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Observation of Current-Driven Ion Sound Wave in a Turbulently Heated Plasma (THE MACH II)

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

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Abstract

Dynamic behaviors of the turbulence are measured in a turbulently heated plasma by microwave scattering method. Scattered signals are observed at the time before the plasma becomes resistive. The phase velocity of the wave increases with time. The value of the phase velocity is found to be consistent with that of the ion sound wave propagating across the magnetic field, when the increase of the phase velocity is interpreted as due to the increase of the electron temperature.

Many experiments on turbulent heating by high current discharge along the magnetic field have been made both in linear as well as in toroidal devices,[1)-4)] and it has been shown that the ion temperature of the plasma becomes about 1 keV. However, the turbulent waves which are responsible for the particle heating have not been clearly identified. Buneman[5)] proposed one mechanism; a fast-growing instability is excited whenever the electron drift velocity exceed the thermal velocity. Ion sound waves may also be driven unstable by the current. There have been reported a few experiments in toroidal devices, where the ion wave turbulence or the Buneman instability has been said to be responsible for the particle heating.3), 6)

In this letter, we describe the experimental results of the temporal development of the turbulence as measured by the microwave scattering method, and show that the ion wave turbulence observed here also seems to play an important role in ion heating. A few experiments were reported on the microwave scattering from the turbulently heated plasma,[7)-9)] but the frequency resolution was not so good as for the waves to be identified.

The experimental arrangement is shown schematically in Fig.1. The experiment is carried out in a linear machine, THE MACH II device.[10)] The device has a pair of hollow electrode with an inner diameter of 3 cm, separated by 135 cm each other. A helium plasma produced by a conical theta pinch gun is introduced through the electrodes in the discharge tube, where a mirror magnetic field is applied. Its initial electron density and temperature are $N_e \simeq 1 \times 10^{13}$ cm^{-3} and T_e=5-8 eV, respectively, in this experiment, and the strength of the magnetic field is fixed on 7 kG at a diagnostic port. The electrode voltage for heating the plasma is supplied from two series-connected capacitors of 2.2 μF each, with charging voltage up to 15 kV to give 1.1 μF at 30 kV.

Microwave scattering system is as follows. A 400 mW microwave of frequency $\omega_i/2\pi$ =72 GHz is launched perpendicularly to the plasma column through a transmitter horn. The electric field vectors $\mathbb{E}_i$ and $\mathbb{E}_s$ of the incident and scattered waves are parallel to the column axis. The scattered signal received by the receiver horn is detected by a homodyne system. The resulting beat signal is amplified by a wideband preamplifier having a pass band from 0.1 to 400 MHz. The output signal of the preamplifier is split into six separate channels, each having different frequency pass band, by means of filters. The bandwidth of the filters is 60-90 MHz. The filter outputs are then fed to diode detectors followed by video amplifiers. In the present experiment, the scattering angle θ_s is fixed at 90°. The perpendicular wavenumber of the density fluctuations to be detected is determined from the relation $k_\perp=2K_i\sin(\theta_s/2)$, i.e., $k_\perp$ =21.3 cm^{-1}, where K_i is the wavenumber of the incident wave. The diameter of the plasma column is limited to about d=3 cm by the heating electrodes, and the incident microwave beam has a transverse width of 2 cm on the center of the plasma column. Thus, the present system receives the signals scattered from radially as well as azimuthally propagating waves, if they are present simultaneously.

The temporal behaviors of the various quantities are shown in Fig.2. They are, from top to bottom, the heating current, heating voltage, microwave radiation at 48 GHz, and the video output of the scattered signals detected through the filters having the different center frequencies as indicated in the figure, respectively. It is seen that the density fluctuations with frequency of about 50 MHz appear at first, i.e., at $t \simeq 0.8\ \mu$sec, and then those with frequency of about 100 MHz succeed. When the plasma becomes resistive, i.e., at $t \simeq 1.4\ \mu$sec, signals are observed in most channels. The microwave radiation signal is also observed at this time, and the ratio of the scattered signal to the radiation noise is not so large.

In order to obtain the detailed frequency spectrum, the density fluctuations through the preamplifier or the filters are directly displayed on an oscilloscope [Tektronix model 7844], and photographed. The oscillatory signals so obtained are once transfered on a memory tape, and then fed to a computer to obtain the autocorrelation functions as well as the power spectral densities of the signals. Figure 3 shows the frequency spectra obtained by analyzing the four successive segments, each having $0.1\ \mu$sec duration, in one oscillogram. In calculating the spectra, the sampling time or the Nyquist period has been chosen to 100/60 nsec and the frequency components higher than 300 MHz have been filtered out from the original signal, so that an aliasing error has been excluded. Since the wavenumber $k_\perp$ is constant in this experiment, i.e., $k_\perp$=21.3 cm^{-1}, the phase velocity $v_{p\perp} = \omega/k_\perp$ is seen to increase with time. The value of $v_{p\perp}$ obtained from Fig.3 (a), (b), (c), and (d) are 5.9×10^6 cm/sec, 1.2×10^7 cm/sec, 2.4×10^7 cm/sec, and 3.6×10^7 cm/sec, respectively. The frequency spread Δf of the spectrum is wider than the one estimated from the instrumental broadening, Δf_b, as follows,[11]

$$\Delta f_b \simeq \frac{v_{p\perp} K_i}{\pi} \cos\frac{\theta_s}{2} \sin\frac{\Delta\theta_s}{2} \simeq 10 \text{ MHz} \qquad (1)$$

for $\Delta\theta_s \simeq 2\pi/K_s L \simeq 10°$, where K_s is the wavenumber of the scattered wave, and L is the effective illumination length of the incident wave.

As is well known in the turbulent heating experiments, electron drift velocity v_d exceeds the electron thermal velocity for a short period just after the application of the heating voltage. Then, the two-stream type of instability can occur. We have observed a corresponding strong microwave emission at 48 GHz at the time t=0.3-0.5 μsec as shown in Fig.2. This value of frequency is roughly the electron plasma frequency $\omega_{pe}/2\pi$. The increase rate of the electron temperature T_e obtained from the ruby-laser scattering began to rise at t=0.4-0.5 μsec, in the previous experiment.[10] The onset time of the electron heating corresponds to the time of occurrence of the microwave emission. When the electron-to-ion temperature ratio T_e/T_i becomes larger than unity, and the condition $v_d > c_s$ is satisfied, the ion sound wave can be generated with frequency components in the range $0 < \omega < \omega_{pi}$, where $\omega_{pi}/2\pi$ is the ion plasma frequency, $c_s=(T_e/m_i)^{1/2}$ is the ion sound velocity, and m_i is the mass of an ion. In this experiment $\omega_{pi}/2\pi \simeq 300$ MHz, and the values of frequency shown in Fig.2 and Fig.3 are included in this range.

Meanwhile, the ion sound wave propagating across the magnetic field satisfies the dispersion relation, for $\Omega_i^2 \ll k^2 T_e/m_i$,

$$\omega^2 = (k_\perp^2/k^2)\Omega_i^2 + k^2(T_e/m_i), \qquad (2)$$

where $\Omega_i/2\pi \simeq 3$ MHz is the ion cyclotron frequency. Knowing the values of $k_\perp$ and ω, the electron temperature can be calculated from Eq.(2), provided that $k \simeq k_\perp$. In Fig.4 the dots show the values of T_e thus obtained. For the sake of reference, the value of T_e obtained in the previous experiments by means of laser scattering[10) (for $T_e \lesssim 40$ eV) and X-ray measurements[12) (for $T_e \gtrsim 4$ keV) are also shown by circles in Fig.4. The agreement with each other is good.

From the density fluctuation measurement by the capacitive probe, the phase velocity parallel to the magnetic field $v_{p\parallel}$ is estimated to be about 2×10^8 cm/sec at the time when plasma becomes resistive. This value of $v_{p\parallel}$ is slightly less than the electron drift velocity calculated from the relation $v_d \simeq 4I_H/\pi d^2 e N_e$ for $I_H \simeq 7$ kA, $d \simeq 3$ cm, and $N_e \simeq 10^{13}$ cm^{-3}, i.e., $v_d \simeq 6 \times 10^8$ cm/sec, and can be interpreted as the parallel component of the ion sound wave propagating along a direction 80° from the magnetic field. Thus, the assumption of $k \simeq k_\perp$ in Eq.(2) does not introduce so much error for estimation of T_e.

Finally, it is noted that the ion sound waves would be Landau-damped when the ion thermal velocity approches the phase velocity of the wave. Let us suppose that this gives the upper limit for T_i. By equating the value of $v_i = (2T_i/m_i)^{1/2}$ to the phase velocity

$v_p=(T_e/m_i)^{1/2}$ we obtain $T_i \lesssim T_e/2$. This relation is consistent with the experimental results for the plasma in the resistive phase.

In conclusion, we have observed the microwave scattering from turbulently heated plasma. The observed frequency spectrum is fairly coherent at first, the center frequency increases with time, and the spectrum is found to broaden when plasma becomes resistive. The value of $v_{p\perp}$ is consistent with that of the ion sound wave propagating across the magnetic field. The increase in $v_{p\perp}$ is interpreted as due to the increase of the electron temperature. This results supports Hatori and Sugiharas' model for high energy tail formation of ion distribution in turbulently heated plasma, in which the ion resonance region has been required to move toward high velocity regime with time.[13)]

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Figure Captions

Fig. 1. Schematic diagram of the experimental arrangement.

Fig. 2. Typical oscillograms of the heating current I_H, the heating voltage V_H, the microwave radiation power P_{μ} at 48 GHz, and the scattered power P_s. The oscillogram of the radiation power is not the one obtained simultaneously with the others.

Fig. 3. Frequency spectra of the scattered power at the different time in the one oscillogram.

Fig. 4. Electron temperature as a function of time. The dots are obtained from E_q.(2) and the measured value of ω and $k_{\perp}$. The circles are obtained by laser scattering[10] for $T_e \lesssim 40$ eV and X-ray measurement for $T_e \gtrsim 4$ keV.

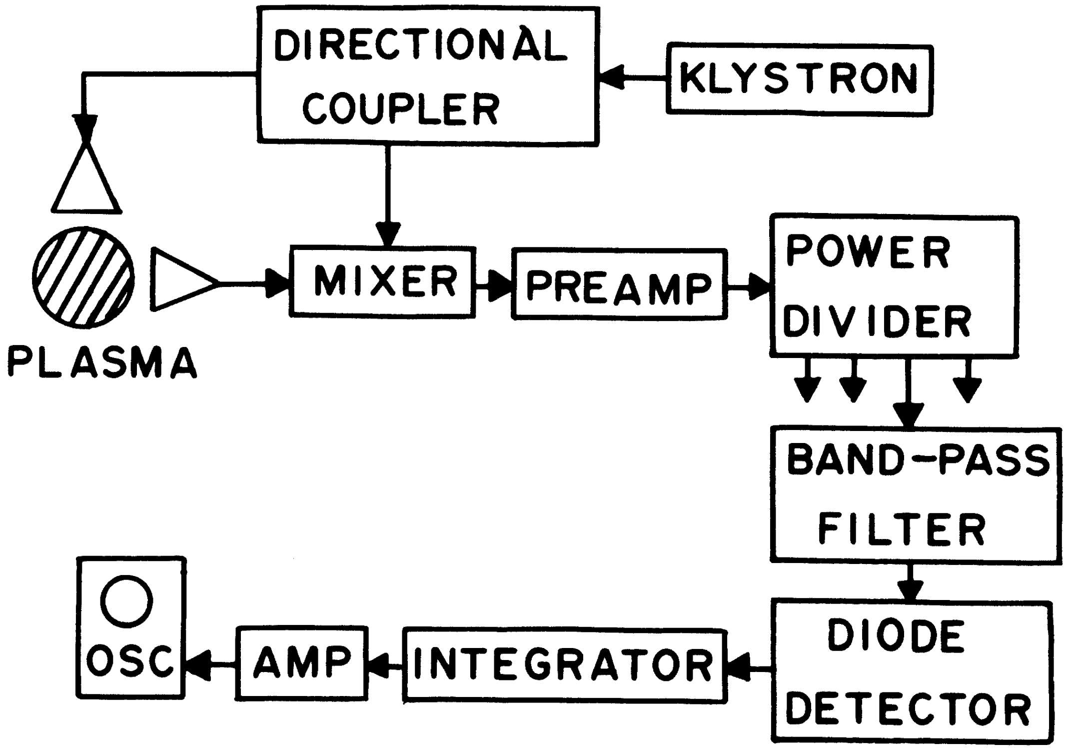
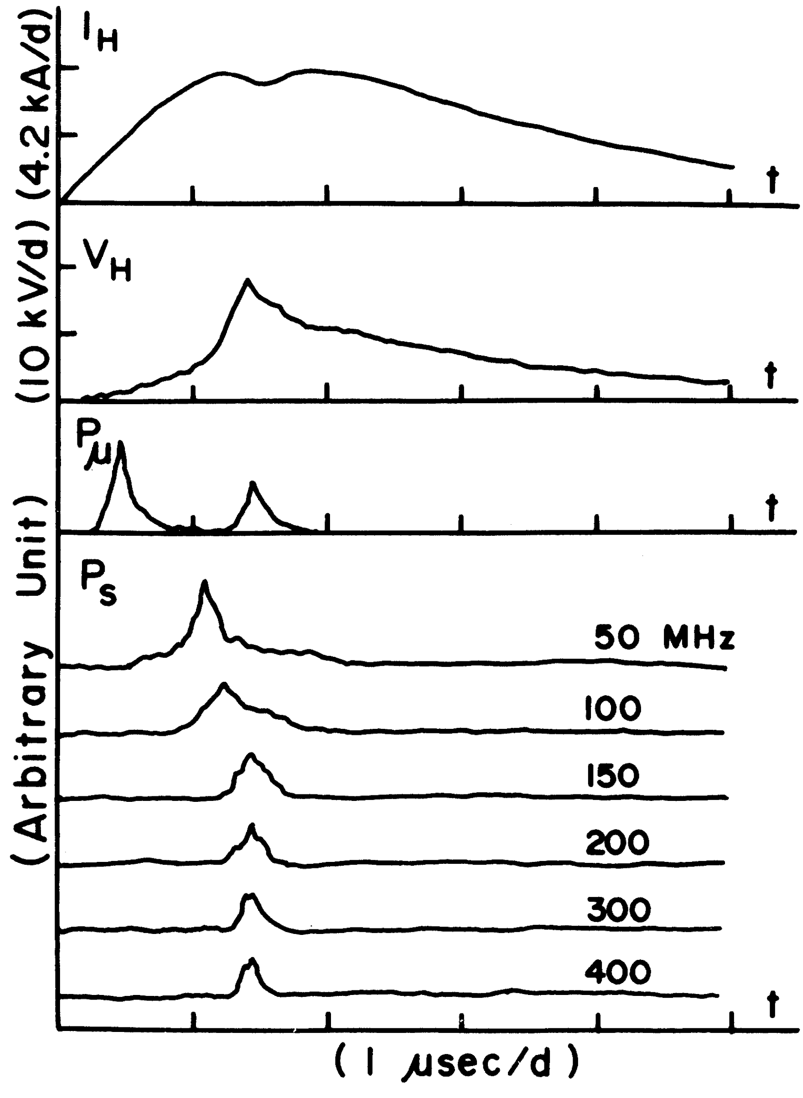

DIRECTIONAL COUPLER
KLYSTRON
PLASMA
MIXER
PREAMP
POWER DIVIDER
BAND-PASS FILTER
DIODE DETECTOR
INTEGRATOR
AMP
OSC

Fig. 1



I_H
(4.2 kA/d)
V_H
(10 kV/d)
P_μ
P_s
(Arbitrary Unit)
t
t
t
t
50 MHz
100
150
200
300
400
(1 μsec/d)

Fig. 2

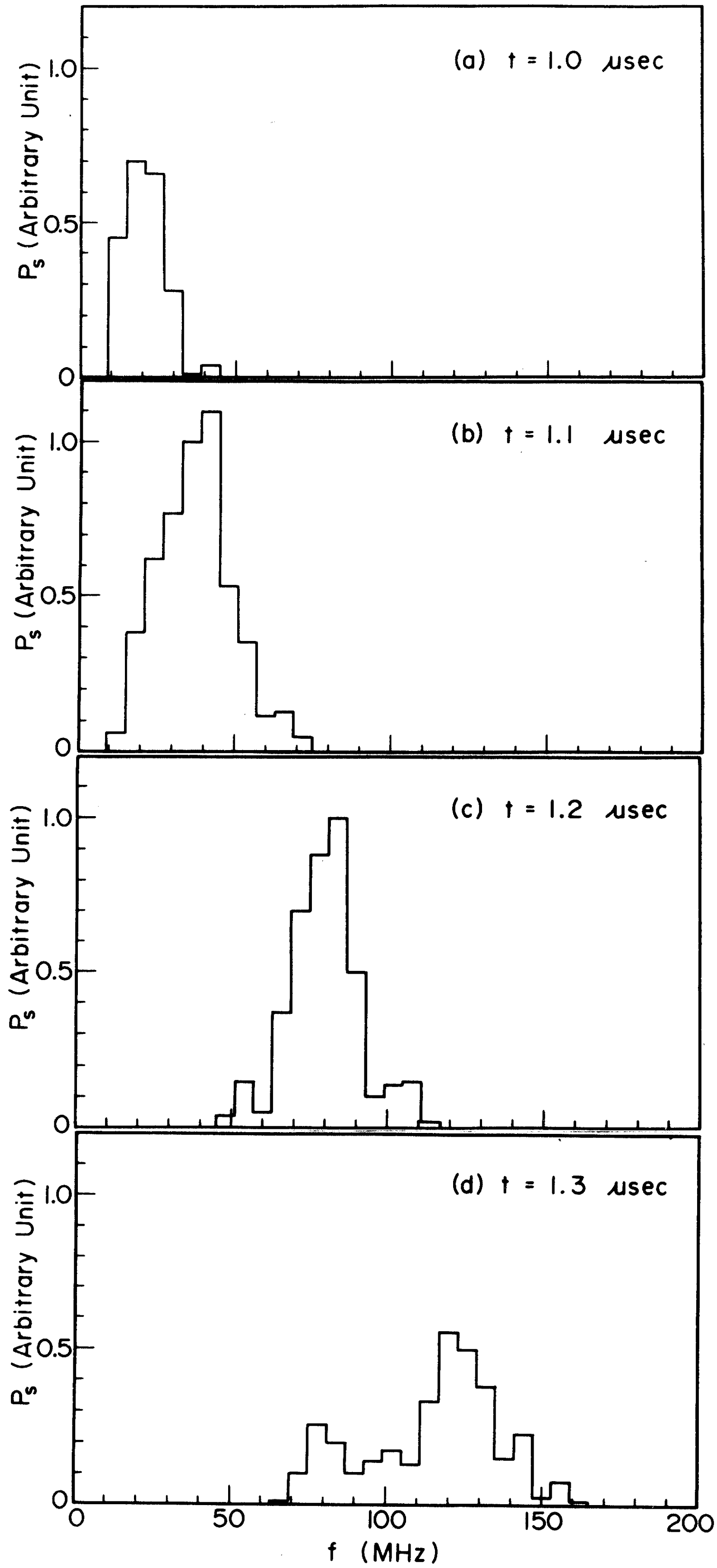

(a) t = 1.0 μsec
(b) t = 1.1 μsec
(c) t = 1.2 μsec
(d) t = 1.3 μsec
P_s (Arbitrary Unit)
1.0
0.5
0
50
100
150
200
f (MHz)

Fig. 3

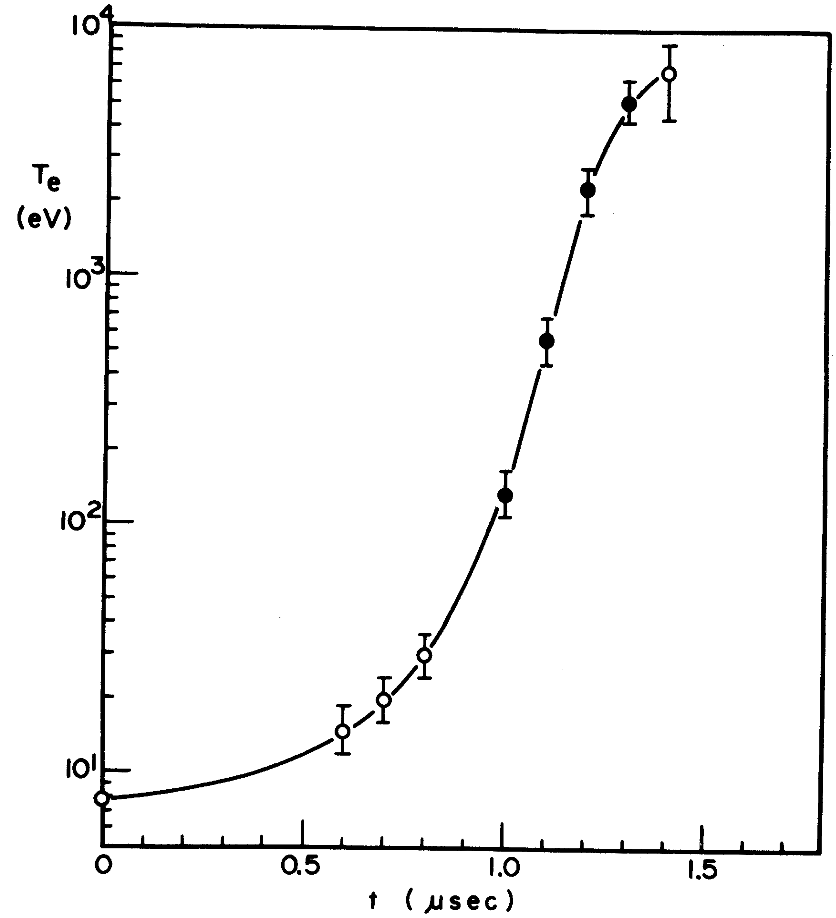


Fig. 4