CONF 790571-1

Lawrence Livermore Laboratory

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June 16, 1977

MASTER

This paper was presented at the Anomalous Absorption Conference, Vancouver, B.C., May 10-12, 1977

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Wave-Breaking Amplitudes in Warm, Inhomogeneous Plasmas

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Abstract

The effect of plasma temperature on reducing the wave-breaking amplitude of resonantly-driven fields is shown. Some applications to laser fusion are given.

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*Research performed under the auspices of the U.S. Energy, Research and Development Administration under contract No. W7405-ENG-48.

A problem of both basic interest and practical importance is the amplitude to which plasma waves can be resonantly driven in inhomogeneous plasma. For example, calculations of this amplitude are useful in order to understand the scaling of the energy of the heated electrons produced in resonance absorption of intense laser light. It is well-known^(1,2) that the plasma temperature has an important effect on the wave-breaking amplitude indirectly since it controls the amount of nonlinear steepening of the density profile near the critical density. We show that the temperature also has a significant direct effect on the wave-breaking amplitude; i.e. an effect which persists even when the density scale length is held fixed. A simple theory of this effect is compared with simulation results, and some applications to laser fusion are given.

To investigate how the temperature affects the wave-breaking amplitude even in a fixed density profile, we have used a 1-D electrostatic particle simulation code to follow the evolution of an inhomogeneous plasma driven by an oscillating electric field. This so-called capacitor model³⁻⁵ is the simplest model of resonance absorption and has been widely used in the past.

A plasma with a linear density gradient from 0 to $2n_{cr}$ (the critical density) is set up, and an oscillating field of the form $E_0 \cos \omega_0 t$ is applied starting at time $\omega_0 t = 0$. Here ω_0 is the plasma frequency at the $n = n_{cr}$. A vacuum region surrounds the plasma on the low density side, and on the high density side the heated electrons are re-emitted with their initial thermal temperature.

Fig. 1 shows simulation results for the peak electric field amplitude at the time of initial wave-breaking as a function of the thermal velocity

of the background plasma. For these results the density scale length and driver amplitude (E_0) are held fixed. Note the pronounced effect of plasma temperature. In the cold plasma limit (electron thermal velocity $v_e = 0$), the simulation results agree with the cold wave-breaking prediction⁴ for the given scale length and driver amplitude. However, the wave amplitude becomes significantly reduced as the temperature increases. We note that in all these cases wave-breaking (electron "trapping") is occurring in the nonlinear state. One important consequence of the wave-breaking taking place at lower amplitudes is that the transition to the purely thermal convection regime occurs at higher temperatures than previously estimated.

Some simple theoretical estimates for wave-breaking in warm plasmas can be given. The basic idea is to take the cold plasma model⁴ - which is analytically tractable - to describe the initial wave growth, but to then estimate when the faster particles will undergo wave-breaking in this field. Hence in this model, the wave is being built up and supported by the main body of slow electrons and is being damped by a much smaller number of faster electrons.

In the cold plasma model the wave amplitude is peaked at the critical density (where it is most resonant) and grows linearly in time. As its amplitude increases, the field becomes more localized about its resonance point. Wave-breaking finally occurs when the field is sufficiently large in amplitude and narrow in spatial extent that electrons interact with it non-adiabatically; i.e. when electrons traverse the field in a time $\approx 1/\omega_0$. Then such electrons see a nearly constant field and are efficiently accelerated, thereby damping the field.

The cold plasma model gives

$$l = \frac{4L}{\omega_0 t} \quad (1)$$

$$v_w = v_d \frac{\omega_0 t}{2} \quad (2)$$

where l is an effective width of the driven field, L is the density scale length at the critical density, and v_w (v_d) is the oscillation velocity of an electron in the driven (driver) field. Neglecting thermal effects, wave-breaking occurs when $\frac{v_w}{v_d} \approx \omega_0$. From (1) and (2), we then obtain $v_w = \sqrt{2v_d \omega_0 L}$, which is the well-known cold plasma prediction.

The effect of plasma temperature can now be estimated. The point is that the wave-breaking condition is more readily satisfied by the faster particles in the thermal distribution. Since a Maxwellian distribution falls off so rapidly in velocity, we will take the fastest particles to have a velocity of $\approx 3 v_e$. The modified wave-breaking condition becomes

$\frac{l}{v_w + 3v_e} \approx \omega_0$. From (1) and (3), we then obtain

$$v_w = \frac{-3v_e + \sqrt{9v_e^2 + 8L\omega_0 v_d}}{2} \quad (3)$$

As shown by the solid line in Fig. 1, this simple estimate is in reasonable agreement with the simulation results. It is plausible that the theory is somewhat high, since this model neglects the thermal pressure of the plasma which also acts to reduce the driven field.

Let us now compare our predictions for the wave-breaking amplitude with some results from a 2-D simulation of resonance absorption published

in Reference 1. In that example, n-polarized, 1.06 μ wavelength laser light with an intensity of 10^{16} W/cm² was incident at an angle of 24° onto a plasma slab. The plasma had an electron temperature of 4 keV and an initial linear density profile with scale length $k_0 L = 10$. The initial wave-breaking amplitude was observed to be $\frac{v_W}{c} = .29$. For this example, the corresponding parameters in the capacitor model are $\frac{v_d}{c} = .011$, $\frac{v_e}{c} = .088$ and $k_0 L = 10$. The cold plasma prediction for the wave-breaking amplitude is then $\frac{v_W}{c} = .47$, which is significantly larger than observed in the simulation. However, our simulation of the capacitor model including thermal effects for the given parameters yields $\frac{v_W}{c} = .3$, in quite good agreement. (The theoretical estimate in Equation 3 gives $\frac{v_W}{c} = .35$.) Hence warm plasma effects do significantly affect the wave-breaking amplitude as suggested in Reference 1.

We note that relativistic effects do not significantly affect the above result, as has been recently claimed.⁷ The simulations of the capacitor model have been extended to include a relativistic equation of motion. The initial breaking amplitude in the example discussed above was found to be the same within a few percent. As a confirmation, the original 2-D simulation was then re-run⁸ with relativistic effects omitted. Again the initial wave-breaking amplitude was the same within a few percent.

One interesting consequence of these calculations can be noted. Although (in a fixed profile) the temperature decreases the amplitude of the resonantly-driven field, it does not strongly affect the heated electron energy. For example, the maximum energy gained by an electron is

$$\epsilon_{\max} \approx e E_w \ell,$$

where ℓ is again the distance over which an electron is resonant with the

wave. Using Eq. (3) and $L = \omega_0 (v_H + 3v_e)$, we obtain

$$\epsilon_{\max} = eE_d L,$$

which is the result for a cold plasma. Physically, because of thermal effects the field is at a lower amplitude but it is broader in spatial extent, and these two effects tend to compensate one another. The capacitor model simulations support this prediction. The maximum heated electron energy varied by less than about 10% when the background electron temperature was changed by a factor of 100.

This result indicates that the principal temperature dependence of the heated electrons arises from the temperature dependence of L , the local density scale length at the critical density. This explains why previous theoretical estimates¹ of the heated electron energies using the cold plasma prediction with the steepened scale length worked rather well.

Based on this result we can now estimate some scalings of the hot electron energy due to resonance absorption (in the wave-breaking regime) in laser fusion applications. To relate E_d to the incident laser light intensity, simply balance the absorbed energy flux with the energy flux predicted from the capacitor model,

$$f \frac{cE_L^2}{8\pi} = \frac{\omega_0 L}{8} E_d^2,$$

where f is the fractional absorption, E_L is the electric field amplitude of the light (in vacuum), and ω_0 is the laser light frequency. This gives

$$E_d = E_L \sqrt{\frac{cf}{\pi\omega_0 L}}$$

The maximum heated electron energy then becomes

$$\epsilon_{\max} = eE_L L \sqrt{\frac{f_c}{\pi \omega_L L}}$$

Note that if E_L and f are held constant, $\epsilon_{\max}$ scales as $L^{1/2}$, and so the heated energy scales more weakly with temperature than L does. Furthermore if the background temperature and f are held constant, $\epsilon_{\max}$ scales more weakly than the square root of the incident light intensity (I_L) since L decreases with increasing intensity.⁹ For example, with $L \propto I_L^{-5}$ as has been recently computed,¹⁰ we then estimate that the heated energy varies as I_L^{β} , where $\beta \approx .25$. This dependence for the heated energy compares favorably with that found in large 2-D computer simulations of resonance absorption¹⁰⁻¹¹ and also with that deduced from high energy x-ray spectra.¹²

In summary, we have found that the plasma temperature plays a significant direct role in determining the wave-breaking amplitude of resonantly driven plasma waves. This temperature effect was calculated in simulations using the capacitor model, and a simple theory was developed. Our results were used to interpret some 2-D simulations of resonance absorption of laser light and to estimate some scalings of resonantly-heated electron energies.

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REFERENCES

1. K. G. Estabrook, E. J. Valeo and W. L. Kruer, Phys. Fluids 18, 1151 (1975).
2. D. W. Forslund, J. M. Kindel, K. Lee, E. L. Lindman, and R. L. Morse, Phys. Rev. A11, 679 (1975).
3. J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. F. Rudsinski, Phys. Rev. Letters 28, 795 (1972).
4. P. Koch and J. Albritton, Phys. Rev. Letters 32, 1420 (1974).
5. J. DeGroot and J. Tull, Phys. Fluids 18, 672 (1975).
6. T. P. Coffey, Phys. Fluids 14, 1402 (1971).
7. J. F. Drake and Y. C. Lee, Phys. Fluids 19, 1772 (1976).
8. K. G. Estabrook (private communication).
9. E. Valeo, W. Kruer, K. Estabrook, B. Lengdon, B. Lasinski, C. Max and J. Thomson, in Plasma Physics and Controlled Nuclear Fusion Research - 1976 (International Atomic Energy Agency, Vienna, 1977).
10. Kent Estabrook, Bull. Am. Phys. Soc. 21, 1067 (1976).
11. D. W. Forslund, Bull. Am. Phys. Soc. 21, 1066 (1976).
12. K. Manes, H. Ahlstrom, R. Haas and J. Holzrichter, Lawrence Livermore Laboratory UCRL-76771 (1976); to be published.

FIGURE CAPTION

Fig. 1 The initial wave-breaking amplitude as a function of the background plasma. The points are simulation results and the dashed line is a theoretical estimate. The parameters are $L = 500 \delta$, $v_d = 2 \omega_0 \delta$, where δ is the cell size.

FIG. 1

FIG. 2