

JxB heating by very intense laser light

W. L. Kruer, and Kent Estabrook

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modes. By assuming that the nonlinear interaction occurs in the inner layer of the tearing mode, we found that the background turbulence gives rise to an effective resistivity term, which is, however, four orders higher in the derivatives than the collisional resistivity term. When the fluctuation level is sufficiently high, the turbulent resistivity takes the place of the collisional resistivity and leads to an enhanced tearing instability.

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^{a1}Permanent address: Department of Physics, Quaid-i-Azam University, Islamabad, Pakistan.

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J × B heating by very intense laser light

W. L. Kruer and Kent Estabrook

University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

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Plasma heating by the oscillating component of the pondermotive force of a very intense light wave is discussed.

The absorption of very intense light is a problem of great interest to anyone studying ICF applications of CO₂ lasers. There is, of course, the well-known mechanism of resonance absorption,¹ which can be strongly enhanced by both cratering² and rippling³ of the critical density surface. We have recently explored another little-known mechanism, which can play a significant role at very high intensities commonly used in CO₂ experiments. This so-called J × B heating⁴ is caused by the electrostatic field driven by the oscillating component of the pondermotive force of the laser light. Here we present a model calculation to show that the driven electrostatic field is sizable for high-intensity light. We then present computer simulations of the J × B heating, which demonstrate significant absorption of very intense light into electrons with a modest temperature.

We begin with a model calculation to illustrate the physics of this coupling mechanism. Consider a linearly polarized light wave with electric field amplitude $E = E_L(x)$

$\times (\sin \omega_0 t) \hat{y}$. The pondermotive force f_p exerted by this field is readily derived in the usual way to be

$$f_p = -\frac{m}{4} \frac{\partial}{\partial x} v_L^2(x) (1 - \cos 2\omega_0 t) \hat{x}, \quad (1)$$

where $v_L = eE_L/m\omega_0$, and, for simplicity, we have neglected thermal and relativistic effects. The time-averaged part produces steepening of the density profile, and the oscillating component can lead to heating. In effect, the oscillating pondermotive force corresponds to driving the plasma with an electrostatic field E_d , where

$$\frac{eE_d}{m} = \frac{1}{4} \frac{\partial}{\partial x} v_L^2(x) (\cos 2\omega_0 t). \quad (2)$$

Since the magnitude of E_d is proportional to $v_L \partial v_L / \partial x$, significant absorption is expected only for very intense light.

To estimate the size of the driver field, we consider an intense planar light wave normally incident on an inhomogeneous slab of plasma and use the model of Lee *et al.*⁵ to

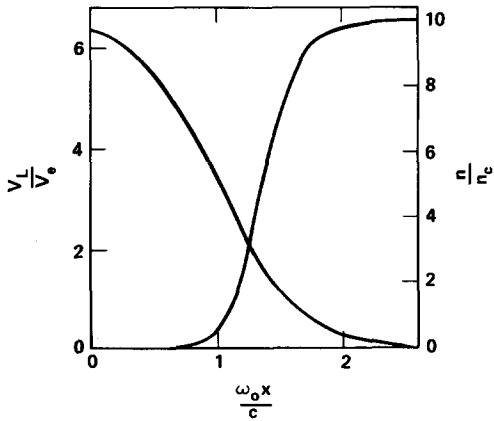


FIG. 1. The spatial variation of the transverse electric field ($v_L = eE_L/m\omega_0$) and the plasma density in the light-plasma interface. For this example, $(v_{fs}/v_e)^2 = 10$.

compute $E_L(x)$ in the strongly steepened light-plasma interface. For intense fields, the density variation is large, and a numerical solution of the model equations is needed. Figure 1 shows a typical result for the spatial variation of the amplitude of the transverse electric field and the plasma density in the interface. For this example, $(v_{fs}/v_e)^2 = 10$, where $v_{fs} = eE_{fs}/m\omega_0$, E_{fs} denotes the free-space value of E_L , and v_e is the electronic thermal velocity. As expected from the pressure balance, the plasma is steepened by the intense, reflecting light wave to a density of $n_c(v_{fs}/v_e)^2$, where n_c is the critical density. Both the transverse field and the density vary quite rapidly in the interface.

Given $v_L(x)$, we can evaluate the magnitude of the driver field caused by the oscillating ponderomotive force. For example, at the location where the driver field would be most enhanced by the plasma response ($n \simeq 4n_c$), we find that

$$\frac{eE_d}{m} \simeq 0.6 \left(\frac{v_{fs}}{v_e} \right)^{1.8} \frac{v_e^2 \omega_0}{c}. \quad (3)$$

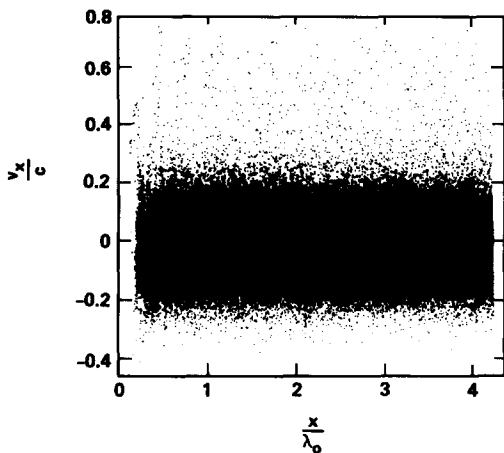


FIG. 2. An electron phase space at $\omega_0 t = 80\pi$ from a computer simulation of $\mathbf{J} \times \mathbf{B}$ heating. The incident light intensity was $I\lambda_\mu^2 = 10^{18} [(W - \mu^2)/\text{cm}^2]$. The plasma was initially an overdense slab with density $n = 100n_{cr}$, an electron temperature $\theta_e = 4$ keV, an ion-electron mass ratio of 1836, and $T_e/T_i = 30$.

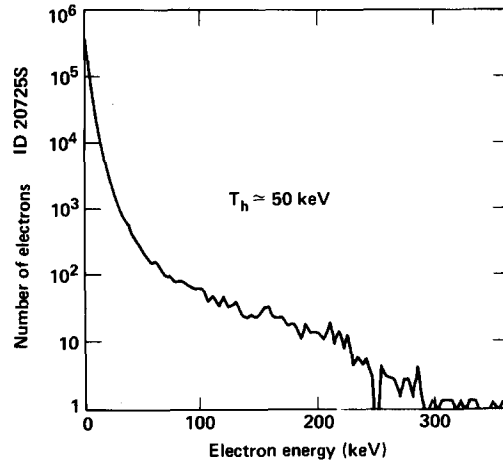


FIG. 3. A plot of the electron distribution at $\omega_0 t = 80\pi$ in a computer simulation of $\mathbf{J} \times \mathbf{B}$ heating. The parameters are those for Fig. 2.

Although relativistic effects should be included for more quantitative estimates, the magnitude of this field is clearly significant when the incident light is very intense. The oscillating electrostatic field has a strong spatial variation in the light-plasma interface and will heat electrons that interact nonadiabatically with it.

To compute the absorption and electron heating, we have carried out computer simulations using a 1.5-dimensional particle code with electromagnetic fields and relativistic particle dynamics. In our simulations, we consider the propagation of an intense, planar light wave from vacuum onto a plasma slab. The plasma begins as an overdense slab with density equal to the upper density expected in the final steepened state; i.e., $n/n_c = (v_{fs}/v_e)^2$. The reflected light waves are allowed to escape into vacuum at the left boundary, and heated electrons are replaced with incoming thermal electrons at the right boundary. The evolution is followed until a quasisteady state is attained.

Our simulations demonstrate significant heating when the light is very intense. As illustrated by the plot of electron phase space in Fig. 2, electrons are accelerated and then beamed into the plasma by the oscillating ponderomotive force. The effective temperature of the heated electrons is relatively modest, as shown by the plot of the electron distribution function in Fig. 3. In this example, the product of incident intensity and wavelength squared is $10^{18} \text{ W } \mu\text{m}^2/\text{cm}^2$ (i.e., $I \simeq 10^{16} \text{ W/cm}^2$ for CO_2 light), and the initial electron temperature of the dense plasma slab is 4 keV. The time-averaged absorption is about 11%. Note that the heated tem-

TABLE I. The time-averaged absorption measured in simulations with different incident intensities and background electron temperatures.

T_e (keV)	$I\lambda_\mu^2$ ($\text{W } \mu\text{m}^2/\text{cm}^2$)	f_{abs}
4	10^{17}	0.015
4	3×10^{17}	0.06
4	10^{18}	0.11
12	3×10^{17}	0.05
12	10^{18}	0.17
40	10^{18}	0.13

perature is about 50 keV.

Table I shows the averaged absorption measured in a number of simulations with different incident intensities and background electron temperatures. As expected, the absorption is strongly dependent on intensity, ranging from 1% or 2% at $I\lambda_\mu^2 = 10^{17} \text{ W } \mu\text{m}^2/\text{cm}^2$ to between 10% and 15% at $I\lambda_\mu^2 = 10^{18} \text{ W } \mu\text{m}^2/\text{cm}^2$. A weak dependence of the absorption on background electron temperature is also evident.

Of course, these one-dimensional simulations of normally incident light are intentionally ideal to isolate this physical process. Two-dimensional simulations of obliquely incident, p -polarized light show that resonance absorption is then quite efficient. The fractional absorption in a steepened profile peaks at about 50% for angles of incidence of about 20° and can be even larger when the critical surface becomes cratered and rippled. The heated electron temperature θ_h caused by resonance absorption is quite large at high intensity; for example, $\theta_h \sim 200 \text{ keV}$ for $I\lambda_0^2 = 10^{18} \text{ W } \mu\text{m}^2/\text{cm}^2$ and a background temperature of 4 keV. Two-dimensional simulations of normally incident light would include the oscillating two-stream and ion-acoustic decay instabilities. Simulations⁶ have indicated that the absorption caused by these instabilities is modest in a steepened density profile, i.e., roughly 10% or less. The electrons are heated primarily along the electric vector of the light, in contrast to heating by resonance absorption and by the oscillating pondermotive force discussed here. For comparison, we note that the oscillating pondermotive force produces a fractional absorption of order 10% only when the light intensity is extremely large. The heated electrons are beamed inward and have a relatively modest temperature, given such a high light inten-

sity. Since this process depends on the oscillating component of the pondermotive force, we do not expect it to be strongly modified if resonance absorption and parametric instabilities are simultaneously operative.

In summary, we have demonstrated a novel mechanism for the absorption of very intense laser light. The oscillating component of the pondermotive force generates an electrostatic field, which leads to electron heating. A model calculation shows that the electrostatic field is sizable for very intense light. Computer simulations with a relativistic particle code demonstrate significant absorption into electrons with a relatively modest temperature.

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Filamental quenching of the current-driven ion-cyclotron instability

Steven L. Cartier, Nicola D'Angelo, Peter H. Krumm,^{a)} and Robert L. Merlino

Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

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Experimental evidence is presented on the effect of the finite width of the current channel for the excitation of the current-driven ion-cyclotron instability. The results are in agreement with the nonlocal theory of Bakshi, Ganguli, and Palmadesso [*Phys. Fluids* **26**, 1808 (1983)].

Since their discovery over two decades ago,¹ ion-cyclotron waves have been an area of active research in the laboratory,² in the ionosphere-magnetosphere,³ and in the solar corona.⁴ The current-driven ion-cyclotron wave instability received its first theoretical treatment in the (local) theory of Drummond and Rosenbluth,⁵ appropriate to a uniform, magnetized plasma, without magnetic shear, in which elec-

trons drift along **B** field lines with the same drift velocity \mathbf{v}_D , at all points in the plasma. Their treatment, however, could not allow, among other things, for the effect that the finite width of the current channel of most laboratory experiments has on the excitation of the instability. This has been considered in the nonlocal theories of, e.g., Ganguli and Bakshi⁶ and Bakshi, Ganguli, and Palmadesso.⁷ They find that if the