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84

Foreword

The articles appearing in this document are reprints from other Lawrence Livermore Laboratory reports published in recent months. Therefore, the numbering of such items as figures, tables, and references is not necessarily sequential throughout the document and does not begin with "1."

Contents

Laser-Plasma Coupling (<i>John S. DeGroot, Kurt H. Sinz, Stephen E. Bodner, George F. Chapline, James L. Eddleman, Rickey J. Faehl, and Jonathan I. Katz</i>)	1
Wavelength Dependence of Laser-Light Absorption by Solid Deuterium (<i>James W. Shearer and James J. Duderstadt</i>)	3
References	5

Most experimental approaches to the production of laser-fusion power involve the absorption of laser energy by small pellets of solid deuterium. In order to understand how fusion might be achieved by laser heating, one must first understand the mechanisms by which the laser energy is absorbed. Here we describe the analytic and numerical methods that we use to calculate the absorption of laser light by deuterium pellets.

When high-intensity laser light strikes a pellet, some of the laser energy is absorbed, creating a hot plasma. This plasma then starts to blow off, producing a density profile like that shown in Fig. 15, where the electromagnetic signal (i.e., the laser pulse) is incident on the pellet from the right. Linear response theory shows that this signal will propagate up to the place where the laser frequency ω_0 equals the plasma frequency ω_{pe} . (The plasma frequency is a function of the plasma density: $\omega_{pe}^2 = 4\pi n e^2 / m$, where n is the number of electrons per cubic centimeter and e and m are the charge and mass of each electron.) For neodymium lasers, the laser frequency equals the plasma frequency at a critical density of $n_c = 10^{21}$. For CO_2 lasers, $n_c = 10^{19}$.

The laser energy is attenuated by two physical processes as it travels into the critical radius r_c and critical density. First, there is *collisional absorption*, which is sometimes called inverse bremsstrahlung. Second, there is *collisionless absorption*, which is caused by plasma instabilities and other nonlinear effects. At low temperatures (early in the laser pulse), collisional absorption is the dominant process. At high temperatures (later in the laser pulse), collisionless processes dominate (except perhaps in a higher frequency ultraviolet laser of the future — see the following article).

The plasma instabilities can be viewed in several ways. The simplest is to note that the electric field of the laser light will cause the electrons and ions to oscillate 180° out of phase with each other because of their opposite charges. Thus there will be a high-frequency current in the plasma. Then, appealing to the universally known but unproved theorem that any plasma out of equilibrium will be unstable, we conclude that laser light will most likely produce plasma instabilities. These instabilities produce electric-field fluctuations within the plasma that heat the electrons and ions.

There are very many kinds of plasma instabilities possible, depending on the detail one desires in a

description and the intensity of the laser light. At present, we classify the modes into the six basic categories shown in Table 3.

We think of the first four instabilities in Table 3 as "good" instabilities because they lead to enhanced absorption of the laser energy, primarily by the plasma electrons. The last two we call "bad" instabilities because they lead to partial absorption and partial reflection of the laser energy. Any mechanism that reflects the laser energy has to be paid for with a higher power laser.

Computer Codes and Results

We are using four different plasma-simulation codes to study plasma instabilities (see Table 4). These are particle codes that follow the motions of a very large number of plasma particles in the presence of the laser electromagnetic field and the instability electric fields. Two of the codes, CYCLOPS and TREMP, were developed here at LLL. The other two, MINOTAUR and HYDRA, were developed from codes given to us by the Los Alamos Scientific Laboratory.

Most of the work to date has been done with CYCLOPS and MINOTAUR. Because the wavelengths of the "good" plasma instabilities are much less than the laser wavelength (until the electron temperature reaches hundreds of kilovolts), we started our

Fig. 15. Plasma density n versus radius r for a laser-produced plasma. The laser frequency ω_0 equals the plasma frequency ω_{pe} at a critical density and radius n_c and r_c .

Table 3. Six kinds of plasma instabilities encountered in laser-produced plasmas

Instability	Type	Density regime	Result
Ion-acoustic decay	Three-wave resonant	$\frac{1}{2} n_c \lesssim n \lesssim n_c$	Electron wave and ion waves
Oscillating two-stream	Three-wave resonant	$\frac{1}{2} n_c \lesssim n \lesssim n_c$	Electron waves and ion waves
Electron plasma	Three-wave resonant	$n \approx \frac{1}{4} n_c$	Electron waves
Kinetic ion plasma	Two-wave nonresonant	$n \lesssim n_c$	Ion plasma waves
Stimulated Raman scattering	Three-wave resonant	$\frac{n_c T_e}{mc^2} \lesssim n \lesssim \frac{1}{4} n_c$	Electron waves and electromagnetic waves
Stimulated Brillouin scattering	Three-wave resonant	$\frac{n_c T_e}{mc^2} \lesssim n \lesssim n_c$	Ion waves and electromagnetic waves

Table 4. Computer codes used at LLL to study plasma instabilities

Name	Type	Instabilities being studied
CYCLOPS	One-dimensional electrostatic	Ion-acoustic decay, oscillating two-stream, kinetic ion
MINOTAUR	Two-dimensional electrostatic	Ion-acoustic decay, oscillating two-stream, kinetic ion
HYDRA	Two-dimensional electromagnetic, nonrelativistic	Ion-acoustic decay, oscillating two-stream, kinetic ion with a density gradient
TREMP	Two-dimensional electromagnetic, relativistic	Ion-acoustic decay, oscillating two-stream, kinetic ion with a density gradient; also very intense lasers

simulation studies with the electrostatic codes. They treat the laser field as a spatially uniform high-frequency electric field acting on an initially spatially uniform plasma. The results are outlined below.

The HYDRA two-dimensional electromagnetic code is now being used to calculate the corrections to the electrostatic codes due to both plasma density gradients and the finite laser wavelength. It will also be used in the near future to study stimulated backscattering. Our preliminary results indicate that the plasma-heating and laser-absorption rates are close to those calculated with the electrostatic codes. The inclusion of the electromagnetic properties of the laser signal introduces new phenomena that are not fully understood. These efforts are under intense investigation.

Electron and Ion Heating with Low Laser Powers

By early 1971 a number of laboratories had produced 10^4 to 10^5 neutrons by shining low-power

nanosecond laser pulses (20 to 40 J of energy) on solid deuterium and CD_2 . Here at Livermore our knowledge of instabilities led us to also look for and find a non-Maxwellian hard-x-ray spectrum. Both the hard x rays and the neutrons can be explained by direct heating due to laser-produced plasma instabilities.¹¹

Such low-power lasers can excite both the ion-acoustic decay mode and the oscillating two-stream mode. Each of these modes produces two kinds of waves: a strong oscillation near the electron-plasma frequency and a much weaker oscillation with a frequency spectrum extending up to the ion-plasma frequency. From our calculations, we expect the instability region to be about 10 wavelengths in depth. Most of the laser power is deposited in the high-frequency component of the spectrum, which then heats the electrons; this interaction produces a long non-Maxwellian tail in the electron distribution extending to about 10 times the thermal velocity. The tail produces the hard-x-ray spectrum. The instability-heated electrons flow out of the instability region, and the energy absorbed primarily takes the

form of an increasing region of hot electrons and hydrodynamic expansion.

On a slower time scale, the plasma as a whole moves with approximately the acoustic velocity through the instability region. As the ions move through the region, they are directly heated by the low-frequency component of the plasma turbulence. Although the ions receive only a small fraction of the laser power, their local temperature in the instability region can be comparable to the electron temperature.

We modified CYCLOPS to simulate the loss of electrons from the instability region. At each time step, the velocities of a given number of randomly chosen electrons are reset to their initial values. Having normalized the energies, we find, for example, that a laser power of 3×10^{14} W/cm² can heat the ions directly to more than 1 keV in 40 psec. This ion heating is enough to roughly explain the experimental neutron yields obtained with nanosecond laser pulses. More work is under way to try to obtain a better understanding of these experimental results.

Electron and Ion Heating with Intense Laser Powers

If the laser intensity is increased in the latter part of the pulse to about 10^{17} W/cm², our electrostatic calculations indicate that the laser energy will be strongly absorbed by the plasma. The ion-acoustic decay mode and the oscillating two-stream mode have

been simulated on CYCLOPS and MINOTAUR. Typical absorption distances are roughly 10 to 20 wavelengths of the light, which is several orders of magnitude less than the collisional-absorption length. The resulting electron distributions are fairly close to Maxwellian. The ratio of the ion heating to the electron heating is roughly the mass ratio at this intense power. Any absorption mechanism that took place right at the critical density would appear to be insignificant because so little laser energy would reach the critical density under our conditions of a very hot plasma with a gentle density gradient.

Short-Duration, High-Intensity Laser Pulses

If we consider laser parameters such as an intensity of 10^{17} W/cm² in a pulse only 1 psec long, the target will ionize and heat, but there is not enough time to create the gentle density gradient necessary for the plasma instabilities listed in Table 3. Our parameters now have the light penetrating with a skin depth of c/ω_{pe} at a frequency of $\omega_0 \ll \omega_{pe}$. This case has been simulated with TREMP.

There is an instability present; it is related to the oscillating two-stream instability. The final heated-electron distribution is nearly rectangular, with an electron thermal velocity after heating of about V_0 , the quivering velocity of an electron in the laser electric field. However, very little of the laser energy is absorbed by this mechanism.

WAVELENGTH DEPENDENCE OF LASER-LIGHT ABSORPTION BY SOLID DEUTERIUM

We have performed calculations indicating that solid deuterium absorbs laser light more efficiently as the wavelength of the light decreases. This implies that lasers producing light in the ultraviolet region might be more practical for heating deuterium than the longer-wavelength lasers that we are now working with.

When solid deuterium is heated by a laser beam, the heating occurs not inside the solid but in regions of much lower densities in the plume of plasma that blows off the solid (see the preceding article). The ratio of absorption to reflection of laser light in this plume is a crucial parameter for fusion-power designs because the laser-energy input required is inversely proportional to the fourth power of the efficiency of absorption.¹²

Although many analytical and computational studies have been done, both here and elsewhere, on the absorption of laser light as a function of light intensity, pulse duration, and target design, these studies have all been based on available laser wavelengths — i.e.,

0.69 μ m for ruby, 1.06 μ m for neodymium, and 10.6 μ m for CO₂. To determine if some other laser wavelengths would lead to higher absorption efficiencies, we conducted a computer study of absorption as a function of wavelength, using the numerical code WAZER.¹³ The problems were simple: the targets had one-dimensional slab geometry, and no "prepulse" was included to build up a gradient-density plasma plume beforehand — the plume blew off the solid surface during the calculation.

Two absorption models were used: first, only "classical" electron-ion collisional absorption (inverse bremsstrahlung); second, both classical and "anomalous" (collisionless) absorption. The anomalous term was based on the parametric ion-acoustic instability, whose intensity threshold can be exceeded in a narrow range of densities just below the cutoff density.¹⁴ For those plasma regions which met these restrictive intensity and density criteria, the additional

anomalous absorption was assumed to be saturated and was approximated by $\nu^* \approx \omega_{pi}$, where ν^* is the anomalous collision frequency and ω_{pi} is the ion plasma frequency. This is admittedly only a crude approximation, but it does seem to roughly match simulation-code calculations.

The results of a series of computer runs are presented in Fig. 16, which shows that greater fractions of light are absorbed at longer pulse durations and shorter wavelengths. As expected, the absorption fraction is also increased when anomalous absorption is included in the calculations, especially at longer wavelengths. At the shorter pulse length, however, the anomalous model did not contribute to the absorption as much as expected.

These results can be qualitatively understood by means of an absorption estimate in which the absorption fraction A is calculated by an integral that follows the laser light through the plasma to the reflection point (at the cutoff density), and then back out:

$$A = 1 - \exp\left(-2 \int_0^H K dx\right),$$

where H is the position of the reflection point, K is the linear absorption coefficient, and x is the distance the light has traveled in the plasma. In carrying out the integration, we assume that the density gradient is linear. When the classical absorption coefficient is substituted for K , the result is¹⁵

$$A_{class} = 1 - \exp\left(-\frac{C_0}{T_e^{3/2}} \frac{H}{\lambda^2}\right),$$

where C_0 is (almost) a constant, T_e is the electron temperature, and λ is the wavelength of the laser light.

With our approximate anomalous-absorption model, one obtains an even simpler result:

$$A_{anom} = 1 - \exp\left(-\frac{5H}{\lambda}\right).$$

In either case, we want H to be large enough to keep the absorption fraction close to 1. And in both processes, absorption is related to wavelength in such

Fig. 16. Absorption of laser light on a deuterium slab as a function of wavelength, as calculated with classical (curve A) and both classical and anomalous (curve B) absorption models. Top: results for a long pulse with a duration of about 4 nsec and an intensity of 2×10^{14} W/cm². Bottom: results for a short pulse with a duration of about 0.1 nsec and an intensity of 10^{16} W/cm².

a way that, for a given H , the absorption increases as the wavelength decreases. These general statements are confirmed by the code runs (Fig. 16). Further work is needed to find the best wavelength for a specific target model; our calculations simply show the general trend.

Thus, this work does not rule out the possibility that the absorption efficiency might be increased to more tolerable levels through ingenuity — such as using complicated target designs and carefully programmed pulse shapes. It does imply, however, that designing around the problem becomes more difficult at longer wavelengths, whereas the inherently better absorption at shorter wavelengths permits greater freedom in target design.

We believe that the results of these calculations present a challenge to develop lasers that are more suitable for heating deuterium.¹⁶ Today, neodymium-doped glass and nitrogen/carbon-dioxide lasers are the most technically advanced and most promising for preliminary and intermediate laser-fusion experiments. But for the long term, a powerful, efficient, pulsed ultraviolet laser may be the most promising.

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