# OBSERVATION OF THE LOW-FREQUENCY ION ACOUSTIC INSTABILITY IN THE TURBULENTLY HEATED TRIAM-1 TOKAMAK PLASMA

Mitarai, Osamu
Research Institute for Applied Mechanics, Kyushu University : Research Student

Watanabe, Takechiyo
Research Institute for Applied Mechanics, Kyushu University : Graduate Student

Nakamura, Yukio
Research Institute for Applied Mechanics, Kyushu University : Research Associate

Nakamura, Kazuo
Research Institute for Applied Mechanics, Kyushu University : Research Associate

他

https://doi.org/10.5109/6776453

出版情報：Reports of Research Institute for Applied Mechanics. 28 (89), pp.61-72, 1980-12. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. XXVIII, No. 89, 1980

# OBSERVATION OF THE LOW-FREQUENCY ION ACOUSTIC INSTABILITY IN THE TURBULENTLY HEATED TRIAM-1 TOKAMAK PLASMA

O. MITARAI* , T. WATANABE**, Y. NAKAMURA***,
K. NAKAMURA***, N. HIRAKI***, K. TOI****,
Y. KAWAI****, S. ITOH*****

Density fluctuations in the frequency range of several MHz are observed in the turbulently heated TRIAM-1 tokamak plasma by means of a 4 mm microwave scattering method. It is found from the measurement of the dispersion relation that this instability is considered to be the low-frequency ion acoustic instability propagating nearly perpendicular to the toroidal magnetic field.

***Key words***: Microwave scattering, Low-frequency ion acoustic instability, Turbulent heating

## 1. Introduction

The turbulent heating experiments have been carried out using both toroidal and linear machines, so far. It has been reported[1)~5)] that ion and electron temperatures can be raised up in a short time by passing a turbulent heating current and this heating may be caused by current-driven turbulence. However, such a mechnism has not been clarified experimentally. The main reason is considered to be due to bad confinements of a plasma. In order to heat a well confined tokamak plasma to temperatures of keV by turbulent heating, we have been performing the TRIAM-1 project. The TRIAM-1 machine is a tokamak with high toroidal magnetic fields, which provides a tokamak plasma with a high density of $10^{14}$ cm$^{-3}$ and a high temperature of a few 100 eV. When a strong pulsed electric field is applied to the TRIAM-1 tokamak plasma, an increase in the ion

* Research Institute for Applied Mechanics, Research Student
** Research Institute for Applied Mechanics, Graduate Student
*** Research Institute for Applied Mechanics, Research Associate
**** Research Institute for Applied Mechanics, Associate Professor
***** Research Institute for Applied Mechanics, Professor

temperature from 100 to 300 eV at the plasma center is observed, which has been reported in detail elsewhere[5]. For understanding the mechanism of turbulent heating, it is necessary, first of all, to investigate what types of instabilities are excited, which could be made by measuring the dispersion relation of waves.

A microwave scattering method is a powerful one for measuring the dispersion relation especially in a high temperature plasma. A number of microwave scattering experiments have been performed using the toroidal machines[6] as well as the linear machines.[7] To our knowledge, however, the ion acoustic instability, which is considered to be one of promising candidate responsible for the heating, has not been identified in the turbulent heating experiments in a tokamak plasma. In this paper, we present the first experimental evidence for the excitation of the low-frequency ion acoustic instability by the turbulent heating current in the TRIAM-1 tokamak. In Sec. 2, we describe the experimental apparatus. Experimental results of the power spectrum and dispersion relation of the observed fluctuations are given in Sec. 3. The results of the numerical calculation for explaining the observed dispersion relation are presented in Sec. 4 and discussion and conclusion are given in Sec. 5.

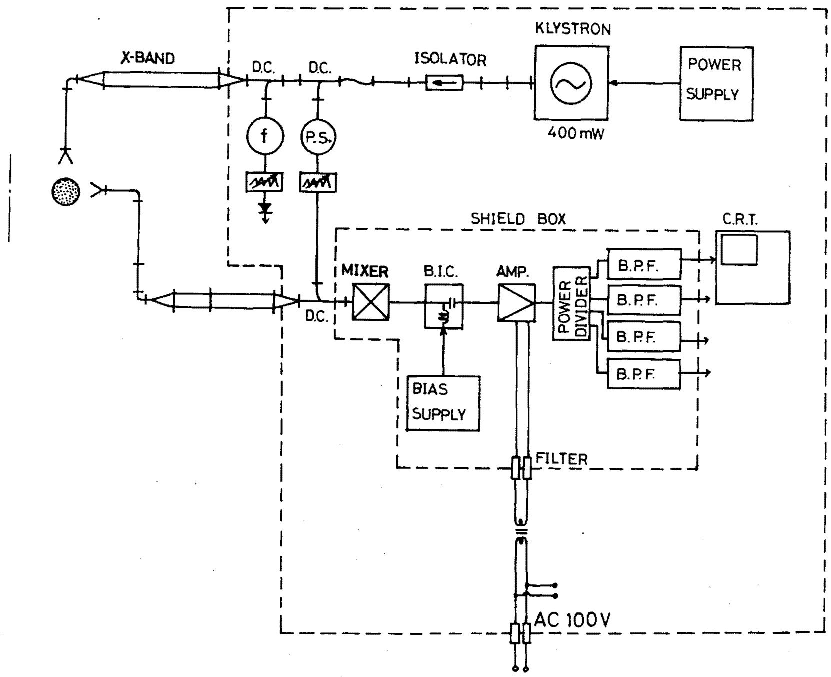



Fig. 1 The 4 mm microwave scattering system.

## 2. Experimental Apparatus

Figure 1 shows the schematic block diagram of the microwave scattering system, which is a conventional homodyne detection system. An incident microwave with a frequency of $f_i=70$ GHz and a power of 0.4 W is launched perpendicular to a plasma column with electric fields polarized in the direction of toroidal magnetic fields. Since antennas are installed outside the vacuum chamber of the TRIAM-1 tokamak[5], it is possible to make measurements of fluctuations for various scattering angles.

The received signal is mixed with the reference signal by the mixer diode (E 965, TRG), which is operated with fixed bias voltages in order to reduce the conversion loss. The output of the mixer diode passes a bias insertion coil and is led to an osciloscope. This bias insertion coil has a flat frequency response from 1 MHz to 1 GHz and is used to apply the DC bias voltage to the mixer diode. This scattering system is shielded by a shield box, as shown by dotted lines, in order to reduce noises from high turbulent heating voltages.

Figure 2 shows the block diagram of the data acquisition method. Wa-

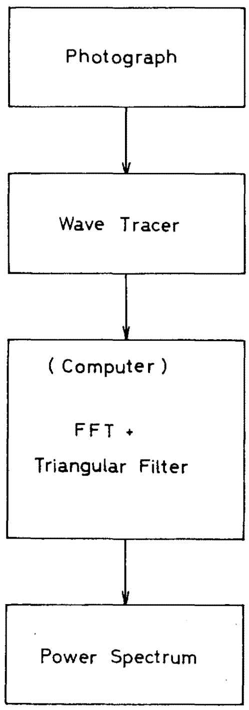


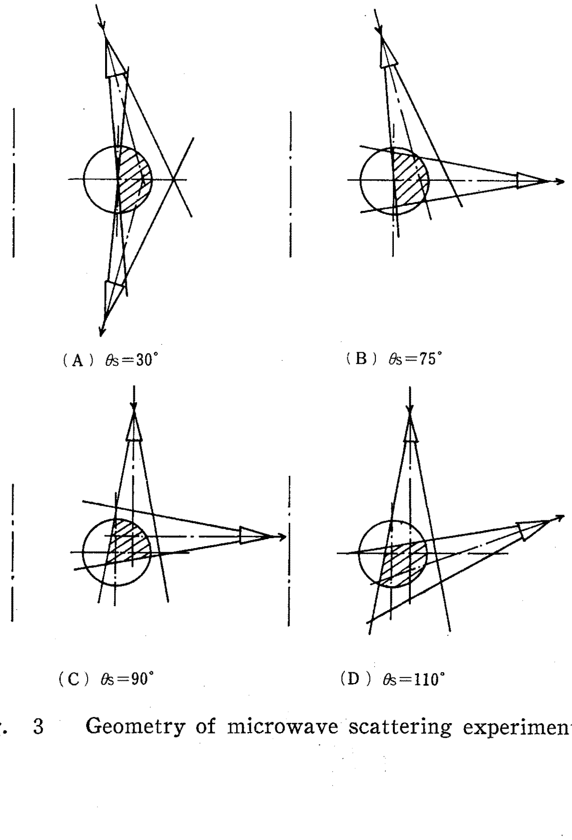

Fig. 2 The data acquisition method of obtaining power spectrum.

veforms recorded on photographs are traced by a wave tracer by manual and resistered on a computer. These data are analyzed by the FFT method. Raw spectrum are smoothed by the triangular window. The resultant spectrum are drawn on a X-Y plotter.

We selected the scattering angles 30°, 75°, 90° and 110° to study the dispersion relation of instabilities excited by the turbulent heating current. Figure 3 is the schematic figure of the scattering arrangement. Here, we defined $\theta_s$ as the angle between the incident wave vector $k_i$ and the scattered wave vector $k_s$. Since the transmitter and receiver horn antennas have a finite beam divergence of about 20° full width at half-maximum in $\boldsymbol{E}$ and $\boldsymbol{H}$ planes, this system can measure only waves propagating almost perpendicular to the toroidal magnetic fields. Therefore, it will be possible to observe only the waves propagaing at the angle between about 80° and 90°.

## 3. Experimental Results

The scattering experiments were performed in the TRIAM-1 tokamak ($R_0$=24.5 cm, $a$=4 cm). In Fig. 4 we show the current and loop voltage



(A) $\theta_s$=30° (B) $\theta_s$=75°

(C) $\theta_s$=90° (D) $\theta_s$=110°

Fig. 3 Geometry of microwave scattering experiments.

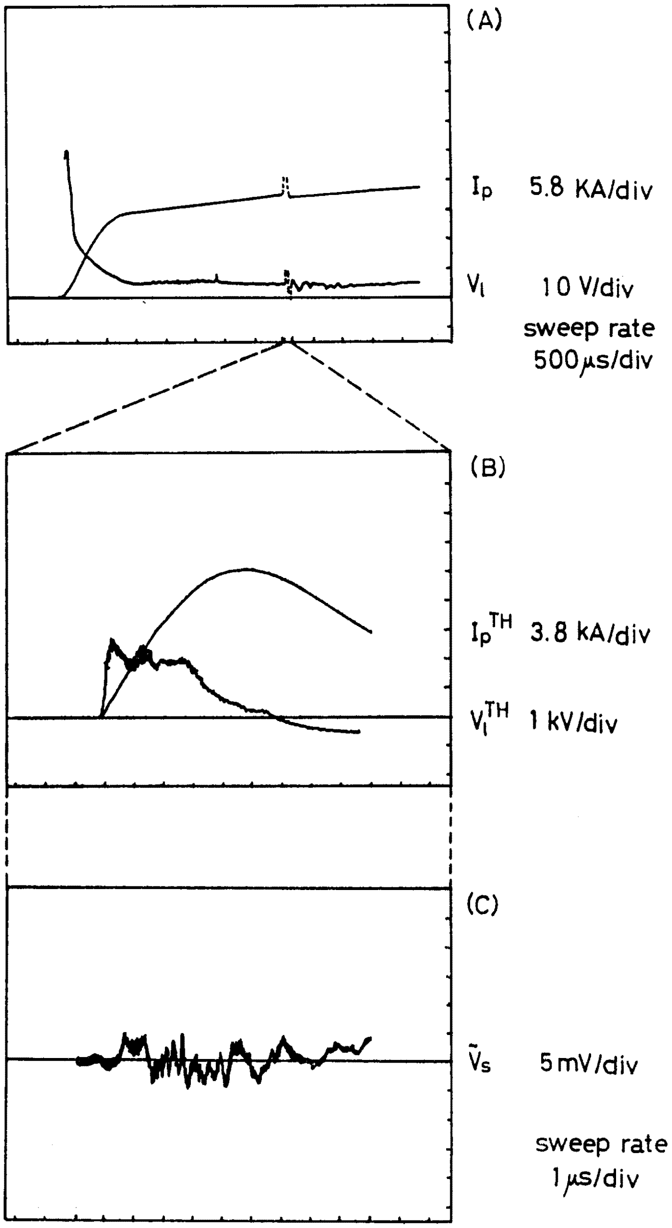
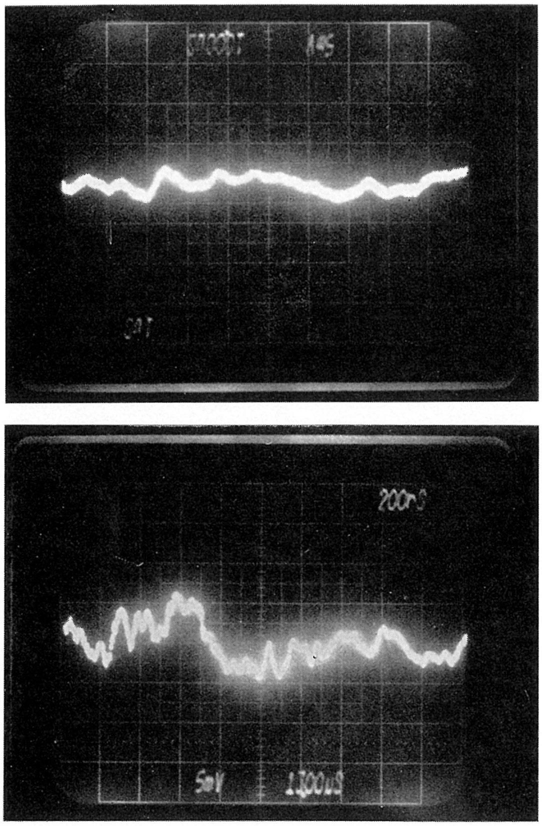



Fig. 4 Typical discharge waveforms and observed scattered signals.

waveforms of the tokamak discharge (A) and the turbulent heating current and voltage waveforms (B). In the same figure, the scattered signal (C), where the turbulent heating current was superimposed, is shown. The main parameters of the turbulent heating experiments are: toroidal magnetic field $B_t$=31 kG, tokamak plasma current $I_p$=15 kA (at 3 ms from the initiation of the discharge) and turbulent heating current $I_p^{TH}$=19 kA (peak value). We made the experiments, keeping the tokamak plasma current as low as possible in order to pass large turbulent heating currents, because the macroscopic stability of the turbulently heated plasma is limited by a safety factor q(a). Figure 4 shows that the fluctuation begins to appear at (1~2) μsec after the application of the turbulent heating voltage.

Figure 5 shows the scattered signals scanned by 1 μsec and 200 nsec. The upper and lower waveforms correspond to the case without and with the turbulent heating current, respectively. It is found clearly from this



(A) without TH current

$\tilde{V}_s$ 5mV/div
sweep rate
1 μs/div

(B) with TH current

$\tilde{V}_s$ 5mV/div
sweep rate
200 ns/div

Fig. 5 (A) The scattering waveform without the turbulent heating current.
(B) The scattering waveform with the turbulent heating current.

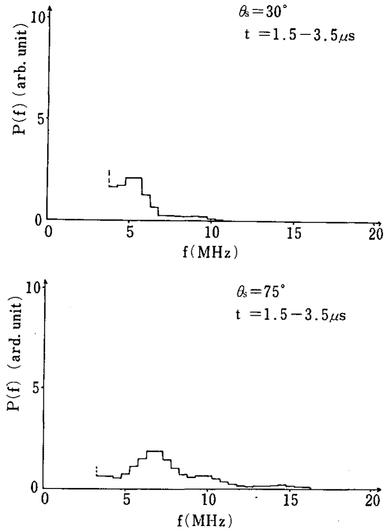



Fig. 6 Power spectrum at 30° and 75° scattering angles.

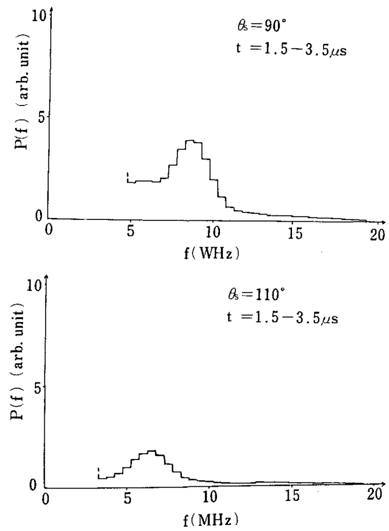



Fig. 7 Power spectrum at 90° and 110° scattering angles.

photograph that fluctuations with several MHz are excited by the turbulent heating current.

We obtained the power spectrum of the fluctuations for the various scattering angles. The typical power spectrum are shown in Figs. 6 and 7. As the scattering angle is increased, peak frequencies become large and the tail of the spectrum becomes broad.

In Fig. 8 we plotted the peak frequencies obtained from the power spectrum as a function of $k_\perp$ vector defined by $k_\perp = 2k_i \sin(\theta_s/2)$. The cross bars indicate the resolution of the $k$ vector obtained from Fig. 3. Note that the frequencies are below the ion cyclotron frequency $f_{ci} = 50$ MHz. The solid line in Fig. 8 is the theoretical prediction of the low-frequency ion acoustic instability, which corresponds to the case "A" in Fig. 9.

Furthermore, we observed that the fluctuation levels increase with increasing the turbulent heating current. This suggests that the observed waves were excited by current-driven instabilities.

## 4. Identification of The Observed Dispersion Relation

To explain the observed dispersion relation, we calculated numerically the dispersion equation of electrostatic current-driven instabilities in the magnetic field. We assume a homogeneous infinite collisionless plasma, in which electrons with a Maxwellian distribution drift toward the magnetic field through stationary ions with a Maxwellian one. The dispersion equation is written as follows[9]:

$$\varepsilon = 1 + \frac{1}{k^2\lambda_D^2}\left\{1 + \frac{\omega - k_\parallel v_d}{\sqrt{2}k_\parallel\sqrt{T_e/m}} \sum_{n=-\infty}^{\infty} Z\left(\frac{\omega - k_\parallel v_d - n\omega_{ce}}{\sqrt{2}k_\parallel\sqrt{T_e/m}}\right) I_n(k_\perp^2\rho_e^2)e^{-k_\perp^2\rho_e^2}\right\}$$
$$+ \frac{T_e/T_i}{k^2\lambda_D^2}\left\{1 + \frac{\omega}{\sqrt{2}k_\parallel\sqrt{T_i/M}} \sum_{n=-\infty}^{\infty} Z\left(\frac{\omega - n\omega_{ci}}{\sqrt{2}k_\parallel\sqrt{T_i/M}}\right) I_n(k_\perp^2\rho_i^2)e^{-k_\perp^2\rho_i^2}\right\}$$
$$= 0 \qquad (1)$$

where $k^2 = k_\parallel^2 + k_\perp^2$, $\theta = \tan^{-1}(k_\perp/k_\parallel)$ and $I_n$ is the n-th order modified Bessel function. The following definition is used as a plasma dispersion function $Z$:

$$Z(\zeta) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty} \frac{e^{-x^2}}{x-\zeta} d\zeta \qquad \text{for Im } \zeta > 0 \qquad (2)$$

and its analytic continuation for Im $\zeta \leqq 0$.

Since the skin layer of the electron temperature has been measured in the turbulently heated TRIAM-1 tokamak plasma by the Thomson scattering method[8], we consider the case where the turbulent heating current passes in the skin layer. Defining $\delta$ as a thickness of the skin current, the ratio of the electron drift velociy, $v_d$, to the thermal velocity, $v_e$, during the turbulent heating is given as follows:

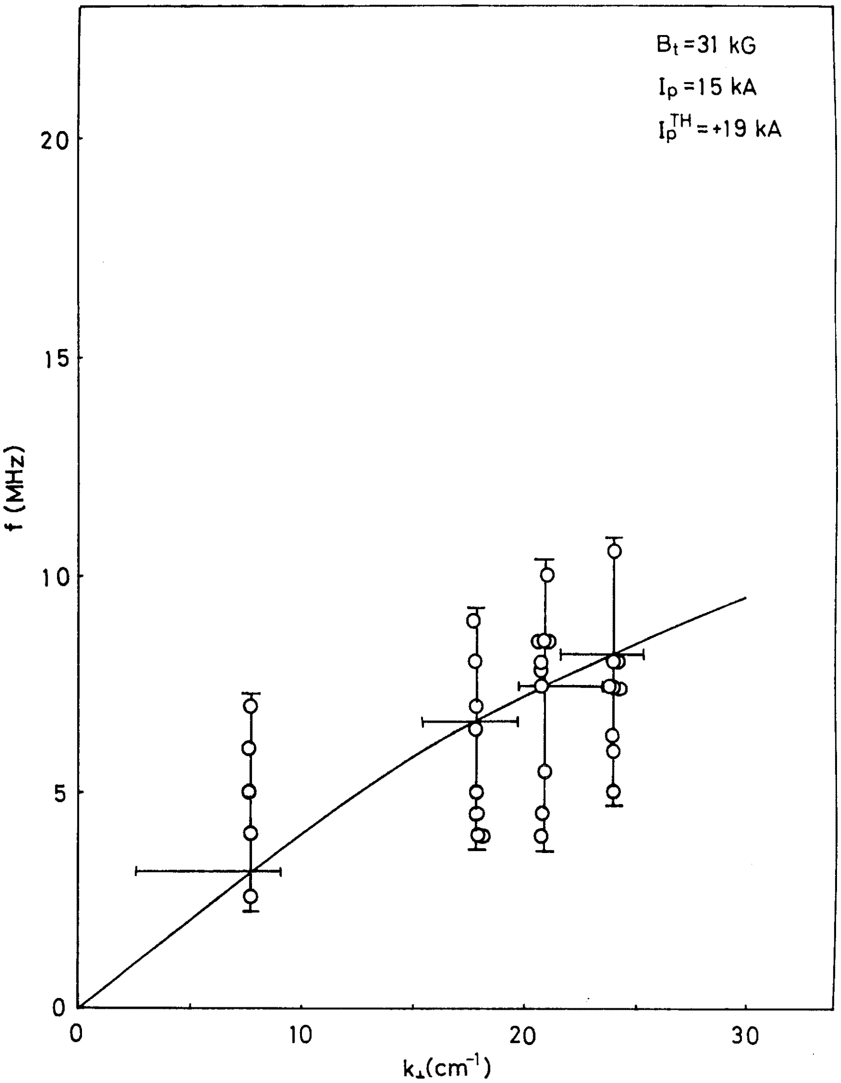



Fig. 8 The measured dispersion relation. Cross bars indicate the resolution of the $k$ vector. The solid line is the theoretical prediction for $n_e=1\times10^{19}\,m^{-3}$, $T_e=200\,eV$, $T_i=20\,eV$ and $\delta=$ 0.5 cm.

$$\frac{v_d}{v_e}=\frac{I_p^{TH}}{n_e e\pi a\delta(2-\delta/a)v_e} \tag{3}$$

where $v_e=\sqrt{T_e/m}$ and a is a plasma radius. To obtain the theoretical dispersion relation, we solved Eq. (1) for $\omega(\equiv 2\pi f+i\gamma)$ as a function of $k_\perp$. The result for the case of Fig. 8 is shown by the solid line in Fig. 8. In this calculation, we used the experimentally determined values as $T_e$, $n_e$ and $\delta$ at the skin layer, while $T_i$ was estimated from the measured profile of the ion temperature without the turbulent heating current. Figure 8 shows that the observed dispersion relation agrees with the dispersion relation of the low-frequency ion acoustic instability.

It is easily demonstrated that the growth rates of the instability are very sensitive to the plasma parameters such as $T_e/T_i$ and $v_d/v_e$. The growth rates for the different parameters are shown by the dotted lines, together with the dispersion relation, in Fig. 9. It is found from this figure that the growth rates become negative as $k_\perp$ increases. In our experiments, the instability was observed at $k_\perp=24$ cm$^{-1}$ so that the growth rate at this value must be positive. Therefore, the case "A" explains well the experimental results.

Furthermore, the growth time measured in the present experiment was of the order of several hundred nsec., which is consistent with a calculated value $t\sim 1/\gamma$. Thus, we conclude that the observed instability is the low-frequency ion acoustic instability excited by the turbulent heating current.

## 5. Discussion and Conclusion

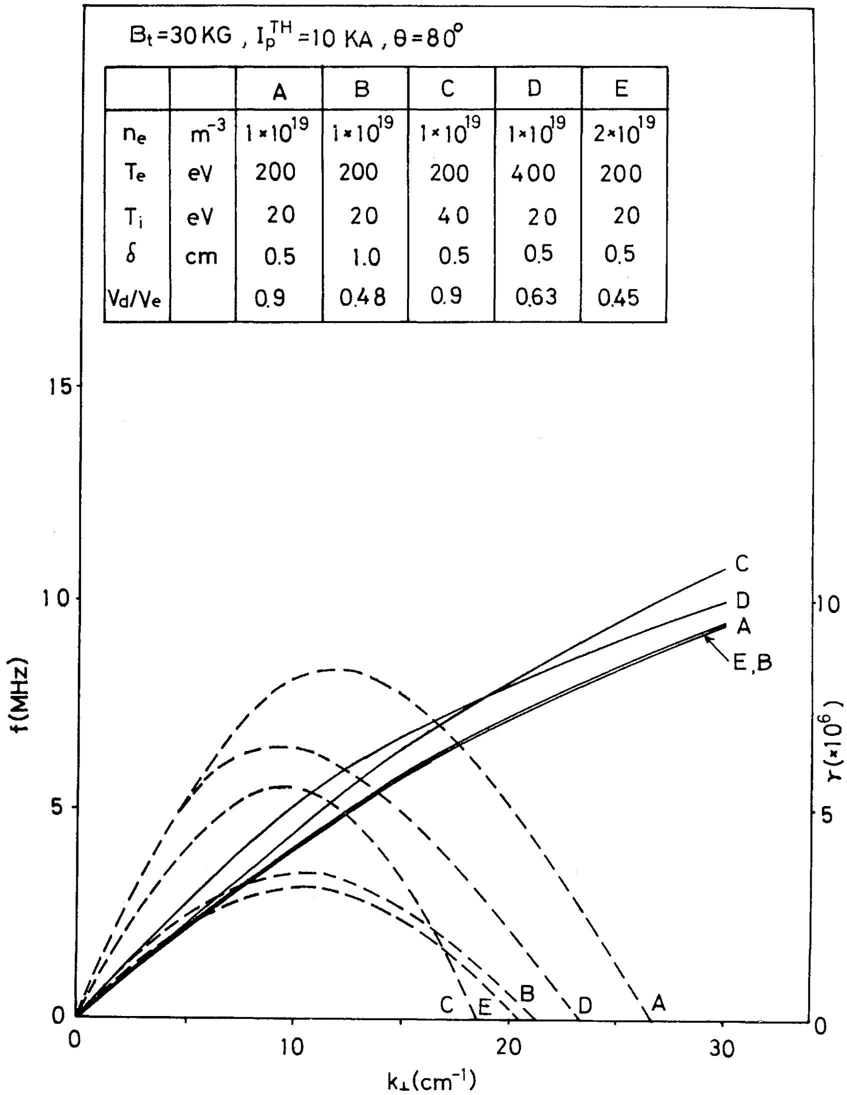
As seen in Fig. 3, the scattering volume is relatively large in the present case. This may be improved by using horn lenses or shorter micro-wavelength sources such as a 2 mm-klystron.

It is shown from the analysis of the dispersion equation (1) that whenever the low-frequency ion acoustic instability is excited, the ion acoustic instability is excited in the larger $k_\parallel$ region. When we choose the parameter of the case of (A), a maximum growth rate is $\gamma=7\times 10^6$ sec$^{-1}$ at $k_\parallel=180$ cm$^{-1}$. Therefore, we expect the excitation of the high-frequency ion acoustic instability having a growth rate much greater than that of the low-frequency ion acoustic instability. To measure such an instability, an infrared scattering method will be useful because of smaller wavelengths.

We applied the theory of the homogeneous plasma to analyze the experimental results in spite of the formation of the skin current. The measured wavelength ($\lambda_{max}=2\pi/k_{min}\simeq 2\pi/0.7\simeq 1$cm) is comparable with the thickness of the skin current. This effect has not been taken into account in the present analysis.

As the turbulent heating current was increased, the fluctuation level became large and the ions as well as electrons were heated. The instability observed here may play an important role in such heating, which is will be reported elsewhere.

In conclusion, density fluctuations in the frequency range of several MHz are observed in the turbulently heated TRIAM-1 tokamak plasma by means




| | | A | B | C | D | E |
|---|---|---|---|---|---|---|
| $n_e$ | $m^{-3}$ | $1\times10^{19}$ | $1\times10^{19}$ | $1\times10^{19}$ | $1\times10^{19}$ | $2\times10^{19}$ |
| $T_e$ | eV | 200 | 200 | 200 | 400 | 200 |
| $T_i$ | eV | 20 | 20 | 40 | 20 | 20 |
| δ | cm | 0.5 | 1.0 | 0.5 | 0.5 | 0.5 |
| Vd/Ve | | 0.9 | 0.48 | 0.9 | 0.63 | 0.45 |

Fig. 9 Calculated dispersion relations for different parameters, where $B_t$=30kG, $I_p^{TH}$=19 kA and $\theta$=80°.

of a 4 mm microwave scattering method. It is found from the measurements of the dispersion relation that this instability is considered to be the low-frequency ion acoustic instability propagating nearly perpendicular to the toroidal magnetic field.

## Acknowledgements

We wish to thank Professor N. Yajima for encouragement and interest. We are also grateful to Mr. H. Nakashima and Mr. S. Kawasaki for technical assistance and Mr. T. Mizota for his helpful discussion about spectrum analysis.

### References

1) S. M. Hamberger and J. Jancarik: Phys. Fluids 15 (1972) 825.
2) H. Schrijver, W. R. Rutgers, J. A. Van Elst, H. A. Post, H. W. Kalfsbeek, H. W. Piekaar and H. DeKluiver: *Proc. V-th Con. on Plasma Phys. and Cont. Nucl. Fusion Res., Tokyo, 1974*, 271.
3) A. Hirose and H. M. Skarsgard: Phys Rev. Lett. 36 (1976) 252.
4) Y. Nakagawa, M. Tanikawa, K. Watanabe, K. Adati, H. Iguchi, K. Ishii, Y. Ito, J. Jacquinot, T. Kawabe, T. Kawamura, K. Muraoka, T. Oda and R. Sugihara: *Proc. V-th Con. on Plasma Phys. and Cont. Nucl. Fusion Res., Tokyo, 1974*, 287.
5) K. Toi, N. Hiraki, K. Nakamura, O. Mitarai, Y. Kawai and S. Itoh: Reports of Research Institute for Applied Mechanics, Vol. XXVII, No. 86, (1980) and to be published in Nucl. Fusion (1980)
6) V. Arunasalam, M. Okabayashi, R. J. Hawryluk and S. Suckewer: Phys. Fluids, 20 (1977) 95.
7) A. Mase, T. Tsukishima, H. Iguchi, Y. Ito and T. Kawabe: Phys. Fluids, 22 (1979) 196.
8) N. Hiraki, K. Nakamura, K. Toi and S. Itoh: Reports of Research Institute for Applied Mechanics, Vol. XXVII, No. 87, (1980).
9) A. B. Mikhailovskii: *Theory of Plasma Instabilities*, (Consultant Bureau, New York -London, 1974).

(Received October 7, 1980)