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Fast wave electron heating experiments focusing on competition between damping mechanisms on Large Helical Device

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Fast Wave electron heating experiments were performed in Large Helical Device. In this experiment, magnetic fields B = 1.5 T and 1.86 T were used. Electron cyclotron emission using modulation techniques of FW injection indicated central electron heating in the 1.5T case with electron cyclotron (EC) and neutral beam (NB). In the 1.86 T case, there was no evidence of direct electron heating. Energetic ions were observed during FW heating of the NB preheated plasma.

Keywords: helical/stellarator configuration, Fast Wave

1 Introduction

The fast wave (FW) can be used for electron heating and current drive in high density, high beta plasmas. FW experiments have been investigated in tokamaks [1-3], and there are many challenging works in helical devices. For a helical demo reactor with very high plasma density (10^{22} m^{-3}), core plasma heating (e.g., by NBI) is key issue. FW is useful for heating the plasma to ignition, because0 there is no high density accessibility limit. Since ion cyclotron heating often creates high energy ions that can damage the antenna and the vacuum vessel, FW electron heating is desirable. In Large Helical Device [4], initial FW electron heating experiments were performed successfully [5]. At high harmonics of ion cyclotron frequency, electron Landau damping (ELD) and magnetic pumping (MP) can dominate over ion cyclotron harmonic damping [6]. However if harmonic number is relative small, there is competition between damping mechanisms. Researching this competition is same issue in toroidal deveice (tokamak and helical). In this experiment, magnetic fields B = 1.5 T and 1.86 T were used. By using this magnetic field, FW run across 2nd, 3rd, 4th, 5th ion cyclotron resonance layer. In the present paper, details of the magnetic configuration is described in Sec. 2. Section 3 describes experimental results. Section 4 is denoted to discussion, and the results are summarized in Sec 5.

2 Locations of electron/ion cyclotron resonance layer

Since the LHD antenna [7] is not arrayed, the $k_{\parallel}$ (wavenumber parallel to the magnetic field) spectrum

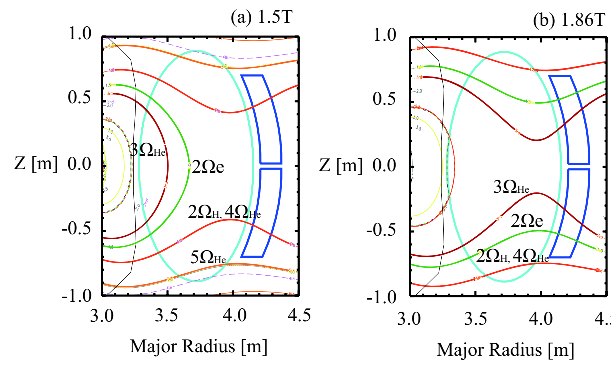

Fig. 1 Cyclotron resonance layers in the case of B = 1.5T (a) and 1.8T (b).

is broad and centered around zero.For effective Landau damping, $\omega/(k_{\parallel}v_{the}) \cong O(1)$, high electronn temperature is needed. Here ω is the FW angular frequency and v_{the} is the electron thermal velocity. The experiments were conducted under 2 conditions with different magnetic field strength (B=1.5T and 1.86T). Figure 1 shows the layers of cyclotron resonance. In this calculation, $n_{e0} = 3.0 \times 10^{19}\mathrm{m}^{-3}$ and the wavenumber parallel to the magnetic field line $k_z = 5\mathrm{m}^{-1}$ are used.In the 1.5 T case, the elenctron second cyclotron resonance layer crosses the magnetic axis, so pre-electron heating is desirable. FW would be coupled with high energy electrons. And the hydrogen second harmonic cyclotron resonance ($2\Omega_H$) layer exists around $\rho = 0.5$. There is competition between CD (cyclotron damping) and ELD/MP. In the 1.86 T case, the $2\Omega_H$ layer exists around $\rho = 0.9$. If cyclotron damping is week, FW wold be absorbed by electrons.

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3 Experimental results

3.1 EC electron heating and the high energy ion tail by FW

Figure 2 shows electron temperature profile before and after EC injection in both cases. Horizontal axis indicates Major radius. Electron temperature is measured by Thomson scattering. Bulk electron temperature around plasma center is increased in 1.5T case. In 1.86T case, Electron heating is weak, and there is not clear difference of electron temperature profile between before and after. Figure san shows the time evolution of a FW heating discharge. The electron density was measured with a FIR interferometer, the radiation power was measured with a bolometer, and loading shows coupling between FW and plasma. In this shot, IC power up to 1MW was injected into hydrogen plasma with line integrated densities of $2 \times 10^{19}\mathrm{m}^{-3}$.

The ion energy distribution in the discharge of figure 3 is described in Fig. 4. Plots is the count number of neutral particles for 0.1 s. Label indicates start time of measurements in the discharge of figure san. High energy ion tail were observed in both cases. It might be caused by cyclotron damping (2nd Ω_H). There are high energy ion tail above 120 eV in 1.5T case. On the other hand, no energetic ion was observed in 1.86T case. Ion cyclotron resonant layer in 1.5T case is closer to the plasma center than in 1.86T case, so IC power was absorbed by cyclotron damping in 1.5T case. In both cases, no energetic ions were observed (ne ~ $3.0 \times 10^{19}\mathrm{m}^{-2}$).

3.2 Power modulation experiments

Power modulation experiments were also performed to calculate FW damping profile. Plasma heating profile using FFT analysis are described in Fig. 5 and Fig. 6. Horizontal axis denotes normalized minor radius. In this calculation, ECE signal component synchronizing RF on/off frequency is derived. In these heating phase, stored energy is ~ 400 kJ and electron density is $3 \times 10^{19}\mathrm{m}^{-3}$, and electron temperature in B = -1.86T is lower than Te in B = -1.5T (f_{ICH} ~ 10 Hz). Clear central heating is achieved when central electron temperature is high using ECH in -1.5T case.

In -1.86T, phase differences are not changed in each heating phase, and plasma heating position is approximately same, and those are at plasma edge (ρ ~ 0.8, 0.9). 2nd ion cyclotron damping is strong candidate in each heating because slowing down time is not much difference and effective heated position is very close to 2nd ion cyclotron resonances.

3.3 Plasma loading

Figure 7 shows that antenna loading comparison between two magnetic field. In this shot, electron density gradually increased by usin gas puffing and electron densities

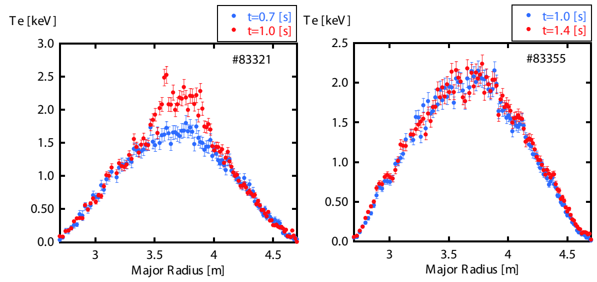

Fig. 2 Te profile measured by Tomson scattering. (a) 1.5T case and (b) 1.86T case.

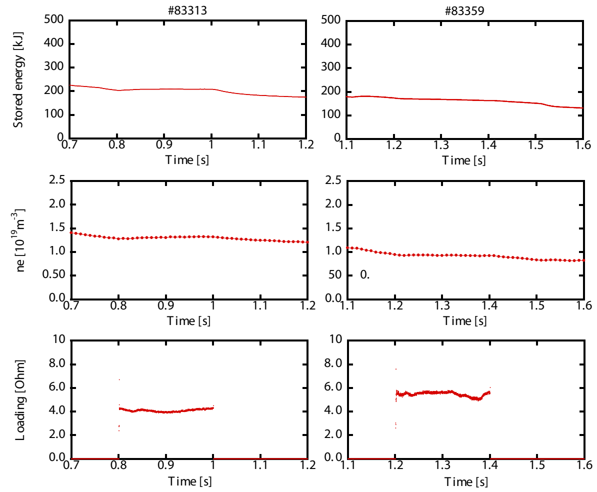

Fig. 3 Time evolution of plasma parameters in hydrogen plasma discharge. (a) -1.5T (b) -1.86T. FW are launched for 0.2 s.

are similar to each discharges. However the characteristics of antenna loading are much different. In spite of increasing electron density, loading decreased. In 1.5T case, antenna loading is gradually decreased and that loading is stable. However, in 1.86T case, antenna loading is drastically changed during FW injection and there are eigen mode and RF injection is unstable.

4 Discussion

As described in Fig. 7, -1.5T case plasma is more suitable for FW injection than -1.86T case. Electron temperature change is conceivable as one the reason of this. Figure 8 shows that time evolution of the electron temperature at the center and edge of the plasma. Electron temperature Te is obviously decreased (from 2 keV to 1.5 keV), and decreasing ratio of the Te is similar at center and edge (-1.5T). There is no difference of Te between t = 0.5s and t = 1.5 s, and Te is kept constant (~ 2 keV) or very weakly decreased (-1.86T). ELD and TTMP is strongly related to electron beta be, and high Te is required for wave damping through ELD and TTMP when the be has a few %.

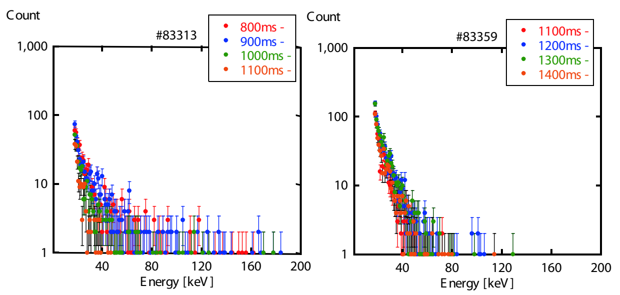

Fig. 4 Temporal change of the ion energy distribution in the discharge of Figure 3.

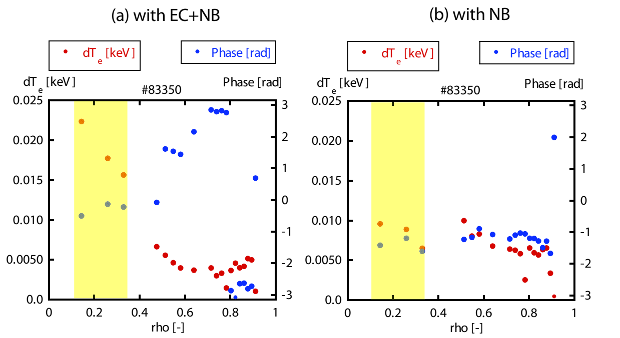

Fig. 5 FW deposition profile in the case of -1.5T. (a)with EC + NB (b)with NB.

5 Conclusions

Comparing cyclotron damping with electron Landau damping (ELD) / transit time magnetic pumping (TTMP), the experiment with different cyclotron resonances (-1.5T, -1.86T) is tried on LHD. Ion acceleration is observed in -1.5T and -1.86T. In -1.5T case, and they are strongly related to electron densities. According to FFT analysis, heating position is much different in -1.5T and -1.86T, and there are no differences of phase delay with -1.86T in each heating phases. The characteristic of antenna loading is different in these ICRF resonances, and the antenna loading is fluctuated in B of -1.86T.

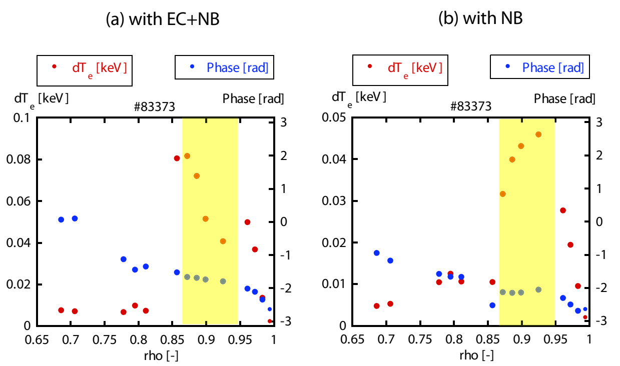

Fig. 6 FW deposition profile in the case of B = -1.86T. (a)with EC + NB (b)with NB

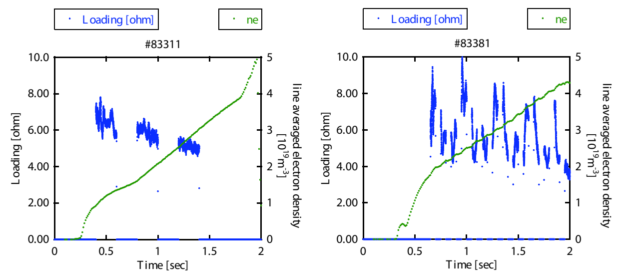

Fig. 7 Dynamic change of the plasma loading and line averaged electron density. Electron density increased by gas puffing.

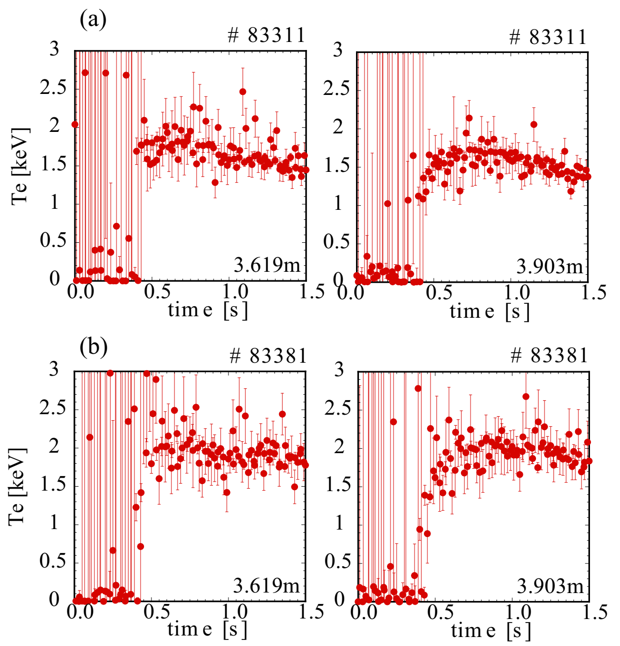

Fig. 8 Time evolution of electron temperature. (a)-1.5T (b)-1.86T.

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