*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.104 (2005)*

Measurement of Absorption and Scattering of High Power EC Waves in Heliotron J

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Abstract

High power electron cyclotron (EC) waves are measured in the helical-axis heliotron device, Heliotron J. The single pass absorption efficiency of the second harmonic X-mode is estimated by measuring the polarization of the EC waves after propagating in plasmas. The estimated efficiency is nearly 100 % at n_e=0.5×10^{19} m^{-3}, which is close to a ray tracing calculation result. Coherent modes of 10 kHz are observed in the millimeter waves scattering, which has a high correlation with density and magnetic fluctuations.

1. Introduction

The electron cyclotron heating system provides plasma production, electron heating and current drive in tokamaks and helical systems. The high single pass absorption of EC waves is desired for effective localized heating and current drive. The absorption efficiency and its profile are usually measured by several methods such as a heat transport analysis using electron cyclotron emission. In this paper, we present a method to estimate the power absorption efficiency of the second harmonic X-mode by measuring the wave polarization. The second harmonic O-mode is used as a reference signal. The high power EC waves are also considered as a tool to measure the density fluctuation. Coherent modes observed in the ECH plasmas are analyzed.

2. Experimental setup

Heliotron J is a helical-axis heliotron device to develop quasi-isodynamic configurations with continuous helical windings as a new heliotron concept [1]. Plasmas are routinely produced and heated by using a 70GHz 400kW ECH system. A non-focused Gaussian beam is injected from the top of the torus at the straight section where the B contour has a saddle type shape [2]. The polarization of injected waves is controlled by a polarizer assembled on a miter bend in the HE_{11} mode transmission line. Diode detectors are installed on the top and bottom ports at the same poloidal cross section as the ECH launcher. A SiN window tolerating high power EC waves is located at the facing port, through which the forward waves escape from the Heliotron J chamber. This corresponds that the forwardly scattering angle is nearly 0 deg. Since the forward wave power is as high as a few kW, an attenuator is inserted to reduce the EC power into mW level so as to use commercial crystal diode detectors safely. The detector is rotatable in 360 deg so that the polarization of forward waves can be measured. The other crystal diode detectors, which detect the two cross polarization waves simultaneously, are installed at a power monitor in the transmission line to measure the reflected waves.

3. Estimate of absorption efficiency

Figure 1 shows an example of the time evolution of ECH plasmas in Heliotron J. The magnetic field configuration is chosen to be "standard configuration", and the magnetic field strength is 1.25 T at the magnetic axis. The plasma is produced a few msec after the 70 GHz ECH is turned on. Before the plasma production, the waves propagate as electromagnetic waves in vacuum. We confirmed that the polarization of forward waves agreed with that expected from the launched polarization. As the electron density evolves, the finite signal with fluctuations is observed.

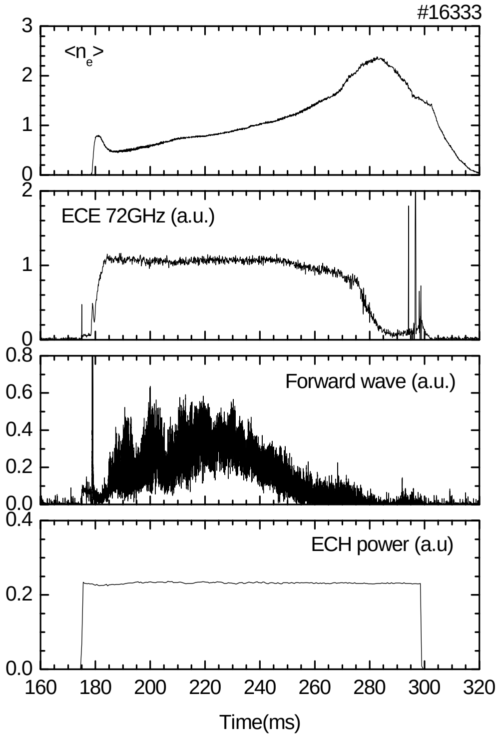

Fig. 1 Time evolution of ECH plasma in Heliotron J

The single pass power absorption of the second harmonic X-mode is examined based on the polarization measurement of the forward waves. The intensity ratio and phase difference between the X- and O-modes after propagating the plasma are determined by estimating the ratio of the maximum and minimum intensities of detector signal and their phase shift relative to the original waves. Suppose that the electric fields of the O- and X-modes are written as $E_O = E_O(\sigma e_x + i e_y)$ and $E_X = E_X(e_x - i\sigma e_y)\exp(i\delta)$, where σ is the ellipticity of polarized waves determined by the angle between the wave vector and magnetic field, δ the phase difference between the O- and X-modes, and e_x and e_y the unit vectors. If the polarization parameters, the rotation angle of major axis α and ellipticity angle β are given, the phase difference δ is obtained by

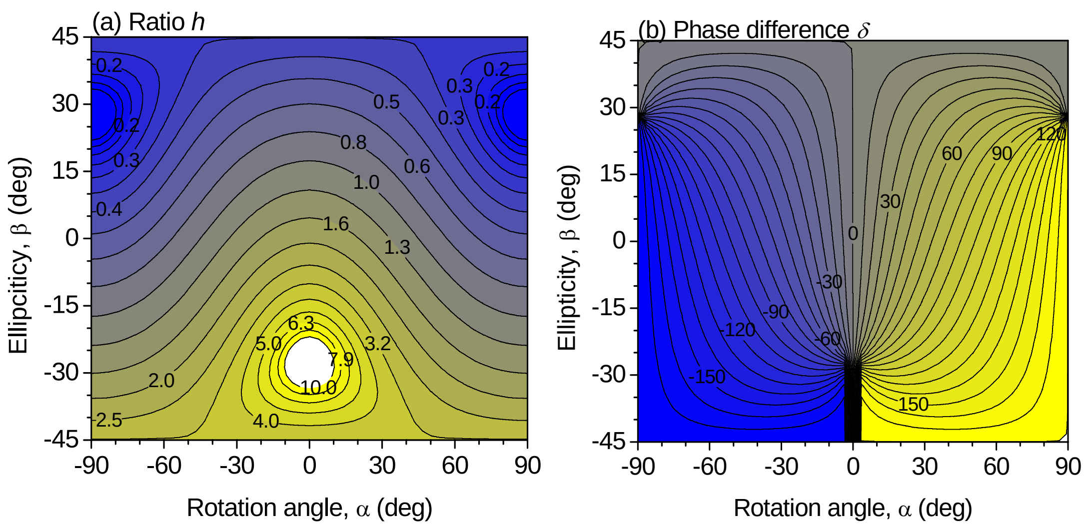

Fig. 2 Mode mixture of forward waves in Heliotron J, (a) ratio, h and (b) phase difference, δ

$$\tan\delta = -\frac{\left(1+\sigma^2\right)\left(1-\tan^2\beta\right)\tan\alpha}{\left(\sigma-\tan\beta\right)\left(1+\sigma\tan\beta\right)\tan^2\alpha-\left(1-\sigma\tan\beta\right)\left(\sigma+\tan\beta\right)}. \quad (1)$$

The ratio of the X-mode intensity to the O-mode intensity h ($\equiv E_X/E_O$) is

$$h = \frac{1-\sigma\tan\beta}{\cos\delta\left\{\tan\alpha\tan\delta+\sigma+\tan\beta\left(1+\sigma\tan\alpha\tan\delta\right)\right\}}. \quad (2)$$

Figure 2 shows the parameters, h and δ, as a function of the polarization parameters. Since the ratio h is uniquely determined when the polarization parameters are known, the single pass absorption rate can be estimated based on the reference O-mode intensity. Figure 3 shows the experimental result on the dependence of the DC component on the detector rotation angle. The polarization parameters are estimated to be α=75 deg and β=26 deg. The ellipticity σ is given as 0.52 in this experiment and the injection EC waves has 90 % of the X-mode and 10 % of the O-mode in power. From these parameters, we have h=0.16 and δ=130 deg, resulting that the single pass absorption rate is estimated to be 99.7 %.

The single pass absorption of second harmonic X-mode is numerically calculated by a ray tracing code, TRECE [3][4]. The TRECE code has a capability to handle three-dimensional plasmas and magnetic configurations. Figure 4 shows the density dependence of the single pass absorption rate of the X- and O-modes. The single pass absorption rate of the X-mode ranges from 92 to 96 % at $n_e(0)$=0.6-1.0×10^{19} m^{-3}, while the absorption rate of the O-mode is as low as 10 % due to low optical thickness. This absorption rate of the X-mode is close to the experimental result, indicating that the power absorption of X-mode can be measured based on the reference O-mode without direct power measurement.

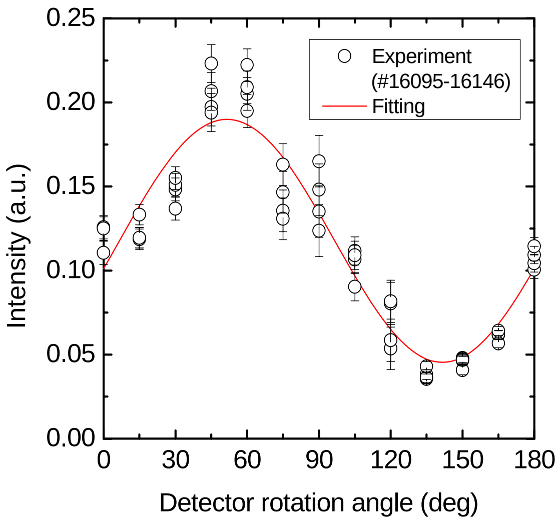

Fig. 3 Dependence of measured EC wave intensity on detector rotation angle

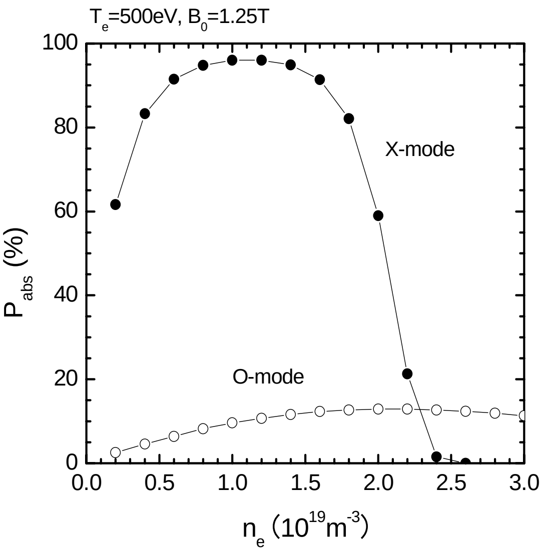

Fig. 4 Ray tracing calculation of single pass absorption rate

4. Fluctuation study

Since the scattering parameter, α ($\equiv k\lambda_{De}$)$^{-1}$, is α=4.60/sinθ_s, at n_e=0.5×10^{19} m^{-3} and T_e=500 eV, the measured scattered signal may be regarded as collective scattering in all the forward, 90 deg and backward scattering. Here θ_s is the scattering angle. The time evolution of power spectrum in the forwardly scattered waves is given by the Fourier analysis.

Depending on the magnetic configurations, coherent modes of 10 kHz have been observed at n_e>0.5×10^{19} m^{-3}. As shown in Fig. 5, the modes have a high correlation with the electron density measured by a microwave interferometer or the magnetic fluctuation measured by magnetic probes. According to the magnetic probe measurement, this mode is considered to be a pressure driven MHD instabilities since its amplitude scales with the plasma beta although no major rational surfaces exists and the Mercier criterion is stable.

The scattering signal also has incoherent modes induced by plasma turbulence. A statistical analysis using the probability density function (PDF) is performed when no coherent modes are excited. The third moment S representing the skewness and the fourth moment F representing the flatness are examined, which are S=0 and F=3 for the Gaussian distribution. The time evolution of the ECH plasma shows that PDF deviates from the Gaussian distribution: S ranges from 0 from 1, and K ranges from 3 to 6, depending on the electron density and magnetic configurations.

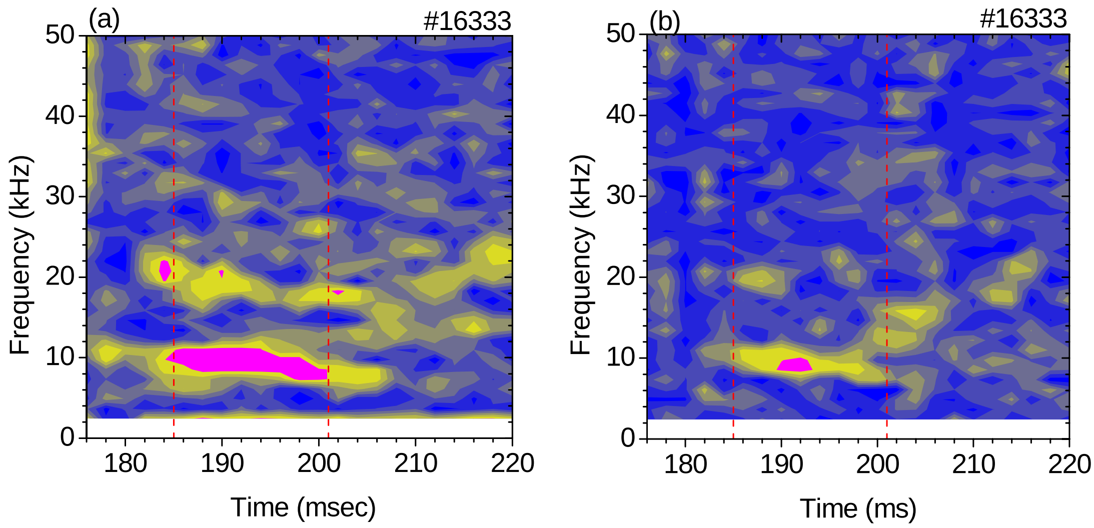

Fig. 5 Correlation of forwardly scattered EC waves with (a) core electron density and (b) magnetic fluctuation.

5. Conclusion

The single pass absorption efficiency of the second harmonic X-mode has been estimated by measuring the polarization of forward waves in Heliotron J. The estimated absorption rate is close to a ray tracing calculation result, suggesting that this method may be useful for investigating the absorption property in low density plasmas. Further studies as the dependence on the electron density and launched polarization will be performed in the future. The millimeter wave scattering has been also analyzed. Coherent modes of 10 kHz has been observed in the ECH plasma, which has a high correlation with the density and magnetic fluctuations.

Reference

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