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ICRF Heating using Folded Waveguide Antenna on LHD

TORII Yuki[1], KUMAZAWA Ryuhei, WATARI Tetsuo, MUTOH Takashi, SEKI Tetsuo, SAITO Kenji, YAMAMOTO Taro[1], TAKEUCHI Norio[1], SHIMPO Fujio, NOMURA Goro, MATSUSHITA Hiroyuki[1], WATANABE Tsuguhiro and LHD Experimental Groups I / II

National Institute for Fusion Science, Toki 509-5292, Japan

[1] Nagoya University, Nagoya 464-8603, Japan

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Abstract

Using a folded waveguide (FWG) antenna in the ion cyclotron range of frequency, a plasma production and heating experiment was carried out on the large helical device in National Institute for Fusion Science, which was the first experiment in the torus system. In the 4th experimental campaign in 2000–2001 this antenna produced the plasma at the average electron density up to 3×10^{18} m^{-3}. In this campaign, the pure hydrogen plasma was produced mainly using the frequency of 25 MHz in the magnetic field strength of 2.6–2.8 T.

It is planned that an ion Bernstein wave heating will be carried out to heat the plasma at a higher frequency, i.e. 37.43 MHz (second harmonic resonance of FWG antenna). In the helium plasma produced by electron cyclotron heating, the antenna launches the wave of the frequency $\omega \sim 3\omega_{\mathrm{cHe}}$ at the antenna front. A spatial distribution of the wave energy damping was calculated using the dispersion relation of ion Bernstein wave and an analytical expression of the magnetic field strength with a rotating helical coordinate system. The propagating wave was absorbed near the resonance of $\omega \sim 2\omega_{\mathrm{cHe}}$.

Keywords:

ICRF heating, LHD, folded waveguide antenna, ion cyclotron wave, ion Bernstein wave

1. Introduction

In the 4th experimental campaign on the large helical device (LHD), a plasma was produced using a folded waveguide (FWG) antenna. The obtained plasma densities reached 3×10^{18} m^{-3}. This becomes a target plasma of neutral beam injection or ion cyclotron range of frequency (ICRF) heating. This is the first demonstration of the plasma production using an FWG antenna in the magnetic confinement device. The mechanism of the plasma production was investigated in the propagation of the shear Alfven wave.

In the lower magnetic field or at the higher frequency, the FWG antenna can launches ion Bernstein wave (IBW). In the PBX-M, a transport barrier was observed in neutral beam injection discharge plasma with IBW heating, and the density and the temperature profile was peaked [1]. A high performance of the confinement is expected at the IBW heating. It is important for an effective IBW heating that the heating characteristics in the LHD magnetic configuration are investigated beforehand. In this study IBW is launched at the outside of the last closed flux surface in the low field side. The wave propagates toward core and damps at the second harmonic cyclotron layers of Helium ions.

2. Folded Waveguide Antenna

A cutoff frequency is determined by the width of the waveguide, i.e., $f_{\mathrm{cutoff}} = c/2a$, where c and a are the light velocity and the antenna width. For ICRF wave

Corresponding author's e-mail: torii@nifs.ac.jp

launching, an antenna width needs to be wider than 5 m. The antenna size is made smaller by folding the antenna many times [2] as shown Fig. 1.

An mock-up FWG antenna was tested and demonstrated as an application of the LHD [3]. The FWG antenna is folded 23 times. The FWG antenna is electrically shorted at the front by polarization plates so that high voltage does not appear near the plasma and that the wave number parallel to the magnetic field, $k_{\parallel}$ is minimized.

The FWG antenna is installed at the horizontal port [4] of LHD. The location of the antenna, magnetic surfaces, and the resonance layers are shown in Fig. 2. It has an angle with respect to the equatorial plane so that the RF electric field is parallel to the magnetic field at the last closed magnetic flux surface for the purpose of the slow wave excitation.

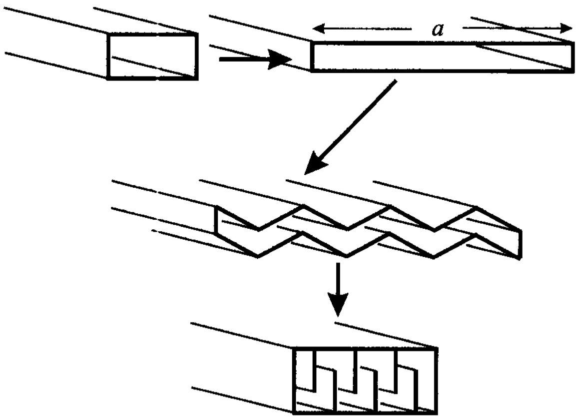

Fig. 1 A concept of the FWG antenna. The antenna is the waveguide antenna folded many times. The antenna width is denoted by '*a*'.

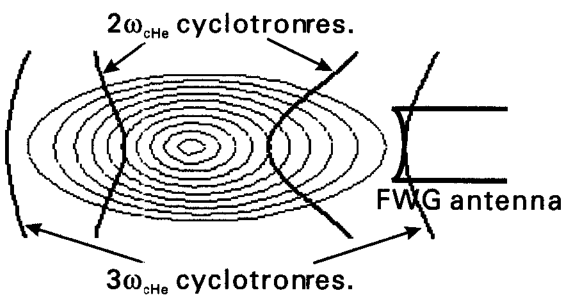

Fig. 2 A schematic drawing of the FWG antenna in LHD. The second and third helium cyclotron resonance layers (f=37.43 MHz, B_{ax}=2.7 T) are also shown.

3. Shear Alfvén Wave Heating

In the 4th experimental campaign, the plasma production experiment by the FWG antenna was carried out [5]. Plasmas were produced and the achieved electron density was 3×10^{18} m^{-3}. This is the first demonstration in magnetic confinement devices.

The experiment was carried out in a hydrogen plasma and the applied frequency was 25.33 MHz (TE_{10} mode). It was confirmed that the achieved density depended on the magnetic field strength. Figure 3 shows its dependence. The dots are the experimentally achieved line averaged electron density. The density increases with the magnetic field strength. A dispersion relation of ICRF wave reflects this phenomenon [6],

$$\frac{{\omega_{\mathrm{cH}}}^2}{\omega^2} \cong 1 + \frac{{\omega_{\mathrm{pH}}}^2}{c^2}\left(\frac{1}{k_{\parallel}^2} + \frac{1}{k_{\parallel}^2 + k_{\perp}^2}\right), \tag{1}$$

where ω_{cH}, ω, ω_{pH}, c, and $k_{\perp}$ are a hydrogen cyclotron frequency, an applied frequency, a hydrogen plasma frequency, a light velocity, and a wave number perpendicular to the field, respectively.

The propagation area of shear Alfvén wave was calculated at the various electron density and the magnetic field strength. In this calculation, a cold approximation was used and the electron density profile was assumed to be $n_e=n_{e0}(1-\rho^8)$, where n_{e0} and ρ are

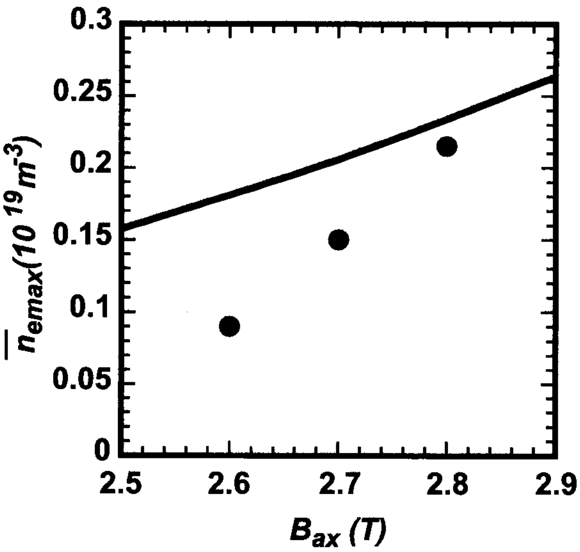

Fig. 3 Dependence of achieved electron density on magnetic field strength. The dots are experimentally achieved line-averaged electron density. The solid line is the line-averaged electron density at which the calculated shear Alfvén wave propagation area is the largest.

central electron density and a normalized minor radius, respectively. The dependence of the line-averaged electron densities where the propagation region is the largest on the magnetic field strength is also plotted in Fig. 3 as solid line. The experimentally achieved electron densities qualitatively agree with the calculated ones. It is concluded that the plasma was produced by the shear Alfvén wave.

4. Propagation and Absorption Area of Ion Bernstein Wave

The FWG antenna also launches the ion Bernstein wave at the higher frequency, f=37.43 MHz (TE_{20} mode). The calculation of the IBW propagation is required for the efficient launching IBW.

4.1 Dispersion relation of ion Bernstein wave

The dispersion relation of the electrostatic wave is given by a following equation [7],

$$D = k_\perp^2 + k_\parallel^2 + \sum_\alpha \frac{2\omega_{p\alpha}^2}{v_{t\alpha}^2} \sum_{l=-\infty}^{\infty} \exp(-\mu_\alpha) I_l(\mu_\alpha) \left\{1 + z_{0\alpha} Z(z_{l\alpha})\right\} = 0 \qquad (2)$$

and

$$\mu_\alpha = \frac{k_\perp^2 v_{t\alpha}^2}{2\omega_{c\alpha}^2}, \quad z_{l\alpha} = \frac{\omega - l\omega_{c\alpha}}{k_\parallel v_{t\alpha}} \qquad (3)$$

where $v_{t\alpha}$, $\omega_{p\alpha}$, $I_l(x)$, and $Z(x)$ are a thermal velocity of species α, a plasma frequency, an l-th order modified Bessel function, and a plasma dispersion function, respectively.

For the simplicity following assumptions are employed; electrons absorb the wave energy through Landau damping. A finite Larmor radius effect of electron is ignored. Ions absorb it through a fundamental, a second and a third harmonic cyclotron damping. A finite Larmor radius effect of helium ion is very small, and phase velocity parallel to the magnetic field is much larger than the thermal velocity of ions. Then the above dispersion relation is simplified in the following equation;

$$D = k_\perp^2 + k_\parallel^2 + \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right) - \frac{2\omega_{pe}^2}{v_{ti}^2}\left(\mu_i \frac{\omega_{ci}^2}{\omega^2 - \omega_{ci}^2} + \mu_i^2 \frac{\omega_{ci}^2}{\omega^2 - 4\omega_{ci}^2} + \frac{3}{8}\mu_i^3 \frac{\omega_{ci}^2}{\omega^2 - 9\omega_{ci}^2}\right) = 0 . \qquad (4)$$

4.2 Radial distribution of perpendicular wave number of IBW

The parameters of the target helium plasma are assumed; Temperature profile is $T_\alpha = T_{\alpha 0}(1-\rho^2)$ at the plasma core region of $0<\rho<0.8$ and $T_\alpha = T_\alpha^* \exp(-\rho/\rho_{T\alpha}^*)$ at the peripheral region of $\rho>0.8$. Density profile is $n_\alpha = n_{\alpha 0}(1-\rho^8)$ also at $0<\rho<0.9$ and $n_\alpha = n_\alpha^* \exp(-\rho/\rho_{n\alpha}^*)$ at $\rho>0.9$. Constants of T_α^*, n_α^*, $\rho_{T\alpha}^*$, and $\rho_{n\alpha}^*$ are determined as the temperature and the density profiles at the peripheral region are connected with ones at the core region continuously and smoothly. The magnetic field strength is available analytically using a rotating helical coordinate system [8]. Characteristics of the analytical magnetic field agree well with the actual one calculated using Biot-Savart's law.

The wave number perpendicular to the magnetic field, $k_\perp$ was calculated numerically by solving the dispersion relation, eq. (2) using plasma parameters and the magnetic strength. The complex Newton method was used to solve a real part and an imaginary part of $k_\perp$. Figure 4 shows a profile of the real and the imaginary part of the wave number. In this calculation, following parameters were used: f=37.43 MHz, B_{ax}=2.7 T (R_{ax}=3.6 m), $n_{e0}=5.0\times10^{18}$ m^{-3}, and $T_{e0}=T_{He0}$=200 eV. Here plotted are profiles of the electron density, the electron temperature and the ratio of the applied frequency to the helium cyclotron frequency, ω/ω_{cHe}. The wave number parallel to the magnetic field was fixed at $k_\parallel$=3.0 m^{-1}. Summation of the cyclotron harmonics was carried out over l=0, ±1, ···, ±9.

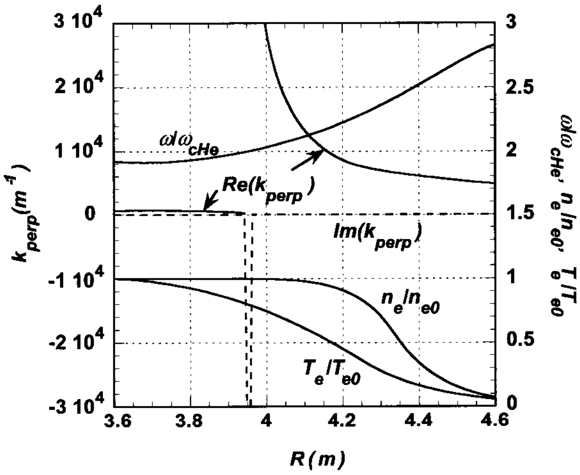

Fig. 4 A perpendicular wavenumber $k_\perp$ profile. The density, temperature, and magnetic field strength profiles are also shown.

The wave propagates from the FWG antenna (R=4.6 m) near the helium third harmonic cyclotron resonance layer, as shown in Fig. 2, into the plasma core. As the wave approaches the second harmonic resonance layer, the real wave number increases. The absolute value of the imaginary one also increases sharply just in front of the layer. This wave number is a negative value because of the characteristics of the IBW of the backward wave. The wave energy is absorbed by helium ions. At the wave passes the second cyclotron resonance layer, the wave number decreased sharply as shown in Fig. 4.

5. Summary

In the LHD, a folded waveguide antenna is installed. The antenna is a waveguide antenna folded 23 times in order to reduce the cutoff frequency to the ICRF. Plasma is produced by shear Alfven wave launched by this antenna. The achieved electron density is increased with the magnetic field strength. This phenomenon is explainable by the shear Alfven wave propagation.

The FWG antenna launches the ion Bernstein wave at the higher frequency. The wave number perpendicular to the magnetic field, $k_\perp$ was calculated numerically. The calculation was carried out with the constant $k_\parallel$ on the equatorial plane. The waves propagates into the plasma core region and the energy is expected to be absorbed by ions at the second cyclotron resonance layer.

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