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Stochastic Ion Heating Due to the Parametric Ion-Acoustic Decay Instability*

H. W. Hendel† and J. T. Flick
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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We report intense stochastic ion heating comparable to the electron heating, proportional to the energy density of the fluctuating electric fields of the ion-acoustic component of the decay instability. The ion-temperature rise time is comparable to, but longer than, the instability growth time, and many orders of magnitude shorter than collisional relaxation times.

Recently, in connection with laser-ignited thermonuclear fusion and with (laser) heating of magnetically confined fusion plasmas, strong interest has been created in the mechanism generating intense and fast ion heating during laser irradiation of a (pellet) plasma and giving rise to the large observed neutron yield of close to 10^4 neutrons for a laser-pulse duration of a few nanoseconds.[1] Although early calculations considered only the transfer of laser electromagnetic energy to kinetic energy of the electrons, lately computer experiments have been reported designed to elucidate the more important mechanism of ion heating in order to explain the neutron production. Two-dimensional computer calculations which neglect instability-generated effects predict far fewer neutrons than are observed, but, when parametric ion-acoustic instabilities are included, computer simulations indicate sufficient ion heating to explain the observed neutron yield and an ion temperature approaching the electron temperature.[2] Experimentally, electron heating[3] and production of fast electrons[4] due to parametric ion-acoustic instabilities have been demonstrated before, and the parametric excitation of waves in laser–solid-target experiments has been reported.[5]

We report results of ion-heating experiments (i.e., where the entire distribution function is affected, not just its tail) using a plasma rather different from a laser-fusion plasma; however, the important characteristic, ion heating by the ion-acoustic decay instability, is present. The plasma (K or Cs) is of medium density ($n \approx 10^{10}$ cm^{-3}), at low temperature ($T_e \approx T_i \approx 1$ eV), and the instability is the parametric ion-acoustic decay instability due to an electromagnetic pump, which is the driving mechanism of interest in laser-fusion plasmas. The experiments are performed in both pulsed and steady-state operation of the pump.

The significant results of this work are measurements of intense ion heating comparable to the electron heating, proportional to the energy density of the instability, and the conclusive relation of this stochastic ion heating to the fluctuating electric fields of the ion-acoustic component of the decay instability. Ion-temperature rise times τ_H are longer, but of the order of the instability growth times ($1/\omega_{pi} < 1/\gamma < \tau_H \ll 1/\omega_{ci}$) and many orders of magnitude shorter than electron-ion collisional relaxation times, indicating that ion heating by the ion-acoustic decay instability is the only mechanism which can account for the opservations. Ion heating rates agree reasonably well with the computer simulations of Ref. 2 and with a simple theory given here.

Onset of the parametric ion-acoustic decay instability takes place in our plasma when the electron drift velocity due to an electromagnetic or electrostatic rf pump field at ω_{pe} reaches $\sim 0.05 v_{e\text{th}}$. The pump wave generates two decay waves, an electron plasma wave at $\sim\omega_{pe}$ and an ion sound wave, $\omega_i \simeq k_i v_i$. The identification of this instability has been described before,[3] based on measurements of ω and k of pump and decay waves, onset threshold, anomalous absorption, and other parameters. The instability extracts energy from the pump, which thus exhibits enhanced absorption,[3] and this energy is transferred to the particles by wave-particle interactions. The instability spectrum does not contain any ion-cyclotron components, which would make the results less surprising.

The experiments were performed on the Princeton Q-1 thermally ionized potassium plasma, 126 cm long and 3 cm in diameter. Collisions with neutrals are negligible. The instability could be excited with a resonance cavity, with one or two ring-shaped electrodes surrounding the plasma, and with one or two grids immersed in the plasma. The region of the rf-plasma interaction is small relative to the plasma column length. The pump electric field is aligned parallel to the confining magnetic field. $\omega_{ce}/\omega_{pe} = 2-6$, $\nu_{ei} \simeq \omega_{pi}$; the collisionless skin depth $(c/\omega)(\omega_{pe}^2/\omega^2 - 1)^{-1/2} > r_{\text{plasma}}$, so that penetration of the wave into the plasma is assured. Electron temperatures were determined with Langmuir probes and from floating potentials. Perpendicular ion temperatures were measured using ion temperature probes,[6] which can be considered ion-collecting Langmuir probes with a mechanical limiter which prohibits electron flow to the collector and accepts only large Larmor-radius particles, i.e., ions. We obtained straight lines on the I/V semilog probe characteristic over more than two decades, indicating both effective electron-current suppression and presence of a Maxwellian distribution for the bulk of the heated ions. Ion velocities are isotropic because of interaction with the spatially randomized instability.

To calculate stochastic ion heating[7] by the steady-state fluctuating electrostatic fields of the ion sound spectrum of the parametric decay instability, we use a one-dimensional quasilinear approach, and assume a collisionless plasma with $E^2/4\pi nT \ll 1$ (E^2 is the total ion-wave energy density) to derive a diffusion equation for the ion distribution function f_i:

$$\frac{\partial f_i}{\partial t} = \frac{\partial}{\partial v}\left[D(v)\frac{\partial}{\partial v} f_i\right]. \qquad (1)$$

We choose a Gaussian spectral density to represent the steady-state ion sound spectrum:

$$G(k,\omega) = \frac{2}{\sqrt{\pi}}\frac{E^2}{\Delta\omega}\exp\left[\frac{-(\omega-\omega_i)^2}{(\Delta\omega)^2}\right]\delta(k-k_i). \qquad (2)$$

Here $\Delta\omega$ is the width of the fluctuation spectrum with total energy density E^2 at the sound frequency ω_i. The spectrum is assumed to have a well-defined wave number k_i. Solving for D,[8]

$$D(v) = \frac{2}{\sqrt{\pi}}\frac{e^2E^2}{M^2\Delta\omega}\exp\left[\frac{-(k_i v-\omega_i)^2}{(\Delta\omega)^2}\right]. \qquad (3)$$

Note that only ions in the velocity range $(\omega_i - \Delta\omega)/k_i < v < (\omega_i + \Delta\omega)/k_i$ diffuse in velocity space. For $T_e \simeq T_i$, parametrically driven ion-acoustic waves are strongly Landau damped, and $\Delta\omega \approx \omega_i$, $\omega_i/k_i \approx v_{i\text{th}}$; thus the entire ion distribution function f_i is affected by the stochastic acceleration. However, if $T_e/T_i \gg 1$, then $\Delta\omega \ll \omega_i$, $\omega_i/k_i \gg v_{i\text{th}}$, since very little ion Landau damping occurs, and only the tail of the ion distribution is heated. Inclusion of acoustic wavelength spread would lead to a broader effective spectral bandwidth, and hence more effective ion heating.

Evaluation of the second moment of f_i for the case of $T_e \simeq T_i$ gives the rate of increase of the ion temperature,

$$\partial T_i/\partial t \simeq e^2E^2/M\Delta\omega. \qquad (4)$$

Figure 1 shows ion and electron temperatures, instability potential amplitudes (at $\sim\omega_{pe}$), floating potential, and plasma density, as a function of

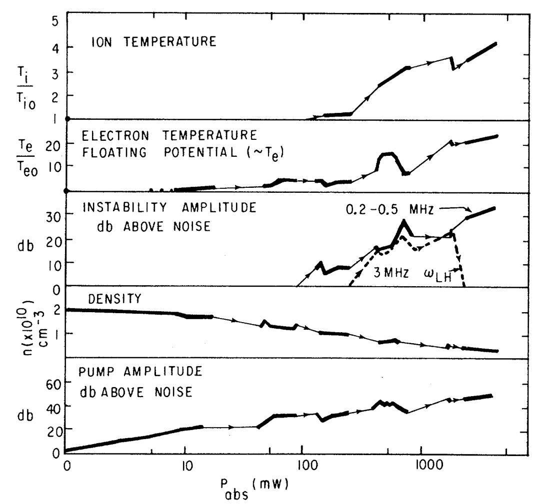

FIG. 1. Variation of T_i, T_e, instability amplitude (at ω_{pe}), density, and electromagnetic pump amplitude with absorbed power; $n = 2\times 10^{10}$ cm^{-3} (K), $B = 3$ kG, $f_{\text{pump}} = 400$ MHz. Total absorbed powers (including circuit losses) are indicated. Arrows indicate abrupt changes in absorbed power due to mode changes.

absorbed power, measured in steady-state operation. As the absorbed power is increased, for the stable plasma, the plasma parameters are only slightly affected. Onset of instability and increase of amplitude lead to an increase in electron and ion temperatures, with $T_e > T_i$. As a result of the steady-state operation, changes in instability mode and amplitude are reflected in changed absorption and abrupt variation of all plasma parameters. The ion temperature is approximately constant radially and is slightly reduced axially away from the heating region, as expected from the large Larmor radius of the hot ions and the relatively good confinement.

Since equilibrium ion temperatures in Q devices are largely determined by the ion confining sheaths at both ends of the plasma column (which accelerate the ions into the plasma), we must determine whether such a trivial effect may be at work heating the ions. Plasma potential measurements showed that sheath acceleration is reduced for the heated plasma, in both the axial and the radial directions. In addition, the pulsed heating experiments discussed below show temperature rise times much shorter than the time of ion diffusion over the plasma length, and indicate that the ion temperature increase originates in the rf interaction region, excluding sheath acceleration by the end plates. Acceleration of ions by hot electrons is excluded by the measured axial potential distribution. Note that for our plasma most of the absorbed pump power is flowing with the electrons into the endplates as a result of the high electron thermal conductivity in the parallel direction. This possibility of keeping the electron temperature down may exist in other plasmas of interest and may be important in keeping the sound velocity close to the ion thermal velocity and thus ensure efficient ion heating.

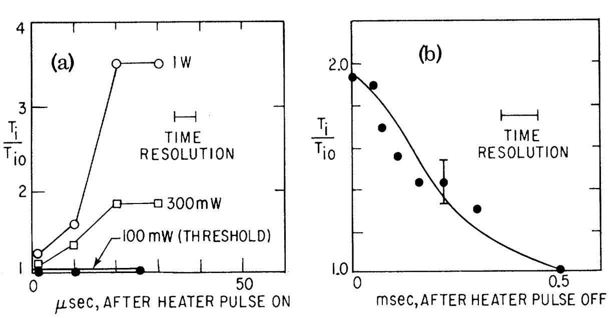

FIG. 2. (a) Ion temperature rise after turn on of a 400-MHz rf heating pulse; $n = 2.5\times10^{10}$ cm^{-3} (K), $B = 2$ kG. (b) Ion temperature decay after turn off of 300 MHz heater; $n = 5\times10^{10}$, $B = 3$ kG.

Figure 1 also indicates a reduction in plasma density due to the increased temperature in the heated region. This reduction in density can lead to lowering of the instability intensity by reducing ω_{pe} to far below ω. Ion-temperature rise and decay times measured in pulsed operation are shown in Fig. 2. The rapid rise time of approximately 10 μsec is slightly longer than the instability growth times, in agreement with our expectations based on stochastic heating by spatially randomized instability electric fields. The 5-μsec resolution of the ion-temperature measurements is achieved by triggering the (fast) heater pulse with a variable time delay relative to the (slower) probe sweep. Variation of the delay gives the I-V characteristic. Ion-temperature decay times, when the whole plasma is heated, are consistent with ion confinement times.

Figure 3 shows a comparison of measured instability ion-acoustic fluctuation energy (square of potential amplitude Φ) and ion temperature with Eq. (4) for a Cs plasma, demonstrating proportionality, in the lower part, between ion temperature and ion-acoustic wave energy. The the-

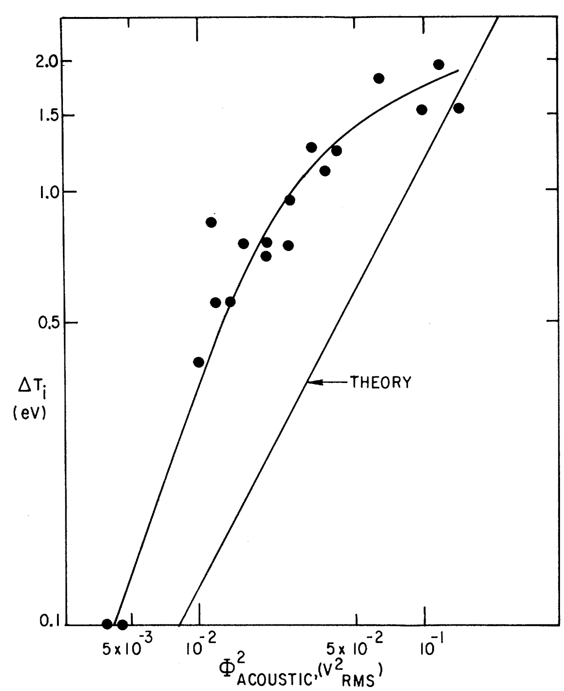

FIG. 3. Ion temperature versus squared rms potential amplitude of ion sound spectrum of parametric instability, and comparison with stochastic heating theory; $n = 2\times10^{10}$ cm^{-3} (Cs), $B = 4$ kG, T_i (cold) = 0.6 eV. The absence of data for small ΔT_i is due to the hard, abrupt mode onset.

oretical curve is calculated by assuming that the time during which an ion is heated is given by $L/V_{i\text{th}}$, where L is the axial length of the destabilized region and $V_{i\text{th}}$ the unheated thermal velocity. The wavelength (necessary to calculate E^2), L, and T_i are determined from measurements. Heat losses are neglected. Similar measurements for a K plasma result in slightly lower (2×) temperature saturation, which may be due to increased ion heat losses in this case or to small changes in the instability parameters. When the pump frequency is raised to 1.5–2 times the plasma frequency, no ion sound fluctuations and no plasma heating are observed, as expected from the theory of the parametric decay instability: The instability can no longer be excited.

Several important considerations of a general nature arise from this work. First, the stochastic heating observed in the present experiments is a very efficient mechanism; we are not aware of comparable ion temperature increases in Q devices in other experimental work (excluding possibly ion-cyclotron heating). Second, the ion-temperature rise time measured is short, since it is limited by the instability growth time $1/\gamma \simeq 1/\omega_{pi}$ and not the collisional electron-ion relaxation time, $\tau_{\text{relax}} \gg 1/\gamma$. Third, the role of parametric ion-acoustic instabilities in ion heating by electromagnetic waves has been demonstrated experimentally, in agreement with predictions, indicating the importance of this instability for present laser-ignition fusion experiments and possibly for heating of magnetically confined plasmas in general. Finally, we note that the ion heating mechanism discussed may play a role in other experimental situations where large-amplitude electrostatic plasma waves are present to produce parametric effects; and that such large-amplitude plasma waves may be generated by other mechanisms besides external rf fields, e.g., by the interaction of intense electron beams with plasmas.

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Note added.—After this paper was submitted there appeared a Letter by McCall *et al.*,[9] showing that present neutron emission may be adequately explained by electron heating and electrostatic ion acceleration. They conclude that the absence of anomalous ion heating is not proved, but may be unimportant in reported experiments. We note that in Ref. 5, where parametric instabilities were observed, the laser pulse duration was about 30 nsec, in comparison to 25 psec in McCall *et al.*,[9] and that a certain time may be necessary to establish plasma density and density gradients (steep gradients would require excessive pump fields), and that, in addition, in such geometry other effects may further reduce the instability growth rate.

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†On leave of absence from RCA, Princeton, N. J. 08540.

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