heating, magnetic shear, polarization

1. Introduction

Electron cyclotron heating (ECH) is recognized as an important heating scheme for producing and heating currentless plasmas in helical system [1,2]. The ECH power is preferably absorbed in a single path for localized heating, effective current drive and accurate transport study. The launching conditions have been determined only by the direction of the resonant magnetic field so far. In heliotron/torsatron configurations, however, the magnetic shear is so strong that it can affect the wave propagation and absorption. The launched millimeter wave is coupled to propagating modes such as ordinary (O-) and extraordinary (X-) at the plasma peripheral region where the magnetic field direction is different from the resonant magnetic field direction. The polarization of the electron cyclotron wave rotates with the magnetic field in the plasma, and the wave does not reach the resonance layer with the same polarization it had at its source. Furthermore, the propagating modes do not propagate independently due to the mode coupling. It is important to control the polarization of the launched wave in order to obtain high single pass absorption even for perpendicular beam injection.

Effect of magnetic shear has been studied from a viewpoint of diagnostics such as electron cyclotron emission, polarimetry and reflectometer. Bell *et al.* [3] investigated the polarization rotation of the third harmonic X-mode from a plasma in ATF. The polarization rotation in approximately 15 deg increments was observed. We apply the method used for the plasma diagnostics to the ECH.

In this paper, the ECH launching conditions will be studied in heliotron/torsatron configurations. The propagation and absorption of the second harmonic O- and X-modes are calculated including the magnetic shear effect. The polarization control experiment in

*Corresponding author's e-mail: nagasaki@iae.kyoto-u.ac.jp

Heliotron E will be shown and compared with the calculation results.

2. Effect of Magnetic Shear on Wave Propagation and Absorption

In Heliotron E, the 106.4 GHz ECH power is injected perpendicularly from the horizontal port. In this poloidal section, the toroidal and poloidal magnetic field components are dominant, while the radial component is negligibly small, $|B_\rho/B| < 3\times10^{-5}$. The poloidal field component spatially varies, and is comparable with the toroidal field component at the plasma edge. The angle defined by $\theta=\cos^{-1}(B_\phi/B)$ changes from -50 deg to 45 deg through the propagation path, and the magnetic shear defined by $\phi=\mathrm{d}\theta/\mathrm{d}\rho$ ranges from -200 deg/m to -100 deg/m. Here B_ϕ and B are toroidal and total magnetic field strength, respectively. Note that the term, 'magnetic shear', is defined to be angular gradient in the radial direction, not the conventional plasma usage denoting the change in the rotational transform, $\mathrm{d}\iota/\mathrm{d}\rho$.

The propagation and absorption of second harmonic modes are numerically calculated by solving one-dimensional coupled equations that include the magnetic shear terms [4]. The magnetic field B is assumed to be sheared in a slab geometry. The cyclotron damping is included in this calculation, but thermal and relativistic effects on the propagation are neglected in order to clarify the shear effect. The polarization of the launched wave is determined by two parameters, the rotation angle, α, and the ellipticity, β.

Figure 1 shows the examples of the wave propagation in Heliotron E configuration. The launched wave is linearly polarized, and its electric field is normal to the resonant magnetic field. At $B(0)=1.84$ T, the resonance layer is located at the high field side (helical coil side), and the wave beam does not cross it. Both the X- and O-modes propagate without the cyclotron damping. It can be seen that the power fraction oscillates along the propagation path due to the mode coupling through the magnetic shear. At $B(0)=1.90$ T, the propagating modes cross the resonance layer, and the second harmonic X-mode is strongly damped at the resonance layer due to a thick optical depth, while the second harmonic O-mode are weakly damped. If we launch the ECH power on this polarization condition, only 63 % of the total power should be absorbed in the single path. The absorption rate is a function of the polarization parameters of the launched wave. It is a sinusoidal function of the rotation angle, α, and is also dependent on the ellipticity, β, and the rotation direction. The best single pass absorption is obtained at the condition, $\alpha=-35$ deg (closely perpendicular to the edge magnetic field), $\beta=15$ deg and left-hand rotation for typical density range in the Heliotron E plasma.

3. Experimental Results

Polarization control experiments have been conducted using the 106.4 GHz second harmonic ECH in Heliotron E. The launched beam is focused around the magnetic axis, passing through the magnetic axis [5]. A polarizer installed in the HE_{11} transmission line can control the polarization of the launched wave [6]. The polarization parameters, which have been measured experimentally in the low power (mW) test, are functions of a polarizer rotation angle. For the polarizer applied in this experiment, the electric field can be rotated arbitrarily by 180 deg, and its ellipticity is less than 20 deg.

A currentless plasma is produced by the 106.4

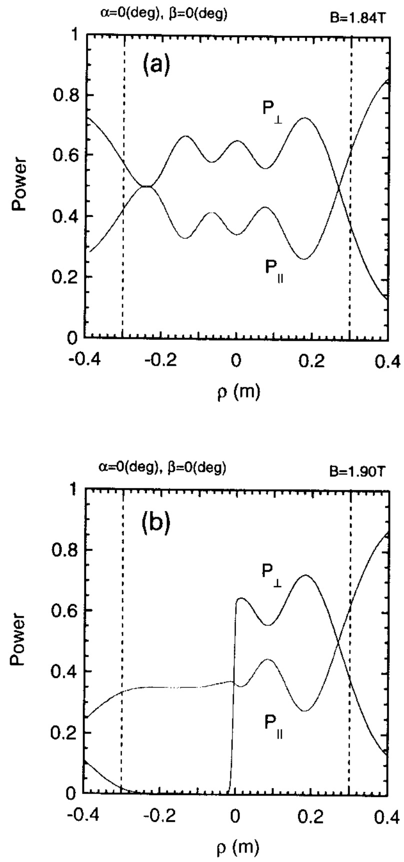

Fig. 1 Propagation and absorption of second harmonic electron cyclotron wave in Heliotron E plasma, (a) $B(0)=1.84$ T and (b) $B(0)=1.90$ T. The dashed line denotes the plasma boundary.

GHz ECH of 350 kW power, and then the NBI of 2 MW power is injected. During the NBI pulse, the ECH power is injected again. Since the plasma beta is low, $\bar{\beta} \le 0.5$ %, and the plasma current including bootstrap and Pfirsch-Schlüter currents are low, $I_p \le 3$ kA, a modification of the magnetic field configuration can be neglected. Since the power deposition profile could not be measured, the behaviour of the electron temperature was investigated as a measure of the single pass absorption rate. Figure 2 shows the dependence of measured electron temperature and calculated single pass absorption rate on the rotation angle, α, in both ECH and ECH+NBI plasmas. In the ECH plasma, the change in $T_e(0)$ is about 0.6 keV, depending on the polarization rotation angle. The maximum electron temperature is obtained when the electric field of the launched wave is off-normal to the resonant magnetic field. The

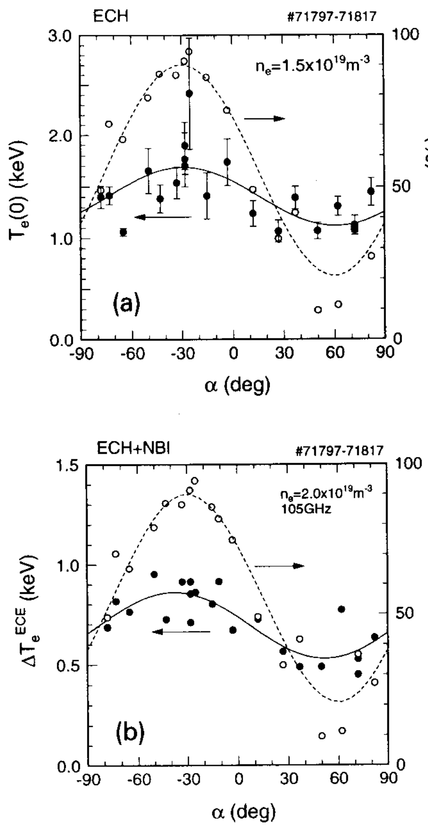

Fig. 2 Comparison of experimental and numerical calculation results: (a) central electron temperature of ECH plasma, (b) electron temperature increment of NBI plasma by superposing ECH. The open and closed circles denote the calculated single pass absorption rate and the measured electron temperature, respectively.

estimated tilting angles are −29 deg and −36 deg in ECH and ECH+NBI plasmas, respectively, which agree well with the calculated one, −30 deg.

The T_e profile can be controlled by the polarization. The peaking factor of the electron temperature, $\eta_{Te} = T_e(0)/T_e(a/2)$, ranges from 1.5 to 2.4 in the ECH plasma, indicating that the T_e profile changes from a broad one to a peaked one, which depends on the rotation angle. A similar tendency is found in B scanning experiments [7]. A slight decrease in the magnetic field strength makes a drastic decrease in the central electron temperature. The peaking factor, η_{Te}, changes from 1.2 to 2.8, when the central magnetic field increases from 1.86 T to 1.90 T. The resonance position around the center can not account for this change in the peaking factor. Although the resonance position is almost the same, $r/a \sim 0.15$, for $B(0)=1.88$ T and $B(0)=1.96$ T, η_{Te} is low ~2.0 at $B(0)=1.88$ T while it is kept ~2.6 at $B(0)=1.96$ T. This change can be explained by the single pass absorption. The critical magnetic field for $T_e(0)$ agrees well with that for the single pass absorption rate calculated by a ray tracing code. The calculated single pass absorption rate is 3 % at $B(0)=1.86$ T and 97 % at $B(0)=1.90$ T. Thus we may conclude that in the polarization control experiment, the peaked T_e profile is obtained at the single pass dominant X-mode heating, while the broad T_e profile is obtained at the multi-pass dominant O-mode heating.

The ion confinement is also affected by the wave polarization. It has been reported that a superposition of the second harmonic on-axis ECH degrades the ion confinement in the NBI plasma [8]. The central ion temperature starts to decrease after the ECH turn-on, and recovers after the ECH turn-off. The decrease in the ion temperature is up to 100 eV, and dependent on the polarization rotation angle. The tilting angle of the launched wave estimated from the ion temperature is −34 deg, indicating that the ion confinement is most degraded at the single pass dominant on-axis ECH.

4. Conclusion

The ECH launching conditions were studied in heliotron/torsatron configurations. The magnetic shear has an important role in the propagation and absorption of electron cyclotron wave. The polarization should be carefully controlled depending on the magnetic field structure even for the perpendicular launching case. Experimental results in Heliotron E showed that the best-localized heating is obtained when the electric field of the launched wave is off-normal to the resonant magnetic field. The tilting angles quantitatively agree with theoretical calculation results including the magnetic shear terms.

This physical mechanism holds true in other helical device such as CHS and LHD. The calculation results show that the best launching conditions are $\alpha=25$ deg, $\beta=15$ deg and right-hand rotation in 106.4 GHz ECH in CHS, and $\alpha=-30$ deg, $\beta=5$ deg and left-hand rotation for 84 GHz in LHD. The rotation angle has an opposite sign in CHS, because the helical coil has a right-handed winding in Heliotron E, while it has a left-handed winding in CHS.

These results also indicate that the conventional ray tracing code in which the modes are assumed to propagate independently may not give us the accurate wave propagation and absorption in heliotron/torsatron configurations. Improvement of the ray tracing code would be required.

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References

[1] V. Erckmann and V. Gasparino, Plasma Phys. Control. Fusion **36**, 1869 (1994).

[2] M. Wakatani and S. Sudo, Plasma Phys. Control. Fusion **38**, 937 (1996).

[3] G. L. Bell, R. F. Gandy and J. B. Wilgen, Nucl. Fusion **33**, 875 (1993).

[4] K. Nagasaki and A. Ejiri, Nucl. Fusion **35**, 609 (1995).

[5] K. Nagasaki *et al.*, Fusion Technol. **32**, 287 (1997).

[6] K. Nagasaki, A. Isayama and A. Ejiri, Rev. Sci. Instrum. **66**, 3432 (1995).

[7] K. Nagasaki *et al.*, *to be published in* J. Phys. Soc. Jpn. (1998).

[8] K. Ida *et al.*, *16th IAEA Fusion Energy Conference, Montreal, Canada, 1996, IAEA-CN-64/CP-5.*