LETTERS

OBSERVATION OF FAST WAVE AND MODE-CONVERTED ION BERNSTEIN WAVE BY MAGNETIC PROBES AND 2-MM MICROWAVE SCATTERING

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ABSTRACT. The observation of mode conversion during ICRF heating in a deuterium-hydrogen plasma is described. The mode-converted ion Bernstein wave is detected near the ion-ion hybrid resonance layer by 2-mm microwave scattering. In addition, a fast magnetosonic wave is also observed by magnetic probes inserted into the plasma. The plasma dispersion of both waves as determined experimentally agrees well with the results of calculations for a hot plasma.

1. INTRODUCTION

RF heating in the ion cyclotron range of frequencies (ICRF) is expected to be a very attractive method of additional heating [1–4]. Mode conversion [5] plays an important role in ICRF heating of a mixed-species plasma. The fast magnetosonic wave excited by an antenna located on the high-field side is converted into an ion Bernstein wave near the ion-ion hybrid resonance layer. This electrostatic wave is effectively absorbed and heats the plasma. The wave-number of the mode-converted ion Bernstein wave was measured by far-infrared laser scattering in Microtor [6]. The amplitude of both the fast and the ion Bernstein waves was measured by CO_2 laser scattering in TFR [7]. This fast wave was observed indirectly through the coupling between the fast wave and a low-frequency drift wave.

In this letter, the results of measurements of the wave-number of both the fast and the ion Bernstein waves in TNT-A [8] are described. The fast wave is measured directly by magnetic probes [9], and the ion Bernstein wave is measured by 2-mm microwave scattering. The wave-number of the fast wave is obtained by measuring the phase shift with magnetic probes.

2. EXPERIMENTAL ARRANGEMENT

TNT-A is a non-circular tokamak with a major radius of 40 cm and a minor radius of 7.4 cm. The toroidal magnetic field is up to 4.5 kG, and the plasma current is 6 kA. The RF generator frequency is 5.6 MHz, approximately the cyclotron frequency of hydrogen, f_{CH}, and the externally driven wave is excited from a half-turn antenna located on the high-field side. The power coupled to the plasma in this experiment lies in the range from 5 to 10 kW.

The electron density fluctuations are measured by a 2-mm wave scattering system. This system is located at a toroidal angle of 90° away from the antenna. The injection and receiver horns are located above and below the plasma in the vessel as is shown in Fig.1.

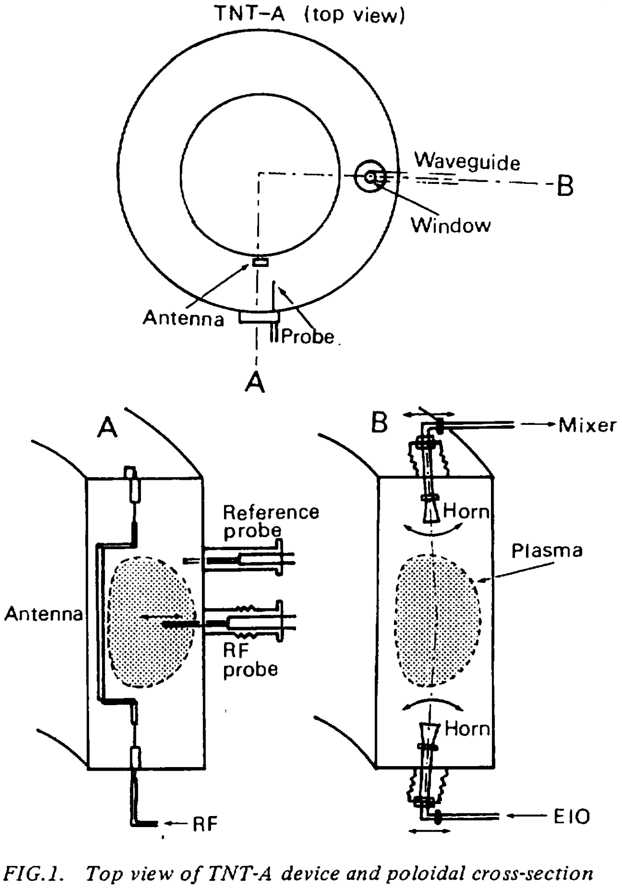

FIG.1. Top view of TNT-A device and poloidal cross-section at locations of antenna (RF probe) and 2-mm microwave scattering system. Wave in ICRF is excited by antenna on high-field side.

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Both horns are movable in radial direction through ±2 cm and can be rotated in the poloidal direction through ±5° in order to change location and angle of the scattering. The analysed wave-number $k_\perp$ is varied in the range $0.5\ \mathrm{cm}^{-1} < k_\perp < 5\ \mathrm{cm}^{-1}$, and the wave number resolution $\Delta k_\perp$ is $0.5\ \mathrm{cm}^{-1}$. The location of the scattering volume is near the plasma centre, where the effect of the poloidal field is neglected. The 'waist' of the scattering volume is 3 cm in the *equatorial plane of the plasma.* Homodyne detection is employed in these measurements. The scattered signal, shifted in frequency by the wave frequency (= 5.6 MHz), is down-converted in a GaAs Schottky-barrier diode mixer. The output from this mixer is amplified with a maximum gain of 40 dB. The amplitude of the scattered power is measured by using a spectrum analyser as tuned amplifier.

Two magnetic probes are located 4° toroidally away from the antenna. One (RF probe) is moved from the centre to the edge of the plasma, while the other one (the reference probe) is fixed outside the plasma. These probes have a rectangular coil, 2 mm X 5 mm in cross-section, wound on a polytetrafluoroethylene (PTFE) tube and protected by an alumina tube, whose inner and outer diameters are 3 and 5 mm, respectively. The amplitude of the fast magnetosonic wave is measured by the RF probe, and the phase shift is obtained from the signals of the RF and reference probes.

3. ION BERNSTEIN AND FAST WAVES

A typical example for the frequency spectrum of the scattered signal at $k_\perp = 1.0\ \mathrm{cm}^{-1}$ is shown in Fig.2. The central peak corresponds to the excitation frequency.

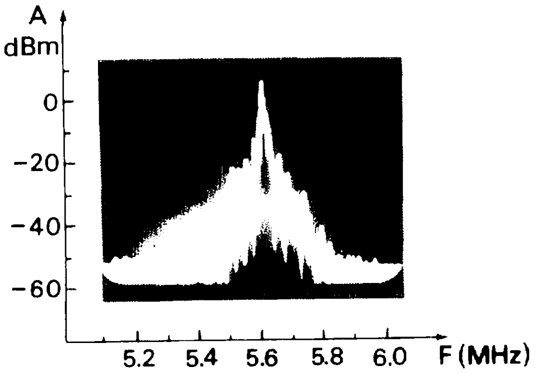

FIG.2. Spectrum of scattered signal. Horizontal axis: frequency (0.1 MHz/div); vertical axis: power (10 dB/div). Central frequency F = 5.6 MHz; band width BW = 10 kHz.

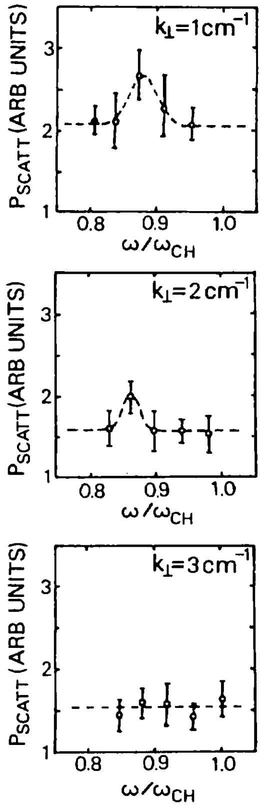

FIG.3. Dependence of scattered power of ion Bernstein wave on toroidal field (ω/ω_{CH}) ($f = 5.6$ MHz) for several $k_\perp$ wave-numbers. Error bars indicate amount of power scatter in ten shots. Plasma parameters: $n_e(0) = 1.5 \times 10^{13}\,\mathrm{cm}^{-3}$, $n_H/n = 0.2$, where $n = n_H + n_D$.

A broad spectrum of the scattered signal spreads 500 kHz around the central line. This broad spectrum is not observed without the incident 2-mm microwave, and the signal-to-noise ratio is 10 dB at the externally excited frequency. The shape of the broad frequency spectrum about 5.6 MHz is similar to that of the low-frequency spectrum caused by the drift wave. The broad frequency spectrum is due to a non-linear coupling between the fast wave and the low-frequency drift wave as was suggested by the TFR group.

The toroidal field is changed shot by shot from 3.5 to 4.5 kG in order to study the dependence of the amplitude of the scattered signal at the excitation frequency on the toroidal field, i.e. ω/ω_{CH} is varied, where $\omega_{CH} = 2\pi f_{CH}$. The scattering angle is also varied in order to investigate the dispersion relation. The amplitude of the scattered signal has a peak at $\omega/\omega_{CH} = 0.8$–0.9 when the hydrogen concentration is 20% in a D-H plasma. The values of ω/ω_{CH} at the peak change with $k_\perp$ as is shown in Fig.3. No peak is

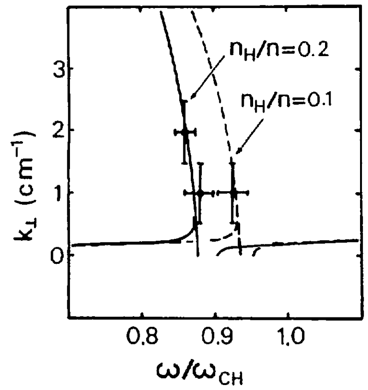

FIG.4. Experimental points and theoretically determined curves of dispersion of mode-converted ion Bernstein wave in D-H plasma. Plasma parameters used for calculation: $n_e = 1.5 \times 10^{13}$ *cm*$^{-3}$, $T_e = 100$ *eV,* $T_i = 30$ *eV,* $f = 5.6$ *MHz,* $k_\parallel = 0.05$ *cm*$^{-1}$*. Closed circular and solid lines are for* $n_H/n = 0.2$*; open circular and dashed ones for* $n_H/n = 0.1$*, where* $n = n_H + n_D$.

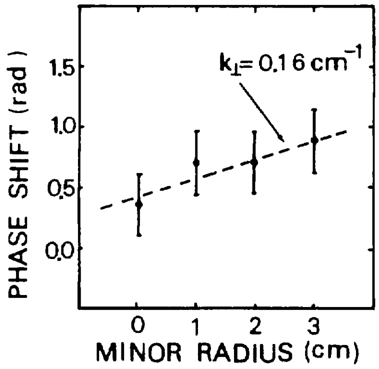

FIG.5. Radial dependence of magnetic-field phase shift for fast wave at $f = 5.6$ *MHz and* $\omega/\omega_{CH} = 0.9$.

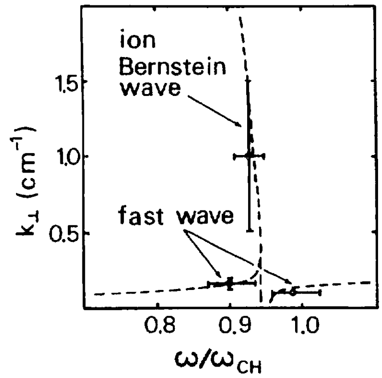

FIG.6. Experimental points and theoretical dispersion of fast and mode-converted ion Bernstein waves in D-H plasma. Plasma parameters used for calculation: $n_H/(n_H + n_D) = 0.1$, $n_e = 1.5 \times 10^{13}$ *cm*$^{-3}$, $T_e = 100$ *eV,* $T_i = 30$ *eV,* $f = 5.6$ *MHz,* $k_\parallel = 0.05$ *cm*$^{-1}$.

observed at $k_\perp > 3.0$ cm^{-1}. This fact is due to damping as the wave propagates towards large $k_\perp$ values.

The mode can be identified by comparing the measured wave dispersion with the theoretical value (numerical solution of the hot-plasma dispersion equation [10]) of the ion Bernstein wave. To verify the identity of this mode, the wave dispersion is examined for different concentration ratios $n_H/(n_H+n_D)$, where n_H and n_D are the hydrogen and deuterium densities, respectively. As is shown in Fig.4, the experimental dispersion agrees with the computed one in the two cases of a hydrogen concentration of 10 and 20%. In both cases, the plasma parameters are: central electron density $n_e(0) \approx 1.5 \times 10^{13}$ cm^{-1}, electron temperature $T_e(0) \approx 100$ eV, ion temperature $T_i(0) \approx 30$ eV, and plasma current $I_p \approx 6$ kA. According to a Fourier transformation of the excited electric field in the cold-slab model [11] with boundary conditions at antenna and walls, the $k_\parallel$ spectrum of the fast wave spreads from 0 to 0.08 cm^{-1} and has a peak at $k_\parallel = 0.05$ cm^{-1} (toroidal mode number n = 2).

The fast mode is observed with a magnetic probe inserted into the plasma. The phase shift at several radial locations is measured by RF and reference probes as is shown in Fig.5. The wave-number is obtained from the slope of the line fitted by the least-squares method.

The fast and ion Bernstein modes are observed in the same range of ω/ω_{CH} values by magnetic probes and 2-mm microwave scattering. The two modes are identified by comparing the measured and theoretical wave dispersions, which are summarized in Fig.6. The wave-numbers are measured at $\omega/\omega_{CH} = 0.90$ and 0.98 by magnetic probes and at $\omega/\omega_{CH} = 0.93$ by microwave scattering. These wave-numbers are measured at the same location (0 cm $\leqslant r \leqslant$ 3 cm), hydrogen concentration (10%) and frequency (5.6 MHz), but with different toroidal fields. The magnetic probe is scanned by 3 cm to measure the phase shift. The error bars of ω/ω_{CH} are determined from the scanning length ($\Delta r = \pm 1.5$ cm), considering the effect of the spatially varying magnetic field. The plasma parameters used in this calculation are $n_H/(n_D + n_H) = 0.1$, $n_e = 1.5 \times 10^{13}$ cm^{-1}, $T_e = 100$ eV, $T_i = 30$ eV, and $I_p = 6$ kA. The ion Bernstein wave is observed at $\omega/\omega_{CH} = 0.93$, and the fast wave at $\omega/\omega_{CH} = 0.90$ and $\omega/\omega_{CH} = 0.99$. The agreement of the experimental with the theoretical wave dispersion values confirms the fact of mode conversion near the ion-ion hybrid resonance layer.

4. CONCLUSIONS

The initially excited fast wave and the mode-converted ion Bernstein wave are measured near the ion-ion hybrid resonance layer ($\omega/\omega_{CH} = 0.8 \sim 1.0$) in a deuterium-hydrogen plasma. A magnetic probe inserted into the plasma measures the fast wave dispersion through the phase shift at several radial locations. The amplitude of the electric field of the incident fast wave is calculated from the magnetic field according to the cold-slab model with boundary conditions at antenna and walls. The amplitude is $1000\ \mathrm{V \cdot m^{-1}}$ at the location of the probes when the current flowing in the antenna is 130 A. The ion Bernstein wave dispersion is first measured by 2-mm microwave scattering at several wave-numbers ($k_{\perp} < 3.0\ \mathrm{cm^{-1}}$), the toroidal field being varied. The amplitude of the electric field of the mode-converted ion Bernstein wave is roughly estimated from the density fluctuation level [12]. The amplitude is $20\ \mathrm{V \cdot m^{-1}}$ at the location of the scattering volume. The amplitude of the electric field of the ion Bernstein wave at a toroidal angle of 90° away from the antenna is 2% of that of the incident fast wave at a toroidal angle of 4° away from the antenna. Both modes as measured experimentally agree with the theoretical wave dispersion obtained by a numerical solution of the hot-plasma dispersion equation.

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CURRENT GENERATION IN TOKAMAKS BY PHASED INJECTION OF PELLETS

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ABSTRACT. By phasing the injection of frozen pellets into a tokamak plasma, it is possible to generate current. The current occurs when the electron flux to individual members of an array of pellets is asymmetric with respect to the magnetic field. The utility of this method for tokamak reactors, however, is unclear; the current, even though free in a pellet-fuelled reactor, may not be large enough to be worth the trouble. Uncertainty as to the utility of this method is, in part, due to uncertainty as to proper modelling of the one-pellet problem.

1. INTRODUCTION

There is a continuing search for the most efficient means of generating continuous toroidal current in a tokamak. The object of such means is to replace the conventional inductive means, the Ohmic coils, which can operate only in a pulsed mode. The drawbacks to the steady-state methods that have so far been suggested lie primarily in their large power requirements.

In general, to generate current, an asymmetry must be introduced into the toroidal geometry so that one toroidal direction is favoured over the other. To accomplish this, there are a limited number of external things that can be brought to bear on the tokamak, namely various particle beams or travelling waves.