Wave Characteristics in the Electron Cyclotron Range of Frequencies in Overdense Plasmas in the Internal Coil Device Mini-RT^{*)}

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In the internal coil device Mini-RT, overdense plasmas have been observed, and heating by electron Bernstein waves (EBWs) is expected. EBWs, which have no cutoff density, are electrostatic-mode waves converted from the electromagnetic mode. To examine mode conversion in Mini-RT experiments, we are attempting to investigate the propagation of waves in the electron cyclotron range of frequencies (ECRF) in overdense plasmas. We injected diagnostic microwaves (typically 1 GHz) into a plasma produced by 2.45 GHz microwaves and directly measured their characteristics by inserting various probing antennas into the plasma with an interference system. Electromagnetic field measurements revealed a long-wavelength mode in the area with lower density than the upper hybrid resonance (UHR) region. In the area with higher density than that of the UHR region, waves having the characteristics of EBWs were observed; namely, short wavelength (~20 mm), electrostatic mode, longitudinal polarization, and backward wave mode. These results suggest that EBWs were mode converted from electromagnetic waves at the UHR.

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1. Introduction

The Mini-RT is an internal coil device that was constructed to confine high-beta plasma by a magnetic field similar to that of a planet. In this device, so-called overdense plasmas have been observed with levitation of an internal superconducting magnet coil [1], and heating with electron Bernstein waves (EBWs) is expected. EBWs have several characteristics:

- 1. They have no cutoff density,
- 2. They are electrostatic-mode waves,
- 3. They are excited by mode conversion from electromagnetic waves in a plasma,
- 4. Their typical value of the wavelength is of the order of the Larmor radius,
- 5. They are longitudinally polarized,
- 6. They have negative group velocity (backward wave), and
- 7. Their group velocity is in the range of the electron thermal velocity.

Since the cutoff density exists, it is difficult to generate and heat the high-density plasma with electron cyclotron heating (ECH). Therefore, EBW heating is expected to be one of the most promising methods for generating and heating high-density plasmas. Inserting antennas enables the direct investigation of waves in the plasma. S. Gurber and G. Bekefi investigated longitudinal waves in a magnetically confined linear device [2]. A drastic change in wavelengths was observed with increasing magnetic field strength. H. Sugai verified experimentally that short-wavelength waves excited around the upper hybrid resonance (UHR) were mode-converted EBWs [3]. Y. Y. Podova *et al.* demonstrated mode conversion from O-mode to X-mode waves around a cutoff layer and a phase jump around the UHR on the WEGA stellarator [4].

To examine mode conversion in Mini-RT experiments, we are attempting to investigate the propagation of waves in the electron cyclotron range of frequencies (ECRF) in overdense plasmas.

2. Plasma Production in Mini-RT

The Mini-RT device has an internal coil with a hightemperature superconductor (HTS) that produces a purely poloidal magnetic field in a vacuum vessel. The internal coil is cooled by helium gas, and direct excitation produces a persistent current of 50 kA turns.

A Plasma is produced in the Mini-RT by ECH with continuous X-mode microwaves at 2.45 GHz and 2.5 kW. Microwaves generated in a magnetron are sent to an isolator and launched with a horn antenna. The plasma confine-

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Fig. 1 Cross section of the Mini-RT device.

ment region can be changed easily by applying a levitation coil current. A typical magnetic configuration is shown in Fig. 1. The separatrix appears near the levitation coil, and the plasma is confined in the inner region of the separatrix.

3. Experimental Setup

In the Mini-RT device, waves at frequencies lower than 2.45 GHz are injected to diagnose wave propagation in overdense plasmas; the plasma produced by 2.45 GHz microwaves acts as an overdense plasma with respect to lower frequency diagnostic waves. In this study, diagnostic X-mode waves at 1 GHz and 10 W are injected from the low field side. To prevent the 2.45 GHz microwaves used for plasma production from affecting the diagnostic circuits, a band pass filter was installed. To examine the mode conversion of waves from electromagnetic to electrostatic mode, the electromagnetic and electrostatic components (x, y, and z correspond to the radial, toroidal, and poloidal components, respectively) are measured simultaneously by probing antennas inserted directly into the plasmas.

3.1 Probing antennas

Three types of probes are inserted: pole antennas (for the electric component), loop antennas (for the magnetic component), and triple probes (for the density).

The pole antenna emits induced voltage signals by detecting the electric field on its element (element length: 37.5 mm pole for X-mode and O-mode waves and 2 mm tip for EBWs), whereas the loop antenna does so by changing the magnetic flux through its loops. The type of loop antenna shown in Fig. 2 is called a King probe. The outer sheath shields the inner signal line from external electric fields, and the generated voltage appears across the central sheath gap [5]. To avoid a lopsided voltage distribution along its loop, the loop used in this study is much smaller than the wavelength. The loop is 5 mm on a side; its inductance is 0.383 nH, and the characteristic impedance of the



Fig. 2 Magnetic loop antenna.



Fig. 3 Measurement system.

measurement system is 50 Ω , resulting in a time constant of 7.67 ps.

3.2 Interferometry system

Interferometry enables us to obtain a snapshot of the electric or magnetic field. Figure 3 shows a schematic diagram of the diagnostics. Probing antennas detect the injected diagnostic microwaves and send them to the mixer. They are modulated by IQ demodulators and output as sine and cosine components that contain information on the amplitude and phase of the electromagnetic field.

3.3 Measurement of group velocity

The group velocity of EBWs is in the range of the electron thermal velocity, e.g., $\sim 2.0 \times 10^6$ m/s at $T_e \sim 10$ eV. Injecting wave packets into the plasma and detecting the spatial dependence of their arrival time enables us to obtain the group velocity experimentally [6]. To inject ultrashort-pulse microwaves (~ 10 ns), we use a PIN diode switch that is open while the gate signal exceeds a threshold voltage. The signal detected by an antenna is processed directly by an oscilloscope without modulation. Note that this group velocity measurement is not conducted at the same time as interferometry measurements.

4. Experimental Results4.1 Interferometry measurement

Figure 4 shows the density profile measured by the triple probe and the sine and cosine components of wave signals measured by the probing antennas. The cutoff density for 1.0 GHz microwaves is $1.24 \times 10^{16} \text{ m}^{-3}$; that is, the region inside the major radius $R \sim 280 \,\mathrm{mm}$ is the evanescent region for diagnostic microwaves, and the UHR is located in the outer region of the core plasma, with $R \sim 290$ mm. The electromagnetic field measurements in Figs. 4 (c), (d), and (e) show a long-wavelength mode in the area with lower density than that of the UHR region. This corresponds to an electromagnetic wave mode excited by excitation antennas on the outside of the plasma. In the radial electric field measurement, shown in Fig. 4 (b), a short-wavelength mode is observed in the area with higher density than the UHR region; waves in this mode can propagate in the evanescent region and are excited around the UHR region. The wavelength is around 20 mm and is evaluated from the waveforms, which exhibits a refractive index of ~ 15 . In this area, electromagnetic-mode waves are damped, which suggests that the short-wavelength-mode waves shown in Fig. 4 (b) are electrostatic-mode waves excited by conversion from electromagnetic-mode waves.

Figure 5 shows radial profiles of the phases in Figs. 4 (b) and (e). The phase is a function of the spatial position and length of the transmission lines; the gradient of the phase gives the wave number vector. The figure confirms a reversal of the phase gradient around the UHR in electrostatic-mode waves. This suggests a change in the direction of the phase velocity, and Fig. 5 shows that the phase velocity at R < 255 and 260 < R < 280 is opposite to that in other regions. Thus, this electrostatic wave is a backward wave.

4.2 Group velocity measurement

The arrival time of wave packets is clearly delayed in the core plasma region, as shown in Fig. 6 (a). The time delay in Fig. 6 (b) is defined as the difference in time between the pulse injection trigger signal and the signal collected by the probing antenna. The gradient of the arrival time gives the group velocity. Since only a few nanoseconds are required for microwaves to propagate dozens of centimeters at the speed of light, a significant delay in the arrival time is shown at 240 < R < 260 mm. The group velocity estimated from Fig. 6 (b) is about 1.0×10^6 m/s, which is of the order of the electron thermal velocity and represents an electron temperature of ~ 3.1 eV.

5. Discussion

As shown in the previous section, we observed signals



Fig. 4 Electron density and electromagnetic field profiles.



Fig. 5 Phase profiles.

having most of the characteristics of EBWs: propagation in the evanescent region, excitation around the UHR, short wavelength, electrostatic mode, and backward wave mode. However, quantitative discrepancies exist between the observations and the theoretical values.

Figure 7 shows the radial profile of the refractive index, which is calculated by solving the dispersion relation. The refractive index of the EBWs is greater than 100, i.e., their wavelength is less than 3 mm, whereas the experimentally observed wavelength is somewhat longer



Fig. 6 Group velocity measurement.



In addition, the interferometry measurements and the group velocity measurements indicate different excitation locations for the EBWs. This difference appears to arise from current decay in the superconducting internal coil. The group velocity was measured 30 minutes after the electromagnetic field was measured, and the current value of the internal coil was attenuated at that time. The current decay indicates that the plasma confinement region becomes smaller and the location of the resonance layer moves to the inner region.

Diagnostic microwaves injected on the outside of the plasma (fast X-waves) propagate toward the center of the vacuum vessel and are reflected at the R-cutoff. If the evanescent region is sufficiently thin, tunneling of the incident fast X-waves occurs, and slow X-waves are converted to EBWs at the UHR. Therefore, around the UHR, both the electrostatic mode (EBWs) and electromagnetic mode (slow X waves), whose refractive index is about 10, exist. A local maximal value appears in Fig. 4 (e) at the UHR, and this electromagnetic short-wavelength mode is not EBWs but slow X-waves. Thus, these experimental results probably demonstrate the process of mode conversion.

6. Summary

In the internal coil device Mini-RT, which was constructed to confine high-beta plasmas, overdense plasma is produced when the internal floating coil is magnetically

Fig. 7 Refractive index profile.

levitated, and EBW heating is expected.

To investigate the propagation of waves at the ECRF, we injected diagnostic microwaves of lower frequency than those used for plasma production and directly measured their wave characteristics by inserting probing antennas into the plasma.

Electromagnetic field measurements with an interference system in the area having higher density than that of the UHR region showed wave characteristics that correspond to those of EBWs: short wavelength (~ 20 mm), electrostatic mode, longitudinal polarization, and backward wave mode. In the area with lower density than that of the UHR region, these characteristic were not observed. In addition, magnetic field measurements suggest possible tunneling of the incident fast X-waves.

Group velocity measurement shows a significant delay in the arrival time for the velocity of light in the core plasma region. The difference in the arrival time of wave packets indicated a group velocity of the order of the electron thermal velocity.

These results suggest that EBWs were mode converted from electromagnetic waves at the UHR.

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