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Hot-electron production due to the ion acoustic decay instability in a long underdense plasma

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Laboratory and particle simulation experiments are used to show that moderate-power microwaves (laser light) $[I\lambda^2/T_e(\mathrm{W/cm^2})(\mu\mathrm{m^2/keV}) \lesssim 5\times 10^{14}$ for $ZT_e/T_i=10]$ strongly heat hot electrons due to parametric instabilities in an underdense plasma, when the microwaves are incident on a large-scale-length plasma. The anomalous collision frequency is as high as $\nu^*/\omega_0 \sim 4\times 10^{-2}$. The hot electrons are strongly heated due to the large size of the instability region.

The possibility of using lasers to compress and heat a pellet to thermonuclear conditions has been under intense investigation. Recently, there has been great interest in the interaction of moderate intensity laser light with a large density scale length pellet such as would occur in a laser driven pellet reactor. When moderate intensity laser light is incident on a large density scale length plasma, the density profile is modified to a shelf-step, i.e., an underdense shelf followed by a sharp density rise through the critical surface (where the laser light frequency equals the plasma frequency). It has been shown[1,2] that parametric instabilities excited on the steepened critical surface result in significant laser absorption and hot-electron production.

We present here a new important heating regime in which the ion acoustic decay instability is excited in the long underdense plasma shelf if the shelf density is high enough, i.e., $n/n_c \gtrsim 0.6$ to 0.8, n_c is the critical density. The shelf density is determined self-consistently by the laser intensity, and is above $0.6n_c$ for moderate intensity laser light ($I\lambda^2/T_e < 10^{15}$ W/cm^2·μm^2/keV). We find both experimentally and computationally that hot electrons are heated by the electron plasma waves excited by parametric instabilities on the density shelf. This strong heating was not seen in previous computer simulation calculations in which an infinite medium was modeled. It is also noted that this hot-electron heating is not due to resonance absorption.[3] A very large amplitude plasma wave is excited in a narrow region near the critical region in resonance absorption. Electrons are strongly heated because the wave amplitude is large. Resonance absorption is important when a high intensity laser is interacting with a small scale length plasma. In contrast, for the present instability, a relatively small amplitude plasma wave is excited over a wide region. Hot electrons are strongly heated (in spite of the small amplitude plasma wave) because of the large size of the instability region. Al-Shiraida *et al.*[4] have recently observed enhanced ion fluctuations in an underdense plasma ($n/n_c \sim 0.7$) irradiated by a CO_2 laser. There are indications that the ion waves are excited by parametric instabilities in the underdense plasma.[5]

Our experiments were performed in the University of California, Davis (UCD) Prometheus I and III devices. The Prometheus III device is an enlarged version of the Prometheus I device.[6] The diameter of the experimental region is expanded to 60 cm in Prometheus III so the microwaves (frequency, $\omega_0/2\pi=1.2$ GHz) propagate to higher densities ($n_{\mathrm{cut}} \simeq 0.9n_c$). Also the density scale length is much larger in Prometheus III ($L/\lambda_{De} \lesssim 10^4$). The experimental region is an oversized waveguide. A predominately *TM* mode is driven in the oversized waveguide by first exciting a TM_{10} mode in a smaller waveguide (diameter is 26 cm) in which all other TM modes are cut off. A conical section gradually transforms the microwaves from the small waveguide to the oversized waveguide. The TM_{10} mode is predominantly excited, so the microwave electric field near the center is along the axis of the plasma chamber. The experimental region is divided into right and left cylinders by a thin sheet of ceramic. This sheet is transparent to microwaves, but is a solid wall to plasma. The plasma density increases slowly with distance from the ceramic sheet due to the nonuniformly spaced tungsten filaments (cathode) in the overdense region. The experiments are mainly made in the Prometheus III device unless stated otherwise. The experiments are performed in the afterglow plasma so that the unheated electron distribution function is Maxwellian. Coaxially shielded tiny wire probes (length $\simeq 0.3$ cm, and diameter $\simeq 0.013$ cm) are used to measure both the electron plasma waves and the ion acoustic waves. One-sided planer disk probes are used to measure the energy distribution function of electrons moving up (forward probe) and down (backward probe) the axial plasma density gradient. A computerized (Digital Equipment Corp. LSI-11) data acquisition system[6] is used to acquire and analyze the data.

Typical plasma parameters are argon gas pressure $0.3\sim 0.7$ mTorr, critical density $n_c=1.8\times 10^{10}$ cm^{-3}, the unheated electron temperature $T_{e0}=1\sim 3$ eV, temperature ratio, $T_{e0}/T_i \approx 10$, and the maximum microwave available power is 12 kW [$v_0/v_{e0} \simeq 0.5$ (Prometheus III) and $v_0/v_{e0} \simeq 1.2$ for (Prometheus I) $T_{e0}=1$ eV, where v_0 is the quiver velocity of the electrons in the incident microwave electric field].

We find that ion acoustic and electron plasma waves are excited near the critical surface if the microwave power is above a well-defined threshold value ($P_T \approx 3.5$ W, $v_0/v_{e0,T} \approx 9\times 10^{-3}$, which approximately agrees with the theoretical threshold of

$$v_0/v_{e0\ \mathrm{theor}} \approx 2.8[(\nu_{en}/\omega_e)(\Gamma_i/\omega_i)]^{1/2} \approx 5\times 10^{-3},$$

where ν_{en} and Γ_i are the electron-neutral collision frequency and the ion Landau damping coefficient). The waves are excited in the direction of the microwave field. These waves satisfy the usual[7] frequency matching conditions ($\omega_0 \simeq \omega_e + \omega_i$). For higher microwave powers, the plasma density profile is steepened near the critical surface, due to resonance absorption.[3,8] A shelf-step density profile (with a long underdense shelf and steep jump at the critical surface) is observed for higher powers ($P_0 \gtrsim 100$ W, or $v_0/v_{e0} \gtrsim 0.04$). We have obtained a long underdense shelf (the shelf density, $n/n_c \approx 0.7 \sim 0.8$, and length $l/\lambda_{De} \approx 1 \sim 2\times 10^3$) for moderate power microwaves, $P_0 \approx 4$ kW. We can compare this result with the theoretical predictions,[9] shown in Fig. 1 (dashed lines). The self-consistent minimum ($n_{\min}$), maximum ($n_{\max}$), and average density (n_{av}) are shown as a function of $I\lambda^2/T_e$. For

$$P_0 \simeq 4\ \mathrm{kW},\quad I\lambda^2/T_e = 0.4\times 10^{14}\ \mathrm{W/cm^2\cdot\mu m^2/keV}$$

($P_0 = 4$ kW, and the thermal electrons are strongly heated, i.e., $T_e \simeq 5$ eV), so the shelf density (n_{av}) should be $n_s \simeq 0.8 n_c$, and we observe $n_s/n_c \simeq 0.75$, in approximate agreement with theory. For powers above about $P_0 \simeq 100$ W, the shelf density decreases slowly with power since the thermal electron temperature increases with power[10] ($T_e \sim P_0^{1/2}$).

Parametric instabilities are excited on the underdense shelf. The rms ion wave amplitude is plotted versus position in Fig. 2. The strong ion turbulence $\langle(\Delta n/n)^2\rangle^{1/2} \simeq 0.15-0.2$ [Fig. 2(c), solid circles] is consistent with the computer simulation results. The ion acoustic waves propagate down the density gradient from the instability region [Fig. 2(c), empty circles] with the sound speed. The spatial damping rate is observed to be $k_i \simeq 0.18$ cm^{-1}. We have also observed ion waves propagating up the density gradient beyond the critical surface. Hot electrons are strongly heated by the electron plasma waves. Figure 2(a) shows the spatial evolution of the electron energy distribution. Thermal electrons (with a nearly Maxwellian distribution, curve *a* enter the tur-

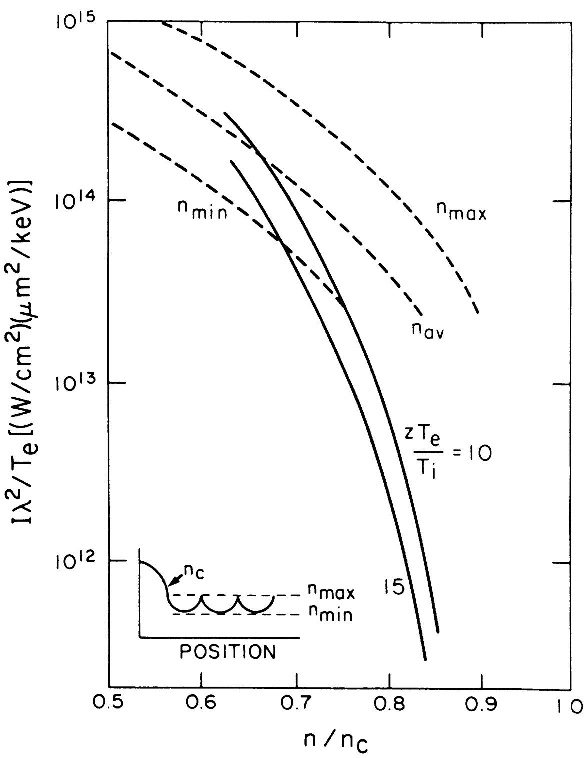

FIG. 1. The self-consistent underdense shelf density (dotted curves) and the threshold for the ion acoustic decay instability (solid curves) are shown as functions of $I\lambda^2/T_e$ and n/n_c, respectively. The inset gives a typical density profile and the definition of $n_{\max}$ and $n_{\min}$. The ion acoustic decay instability is unstable in the regime where the dotted curves are above the solid curves.

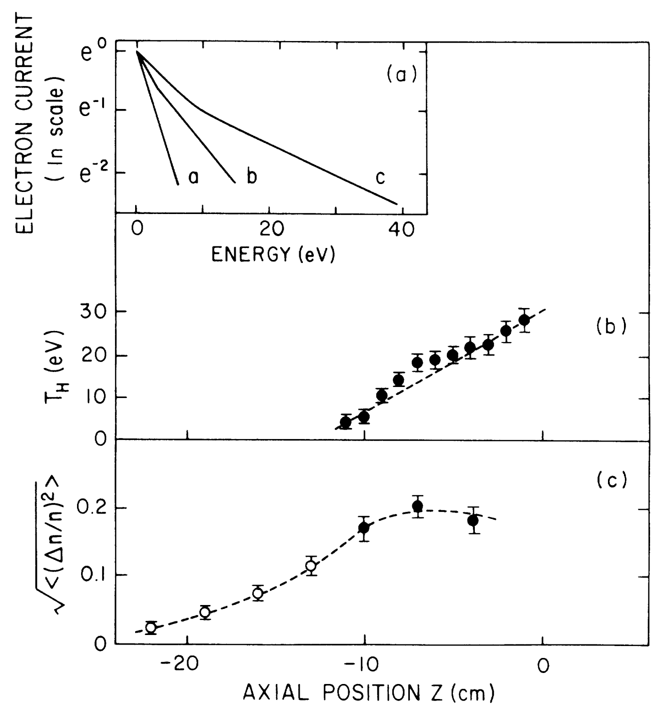

FIG. 2. (a) Electron $I-V$ curves (all electrons with energy above the abscissa are collected), which show electron energy distribution as a function of position (*a*, 15 cm; *b*, 9 cm; and *c*, 2 cm). (b) Hot-electron temperature vs axial position measured from the critical surface. Microwave power, $P_0 = 4$ kW. (c) Ion wave amplitude, $\langle(\Delta n/n)^2\rangle^{1/2}$, vs axial position. The ion turbulence is excited inside (solid circles) and propagate outside (empty circles) the turbulent heating region.

bulence region. Hot electrons are heated as they travel through the turbulence region (curves *b* and *c*). The hot-electron temperature increases with distance as shown in Fig. 2(b).

The plasma density profile near the critical surface is strongly modified due to microwaves. We have shown the self-consistent threshold in Fig. 1 as a function of shelf density. The instability is excited when the threshold (solid lines) are below the self-consistent density (dashed lines). We see that the parametric instability will be excited on the density shelf for moderate intensity microwaves (or laser light) if $I\lambda^2/T_e < 2\times10^{14}$ $W/cm^2 \cdot \mu m^2/keV$ (using the n_{av} curve) for $ZT_e/T_i = 10$ ($z=1$ for microwave experiments). Thus, for the measurements shown in Fig. 2 ($I\lambda^2/T_e \simeq 0.4\times10^{14}$), the instability is above threshold. This moderate intensity regime is currently interesting in laser fusion experiments.

The electrons in the shelf region have a bi-Maxwellian distribution. The temperature of the hot electrons traveling up the density gradient is shown in Fig. 2(b) as a function of position on the shelf. The electrons traveling down the density gradient are also strongly heated, but resonance absorption also heats[3] electrons in that direction.

We can use the measurements shown in Figs. 2(a) and 2(b) to calculate the effective collision frequency, ν^*. Equating the energy flux of hot electrons leaving the heating region to the absorbed microwaves, we have

$$\sqrt{2/\pi}\, n_H v_H T_H = \frac{\nu^* E^2}{8\pi} L_s \ , \tag{1}$$

where n_H is the hot-electron density, $v_H = \sqrt{T_H/m}$, and L_s is the length of the turbulent heating region. The factor of 2 in Eq. (1) accounts for electrons traveling up and down the density gradient. Equation (1) becomes

$$\frac{\nu^*}{\omega_0} \approx \frac{\left[\dfrac{n_H}{n_c}\right]\left[\dfrac{T_H}{T_{e0}}\right]^{3/2}}{2(L_s/\lambda_{De0})(v_0/v_{e0})^2} \tag{2}$$

taking into account the standing-wave pattern of the microwaves. For the case shown in Fig. 2, $P_0 = 4$ kW, or $v_0/v_{e0} = 0.3$, $L_s/\lambda_{De0} \simeq 1.6\times10^3$ ($L_s \simeq 10$ cm), $T_H/T_{e0} \simeq 30$ and $n_H/n_c \simeq 0.1$, we find $\nu^*/\omega_0 \approx 4.5\times10^{-2}$. Hot-electron density is not constant with space, which is the main source of the uncertainty of ν^* shown in Fig. 3. The inset in Fig. 3 shows the hot-electron temperature as a function of microwave power (Prometheus I). Hot-electron temperature increases strongly with the microwave power. One can obtain an empirical relation $T_H \propto P_0^{0.6}$.

We have used a one-dimensional (1D) particle simulation model[11] to calculate the hot-electron production due to the ion acoustic decay instability in the finite length underdense shelf plasma. The computational model has periodic boundary conditions, but artificial cooling of the electrons is used to model[11] the finite length of the shelf plasma. The parameters for the calculations are instability length, $L_s/\lambda_{De} = 10^3$, $T_e/T_i = 10$, and $v_0/v_e = 0.5$. The level of the ion turbulence is set by ion trapping. Thus, as shown in Ref. 11, the anomalous collision frequency is roughly determined only by the temperature ratio. The measured rms ion density fluctuation level is $\langle(\Delta n/n)^2\rangle^{1/2} \simeq 20\%$ [Fig. 2(c)] in agreement with the 15% to 20% level observed in the simulation calculations[11] for $T_e/T_i = 10$.

The results of the particle simulation calculations are shown in Fig. 3 (empty circles). The values of ν^* are estimated from the temporal heating rate of the hot electrons. The saturation amplitude of the electron plasma waves decreases with decreasing plasma density because the phase velocity of the unstable electron plasma waves decreases so that these waves are strongly Landau damped. Therefore, the anomalous collision frequency strongly decreases with the decreasing plasma density. Figure 3 indicates that the experimental result agrees favorably with the particle simulation results with artificial cooling. We have also shown particle simulation results without artificial cooling (empty squares) which corresponds to an infinite system. In this case, the heated electrons stay in the system, which reduces the amplitude of the electron plasma waves because of Landau damping. Therefore, the anomalous collision frequency is much smaller. These values do not compare well with the experimental results.

In summary, we present here a new heating regime of parametric instabilities that is important in a large scale length plasma interacting with a moderate power laser,

$$I\lambda^2/T_e(\mathrm{W/cm^3 \cdot \mu m^2/keV}) < 5\times10^{14}$$

for $ZT_e/T_i = 10$. Hot electrons are strongly heated in the long underdense shelf by parametrically driven tur-

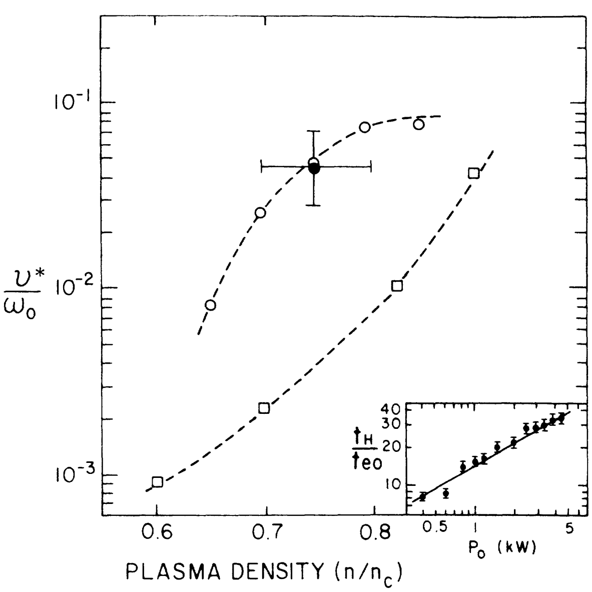

FIG. 3. Anomalous collision frequency ν^*/ω_0 vs plasma density. Solid circle is the experimental result. Empty circles are particle simulation results with artificial cooling, for parameters of $T_e/T_i = 10$, mass ratio $M/m = 100$, $v_0/v_e = 0.5$, and effective shelf length $L/\lambda_{De} = 10^3$. Empty squares are particle simulation results without cooling. The inset shows hot-electron temperature vs microwave power.

bulence. The hot electrons are heated as they travel through the turbulent plasma. The anomalous collision frequency ν^*/ω_0 is as high as 4×10^{-2}. Due to the large size of the instability region, hot electrons are strongly heated. The results agree favorably with particle simulation results in which artificial cooling is used to model the finite shelf length. We have shown[12] recently that the ion acoustic decay instability is important for short wavelength laser ($\frac{1}{2}$ μm) interacting with a large scale length plasma using the GDL system in the Laboratory for Laser Energetics at the University of Rochester.

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