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HIGH-ENERGY ION TAIL FORMATION DUE TO ION ACOUSTIC TURBULENCE IN THE TRIAM-1 TOKAMAK

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The two-component ion energy spectra observed in the TRIAM-1 tokamak are explained as a result of the high-energy ion tail formation due to ion acoustic turbulence driven by a toroidal current pulse for turbulent heating.

Key words : High-energy ion tail, Ion acoustic turbulence, TRIAM-1 tokamak, Toroidal current pulse, Turbulent heating

1. Introduction

Turbulent heating is based on the principle that by driving a sufficiently large current through a plasma, instabilities will be produced that give a resistivity much higher than the classical collision value, thus permitting rapid heating. Buneman[1,2] proposed one mechanism, a fast-growing instability excited whenever the electron drift velocity exceeds the thermal velocity. Ion acoustic waves may also be driven unstable by the current[3,4]. Many experiments have been executed to explore turbulent heating not only in linear machines[5~10] but also in toroidal devices[11~24]. The TRIAM-1 tokamak[25~30] was constructed to extend these experiments to larger scale so that the plasma could be confined in a stable equilibrium configuration, specifically a tokamak.

Ion energy spectra in turbulently heated plasma are frequently observed to have two components and temperatures of the high energy components (tail ions) are sometimes ten times higher than that of the low energy components (bulk ions)[7,8,12]. The fraction of the high energy tail with respect to the total density is usually about 10 %. The

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structure of the component is remarkable especially in experiments in which drift currents are along magnetic fields.

We here pay attention to ion heating through absorption of the wave energy of ion acoustic turbulence which is supported by a drift current instability. Hatori et al.[31] proposed a model in which the movement of the resonance region or a temporal variation of T_e is explicitly taken into account and in which a velocity diffuion coefficient in the presence of the ion resonance broadening, u_0 is used. Then they derived a distribution of high energy component (tail) proportional to $\exp(-v/u_0)$. We show that this distribution qualitatively and quantitatively agrees with observed ones.

2. Experimental results

Skin effects in toroidal turbulent heating experiments have been reported by several groups[19,32]. However, little is known of the transport of energy created in the skin layer, whether it is lost to the vacuum wall or it penetrates into the plasma core. In proposed scheme for turbulently heating a large toroidal plasma[33], one crucial assumption is that the thermal energy deposited in the skin layer is rapidly transported toward the plasma core. Otherwise, the electron temperature in the skin layer would become undesirably high, prematurely quenching current-driven instabilities[34].

In the TRIAM-1 tokamak, effective bulk-ion heating in the plasma core was observed when a toroidal current pulse for turbulent heating is applied in the counter-direction with the plasma current as well as in the co-direction[35]. This implies that the thermal energy is deposited in the peripheral plasma at first[36,37], and the energy is transported toward the plasma core. In fact, we observed a low-frequency ion acoustic wave which propagates in the direction almost perpendicular to the toroidal magnetic field by the 4 mm microwave scattering method[38].

In our measurements of charge-exchanged neutral particles from the peripheral plasma by neutral energy analyzer[39], the spectra shown in Figs. 1(a) and (b) were observed[40] before the application of the current pulse just after it respectively. Namely the temperature of bulk ions $T_b=64$ eV was raised up to $T_b=108$ eV by the application of the current pulse, and the tail ion of the temperature $T_t=697$ eV was formed. At the time $t=100\ \mu$s after the current pulse, however, such a high-energy ion tail was not observed and the bulk-ion temperature profile was almost parabolic[41,42].

3. Theoretical explanation

We explain the two components in the ion energy spectra of the peripheral plasma observed just after the application of a toroidal cur-

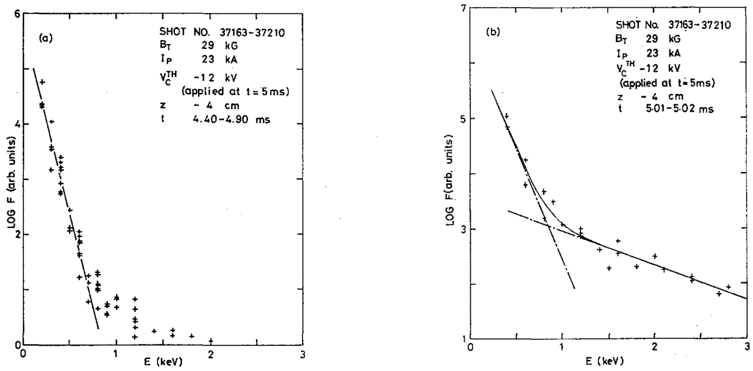

Fig. 1 The ion energy spectra measured at the height $z=-4$ cm (under the torus midplane) before the application of a toroidal current pulse for turbulent heating (a), and at the time $t=10\,\mu$sec after it (b). The fitting lines are expressed as (a) $F=1.74\times10^5 \exp(-E/0.064)$, (b) $F=2.94\times10^6 \exp(-E/0.108)$ and $F=3.80\times10^3 \exp(-E/0.697)$. The negative charged voltage of the codenser V_c^{TH} means the negative polarity of the toroidal current pulse for turbulent heating. The B_T and I_P mean the toroidal field and plasma current, respectively.

rent pulse for turbulent heating in TRIAM-1 by using the model proposed by Hatori et al.[31] as follows.

It is considered that the ion distribution function $f(v)$ follows a Fokker-Planck type equation of the form

$$\frac{\partial f(v)}{\partial v} = \frac{\partial}{\partial v}\left[D(v;\ c_s)\frac{\partial f(v)}{\partial v}\right]. \tag{1}$$

The diffusion coefficient $D(v;\ c_s)$ is given by Dupree's expression[43], i.e.

$$D(v;\ c_s) = \left(\frac{e}{M}\right)^2 \sum_k |E_k|^2 R[kv-\omega,\ D(v;\ c_s)]\,, \tag{2}$$

$$R[kv-\omega,\ D(v;\ c_s)] = \text{Real}\int_0^\infty dt \exp\left[i(kv-\omega)t-\frac{1}{3}k^2 D(v;\ c_s)t^3\right]. \tag{3}$$

The resonance function R is approximated by

$$R[kv-\omega, D(v;\ c_s)] \approx \begin{cases}\pi/ku_0 & \text{for } |kv-\omega|<ku_0/2\,,\\ 0 & \text{for } |kv-\omega|>ku_0/2\,,\end{cases} \tag{4}$$

$$u_0/2 = \left(\frac{D(v;\ c_s)}{3k}\right)^{1/3}. \tag{5}$$

Consequently we have approximately

$$D(v;\ c_s) = \begin{cases}\text{const.}\equiv d & \text{for } |v-c_s|<u_0/2\\ 0 & \text{for } |v-c_s|>u_0/2\end{cases} \tag{6}$$

$$d \approx \frac{\pi e^2}{M^2 k_0 u_0} \sum_k |E_k|^2 \tag{7}$$

Now we make an assumption that c_s increases by following the relation

$$c_s = c_s(t) = (T_e(t)/M)^{1/2} = c_{s0} + At\,, \tag{8}$$

where A is a constant and $c_{s0} = (T_e(0)/M)^{1/2}$.

In order to see the time evolution of $f(v)$, we solve the above diffusion equation (1) with eqs. (6) to (8) after the following normalization

$$v_b f \equiv F\,, \tag{9}$$

$$\frac{t}{(v_b^2/d)} \equiv T\,, \tag{10}$$

$$\frac{v}{v_b} \equiv V\,, \tag{11}$$

$$\frac{c_s}{v_b} \equiv C\,, \tag{12}$$

$$\frac{u_0}{v_b} \equiv U_0\,, \tag{13}$$

$$\frac{Au_0}{d} \equiv K\,, \tag{14}$$

$$\frac{D}{d} \equiv E\,. \tag{15}$$

The normalized equation is

$$\frac{\partial F}{\partial T} = \frac{\partial}{\partial V}\left[E\frac{\partial F}{\partial V}\right], \tag{16}$$

$$E = \begin{cases} 1 & \text{for } |V-C| < U_0/2\,, \\ 0 & \text{for } |V-C| > U_0/2\,, \end{cases} \tag{17}$$

$$C = C_0 + (K/U_0)T \tag{18}$$

The numerical solution is shown in Fig. 2 in case of $C^2=4$, $U_0=1$ and $K=2$. The function $f(v)$ variates as shown by $T=0$, $T=0.1$, $T=0.2$ and $T=0.3$ in the figure.

The plasma parameters and normalizing parameters are as follows:

$$z = -4\,\text{cm}\,,$$

$$n = 2\times 10^{19}\,\text{m}^{-3}\,,$$

$$\frac{\delta n}{n} = 10^{-2}\,,$$

$$T_e = 8T_b\,,$$

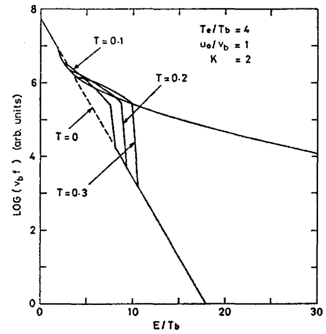

Fig. 2 The time evolution of the high energy ion tail formation due to ion acoustic turbulence.

$$T_b = 108\,\mathrm{eV},$$

$$v_b = \left(\frac{T_b}{M}\right)^{1/2} = 1.02\times10^5\ \mathrm{m/sec},$$

$$k_D = \left(\frac{ne^2}{\varepsilon_0 T_e}\right)^{1/2} = 2.05\times10^4\ \mathrm{m^{-1}},$$

$$d = \left(\frac{\pi}{6}\right)^{3/4}(3k_D)\left(\frac{T_e}{M}\frac{\delta n}{n}\right)^{3/2} = 9.00\times10^{17}\ \mathrm{m^2/sec^3},$$

$$\frac{v_b^2}{d} = 1.15\times10^{-8}\ \mathrm{sec}.$$

In order to see the dependence of the function $f(v)$ at $T=\infty$ on plasma parameters, we investigate the analytical solution in case of $K=0$,

$$f(v) = \frac{1}{2u_0}\exp\left(\frac{c_-}{u_0}-\frac{v}{u_0}\right)\left[\Phi\left(\frac{c_-}{v_b}\right)-\Phi\left(\frac{c_+}{v_b}\right)\right]$$
$$+\frac{1}{2u_0}\exp\left(\frac{v_b^2}{2u_0^2}-\frac{v}{u_0}-1\right)\left[\Phi\left(\frac{c_+}{v_b}-\frac{v_b}{u_0}\right)-\Phi\left(\frac{v+u_0}{v_b}-\frac{v_b}{u_0}\right)\right] \quad (19)$$

$$\Phi(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-t^2}\,dt \quad (20)$$

$$c_\pm = c_{s0} \pm u_0/2 \quad (21)$$

The functions $f(v)$ expressed by this equation are shown in Figs. 3 (a) and (b) in case of fixed C^2 and fixed U_0, respectively.

The function $f(v)$ expressed by eq. (19) has four variables; C^2, U_0, the fraction of tail ions and the temperature of it. The temperature of the tail ions T_t is derived as follows:

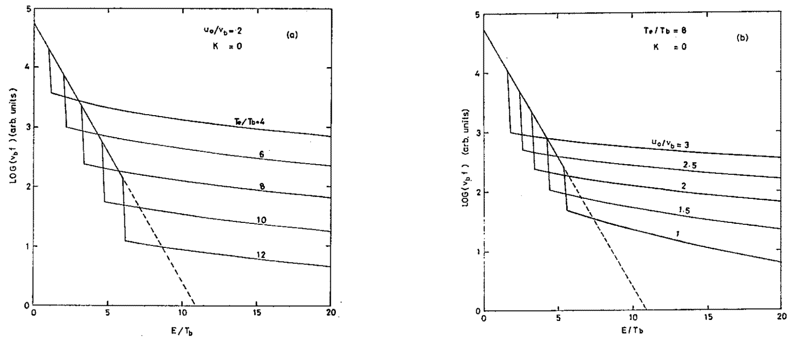

Fig. 3 The different ion distribution functions at $T=\infty$ in case of $K=0$.

$$f(v) \approx \frac{1}{2u_0} \exp\left(\frac{c_-}{u_0} - \frac{v}{u_0}\right)\left[\Phi\left(\frac{c_-}{v_b}\right) - \Phi\left(\frac{c_+}{v_b}\right)\right] \tag{22}$$

$$\frac{1}{T_t} \equiv -\frac{1}{M}\frac{1}{v}\frac{\partial}{\partial v}\ln f \tag{23}$$

$$\frac{T_t}{T_b} = \left(\frac{v}{v_b}\right)\left(\frac{u_0}{v_b}\right) = \sqrt{\frac{E}{T_b}}\left(\frac{u_0}{v_b}\right) \approx \sqrt{10}\, U_0 \tag{24}$$

i.e. U_0 and T_t are not independent. Consequently eq. (19) has three variables. In Fig. 4 are shown the contour lines of E/T_b, where E is the energy of the cross-point of the bulk and tail ion distribution functions.

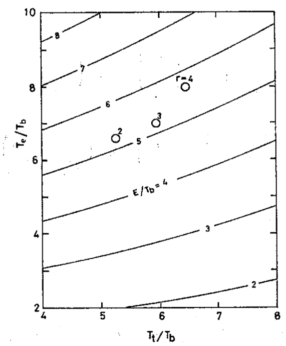

Fig. 4 The contour lines of E/T_b, where E is the energy of the cross-point of the bulk and tail ion distribution functions. The T_t-value in the abscissa is the tail ion temperature at the energy $E=10\,T_b$. The circles indicate the experimental data obtained in the TRIAM-1 tokamak.

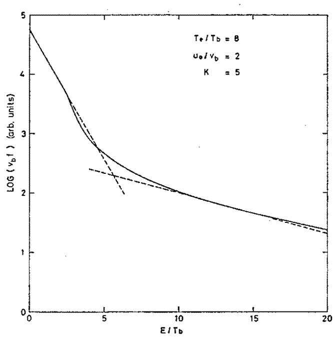

Fig. 5 The comparison of the theoretical spectrum (solid line) and the measured spectrum (dashed line).

The data at $r=4$, 3 and 2 cm are also plotted in Fig. 4. The fact that all the data exist between $E/T_b=5$ and 6 is interpreted as follows: The tail grows no longer, since the ion acoustic instability damps if the fraction of the tail increases or the temperature of it increases[44]. And it should be noticed that we adopted $T_b=108$ eV just after the application of the current pulse for turbulent heating and not $T_b=64$ eV before the current pulse.

For example, the spectrum shown in Fig. 1 (b) is fitted by the curve predicted in this model as shown in Fig. 5. The good fitting may be interpreted that the high-energy ion tail was formed by ion acoustic turbulence.

4. Conclusion

The high energy ion tail observed by neutral energy analyzer can be explained by a theoretical model of high-energy ion tail formation due to ion acoustic turbulence.

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