LETTERS

DIRECT MEASUREMENT OF FAST MAGNETOSONIC WAVE NEAR THE ION-ION HYBRID RESONANCE LAYER BY MAGNETIC PROBES

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ABSTRACT. Direct measurement of the fast magnetosonic wave near the hybrid resonance layer in a deuterium-hydrogen plasma by magnetic probes is described. Externally driven waves in the ion cyclotron range of frequencies (ICRF) are excited by a half-turn antenna located on the high-field side in the TNT-A tokamak. The amplitude and the phase shift of the fast magnetosonic wave are measured by magnetic probes in the equatorial plane of the plasma. The amplitude of the fast magnetosonic wave is damped in the ion-ion hybrid resonance layer, and the wavelength changes at the high-field side near this layer. The amplitude and the phase shift of the wave as measured by the probes agree with those calculated from a cold-slab model.

1. INTRODUCTION

Wave heating in the ion cyclotron range of frequencies (ICRF) is recognized to be an effective method of additional heating; it was studied by various approaches. Improvements in the efficiency of heating and an increase in the ion temperature or a power balance were observed in many experiments [1–3]. Recently, an increase in the RF power level, optimum conditions of ICRF heating and the power balance were studied in PLT [4], JFT-2 [5], and JIPP T-II [6]. However, only few experiments on propagation or mode conversion have been performed, so far.

Mode conversion was observed from density fluctuations by far-infrared laser scattering in Microtor [7] and by CO_2 laser scattering in TFR [8]. Direct measurements of waves in ICRF without ion-ion hybrid resonance layer were made in TPH [9] and the PROTO-CLEO stellarator [10]. In this paper, the results of direct measurements of fast magnetosonic waves near the ion-ion hybrid resonance layer by magnetic probes in TNT-A [11] are presented; damping and phase shift of the wave observed near this layer are discussed, and the experimental results are compared with those from a cold-slab model [12].

2. NUMERICAL CALCULATIONS

The cold-plasma-slab model is used in these numerical calculations, and a rectangular co-ordinate system (x, y, z) is adopted. Uniformity of plasma parameters is assumed in the y- and z-directions; the toroidal magnetic field and the plasma density are supposed to vary as follows in the x-direction:

$$B_t(x) = B_{t0}(1 + x/R_0)^{-1}$$

$$n(x) = n_0(1 - x^2/a^2)$$

The antennas are assumed to be infinite in the y- and finite in the z-direction; the antenna current flows in the y-direction. Walls are infinite in the y- and z-directions. When the electric field E_z is neglected, the following second-order differential equation is obtained:

$$(S - n_z^2)\,\frac{d^2 E(x, k_z)}{dx^2} + \frac{\omega^2}{c^2}\,\{(S - n_z^2)^2 - D^2\}\,E_y(x, k_z) = 0$$

where S and D are defined as in the book by Stix [13], and $E_y(x, k_z)$ is the k_z Fourier component of the electric field $E_y(x, z)$. The component $E_y(x, k_z)$ is derived with boundary conditions at the antennas (j = 1, 2) and the walls (j = 1, 2). The value of $E_y(x, k_z)$ is equal to zero at the walls and continuous at the antennas. The derivative of $E_y(x, k_z)$ with respect to x is discontinuous at the antennas by a quantity $-i\omega\mu_0 J_j(k_z)$, where $J_j(k_z)$ is the k_z Fourier component of the current which flows in antenna j.

The components $E_x(x, k_z)$ and $B_{x,y,z}(x, k_z)$ are derived from $E_y(x, k_z)$ by using Maxwell equations, and the magnetic field $\vec{B}(x, z)$ is derived from $\vec{B}(x, k_z)$ by inverse Fourier transformation. The z-component of $\vec{B}(x, z)$ is compared with the results of probe measurements.

3. EXPERIMENTAL ARRANGEMENT

TNT-A is a non-circular tokamak with a major radius of 40 cm and a minor radius of 7.4 cm, as is shown in Fig. 1. The toroidal magnetic field is up to 4.3 kG, and the RF generator frequencies are 4.0, 4.5 and 5.6 MHz. The power coupled to the plasma in this

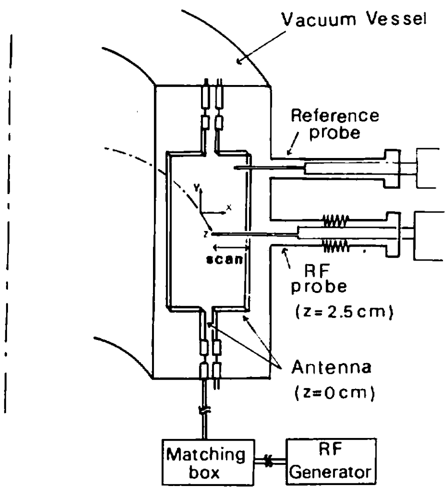

FIG.1. Cross-section of TNT-A device and position of RF antennas and probes. Wave is excited by antenna at the high-field side. Reference probe is fixed outside plasma, and RF probe is scanned from centre to edge of plasma.

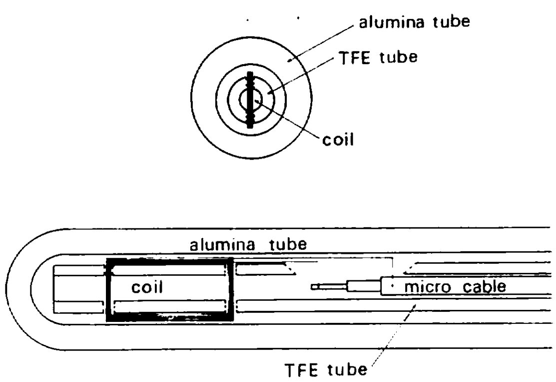

FIG.2. Probe structure. This probe has a rectangular coil, 2 mm X 5 mm, to pick up magnetic field of excited wave in ICRF. The micro cable is used for transmission of signal; it is covered by a polytetrafluoroethylene (TFE) tube. This tube is also covered by an alumina tube, one of whose ends is sealed. Outer diameter of probe: 5 mm; length: 250 mm.

experiment is in the range from 5 to 10 kW, and the externally driven wave can be excited by two half-turn antennas, one of which is located at the high- ($x < 0$ cm) and the other one at the low-field-side ($x > 0$ cm). Both antennas are located on the same poloidal cross-section ($z = 0$ cm). The antenna at the high-field side is used in this experiment.

Two magnetic probes are located near the antenna ($z = 2.5$ cm); one (an RF probe) is used for the measurement and the other one (a reference probe) serves as a reference in measuring the phase shift. The RF probe is moved from the centre to the edge of the plasma, while the reference probe is fixed outside the plasma. The amplitude of the fast magnetosonic wave is measured by the RF probe, and the phase shift is obtained from RF and reference probes together.

A cross-sectional view of the magnetic probe is shown in Fig.2. This probe has a rectangular coil, 2 mm X 5 mm, wound on a polytetrafluoroethylene (TFE) tube and is protected by an alumina tube, whose inner and outer diameters are 3 and 5 mm, respectively. A dummy prove with no coil (i.e. the cable short-circuited) is used to investigate the noise level. The frequency response is flat from DC to 13 MHz, and the signal-to-noise ratio, $S/N = 9$.

4. MEASUREMENT OF THE MAGNETIC FIELD OF THE FAST MAGNETOSONIC WAVE

Deuterium-hydrogen plasma is used to form the ion-ion hybrid resonance layer inside the plasma. The temperature, plasma density and plasma current are low enough ($T_e(0) = 60$ eV, $T_i(0) = 20$ eV, $n_e(0) = 1.0 \times 10^{13}$ (cm^{-3}), $I_p = 6$ kA, $V_l = 5$ V) to allow insertion of magnetic probes into the plasma without serious deterioration of probes or plasma current. The RF probe is moved from the centre to the edge of the plasma only on the low-field side ($x > 0$ cm) unless insertion of the probe changes plasma current, plasma density and antenna loading resistance.

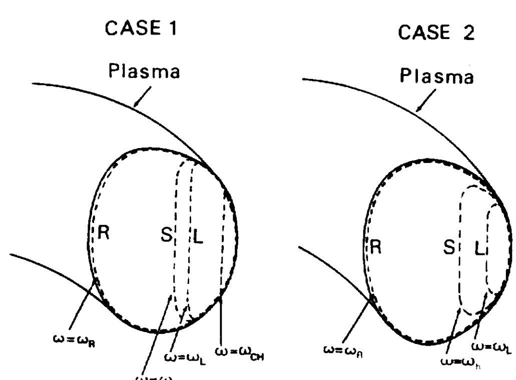

FIG.3. Locations of hybrid resonance layer, L, R cut-off layer and cyclotron resonance layer in case 1 ($n_H/(n_H + n_D) = 0.15$ and $f = 5.6$ MHz) and case 2 ($n_H/(n_H + n_D) = 0.45$ and $f = 4.5$ MHz) for $B_{t0} = 4.3$ kG and $k_z = 2.5$ m^{-1}.

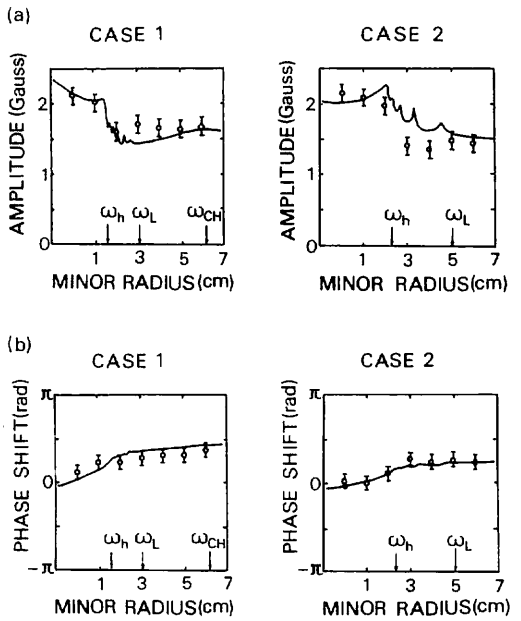

FIG.4. (a) Radial dependence of amplitude of magnetic-field z-component of excited fast magnetosonic wave in case 1 and case 2 for y = 0 cm and z = 2.5 cm. Open circles are results of RF probe measurements and solid lines are calculational curves; ω_h, ω_L, and ω_{CH} designate locations of ion-ion hybrid resonance, L cut-off and cyclotron resonance of hydrogen. (b) Radial dependence of phase shift of magnetic-field z-component of excited fast magnetosonic wave in case 1 and case 2 for y = 0 cm and z = 2.5 cm.

In this paper, two cases of experimental conditions are described. Case 1 is characterized by a hydrogen density ratio of $n_H/(n_H + n_D) = 0.15$, a toroidal field of $B_{to} = 4.3$ kG and an excited-wave frequency of f = 5.6 MHz; case 2 is given by $n_H/(n_H + n_D) = 0.45$, $B_{to} = 4.3$ kG and f = 4.5 MHz, where n_H is the hydrogen and n_D the deuterium density. In case 1, the ion-ion hybrid resonance layer, L, the R cut-off layer and the cyclotron resonance layer are all located inside the plasma. In case 2, the cyclotron resonance layer lies outside the plasma. The locations of these layers in cases 1 and 2 are shown in Fig.3.

The amplitude and the phase shift of the z-component (toroidal component) of the excited magnetic field are shown in Fig.4. The open circles are the measured magnetic fields at several radial locations, and the solid lines are curves calculated by the code described in Section 2. The amplitude of the z-component of the magnetic field of the excited fast magnetosonic wave near the ion-ion hybrid resonance layer decreases in both measurements and calculations as is shown in Fig.4a. This amplitude damping indicates that the fast magnetosonic wave is absorbed near the resonance layer. The phase velocity slows down on the high-field side near the ion-ion hybrid resonance layer as is shown in Fig.4b, which approximately coincides with the value calculated by this code.

5. DISCUSSION AND CONCLUSIONS

In case 1, the hybrid resonance layer, L, the R cut-off layer and the cyclotron resonance layer are inside the plasma. In case 2, there is no cyclotron layer. In both cases, the damping of the fast magnetosonic wave near the hybrid resonance layer is measured. This damping is only observed in mixed-species plasmas. There is no observable damping of the fast magnetosonic wave in the cyclotron resonance layer, nor can standing waves between the walls and the L cut-off layer be observed. In this experiment, the minor radius of the plasma is small compared with the wavelength of the fast magnetosonic wave.

No mode-converted slow wave is measured by the probe. This does not necessarily mean that no mode conversion occurs in the plasma. The size of the RF probe coil is 2 mm X 5 mm, and the wave number resolution in the probe is 5 mm. The maximum wave number measured by the probe is estimated to be 12 cm^{-1}. Moreover, the RF probe responds to all modes of the excited waves in ICRF, so that it is difficult to measure the slow wave.

The amplitude and the phase shift of the fast magnetosonic wave are measured by probes; the results agree with those calculated from the Maxwell equations in a cold-plasma-slab model. This indicates that this model is suitable for TNT-A, whose plasma size is too small to allow a ray trace approximation [14] for the waves in ICRF in the plasma. With these measurements, damping of the fast magnetosonic wave is observed near the ion-ion hybrid resonance layer, which is consistent with the calculational results.

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