Optical Mechanism for Enhanced Absorption of Laser Energy Incident on Solid Targets*

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A resonance absorption occuring in the classical optics of thin films for incident light at the plasma frequency is proposed to explain the reflectance and absorptance observed concurrently with neutron production in the heating of deuterium targets with Nd:glass laser pulses.

The heating of deuterium targets by means of laser radiation is of interest for possible eventual use in thermonuclear fusion. Initially, little absorption of laser energy was predicted because of the expected total reflection from a dense plasma whose plasma frequency was greater than the laser frequency. Experiments indicate, however, that under certain conditions absorption of > 50% of the incident laser energy can occur. Neutrons can be produced in solid deuterium targets by Nd:glass laser pulses with energy $\gtrsim 5$ J delivered in pulses of a few nanoseconds duration. Accompanying neutron production, characteristic reflection and absorption of the laser light is observed as well as hard x rays and high-energy ions.[1]

In this communication we propose a simple, but rigorously solvable, optical model which may explain the enhanced (so called "anomalous") reflection and absorption occurring with neutron production.

Consider p-polarized light (electric vector parallel to the plane of incidence) obliquely incident on a thin film with vacuum on both sides of the film. (The effect we will discuss here is absent for normally incident p- and obliquely incident s-polarized light, since it is essentially a result of matching the normal component of the electric displacement across the boundaries of the film.) See Fig. 1.

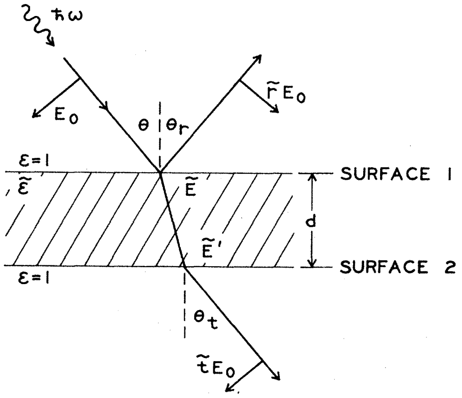

FIG. 1. Diagram for calculations involving p light incident on a film of thickness d and complex dielectric constant $\tilde{\epsilon}$.

From Maxwell's equations or elementary optics, $\theta=\theta_r=\theta_t$ (i.e., specular reflection occurs). Matching of boundary conditions at surfaces 1 and 2 gives the internal fields, reflectance $R=|\tilde{r}|^2$, transmittance $T=|\tilde{t}|^2$, and absorptance $A=1-(T+R)$ of the film.

The general solution of the problem sketched in Fig. 1 is quite complex,[2] but for the special case of a slightly damped Drude free-electron gas described by the complex dielectric constant

$$\tilde{\epsilon}=\left(1-\frac{\omega_p^2}{\omega^2}\right)-i\epsilon_2\simeq\frac{2}{\omega_p}(\omega-\omega_p)-i\epsilon_2,\quad \epsilon_2\ll 1, \tag{1}$$

a resonance peak in film absorptance and reflectance and a resonance dip in transmittance occur at $\omega=\omega_p$, where $\omega_p=(4\pi ne^2/m)^{1/2}$ is the plasma frequency. The special conditions $2\pi d/\lambda\ll 1$, $|\tilde{\epsilon}|\ll 1$, and θ large enough that $|\tilde{\epsilon}|\ll\sin^2\theta$, exhibit the resonances explicitly as[3-5]

$$T_p=[4(\omega-\omega_p)^2+\gamma_d^2]/D,\quad R_p=\gamma_r^2/D,\quad A_p=1-(T_p+R_p)=2\gamma_r\gamma_d/D, \tag{2}$$

where

$$D=4(\omega-\omega_p)^2+(\gamma_r+\gamma_d)^2,\quad \gamma_r=(\omega_p^2 d/2c)\sin\theta\tan\theta,\quad \gamma_d=\omega_p\epsilon_2.$$

The existence of such resonances was first predicted by Ferrell and Stern.[6]

Consider a p-polarized monochromatic incident light beam (for instance, laser light) at frequency ω_L and *assume* the density of free electrons in the film is such that $\omega_L=\omega_p$. We have then (remembering the special restrictions imposed above)

$$T_p=\gamma_d^2/(\gamma_d+\gamma_r)^2,\quad R_p=\gamma_r^2/(\gamma_d+\gamma_r)^2,\quad A_p=2\gamma_r\gamma_d/(\gamma_d+\gamma_r)^2. \tag{3}$$

Let $g=\gamma_r/\gamma_d$ so that

$$T_p=(1+g)^{-2},\quad R_p=g^2(1+g)^{-2},\quad A_p=2g(1+g)^{-2}. \tag{4}$$

We wish to maximize the absorption and therefore set $dA/dg=0$ to obtain $g=1$. With $g=1$ we find $A_{\max}=\frac{1}{2}$ and $T_{\max}=R_{\max}=\frac{1}{4}$.

For a heuristic model of the resonance we are describing, consider the low-density plasma layer as an array of dipole antennas. When the thickness of the film is equal to half the wavelength of the incident light the electrons in the film will resonate in phase with the light. (Because of interference, the normal dipole radiation pattern is constrained to fit the laws of optics.) Maximum absorption by the resonating plasma can thus be expected when the film thickness $d\simeq\lambda_L/2$. While some enhancement of absorption may be expected at $n\lambda_L/2$ with $n=3, 5, \cdots$, the effect will be minor as a result of damping. The resonance is not a simple interference since it vanishes for normally incident light.

Now assume we have a film of plasma with $\omega_p=\omega_L$ in front of another plasma with a higher electron density (bulk-solid density, for example) where $\omega_p\gg\omega_L$. The high-density plasma will act as a mirror and nearly perfect conductor. The situation is diagrammed in Fig. 2. The conditions are a possible result of irradiation of a solid with a laser pulse which has a small precursor ahead of the main pulse.

We appeal to image-charge theory and the antenna-array concept to estimate the behavior of this system. We expect an absorption maximum with a film thickness $d\simeq\lambda_L/4$, since a quarter-wave antenna in front of a perfect conductor acts, when coupled with its image, like a half-wave antenna.

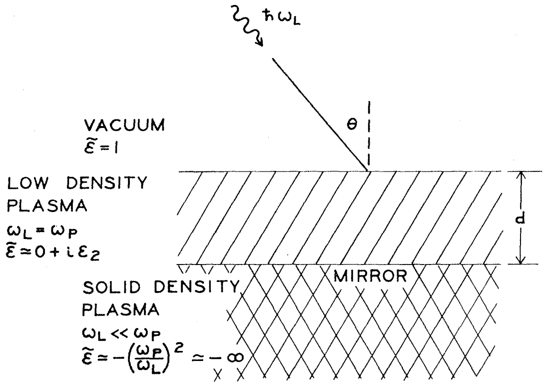

FIG. 2. Model for calculation of absorption with low-density plasma backed by high-density plasma.

We find with the convenient formulation of Wolter[2] that the reflectance for p light non-normally incident on the plasma film with $\omega_p=\omega_L$ in contact with a plasma with $\omega_p\gg\omega_L$ is

$$R_p=(1-2g)^2/(1+2g)^2. \tag{5}$$

The transmittance T_p is identically zero. The notation and assumptions are the same used in obtaining Eq. (4). Thus we have

$$A_p=8g/(1+2g)^2. \tag{6}$$

With $g=\frac{1}{2}$ we find $A_{\max}=1$ and $T_{\max}=R_{\max}=0$. (For p light normally incident and s light at all angles of incidence, $R=1$.) Total absorption can occur for p-polarized light non-normally incident on a thin low-density plasma backed by an overdense plasma. As we expected, the g for maximum absorption is one half that found in the free-film case.

We found that the maximum absorption occurs for $g=\frac{1}{2}$. This implies

$$2\pi d/\lambda=\epsilon_2/\sin\theta\tan\theta, \tag{7}$$

which is consistent with our assumptions that $2\pi d/\lambda\ll1$ and $\epsilon_2\ll\sin^2\theta$. We believe from the antenna analogy that maximum absorption is for $d\sim\lambda_L/4$; which is inconsistent with the assumption $2\pi d/\lambda\ll1$. Upon examining carefully the calculations, one finds that they require $(2\pi d/\lambda)\sin\theta\ll1$ rather than $2\pi d/\lambda\ll1$. Thus with $\sqrt{\epsilon_2}\ll\sin\theta\ll1$, we can have $2\pi d/\lambda\sim1$ while satisfying all the assumptions necessary to the theory. The resonance thickness cannot be uniquely predicted since it depends upon ϵ_2 and 2θ through Eq. (7).

Although we have no definitive estimate of ϵ_2 in the low-density plasma where $\omega_L=\omega_p$, we would expect it to be due largely to inverse bremsstrahlung and to be much smaller than that found for solid-state plasmas. Plasma oscillations in aluminum have been extensively studied, and the complex part of the dielectric constant ϵ_2 is found experimentally to be $\sim\frac{1}{20}$ for aluminum. This would imply that the model presented here is valid (even with the restrictive assumptions made for calculational convenience) for angles of incidence such that $1 \gg \sin\theta \gg \sqrt{\epsilon_2} \sim 0.2$ or $90° \gtrsim \theta \gtrsim 10°$, even in the unlikely event that the damping is as large as that in aluminum plasmas.

The conditions for the resonance are not particularly critical as can be seen with the help of Eqs. (5) and (6). The variation of g (for example, by changing the thickness of the resonance layer) by a factor of 2 either upward or downward changes the absorption for p light from 1 to $\frac{8}{9}$. Notice that as g (or d) becomes either very large or very small, the absorptance vanishes and the reflectance becomes unity. The existence of very similar resonances for a free film and a mirror-backed film is further evidence that the resonance conditions are not critical. Approximate calculations with another discrete density step in front of the resonance layer do not materially change the resonance condition. If one assumes that intense pulses of laser light are unpolarized, then the mechanism discussed here can give a maximum absorption of 50%.

Floux[1] has reported measurements of incident, reflected, and absorbed energy in experiments where the characteristic absorption (and neutron production, etc.) occurred. For an incident laser pulse of 44 J, he measured $A = 0.64$, $R = 0.36$, and $T = 0$ which would agree with the present model if his laser beam contained 64% p light, i.e., had a polarization of 28%. Reflection in the experiments reported by Floux appeared to be specular in agreement with $\theta_r = \theta$ as required by the optical model.[7] In the "real world" of irregular rather than flat surfaces one would expect to find somewhat enhanced scattering in all directions for $\omega_L = \omega_p$, as has been observed for solid-state plasmas.[5]

Experiments indicate[1] that to produce neutrons in solid deuterium targets it is necessary to deliver a small amount of energy to the laser target before the main laser pulse. An extremely small amount of energy would be required to ionize and disperse surface atoms sufficiently to produce the thin low-density plasma layer our model requires.

The energy per unit volume, U, deposited in the assumed low-density plasma layer is

$$U \simeq AE/ad \simeq 4E/a\lambda_L; \tag{8}$$

where $A = 1$ is the maximum absorption coefficient assuming 100% polarized light, E is the incident laser pulse energy, a is the focal area of the beam, and $d = \lambda_L/4$. With the realistic assumptions of $E = 10$ J, $a = 8\times10^{-5}$ cm^2, and $\lambda_L = 1\times10^{-4}$ cm we get an energy density of $U \simeq 5\times10^9$ J/cm^3. To make $\omega_p = \omega_L$, an electron density $n \sim 10^{21}$ electrons/cm^3 is required. We find then that the energy available per particle in the low-density layer is $U/n \sim 10^4$ keV. Of course, when the dynamic problem including hydrodynamics, electronic thermal conduction, and other energy transport mechanisms is considered, the particles will not have MeV energies. Nevertheless, it seems that small numbers ($nad \sim 10^{12}$) of very energetic electrons and ions may be created by the mechanism discussed here.

In conclusion, a Drude free-electron model appears consistent with the heretofore paradoxical association among neutron production, high-energy x-ray emission, high-energy ion emission, and reflection and absorption of laser light incident upon deuterium targets. If the indication of specular reflection and the apparent necessity of a prepulse or shaped leading edge are supported by more definitive experiments than have thus far been performed, then the model discussed above must be given serious consideration. Computer calculations can be used to remove the restrictive assumptions made here (for tractability) both as to plasma density profile and other parameters.[8]

This work grew out of the author's attendance at the Laser Workshop, Rennsselaer Polytechnic Institute, 30 August to 3 September 1971. He wishes to thank particularly F. Floux for discussions which led directly to this paper.

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[1] Second Workshop on Laser Interaction and Related Plasma Phenomena, Rensselaer Polytechnic Institute, Hartford, Connecticut, 30 August to 3 September 1971 (to be published).

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[7] F. Floux, Commissariat a l'Energie Atomique, France (private communication).

[8] J. P. Friedberg and R. L. Morse of the Los Alamos Scientific Laboratory have been studying numerically a resonance of the type discussed above with the assumption of a linear electron density profile. They presented computer-generated films exhibiting the resonance at the Gordon Conference, Laser Interaction with Matter, 23–27 August 1971 (to be published).