Hot Electrons due to Laser Absorption by Ion Acoustic Turbulence

Kent Estabrook
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550
(Received 11 May 1981; revised manuscript received 22 September 1981)

Laser absorption on short-wavelength ion turbulence driven by electron-ion streaming instabilities is considered. Contrary to linear theory, which predicts that the turbulent spectra $\varphi(k)$ peaks at $k\lambda_D \sim 0.5$, basic plasma experiments find $\varphi(k)$ peaks at $k\lambda_D \sim 0.04 - 0.2$ which, this Letter shows by theory and simulation, heats most strongly at densities $(0.7-1.2)n_c$ and produces hot electrons $\sim (5-70)T_e$ (depending on the density) which are another source of preheat that may reduce the compression and yield of laser fusion targets.

PACS numbers: 52.50.Jm, 52.35.Ra

An absorption mechanism for laser light is ion turbulence[1-4] driven by a relative drift between the ions and electrons. The drift is assumed to be caused by an electric field which accelerates thermal electrons into the heating region to replace hot electrons streaming out. This is the same ion turbulence often assumed to be partly responsible for transport inhibition since it is well above theoretical threshold. Some of the laser power is irreversibly absorbed when the electrons oscillating in the laser electric field ($\vec{E}$) couple to the ion waves to drive electron plasma waves (epw) which heat electrons as they damp and break. The wavelength of the epw is dominantly determined by ion acoustic fluctuations. Faehl and Kruer[1] described the fraction of light absorbed and electron distributions produced by a given wavelength of ion fluctuations. This paper extends their pioneering work by using experimentally measured ion-electron drift turbulence spectra[5-10] as input to determine the important features of the absorption. The experiments[5-10] use much smaller densities and much longer time scales than those of laser fusion but $k\lambda_D, v_d/v_e \sim 0.1$ scale similarly. Here $k = 2\pi/\lambda_{epw}$, λ_D is the Debye length, v_d = the drift velocity and $v_e^2 = T_e/m_e$. Data from these experiments[5-10] show that the peak of the spectra from electron-ion drift turbulence is at a surprisingly long wavelength ($k\lambda_D < 0.2$). The significance of the long wavelength is that the epw will have a reasonably large phase velocity, $v_p/v_e = [3+1/(k\lambda_D)^2]^{1/2}$ and hence a fairly hot electron temperature, $T_{hot}/T_e \sim [1.5 + 1/(2k^2\lambda_D^2)] \times$ (a factor of order 1–2) or about 20 for $k\lambda_D \sim 0.2$. The experimentalists actually measure the frequency, f, rather than the wavelength, which are related by $f/f_{pi} = k\lambda_D\{[1+3T_i/(\bar{z}T_e)]/(1+k^2\lambda_D^2)\}^{1/2}$. $\bar{z}$ is the ion charge state. $2\pi f_{pi} = (4\pi ne^2/m_i)^{1/2}$, where n is the electron density. The experiments do not agree on where the frequency peak is and most[5-10] find it between $f/f_{pi} \approx k\lambda_D \approx 0.04$ and 0.2. Some papers[11,12] do find the spectrum peak at $k\lambda_D \sim 0.5$, but they report such small turbulence amplitude $\delta n/n$ that it is not surprising that their results agree with linear theory.[13] Quon, Wong, and Ripin[14] also report the spectrum peak at 0.5, but their v_d/v_e is 4–5, which is much greater than expected for laser fusion plasmas [where v_d is probably $(1-5)c_s$]. Two papers[15,16] use laser spectroscopy to examine the $\delta n/n$ at $k\lambda_D = 0.5$ for laser-produced plasmas and report sizable amplitudes there but do not describe amplitudes at longer wavelengths. This variation in the literature is unfortunate since the total absorption and T_{hot} depends sensitively on the $k\lambda_D$ of the peak. However, the data emphasize the still mysterious nature of the ion acoustic instability. Valuable experiments need to be done that would extend the pioneering work of Offenburger, Ng, and Pitt[15] and Gray *et al.*,[16] who studied the wavelength and angular spectrum of laser-produced plasmas (preferably for a $\lambda_0 \leq 1$ μm heating laser) much like what Slusher *et al.*[11] have done for low-density plasmas.

I begin the analysis with single modes and then extend it to a spectrum of modes. I have analytically calculated the fraction of light absorbed as a function of the ratio of the plasma density to the critical density (n/n_c) and calculated the $k\lambda_D$ of the ion waves using the complex dielectric function of the electron plasma waves at that wavelength and frequency by using the methods of Refs. 1 and 4 (Fig. 1). Since this figure shows each mode separately, it is not applicable to experiments, but separates out the effects of each mode. Figure 1 also shows the results of one-dimensional (1D), electrostatic simulations[17] which had a fixed single sinusoidal mode of an ion wave. All the 1D runs in this paper had pump amplitude $[v_{osc} = eE/(m_e\omega_0)]$ $v_{osc}/v_e = 0.2$,

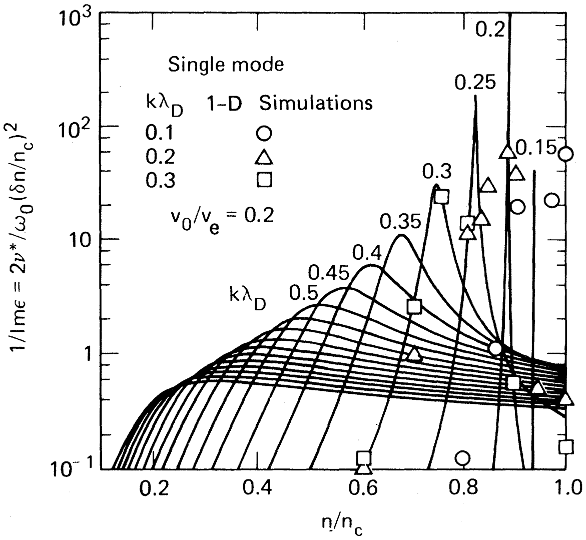

FIG. 1. Effective collision frequency [times $2/(\delta n/n_c)^2$] for single modes of $k\lambda_D$. The solid lines are the analytically calculated $1/\mathrm{Im}\epsilon$.

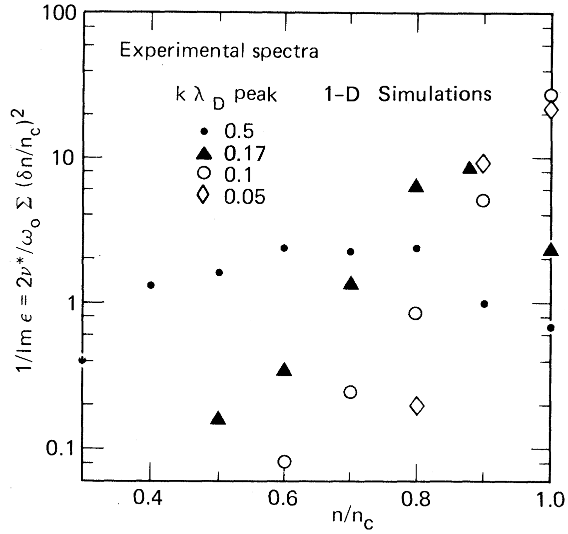

FIG. 2. Effective collision frequency [times $2/(\delta n/n_c)^2$] from ion-electron drift-induced turbulence spectra from Refs. 4–8 with spectral peaks at the $k\lambda_D$ indicated. For $k\lambda_D = 0.5$, 32 modes were used and the longer wavelengths used 64 to 128 modes of random phase. $\Sigma\,[n_i(k)]^2 = 0.01$, rms $(n_i - 1) = 0.07$. To convert this graph into an effective collision frequency, multiply by an assumed turbulence level $[(\delta n/n)\ (n/n_c)]^2/4$. The extra factor of 2 is to convert from 1D to 3D assuming an averaging over angles (Ref. 1). Refs. 5–9 measure $\delta n/n$ to be typically 0.1 to 0.3 for laser fusion regimes. Estimates (Ref. 1) find time averaged $\langle \delta n/n\rangle_t \sim [(1 + k^2\lambda_D^2)^{-0.5} - (3T_i/ZT_e)^{0.5}]^2/3$.

where E is added uniformly to the self-consistent electrostatic field. ω_0 = the angular frequency of $\vec{E}$. A plot of the electron kinetic energy in the simulations revealed that the heating was at first very slow as the epw grew from noise. Then the heating became quite rapid as the epw trapped electrons. Finally the plasma became so hot that the epw became very highly damped and the heating rate dropped to a small value. The measurements of the effective collision frequency (ν^*) were taken during the period of most rapid heating. The simulations ($k\lambda_D \lesssim 0.2$) show that the resonance width of the heating is broader in density than the linear theory due to mode coupling and increased damping by the trapped and heated electrons.

The simulations in Fig. 2 used a fixed spectrum of ion turbulence that matched the shape of the experimental spectrum. The simulation results for absorption and temperatures do depend on the high-frequency falloff [we used $(f/f_{pi})^{-2.3}$], and on the shape for frequencies below the peak. The runs for Fig. 2 were made with the modes in random phase. Changing the random number generator or making the phases all zero (simulating a steepened, sawtooth ion acoustic wave) caused typically factor-of-2 variations in the ν^* and the heated temperatures. Interestingly, runs above critical with peak $k\lambda_D = 0.17$ showed surprising absorption ($\nu^* \sim 0.05$) up to $n/n_c \lesssim 1.2$ with $T_{\mathrm{hot}}/T_e \sim 15$ with reasonable absorption up to $n/n_c \sim 2$.

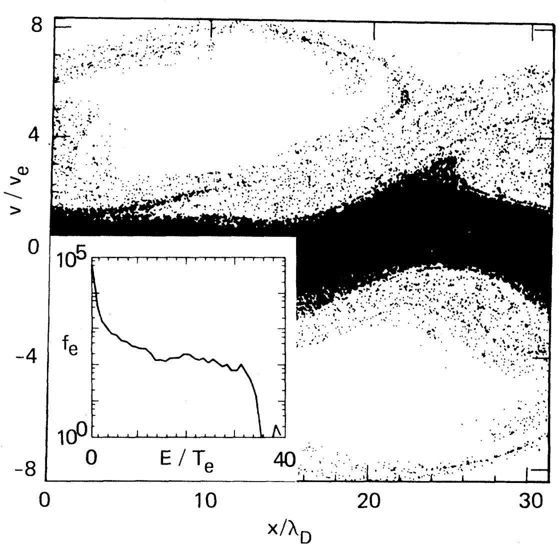

FIG. 3. Electron phase space from a 1D simulation. Fixed single-ion mode $k\lambda_D = 0.2$, $\delta n/n = 0.1$, $n/n_c = 0.87$, and $v_{\mathrm{osc}}/v_e = 0.2$. Note strong trapping for relatively weak pump and cutoff at $v_p + 3v_e$ (see text).

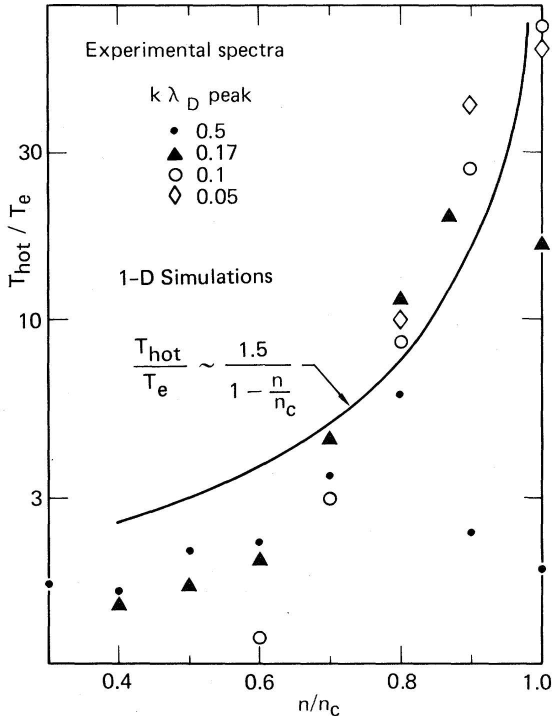

FIG. 4. Heated electron temperature vs density from 1D simulations (Fig. 2). The turbulence spectrum is broad enough so that at high densities the pump couples to its resonant long wavelengths, and at low density it couples to the shorter wavelengths and gives roughly $T_{\text{hot}}/T_e \sim 1.5/(1-n/n_c)$, which is simply found from the Bohm–Gross relation with $T_{\text{hot}}/T_e \sim (v_p/v_e)^2/2$.

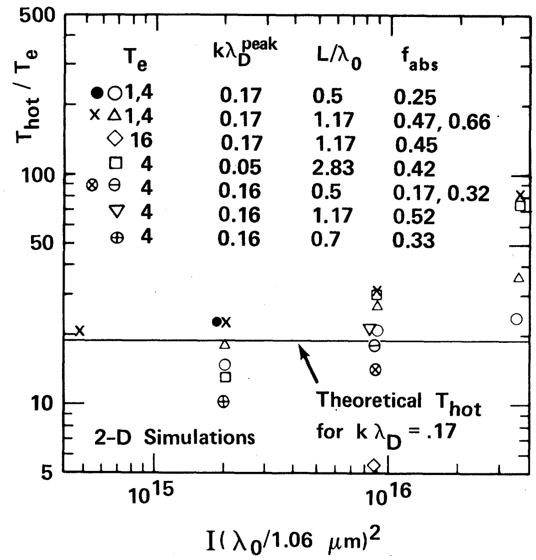

FIG. 5. Heated-electron temperatures from 2D simulations of fixed ion turbulence. f_{abs} is the average fraction light absorbed. Due to the inherent problem of mapping the experimental homogeneous turbulence to a density gradient ($\lambda_D \propto n^{-1/2}$), I tested the sensitivity of T_{hot}/T_e to two kinds of turbulence representations and to a density ($0.6n_c$) shelf (Ref. 19), (plus in a circle, minus in a circle) before critical. The full and empty circles, the triangles, the diamond, and the squares refer to turbulence in which $\varphi\{k\lambda_D[n(x)]\}$ is constant, but not isotropic ($x \parallel \nabla n$). The cross in a circle, the minus in a circle, the inverted triangle, and the plus in a circle refer to homogeneous, isotropic turbulence [$\varphi(k)$ constant in angle, random x, y phases] mapped to $n(x)$ with $\delta n/n$ constant; however $\varphi(k\lambda_D)$ peaks at $k\lambda_D \sim 0.17$ only at $n \sim 0.9n_c$ due to random phases and $\nabla n(x)$. If the ordinate is $T_{\text{hot}}/(T_e + m_e v_{\text{osc}}^2/2)$ the points form a more horizontal line nearer the theory shown. The diamond and square data points may not have enough statistics to resolve higher temperatures.

At constant $n/n_c = 0.87$, $k\lambda_D = 0.17$, I tested the theoretical scaling of $\nu^*/\omega_p = [\Delta(E_{\text{kin}}/E_{\text{kin},0})/\Delta(\omega_p t)](v_e/v_{\text{osc}})^2$, where E_{kin} ($E_{\text{kin},0}$) are the total (initial) kinetic energy, and found the scaling to be quite good for $v_{\text{osc}}/v_e = 0.1, 0.2, 0.3$. I tested the consistency of $1/\text{Im}\epsilon = 2\nu^*/[\omega_0 \sum (\delta n/n_c)^2]$ for rms $\delta n/n = 0.015, 0.05, 0.15, 0.19, 0.38$ and found the scaling [$\nu^* \sim (\delta n/n)^2$] holds for smaller amplitudes (rms $\delta n/n \lesssim 0.05$) and reduces to $\nu^* \sim (\delta n/n)^\alpha$ ($\alpha \lesssim \frac{3}{2}$) for the higher amplitudes due to increased damping from the very rapid heating and rapid mode coupling to higher modes.[2,4] For large pumps the heating rate can be reduced if the electron excursion amplitude $eE_{\text{tot}}/(\omega_0^2 m_e)$ becomes $\gtrsim \lambda_D$.

The fraction light absorbed $= 1 - \exp[-2\pi(\nu^*/\omega_0)(l/\lambda_0)/(1-n/n_c)^{1/2}]$ for each direction,[18] where $l/\lambda_0 =$ the light path length in vacuum wavelengths. An experimental diagnostic of ion turbulence or parametric absorption is red-shifted $2\omega_0$ light.[19]

The electron heating mechanism is trapping (Fig. 3), which can occur even for fairly low v_{osc}/v_e since the electrostatic wave amplitude $\sim v_{\text{osc}}$/damping.[18] The fixed-ion, single-mode kinetic simulations find the heated electron distribution (f_e, insert, Fig. 3) to be approximately a Maxwellian of temperature $T_{\text{hot}}/T_e \approx m_e v_p^2/2$ truncated at speed $\sim v_p + 3v_e$. In runs where the broad ion spectrum of the experiments was used (Fig. 4), the hot distribution was nearly Maxwellian (no truncation, $T_{\text{hot}}/T_e = m_e v_p^2/2$). The broad $\varphi(k)$ heated-electron distribution can be analytically constructed from the sum over k of the truncated single-mode distributions: $\sum[\nu^*(k, \text{Fig. 1})][\varphi(k)]\{\exp[-\text{energy}/T_{\text{hot}}(k)]\}$, where the exponential is truncated at speed $v_p + 3v_e$. T_{hot} increases with time as v_p increases from the heating. The heat flux is in the direction of the laser electric field. I extend the analysis to

2D simulations[20] (Fig. 5). I find the $T_{hot}/T_e \sim 25(L/\lambda_0)^{0.2}$ for $k\lambda$ peak ~ 0.17, $v_{osc} = v_e$ and moving ion runs (parametric decay and oscillating two stream) show $L/\lambda_0 \sim 0.5-0.7$ for the $v_{osc}/v_e \sim 1-0.5$ $[L = n_c(\Delta x/\Delta n)]$. If one considers the electrons to then equilibrate[19] to a hot 3D temperature, the resulting T_{hot} would be $\frac{2}{3}$ that shown. A way to avoid these hot electrons is, of course, to decrease the laser intensity (lower T_e) and/or wavelength (increase n_c) to favor inverse bremsstrahlung absorption $\propto n/T_e^{3/2}$. Possibly reactor targets will have long enough density gradient lengths (or short enough laser wavelength) to absorb before density $0.7n_c$.

We are happy to acknowledge valuable conversations with W. L. Kruer and J. S. DeGroot. This work was performed under the auspices of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

[1]R. J. Faehl and W. L. Kruer, Phys. Fluids 20, 55 (1977).

[2]W. L. Kruer, Phys. Fluids 15, 2423 (1972).

[3]W. M. Manheimer, D. G. Colombant, and B. H. Ripin, Phys. Rev. Lett. 38, 1135 (1977).

[4]J. M. Dawson and C. Oberman, Phys. Fluids 5, 517 (1962); P. K. Kaw, A. T. Lin, and J. M. Dawson, Phys. Fluids 16, 1967 (1973).

[5]R. L. Stenzel, Phys. Fluids 21, 99 (1978) ($v_d \lesssim 0.1v_e$, peak at $\omega/\omega_{pi} \sim 0.18$, $\delta n/n \gtrsim 0.2$).

[6]M. Yamada and M. Raether, Phys. Rev. Lett. 32, 99 (1974) ($v_d \sim 0.1v_e$, peak at $\omega/\omega_{pi} \sim 0.08$, $\delta n/n \sim 0.03 - 0.1$).

[7]Y. Amagishi, Phys. Rev. Lett. 29, 405 (1972) ($v_d \sim v_e$).

[8]Y. Kawai and M. Guyot, Phys. Rev. Lett. 39, 1141 (1977) ($v_d \sim 0.1v_e$, peak at $\omega/\omega_{pi} \sim 0.05$, $\delta n/n \lesssim 0.15$).

[9]W. M. Bollen, J. S. DeGroot, K. Mizuno, R. B. Spielman, and R. L. Walraven, "Experimental Investigation of Current Driven Ion Acoustic Turbulence and Anamalous DC Resistivity" (to be published) (peak at $\omega/\omega_{pi} \sim 0.16$, $\delta n/n \sim 0.2 - 0.3$).

[10]Ch. Hollenstein, M. Guyot, and E. S. Weibel, Phys. Rev. Lett. 45, 2110 (1980) ($v_d/v_e \sim 0.01 - 0.2$, $\delta n/n \sim 0.001 - 0.1$, peak at $\omega/\omega_{pi} \sim 0.04 - 0.09$).

[11]R. E. Slusher, C. M. Surko, D. R. Moler, and M. Porkolab, Phys. Rev. Lett. 36, 674 (1976) ($v_d/v_e \sim 0.1 - 0.18$, peak at $k\lambda_D \sim 0.5$, $\delta n/n \sim 10^{-4}$).

[12]A. Y. Wong, B. H. Quon, and B. H. Ripin, Phys. Rev. Lett. 30, 1299 (1973) ($v_d/v_e \sim 0.3$, peak at $\omega/\omega_{pi} = 0.5$, $\delta n/n = 0.01$); K. Muraoka *et al.*, J. Plasma Phys. 10, 135 (1973) (shock, $T_e = T_i$, peak at $\omega/\omega_{pi} = 0.5$).

[13]J. S. DeGroot, private communication.

[14]B. H. Quon, A. Y. Wong, and B. H. Ripin, Phys. Rev. Lett. 32, 406 (1974) ($v_d/v_e \sim 4 - 5$, $\delta n/n \sim 0.05 - 0.1$, peak at $\omega/\omega_{pi} \sim 0.5$).

[15]A. A. Offenburger, A. Ng, and L. Pitt, Phys. Rev. Lett. 40, 873 (1978).

[16]D. R. Gray *et al.*, Phys. Rev. Lett. 39, 1270 (1977).

[17]Kent Estabrook and J. E. Tull, Lawrence Livermore National Laboratory Report No. UCID-17050, 1977 (unpublished).

[18]W. L. Kruer, private communication.

[19]N. G. Basov *et al.*, *Plasma Physics: Nonlinear Theory and Experiments*, edited by H. Wilhelmsson (Plenum, New York, 1977), p. 47.

[20]Kent Estabrook and W. L. Kruer, Phys. Rev. Lett. 40, 42 (1978).