hybrid widths.[1] However, such calculations apply to high-β situations. One might argue that far from the cusp a high-β situation exists. For our plasma this occurs with $B \approx 1$ G. Since lines of B from this region connect to a region in the center of the cusp whose width is much smaller than any of the measured widths in this experiment, it is unlikely that high-β phenomena are involved.

The time-dependent data have been shown to be generally consistent with the steady-state data. The hybrid half-width is seen to develop early in the evolution of the plasma. A comparison of the time for the width to reach its steady-state value, $\sim 30\ \mu$sec, with the characteristic times of the plasma shows how short this time is. With $n \sim 10^8/\mathrm{cm}^3$ at $B = 250$ G, the ion plasma period is 3 μsec and the ion gyroperiod is 105 μsec. This steady-state width is reached in ten ion plasma periods and in less than half an ion gyroperiod. The plasma itself takes about 800 μsec or 27 times as long to reach its steady-state density. We know of no theory which can explain these results.

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Observation of Flat-Top Velocity Distributions of Electrons in Turbulently Heated Plasmas

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Velocity distributions of the electrons have been measured by a Thomson-scattering method with an eight-channel polychoromator in the initial stage of a linear turbulent-heating experiment. Flat-top distributions were observed associated with high-frequency fluctuations ($\omega \lesssim \omega_{pi}$) just before the onset of fast heating of the electrons. Those results were compared with computer simulations and theoretical analysis based on quasilinear process.

We report experimental observations of flat-top velocity distributions of the electrons in the initial stage of turbulent heating of a plasma by means of Thomson scattering of ruby-laser light with an eight-channel polychromator. High-frequency fluctuations just below the ion-plasma frequency (ω_{pi}) were observed to grow at almost the same time as the flat-top distributions appeared. These facts were considered as an indication of a quasilinear process in the turbulent heating of the plasma.

In turbulent plasmas, wave-particle interactions are quite strong and distortions of the velocity distributions of the electrons and the ions from Maxwellian have been expected.[1-3] Since the phase velocity of ion-acoustic waves in the plasma is less than the thermal velocity of the plasma electrons, the enhanced diffusion in velocity space is expected to bring a flat-top velocity distribution of the electrons, while for the ions hot tails would be formed. Computer simulation[4-6] showed the appearance of the flat-top velocity distribution of the electrons and hot tail of the ion distributions. They showed that the formation of

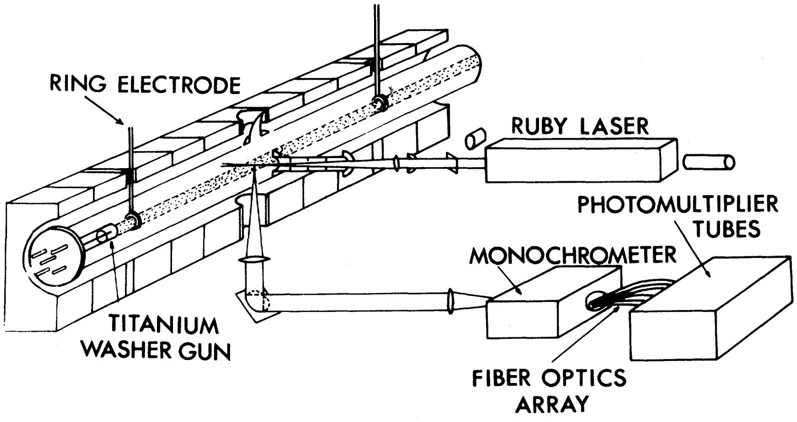

FIG. 1. Schematic of the experimental apparatus (THE MACH II).

the flat-top velocity distribution of the electrons did not limit the growth of the instabilities. Experimentally many authors[7-11] have reported the formation of hot tails on the velocity distribution of ions in turbulent heating of plasmas. There have been many measurements of the electron temperature in turbulently heated plasmas by such methods as diamagnetic loop, x-ray spectroscopy, and atomic beam.[7-14] Those measurements are based on the assumption of spatial homogeneity and Maxwellian velocity distributions. Recently the Thomson scattering method with a ruby laser was applied to the turbulent-heating experiment[15] to investigate distributions of the electron temperature with high resolution in space and time, where Maxwellian velocity distributions were also assumed. Since there are some questions about the reproducibility of the heating process in the time scale of the pulse width of the laser light, a multichannel polychromator is preferable to measure the shape of the velocity distributions.

This experiment has been carried out by use of the Turbulent Heating Experiment (THE) MACH II device[11] (Fig. 1). A hydrogen plasma was produced by a titanium washer gun and injected into the vacuum vessel of Pyrex glass having an inner diameter of 17 cm and a length of about 2 m. The density and temperature of the plasma in the vessel were about 5×10^{12} cm^{-3} and 8 eV, respectively. The strength of the magnetic field was 15 kG except the region of a diagnostic port (7.5 kG). The hollow electrodes for the heating discharge, made of aluminum with inner and outer diameters of 3 and 4.5 cm, respectively, were placed in the vessel separated from each other by 135 cm. They limited the diameter of the initial plasma column to 3 cm before the heating discharge. The electrode voltage and current for heating were obtained from two series-connected capacitors of 2.2 μF each, with charging voltages up to 15 kV to give 1.1 μF at 30 kV. The voltage and current were measured with a voltage divider and with a Rogowski coil placed around the plasma column, respectively, and the resistance of the plasma was computed from these values, taking into account the net inductance of the circuit. Fluctuations in the plasma with a frequency range of up to 1 GHz were measured by use of a floating double probe (copper wires of 0.5 mm diam, 3 mm length, and 2 mm separation).

The optical system for laser scattering is also shown in Fig. 1. The ruby laser beam, having an energy of 10 J and a pulse width of 20 nsec, was introduced at a right angle to the axis of the plasma column. Light scattered at 90° to the direction of the incident beam was collected with an $f/4$ lens and analyzed using an eight-channel polychromator. The scattering measurement was made throughout the heating discharge. Scattered light was viewed from a volume having dimensions 1 mm × 5 mm × 20 mm. The time resolution of the measurements was about 50 nsec.

Figure 2 shows a typical result on the temporal evolution of the spectrum of the scattered light. The time t was measured from the time of initiation of the heating current. Before the onset of the heating discharge, the velocity distribution of the electrons in the plasma was Maxwellian and the temperature was about 8 eV. During the first 0.4 μsec of the discharge no remarkable change was observed. At $t=0.4-0.5$ μsec the electron temperature started to rise and came up to 20 eV at $t=0.6-0.7$ μsec; then the velocity

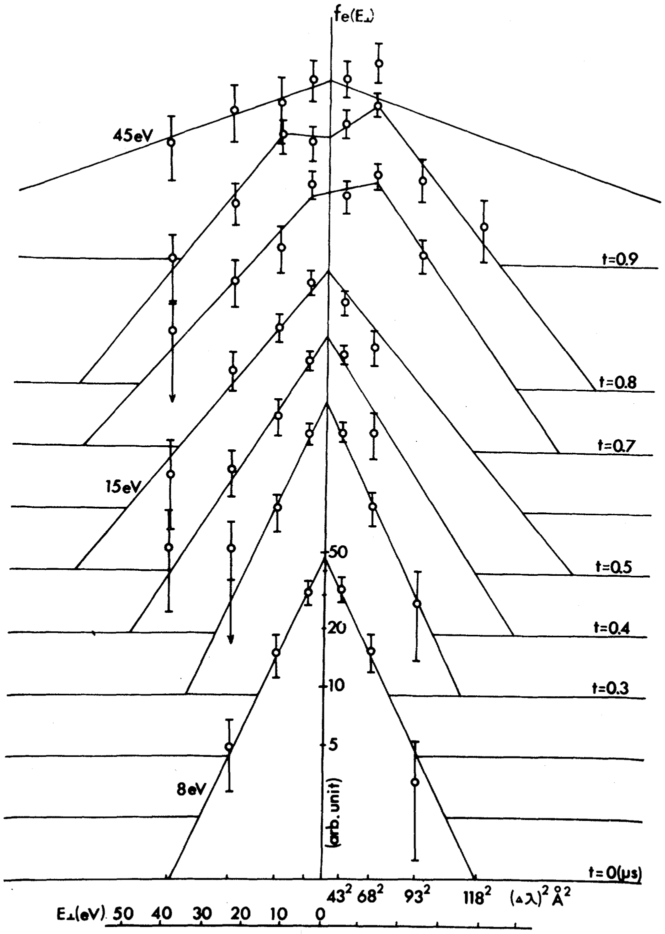

FIG. 2. Temporal evolution of the spectrum of the scattered light.

distribution departed from Maxwellian and became a rather flat-top distribution with an effective temperature $T_e^{\text{eff}} = \langle 1/mv^2\rangle^{-1}$ of 20–30 eV at $t = 0.7$–0.8 μsec. The resistance of the plasma until $t = 0.8$ μsec was less than 1 Ω. Rapid electron heating started at $t = 0.9$–1.0 μsec and immediately scattered-light signals disappeared, coincident with an abrupt increase of the resistance of the plasma (≃3 Ω). Measurements were also made at 1 cm off the axis of the plasma column with scattering volume of 1 mm × 5 mm × 10 mm. In this case, flat-top distributions appeared a little earlier ($t = 0.4$–0.6 μsec) with the effective temperature of 15–20 eV, and signals disappeared at $t = 0.7$–0.8 μsec. These data were found to be quite reproducible when the initial plasma was the same, but the small concavity and asymmetry of the distribution changed shot by shot.

Figure 3 shows typical results on the parallel time development of (a) the heating discharge current, (b) the plasma resistivity, (c) the electron temperature, and (d) the amplitude of the fluctuation with a frequency range around the ion-plasma frequency (ω, 200–400 MHz). In Fig. 3(c) the solid circles show the effective temperature for the flat-top velocity distribution for the electrons. From this figure, it is found that (i) the flat-top distribution starts to appear when the instability starts to grow, and (ii) the instability continued to grow even when the flat-top distribution appeared, and saturated to 5–20 eV at $t = 1.2$–1.5 μsec when the resistance of the plasma became maximum. These instabilities started to be observed when the ratio of the drift velocity v_d to the thermal velocity v_t of the electrons became 0.5–1, and when the ratio T_e/T_i was 1–2. These conditions and the observed growth rate of the waves agreed with those for the excitation of ion-sound waves. Considering

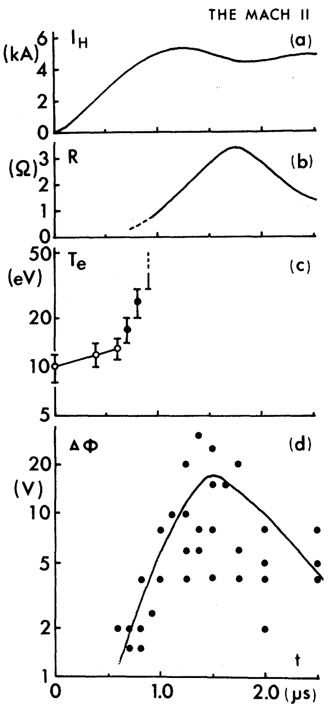

FIG. 3. Parallel temporal development of (a) the current of the heating discharge, (b) the computed resistance of the plasma, and (c) the electron temperature. The solid circles show effective electron temperature from the flat-top velocity distributions. (d) The amplitude of the instabilities with a frequency range of 200–400 MHz.

that the frequency of the observed oscillations is in a region just below the ion-plasma frequency (500 MHz), these instabilities seem to be ion-sound waves with a phase velocity of $c_s = (T_e/M)^{1/2}$, where M is the ion mass.

The observed flat-top velocity distributions of the electrons cannot be attributed to spatial superposition of different local temperatures. The possibility of spatial superposition of locally drifted Maxwellians is also improbable, for the drift velocity across the magnetic line of force is $v_E = E_\perp(k)/B \simeq 1.5\times10^7$ cm/sec for the given magnetic field (7.5 kG) and the observed perpendicular electric field measured by the floating double probe $[E_\perp(k) < 1000$ V/cm$]$; v_E is too small to explain the observed width of the flat-top region ($\simeq 3\times10^8$ cm/sec).

The width of the flat-top region was about 10–20 eV at $t = 0.7$–0.8 μsec. This value is close to either the thermal energy or the drift energy of the electrons in this time interval. If we assume that the wave number in the perpendicular direction $k_\perp$ is the same order of magnitude as that in the parallel direction $k_\parallel$, then the width would correspond to the phase velocity of the waves in the perpendicular direction. As the electron-cyclotron frequency ω_C (21 GHz) was much larger than the bounce frequency of the electron ($\simeq 4$ GHz) in the wave potential of about 1 V with a wavelength of about 10^{-2} cm (here we assumed $\omega/k_\perp = c_s$), we may not see trapping of the electrons in the waves in the direction perpendicular to the magnetic field. From those facts, the flattening of the distribution seems to be due to a quasilinear effect of ion-sound-like waves in the plasma during the course of the turbulent heating discharge.

The simulation done by Biskamp, Chodura, and Dum[4] seems to explain some of the experimental results. Their time for the formation of the flat-top distribution was less than 0.3 μsec, which was about 100 times the ion plasma period; we also can see a flat-top distribution at about the same time. Its appearance did not limit the growth of the instabilities, which is also consistent with the result of the computer simulation.

Another explanation is as follows. We note that in the experiment v_d is of the order of v_t. In this case the electrons are possibly scattered by a resonance $k_\parallel v_d - \omega_C \simeq 0$ in the perpendicular direction.[16] Following the quasilinear theory,[17] we have the velocity-space diffusion coefficient in the perpendicular direction $D_\perp$:

$$D_\perp = \frac{\pi e^2}{m^2}\sum_{\vec{k},n}\left(\frac{n\omega_C}{k_\perp v_\perp}\right)^2 J_n^2\left(\frac{k_\perp v_\perp}{\omega_C}\right)|E_\perp(\vec{k})|^2\delta(k_\parallel v_z - \omega_k - n\omega_C). \tag{1}$$

The terms for $n = \pm1$ mostly contribute to $D_\perp$ and $\delta(k_\parallel v_z - \omega_k \pm \omega_C)$ is approximated by $\delta(k_\parallel v_z \pm \omega_C)$, where $v_\perp$, $v_\parallel$, and J_n are respectively the perpendicular and parallel velocity components and the nth Bessel function. The quantity $(\omega_C/k_\perp v_\perp)^2 \times J_1^2(k_\perp v_\perp/\omega_C)$ has its maximum at $v_\perp = 0$; i.e., the smaller $v_\perp$, the more intense velocity-space diffusion occurs. The growth rate of the perpendicular temperature, $dT_{e\perp}/dt$, is estimated, using parameters in the experiment, to be $T_e^{-1}dT_{e\perp}/dt \simeq (\pi)^{1/2}\omega_{pe} W \simeq 10^8$–$10^7$ sec^{-1}, where $W \equiv \sum_{\vec{k}}|E_\perp|^2/(8\pi n T_e) = 10^{-3}$–$10^{-4}$, which is computed from the experimental value of the potential on the probe of ion-sound instability. Since the experimental result for the heating rate is about 10^7 sec^{-1}, the agreement is good. These two explanations (quasilinear velocity-space diffusion and resonant scattering) and also other possible ones are being checked intensively.

It is noted that flat-top velocity distributions of the electrons were also observed in the bow shock near Earth,[18] which might be produced by the same process. The small concavity[19] and slight asymmetry of the velocity distributions are not understood now.

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