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Measurements of Dispersion Relation of Waves in a Turbulently Heated Plasma by Microwave Scattering Method

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Abstract

The dispersion relation of the waves excited in a turbulently heated plasma has been studied by microwave scattering method, and it is identified to be that of the ion acoustic mode. The phase velocity of the wave has been observed to increase with time, indicating the increase of the electron temperature T_e with time. A space-averaged density fluctuation, as evaluated from a microwave interferometric measurement, has shown to build up at about 0.8 μsec after the initiation of the heating discharge. The time when the density fluctuations saturate is found to correspond roughly to the time of the formation of a high energy tail in the ion distribution function observed in a previous experiment.

In this letter, we report the first observation of dispersion relation of the waves propagating across the magnetic field in a turbulent heating of a plasma measured by microwave scattering method.

Many experiments on turbulent heating of plasmas by high current discharge through the plasma along the magnetic field have been made both in linear as well as in toroidal devices,[1)-4)] and they have been shown that the electron and ion temperature rise up to more than several keV within less than a microsecond. The turbulent waves which are responsible for the fast heating of the plasma, however, have not been clearly identified. When the drift velocity of the electrons in the plasma exceeds certain critical velocity, many micro-instabilities are excited. For example, when the drift velocity is larger than electron thermal velocity, then so-called "Buneman instability" is excited,[5)] and when the drift velocity exceeds the ion acoustic velocity, ion acoustic waves become unstable. There are so many instabilities which are driven by the plasma current. In most of the turbulent heating experiments, the waves in the plasma are picked up by probes, and frequency spectra are obtained.[3), 6)] Microwave scattering method is used in some experiment, however, only frequency spectrum for one fixed wave number is measured.[7)-10)] In our experiment, several array of horns are used to receive scattered microwave signals at different angles in order to obtain the dispersion relation of the waves in the turbulently heated plasma.

The experiment is carried out in a linear machine, THE MACH II device.[10), 11)] In this experiment, a pair of hollow electrodes with an inner diameter of 3 cm, is separated by 57 cm each other, and the strength of the magnetic field is fixed on 5 kG at the diagnostic port.

The microwave scattering system has been also described elsewhere.[10)] A 400 mW microwave of frequency $\omega_i/2\pi$=72 GHz is launched perpendicularly to the plasma column with the wave electric field polarized in the direction of the magnetic field. An array of antennas shown in Fig.1 is installed around the plasma column so that it is possible to make measurements for scattering angles of θ_s=35°, 75°, 90°, 120°, and 180° (i.e., backscattering). Here θ_s is the angle between the incident wave vector $\mathbb{K}_i$ and the scattered wave vector $\mathbb{K}_s$. The antennas are arranged so that $\mathbb{K}_i - \mathbb{K}_s$ is perpendicular to the direction of the heating current. Both the transmitter and receiver horn antennas have a finite beam divergence of about 12° FWHM in the E-plane. 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 by means of filters. Note that the measuring system is sensitive only for the wave propagating at an angle close to 90° with respect to the magnetic field, because of the narrow acceptance angle of the horn antennas.

The pass band of the filter used here extends from 10 MHz to 70 MHz. The filter output is directly displayed on an oscilloscope [Tektronix Model 7844], and recorded. The autocorrelation functions are calculated from the oscillatory signals so obtained, whose Fourier transforms yield the power spectral densities of the electron density fluctuations in the plasma. The time resolution of the measurement is limited by the length of a sample record, 0.1 μsec in the present case, which in turn sets a frequency resolution of no less than 10 MHz. To obtain a smooth spectral distribution, the Hanning window is used. The use of the band pass filter also eliminates the aliasing error.[12)]

The results of the scattering measurements are summarized in Fig. 2, where k is the wave number of the density fluctuations in the plasma which is propagating perpendicularly to the magnetic field, and it is related to θ_s by $k=2K_i \sin(\theta_s/2)$. Typical wave forms of the heating current I_H and heating voltage V_H are also shown in the insert of Fig. 2. Only one value of k is chosen in one shot , because of instrumental limitation. The spectrum obtained in one shot is mostly bell-shaped, whose center frequency varies shot by shot. The spectral width is wider than the maximum instrumental broadening of 11 MHz for θ_s=35°.[13)] The range of the variation of the center frequencies in five shots is indicated by the vertical bar for each value of k in Fig. 2.

It is interesting to note that the instantaneous wave energy distributes approximately along the solid curves shown in Fig. 2. This could happen when the wave energy of the fastest growing mode occuring at a certain frequency and wave number is quickly transfered to other range of frequency and wave number by some nonlinear mechanism such as the mode-mode coupling and parametric decay prosesses, resulting in a broad spectrum. In a stationary ion acoustic turbulence, the wave energy has been already found to distribute approximately along the linear dispersion curve with a finite frequency spread.[13] We may then interpret that the solid curves in Fig. 2 represent the instantaneous dispersion relations for the wave propagating perpendicularly to the magnetic field. Since the observed frequencies are much higher than the ion cyclotron frequency, $\Omega_i/2\pi \simeq 2$ MHz, and lower than the ion plasma frequency, $\omega_{pi}/2\pi \simeq 350$ MHz, the waves which are responsible for the microwave scattering may be identified with the ion acoustic wave propagating almost perpendicularly to the magnetic field. Thus, we have the following dispersion relation; $\omega^2 = (T_e/m_i)k^2$, where m_i is the mass of an ion. The change in the observed phase velocity with time is then interpreted as due to the change in T_e. The values of T_e are found to be 380 eV and 770 eV for t=1.0 μsec and t=1.1 μsec, respectively. The change in T_e in the sampling period of 0.1 μsec could give rise to an apparent broadening of the spectral width. The observed spectral width seems to include this effect. Detailed discussions on the broadening mechanism will be given elsewhere.

In separate experiments with the same machine, the Thomson scattering measurements yielded a value of $T_e \simeq 20$ eV for t=0.7 μsec.[11] The measurement of T_e for $t > 0.8$ μsec was then unable because of onset of instabilities. The X-ray radiations were also observed at $t \simeq 1.4$ μsec when the resistive hump in I_H appeared. A value of $T_e \simeq 7$ keV was obtained by the X-ray measurements.[14] The values of T_e obtained in the present experiment bridge in a consistent way the values of T_e obtained previously by other methods.

With the homodyne system, the scattering measurement for $\theta_s=0°$ reduces to (or completely masked by) an interferometric measurement of the density fluctuations.[15),16)] Assuming a slab geometry of the thickness d for the plasma, the instantaneous phase difference $\phi(t)$ between the local signal and the microwave signal which passed through the plasma slab, is given by $\phi(t)=\phi_1(t)+\phi_0(t)$, with

$$\phi_1(t) = \frac{K_i}{2}\int_0^d \frac{n_1(t)}{n_c}\left\{1-\frac{n_0(x,t)}{n_c}\right\}^{-1/2} dx \quad , \qquad (1)$$

provided $|n_1/n_c| \ll |1-n_0/n_c|$, where $n_0(x,t)$ is a smoothed density after averaging for the fast varying, and small scalled density fluctuation $n_1(x,t)$. The n_c is the cutoff density and ϕ_0 is a constant phase difference in the absence of the density fluctuations. The value of $\phi_1(t)$ is expected to be very small: i.e., $|\phi_1| < 5\times 10^{-2}$ for $|n_1/n_0| \simeq 10^{-2}$, $n_0/n_c \lesssim 0.16$, and $K_i d \simeq 30$ in the present case.

The time varying component of the mixer output $e_m(t)$ is then expressed as

$$e_m(t) \propto \cos(\phi_0+\phi_1) - \overline{\cos(\phi_0+\phi_1)} \simeq -\phi_1(t)\sin\phi_0 \quad , \quad (2)$$

where the bar denotes the time average. Now, since $n_1(x,t)$ is usually propotional to $n_0(x,t)$ for longitudinal waves, we may write as

$$n_1(x,t) \simeq n_0(x,t) \sum_k a_k(x) \cos \omega_k t \quad . \tag{3}$$

Insertion of Eq. (3) into Eq. (1) yields,

$$\phi_1(t) = \sum_k A_k \cos \omega_k t \quad , \tag{4}$$

$$A_k = \frac{K_i}{2n_c} \int_0^d a_k(x)\; n_0(x,t) \left\{ 1 - \frac{n_0(x,t)}{n_c} \right\}^{-1/2} dx \; . \tag{5}$$

Note that even when $a_k(x)$ is assumed to be a homogeneous periodic function of x, the value of A_k does not vanish because of inhomogeneous distribution of $n_0(x,t)$. For a short period of $\Delta t=0.1\ \mu sec$, $n_0(x,t)$ can be looked upon as a constant. The values of $|e_m(t)|^2$ averaged over the short period of 0.1 μsec are plotted as a function of time in Fig. 3. Since the value of $n_0(x,t)/n_c$ is at most 0.16, and expected not to vary drastically during the whole period of the measurement shown in Fig. 3, the value of $\overline{|e_m(t)|^2}$ can be considered to represent $\overline{|\phi_1(t)|^2}$ which in turn gives a measure of the total wave energy W; namely,

$$\overline{|\phi_1(t)|^2} \propto \overline{|n_1(t)|^2} \simeq \frac{n_0}{T_e} W \quad . \tag{6}$$

Thus, Fig. 3 shows approximately the temporal development of W/T_e. The wave energy starts to grow at $t \simeq 0.8\ \mu sec$. Soon later it saturates and then tends to decay slowly. The time when the wave energy starts to decay, roughly corresponds to the time of the formation of the high energy tail in the ion distribution function observed in a previous experiment.[2] This fact suggests that the observed ion acoustic turbulence is responsible for electron and ion heating directly or indirectly. The present experimental results support the result of computer simulation in which the increase of T_e with time is assumed apriori.[17]

In conclusion, we have observed the microwave scattering from a turbulently heated plasma. From the measurements of the power spectral density of the waves, the dispersion relation of the ion acoustic wave is confirmed for the first time in turbulent heating experiments. From an interferometric observation, the temporal development of the total wave energy is deduced. It is pointed out that the ion acoustic turbulence is responsible for ion-heating.

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Figure Captions

Fig. 1. Array of horn antennas used for microwave scattering. The receiver horns correspond to (1) $\Theta_s=0°$, (2) $\Theta_s=35°$, (3) $\Theta_s=75°$, (4) $\Theta_s=90°$, and (5) $\Theta_s=120°$.

Fig. 2. Dispersion relation of wave at various times.

Fig. 3. Values of $\overline{|e_m(t)|^2}$ as a function of time.

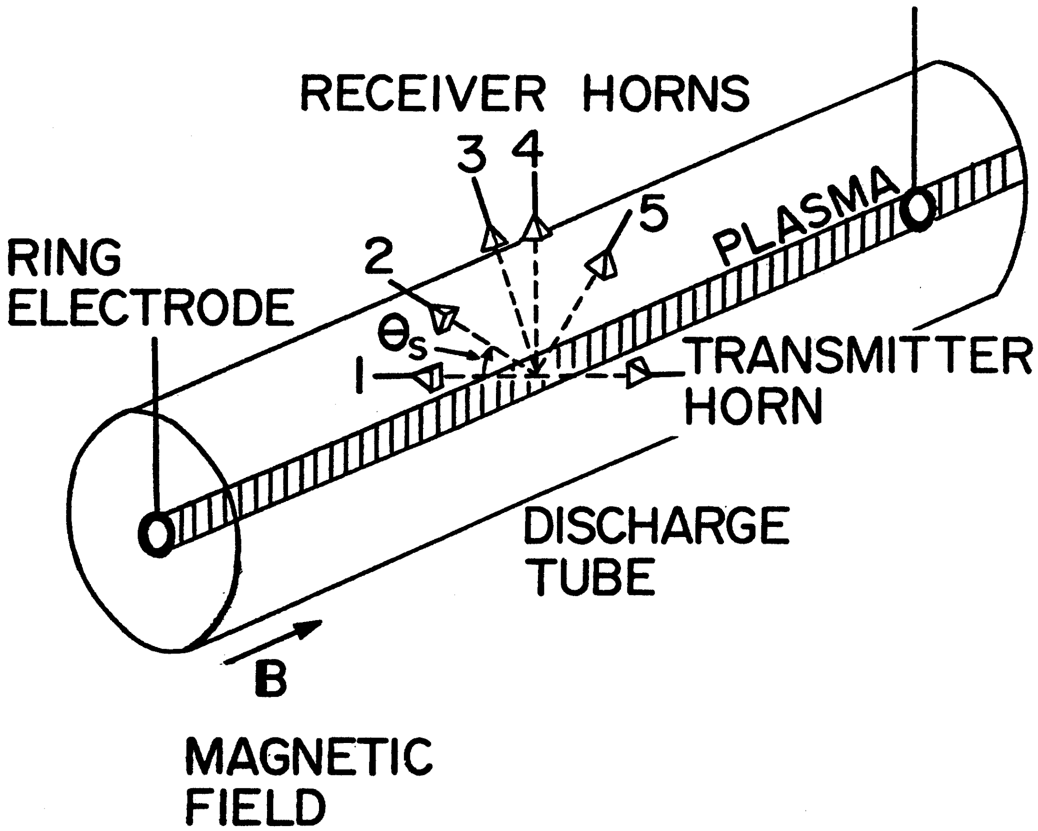
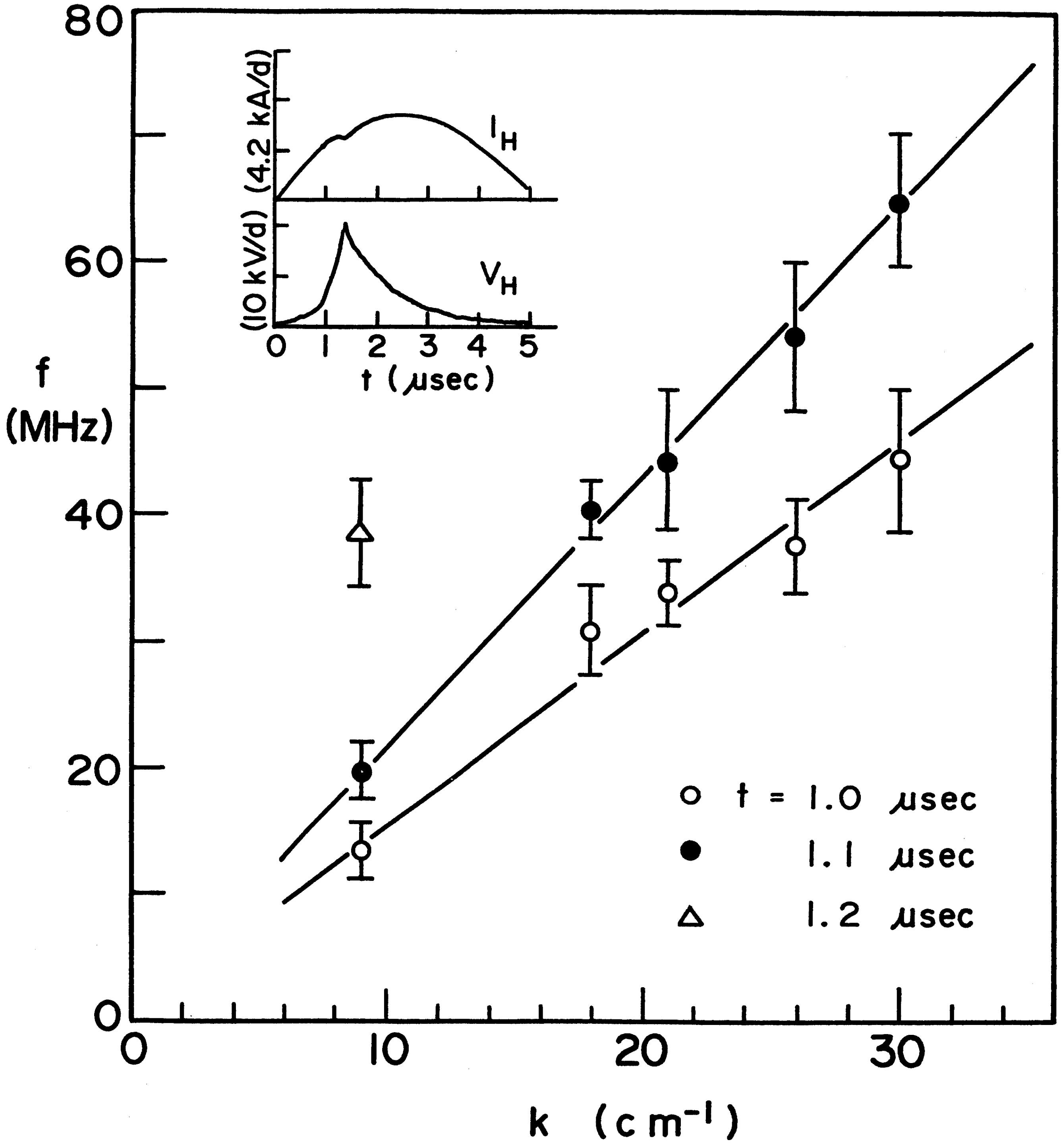

RECEIVER HORNS
3
4
5
2
PLASMA
RING
ELECTRODE
θ_s
1
TRANSMITTER
HORN
DISCHARGE
TUBE
B
MAGNETIC
FIELD

Fig. 1



80
60
40
20
0
f
(MHz)
0
10
20
30
k (cm⁻¹)
(4.2 kA/d)
(10 kV/d)
I_H
V_H
0 1 2 3 4 5
t (μsec)
○ t = 1.0 μsec
● 1.1 μsec
△ 1.2 μsec

Fig. 2

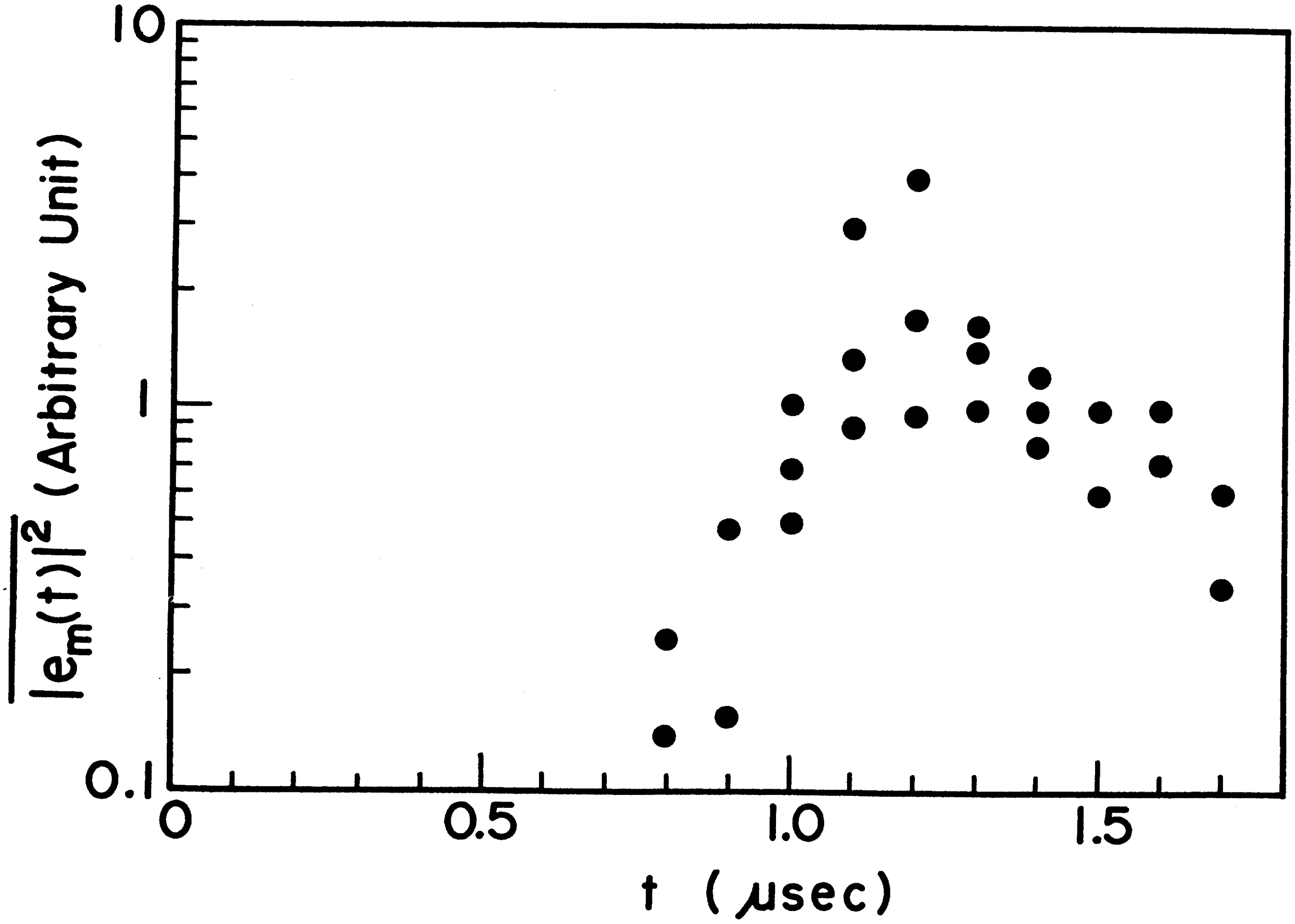


Fig. 3