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CRITICAL CONDITION FOR CURRENT-DRIVEN INSTABILITY EXCITED IN TURBULENT HEATING OF TRIAM-1 TOKAMAK PLASMA

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Critical condition for current-driven instability excited in turbulently heated TRIAM-1 tokamak plasma is investigated experimentally. Resistive hump in loop voltage, plasma density fluctuation and rapid increase of electron temperature in a skin layer are simultaneously observed at the time when the electron drift velocity amounts to the critical drift velocity for low-frequency ion acoustic instability.

Key words: Critical condition, Resistive hump, Density fluctuation Streaming parameter.

1. Introduction

Several further heating methods have been applied to tokamak plasmas and the effective plasma heating has been reported. One such heating method involves turbulent heating by current-driven turbulence, in which a stable confinement of turbulently heated plasma and an application to large tokamak devices are very important problems. Turbulent heating by the application of high electric field ($\gtrsim 100$ V/cm)

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along the toroidal magnetic field has been carried out in several toroidal devices[1)~3)]. In these experiments, however, the turbulently heated plasmas could not be confined successfully because of substantial energy losses. In TRIAM-1, a relatively low electric field, which is higher than a Dreicer field, has been applied to a well-confined high temperature tokamak plasma and the effective ion heating has been observed without deterioration of the confinement properties[4)~6)]. In turbulent heating, it is one of the most important problems to clarify the critical condition for current-driven instability on account of understanding the heating mechanism and optimizing the excitation of turbulence. Moreover, the critical condition is very useful to decide parameters of turbulent heating system in the application to large tokamak devices. The critical condition can be clearly found in our experiment by the application of low toroidal electric field. The threshold current on the onset of current-driven instability is studied by monitoring one turn loop voltage and current of the heating pulse, and measuring a time evolution of electron temperature and plasma density fluctuation in a skin layer. A critical electron drift velocity is estimated from the threshold current and compared with that for low-frequency ion acoustic instability, the dispersion relation of which is identified by a 4 mm microwave scattering method[7)].

2. Experimental Apparatus and Diagnostics

The TRIAM-1 device is a small high-field tokamak, by which a stably confined high temperature plasma can be produced. Main parameters of the TRIAM-1 tokamak and the plasma parameters are summarized in Table 1. The high plasma current density can be attained on account of the large ratio of toroidal magnetic field to major plasma radius ($B_t/R \sim 16$ T/m).

Table 1. Main parameters of the TRIAM-1 tokamak and the plasma parameters.

Toroidal Magnetic Field	$B_t = 40$ kG
Major Radius	$R = 25.4$ cm
Plasma Radius	$a = 4.0$ cm
Plasma Current	$I_p = 15$–47 kA
Plasma Current Density	$\langle j \rangle = 300$–950 A/cm^2
Electron Temperature	$T_e = 200$–640 eV
Ion Tempearature	$T_i = 80$–280 eV
Line Average Electron Density	$\bar{n}_e = 1.5$–22×10^{13} cm^{-3}

For the sake of turbulent heating, the vacuum chamber is insulated by two ceramic breaks in the poloidal direction. Turbulent heating coils are located in the bore of toroidal field coils. A pulsed current for turbulent heating is induced by the discharge of capacitor bank (3.75 μF, 40 kV, 3 kJ) through the primary coil which consists of four loops parallel to the toroidal magnetic field lines. The applied toroidal electric field is below 10 V/cm, but is much larger than the Dreicer field because of the high electron temperature. The current rise time of turbulent heating pulse is about 4 μs and the equivalent pulse width is about 8 μs.

The loop voltage and plasma current induced by a turbulent heating pulse are monitored by one-turn loop and Rogowskii coil, respectively, and we observe an anomalous resistivity of turbulently heated plasma. The electron temperature during the application of heating pulse is measured by a ruby laser Thomson scattering system. Density fluctuations in the skin layer are observed by a 4 mm microwave scattering method, which is a conventional homodyne detection system.

3. Experimental Results

A turbulent heating pulse is applied to a stably confined high temperature plasma ($T_{e0}=240$ eV, $T_{i0}=120$ eV, $\bar{n}_e=2\times10^{13}$ cm^{-3}) at 5 msec after the initiation of discharge, when the toroidal magnetic field is 28 kG and the ohmic heating current is 23 kA. The heating current is

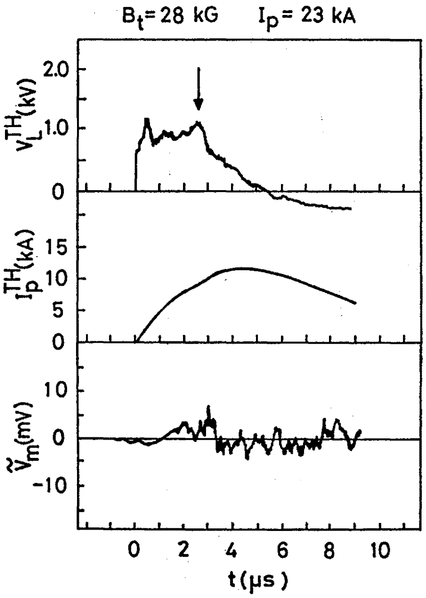

Fig. 1. Loop voltage (V_L^{TH}) and plasma current (I_p^{TH}) induced by a turbulent heating pulse, and density fluctuation measured by a 4 mm microwave scattering method. The resistive hump is shown by an arrow.

superimposed on the ohmic heating current in the same direction as the plasma current. To find a critical condition for current-driven instability excited in this experiment, firstly, we observe an anomalous plasma resistivity which is found in the loop voltage (V_L^{TH}) and the plasma current (I_p^{TH}) induced by the heating pulse. Moreover, density fluctuations in the skin layer are simultaneously measured by a microwave scattering system, which can measure only waves propagating almost perpendicular to the toroidal magnetic field. As shown in Fig. 1, the resistive hump which results from the anomalus resistivity of plasma is observed in the one turn loop voltage of turbulent heating and the density fluctuation begins to appear at the same time as the rise of the resistive hump. In this case the charging voltage of capacitor bank for turbulent heating (V_c^{TH}) is 17.5 kV and it is found that the resistive humps and density fluctuations appear at different times for the other charging voltages. As shown in Fig. 2–3, the resistive humps and

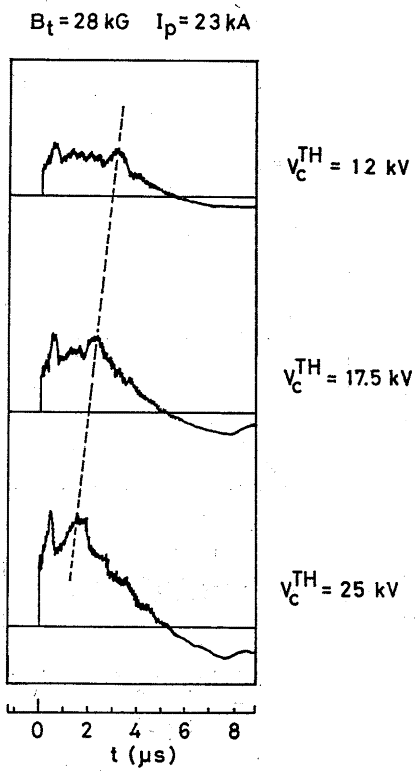

Fig. 2. Change of the time of occurrence of the resistive hump with the increase of charging voltage of capacitor bank.

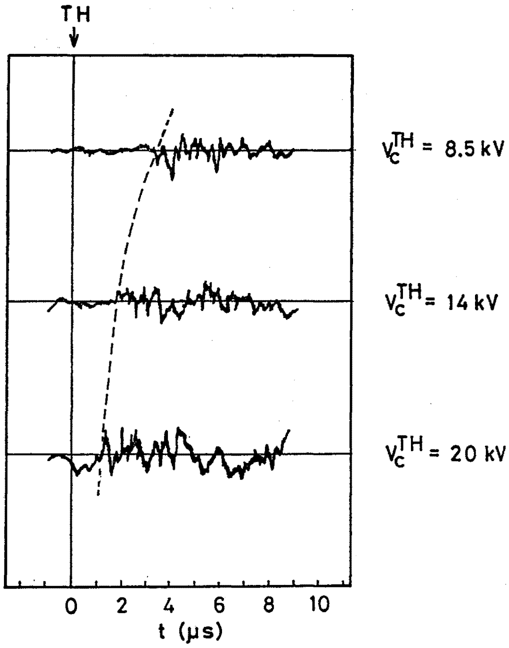

Fig. 3. Change of the time of appearance of the density fluctuation with the increase of charging voltage of capacitor bank.

density fluctuations appear early with increasing the charging voltage of capacitor bank for turbulent heating, that is, with the increase of turbulent heating current. From these figures, it can be considered that there is a threshold current for current-driven instability. In addition, we investigate the time evolution of electron temperature during the turbulent heating pulse. As the electron temperature increases with a skin structure in the radial profile[6], we measure the electron temperature in the skin layer ($r=3.4$ cm). As shown in Fig. 4, the rapid increase of the electron temperature, which is due to the anomalous resistivity resulting from current-driven turbulence, is observed in accordance with the appearance of the resistive hump and the density fluctuation. From the results described above, we can estimate a threshold current for current-driven instability. In Fig. 5, the time of appearance of the resistive hump (t_h) is plotted as a function of charging voltage of capacitor bank for turbulent heating. Open circles indicate the values obtained from the waveform of loop voltage and the time at which the turbulent heating current amounts to 6.9 kA is also shown by a solid line. From this figure, we can see that a threshold current to produce a current-driven turbulence is about 6.9 kA in our experimental conditions.

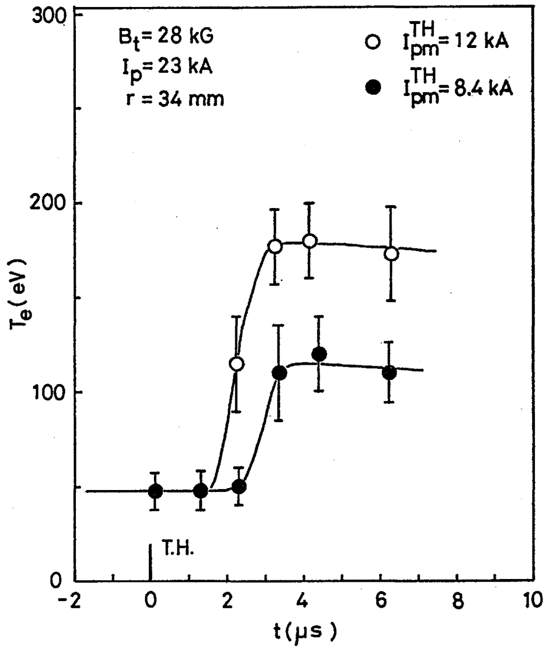

Fig. 4. Time evolution of electron temprature at the skin layer ($r=3.4$ cm) during the heating pulse. Dots and open circles correspond to the charging voltage (V_c^{TH}) of 12 kV and 17.5 kV.

4. Discussion

Here, we shall estimate the streaming parameter (v_d/v_e) in the skin layer during turbulent heating, where v_d and v_e are the electron drift velocity and thermal velocity, respectively. Assuming that a thickness of the skin current is δ, the streaming parameter is written as follows: $v_d/v_e = I_p^{TH}/[n_e e\pi\delta(2a-\delta)v_e]$, where I_p^{TH} is a turbulent heating current, n_e is an electron density in the skin layer and a is a plasma radius. In our experimental conditions, the electron temperature and density in the skin layer before the occurrence of instability are given as follows : $T_e \sim 50$ eV, $n_e \sim 1.5\times10^{13}$ cm^{-3}. Considering that the skin layer of electron temperature is larger than that of turbulent heating current, we can estimate that $\delta \sim 0.6$–0.8 cm from the skin profile of the electron temperature resulting in the turbulent heating. Therefore, for the threshold current of 6.9 kA obtained in our experiment, it follows that $v_d/v_e \sim 0.53$–0.7.

In a 4 mm microwave scattering experiment[7], a dispersion relation of low-frequency ion acoustic instability has been observed. Accordingly,

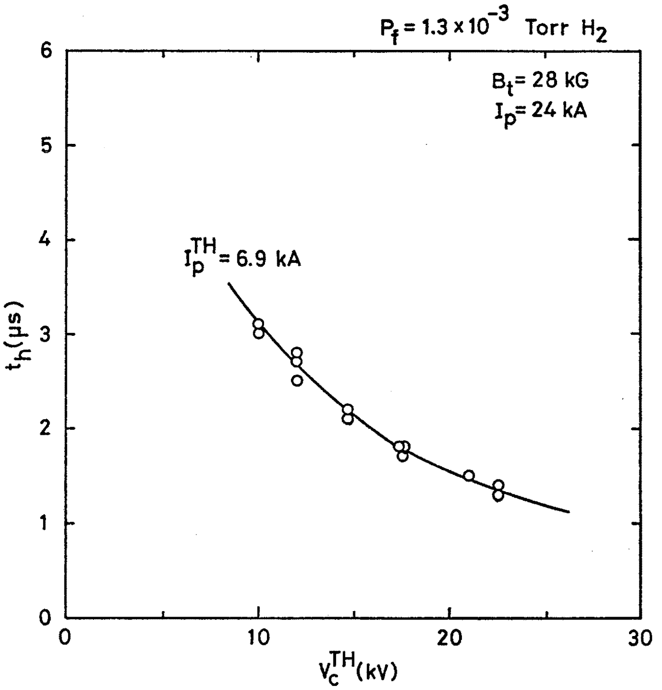

Fig. 5. Dependence of the onset of resistive hump on charging voltage of capacitor bank for turbulent heating. A solid line shows the time at which the turbulent heating current amounts to 6.9 kA.

it is important to estimate a critical drift velocity for low-frequency ion acoustic instability. A dispersion equation of electrostatic current-driven instabilities for a homogeneous, collisionless, magnetized plasma is written as follows[8]:

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

where $k^2=k_{//}^2+k_\perp^2$, I_n and Z are the n-th order modified Bessel function and plasma dispersion function, respectively. Here we search for marginal stability conditions for low-frequency ion acoustic instability. Assuming the growth rate is zero and the critical drift velocity is obtained as a funtion of T_e/T_i by solving the dispersion equation numerically

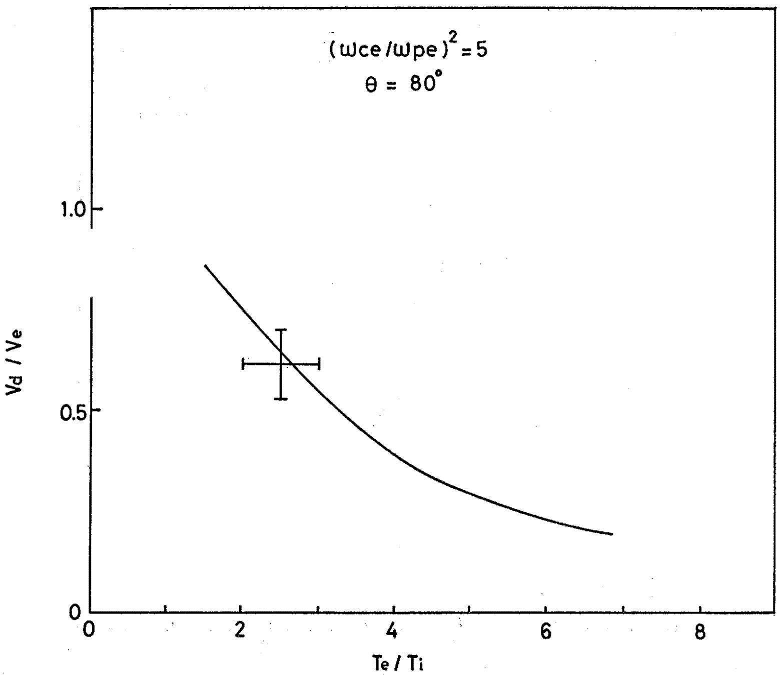

Fig. 6. Critical drift velocity for low-frequency ion acoustic instability as function of T_e/T_i. Experimentally obtained critical condition is shown by a cross bar.

for $(\omega_{ce}/\omega_{pe})^2=5$ and $\theta=\tan^{-1}(k_\perp/k_{//})=80°$. Figure 6 shows the calculated critical drift velocity together with the experimental value. The critical condition for current-driven instability in our experiment is in good agreement with that for low-frequency ion acoustic instability. Thus, it is reconfirmed that the instability excited in turbulent heating is the low-frequency ion acoustic instability and this critical condition is useful for the application of turbulent heating to other tokamak plasmas.

5. Conclusion

We have discussed the critical condition for current-driven instability excited in turbulent heating. The threshold current is confirmed experimentally by observing the resistive hump in the loop voltage, the appearance of density fluctuation and the rapid increase of electron temperature in the skin layer. The critical drift velocity estimated from the threshold current agrees with that for low-frequency ion acoustic instability which has been identified by the measurement of dispersion relation.

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