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LASER LIGHT ABSORPTION DUE TO SELF-GENERATED MAGNETIC FIELDS*

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Abstract

It is shown that even normally incident laser light will be resonantly absorbed near the critical density surface when there are self-generated DC magnetic fields. Theoretical estimates for the coupling mechanism, saturation amplitudes, and absorption are given and tested in computer simulations for parameters characteristic of some recent laser-plasma experiments.

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The identification and calculation of collective mechanisms for the absorption of intense laser light in plasmas is a highly topical and important question. We here discuss a promising mechanism not previously investigated for pellet fusion applications. This mechanism is commonly over-looked because it depends on the existence of the intense self-generated magnetic fields emphasized by recent experimental and theoretical work.¹⁻⁸ Physically the absorption occurs due to electrostatic waves resonantly generated by the oscillation of electrons driven by the $\underline{v}_{os} \times \underline{B}_0/c$ force, where $\underline{v}_{os}$ is the quiver velocity of an electron in the laser light field and $\underline{B}_0$ is the self-generated DC magnetic field. In contrast to the resonance absorption⁹⁻¹¹ usually considered in laser pellet applications, this mechanism is operative even for normally incident light. As we will show, the magnitudes of the DC magnetic fields which have been both experimentally inferred and calculated ($B \sim 4$ MG for Nd light with an intensity of 10^{16} W/cm²) are large enough to make the light conversion to plasma waves sizeable, but not so large as to make the critical surface inaccessible to the light. In contrast, this mechanism is negligible for the case of radiowaves in the ionosphere.⁹

The basic process will be investigated in a simple geometry. Let $\underline{B}_0 = B_0 \hat{x}$, and consider laser light normally incident ($\underline{k} = k(z)\hat{z}$) on a plasma with density $n = n(z)$. The electric vector of the light is orthogonal to $\underline{B}_0$ as it enters the plasma from vacuum. From Maxwell's equations and the linearized plasma equations, we can readily obtain coupled equations for E_y and E_z . Assuming a time-dependence of $e^{-i\omega_0 t}$, we obtain

$$\frac{d^2 E_y}{dz^2} = -\frac{\omega_0^2}{c^2} \epsilon_1 E_y \quad (1)$$

and

$$F_z = - \frac{\omega_{pe}^2}{\omega_o^2 - \omega_{ce}^2} \frac{1\omega_{ce}}{\omega_o} \frac{E_y}{\epsilon_2}, \quad (2)$$

where ϵ_1 and ϵ_2 are the dielectric functions:

$$\epsilon_1 = 1 - \frac{\omega_{pe}^2}{\omega_o^2} \frac{(\omega_o^2 - \omega_{pe}^2)}{(\omega_o^2 - \omega_{UH}^2)} \quad (3)$$

and

$$\epsilon_2 = 1 - \frac{\omega_{pe}^2}{\omega_o^2 - \omega_{ce}^2}. \quad (4)$$

Here ω_o is the light frequency, ω_{pe} the local electron plasma frequency,

$$\omega_{ce} = \frac{eB_o}{mc}, \text{ and } \omega_{UH} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}.$$

Eq. (1) gives the well-known dispersion relation for the extraordinary wave. For laser pellet applications, $\omega_{ce} \ll \omega_o$, and the cut-off density n_{cut} (the density at which propagation cuts off for light waves incident from low density) is determined by $\omega_o^2 = \omega_{pe}^2 + \omega_{pe} \omega_{ce}$. Since $\omega_{ce} \ll \omega_o$, this cut-off density is only slightly less than the critical density n_{cr} (defined by $\omega_o = \omega_{pe}$). For example, for $B = 4$ MG and a Nd laser, $\omega_{ce}/\omega_o = .04$ and $n_{cut} = .96 n_{cr}$.

As is apparent from Eq. (2), the extraordinary wave is partly longitudinal. This electrostatic field is simply the plasma response to the oscillation of electrons in the $\underline{v}_{os} \times \underline{B}_o$ force. Note that this field becomes infinite when $\epsilon_2 = 0$, since the plasma response is then resonant. The resonance occurs at $n_R = n_{cr} \left[1 - \left(\frac{\omega_{ce}}{\omega_o} \right)^2 \right]$, which is essentially the critical density for $\omega_{ce} \ll \omega_o$. Physically, the light

is reflected at the cut-off density ($n_{\text{cut}} < n_R$), but its electric field tunnels into the higher density region, where upper hybrid waves are resonantly driven. Of course, collisions, thermal corrections or non-linear effects keep the resonantly-driven field finite. For light intensities commonly used, E_z is limited by strong wave-breaking as will be shown in the simulations.

The principal features of this absorption mechanism can be obtained rather simply. Since $E_z \equiv E_d/\epsilon_2$, the behavior of the electrostatic fields is determined by the value of the effective driver field E_d at the resonance point. To determine this driver field we need to estimate E_y at the resonance point. Assuming a locally linear density profile,⁹ we first estimate E_y at the cut-off density by analogy to the well-known Airy function solution for the $B_0 = 0$ case and then multiply by the exponential decay of the field to the resonance point. The result is

$$E_d \approx 1.3(k_0 L)^{1/6} E_L \frac{\omega_{ce}}{\omega_0} e^{-\frac{\pi}{2} k_0 L (\frac{\omega_{ce}}{\omega_0})^{3/2}}, \quad (5)$$

where L is the density scale length and k_0 and E_L are the wave number and electric field of the light in vacuum. Although an improved value of E_d can be obtained by a detailed solution of Eq. (1) (as is done in the simulations), this simple estimate will suffice to illustrate the physics which is our principal goal.

Several results are now readily obtained. First, the maximum plasma wave amplitude as determined by wave breaking is

$$E_P = \frac{E_d}{\sqrt{\frac{\chi d}{L}}} + \frac{\sqrt{3} \lambda_{De}}{L}, \quad (6)$$

where $X_d = \frac{eE_d}{m\omega_0}$ and λ_{De} is the electron Debye length. The second term in the denominator represents a thermal correction to the cold plasma prediction. In addition, the absorption efficiency f is obtained by invoking energy balance

$$f \frac{cE_d^2}{8\pi} = \int dz \frac{vE_p^2(z)}{8\pi},$$

where v is the magnitude of the plasma wave damping (either linear or nonlinear). As long as $v \ll \omega_0$, the integral is independent of the detailed value of v (the height of the resonance is $\propto 1/v$, and the width of the resonant region is $\propto v$). Hence, we obtain

$$f \sim 5(k_0 L)^{1/3} \left(\frac{\omega_{ce}}{\omega_0}\right)^2 e^{-\pi(k_0 L)} \left(\frac{\omega_{ce}}{\omega_0}\right)^{3/2}. \quad (7)$$

Defining $\beta \equiv (k_0 L)^{1/3} \left(\frac{\omega_{ce}}{\omega_0}\right)^{1/2}$, we have $f \propto \beta^4 e^{-\pi\beta^3}$, and so the estimated absorption peaks at $\sim 40\%$ for $\beta \approx .8$. This behavior is easy to understand physically. As $\beta \rightarrow 0$ (for example, for $B_0 = 0$), the coupling goes to zero. For large β , the resonance point becomes inaccessible. For laser pellet applications, we will see that β can be $O(1)$ based on recent calculations of the magnitude of the self-generated magnetic fields. It should be noted that the basic mechanism is linear, although the size of the self-generated magnetic field will depend on both the intensity and the uniformity of the irradiation.

To test this coupling, we have carried out simulations using an electromagnetic, relativistic particle code.¹² In choosing the parameters of a representative simulation, we are principally motivated by the recent NRL calculations published in Ref. 1; in particular, we choose $B_0 = 4$ MG, $I = 10^{16}$ W/cm² (Nd light), and a rather short density

gradient length ($l/\lambda_0 = 1.5$). Such a short gradient is also consistent with some recent measurements of the density scale lengths in laser-produced plasmas.¹³ For simplicity we use a fixed, neutralizing ion background, since the basic mechanism is independent of ion motion. In the code, the light is normally incident on an inhomogeneous plasma slab. To model the DC magnetic fields shown by the fluid calculations, we simply impose a constant magnetic field orthogonal both to the density gradient and to the electric field vector of the incident light.

The strong plasma wave generation near the critical density is clearly shown in Fig. 1, which is an electron phase space plot from the simulation. The electrostatic field is clearly limited by wave breaking and reaches a peak value of $eE_p/m\omega_0 c \approx .15$. (The simple estimate in Eq. (6) predicts $eE_p/m\omega_0 c \approx .17$). The time-averaged laser light absorption measured in the simulation is $\approx 15\%$, also in reasonable agreement with the estimate given in Eq. (7) which is 16%. Although modest, this absorption does not require oblique incidence and hence can reduce the sensitivity of the absorption to angle of incidence.

Finally, we have carried out a number of simulations varying both the density gradient and the size of the magnetic field. As shown in Fig. 2, the calculated electrostatic field is quite large and scales in reasonable agreement with the theoretical estimates. The absorptions measured in these short-time simulations also scale in reasonable agreement with the theoretical estimate. For example, when $\beta = .6$ we find an absorption of $\approx 30\%$ (the estimated value is $\approx 35\%$). We emphasize that both the actual scale lengths and the values of B_0

in experiments are not well-known and depend on such features as energy transport inhibition and the radial intensity profile of the light beam. The principal point is that for parameters characteristic of those recently calculated, the self-generated magnetic field can introduce an interesting amount of absorption.

In summary, we point out that this mechanism is operative when $\underline{E}_L \times \underline{B}_O \neq 0$. In the toroidal fields due to $\nabla n \times \nabla T$ sources, the coupling then occurs at preferred locations in the focal spot. Of course, there are a number of other sources of magnetic fields which may change the detailed spatial structure of these fields and even increase their magnitude. Finally, we note that the coupling here investigated may also serve as an interesting diagnostic for the presence of intense self-generated magnetic fields. The simulations indicate a frequency structure on the second-harmonic light which is related to the size of the magnetic field. The use of this frequency structure as a diagnostic is under investigation.

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FIGURE CAPTIONS

- Fig. 1: A plot of electron phase space (p_x vs x) from the simulation at $\omega_0 t = 125.2$. The parameters are $eE_L/mv_0 c = .1$, $v_e/c = .1$, $k_0 L = 10$, $\omega_{ce}/\omega_0 = .04$ and fixed ions.
- Fig. 2: The peak electrostatic field from the simulations as a function of a.) the magnitude of the magnetic field and b.) the density gradient scale length. The dashed line is our theoretical estimate. The parameters of the simulations are $eE_L/mv_0 c = .1$, $v_e/c = .1$ (v_e is the electron thermal velocity), and fixed ions.

Fig. 1

Fig. 2