LASERS AND LASER APPLICATIONS

The conceptual basis of this Laboratory's Laser Fusion Program is inertial confinement fusion by laser-driven implosion of deuterium-tritium (D-T) fuel. The program currently represents about half of ERDA's inertial confinement effort.

During the 1960's, LLL made extensive theoretical and computational studies of the relevant implosion processes. This work, coupled with advances in high-energy laser technology, prompted a scaling-up of our laser-fusion program to its present level.

Our efforts during the past three years have centered on developing the analytical and experimental tools needed for D-T implosion experiments of continuously increasing scale. We now have target-design codes that encompass radiation transport, thermonuclear-burn physics, laser-plasma coupling, and the fluid dynamics of high-density, high-temperature plasma. Sophisticated techniques have been devised for making micro-targets for our present experiments. Finally, we have achieved unmatched developments in high-peak-power, high-brightness laser technology and fully integrated laser test facilities. The future of laser fusion requires predictive capabilities such as those mentioned above as well as developments in experimental hardware. During the past four months, substantial numbers of neutrons — consistently forecast — have been produced from targets containing compressed D-T. These experiments would not have been possible without the prior development of our analytical and experimental tools.

The following article describes a recent advance in our calculational ability to model laser-plasma coupling.

PROGRESS IN THE CALCULATION OF LASER-PLASMA COUPLING

In our recent efforts to analyze laser-plasma coupling calculationally, we have used the ZOHAR two-dimensional code to examine the absorption of laser light by a plasma whose density is inhomogeneous. We found that absorption is most efficient near the critical density (at which the electron frequency in the plasma equals the laser-light frequency) and that, as a result, the density profile in the plasma is greatly steepened near the critical density. The calculations indicate that this region of steepened profile improves the plasma's ability to absorb laser-light energy by resonant absorption and reduces the absorption efficiency of instabilities. Also, we have developed several other codes to explore processes that limit laser-light absorption by scattering the light before the plasma reaches critical density.

One of the most important questions in the laser fusion of pellets is how intense laser light is absorbed or reflected by a plasma. Laser light will propagate in a plasma only as long as the critical density is not exceeded; at critical density the electron frequency of the plasma equals the laser-light frequency — $10^{21}$ cm$^{-3}$ for 1.06-$\mu$m light. Hence in a pellet, the light only penetrates the relatively low-density outer corona. The energy absorbed in this low-density region is then transported into the pellet, where it ablates material and compresses the core. For optimal pellet designs, it is very important to determine the conditions under which the laser light absorbs efficiently.

For the high-intensity laser light used in many pellet designs, classical inverse bremsstrahlung (ordinary joule or collisional heating of the plasma) is very inefficient. The frequency of electron-ion collisions decreases rapidly with increasing plasma temperature. Hence, a hot plasma becomes relatively collision-free, meaning that joule heating becomes small. In practice, this means that electrons can be heated by this classical mechanism only to about 1 keV, which corresponds to an absorbed energy flux on the order of only $10^{14}$ W/cm$^2$.

However, other mechanisms exist to heat even a very hot plasma. A characteristic feature of a plasma is its ability to support plasma waves. In the simplest case,
such waves correspond to oscillations in the density of charge, along with the electric fields associated with these oscillations. These waves are made possible by the long-range nature of the Coulomb force, which allows many electrons to act collectively. There are many different processes in which intense laser light excites plasma waves. These processes are of two general types: absorptive ones, which produce only plasma waves, and reflective ones, which produce both a plasma wave and a scattered light wave.

For a quantitative prediction of laser-light absorption, it is necessary to understand both the detailed nonlinear evolution (variation with intensity) of these different collective processes and their competition with one another. Because the plasma becomes strongly turbulent, computer simulations are required. We have now developed our simulation codes to the point where they self-consistently treat laser light and its scattering, plasma turbulence both parallel and orthogonal to the density gradient, and reaction of the turbulence back onto the plasma-density profile.

Our principal and most advanced code is ZOHAR, a two-dimensional code that solves the complete set of Maxwell's equations and uses fully relativistic particle dynamics.8

Using ZOHAR, we have examined the absorption of light propagating from vacuum into an inhomogeneous plasma slab. We find that the absorption is most efficient near the critical density, at which nearly any spatial variation in plasma density efficiently couples the light into electron plasma waves. Figure 9 illustrates the most important feature found in these simulations, the nonlinear steepening of a plasma-density profile.

Because of strong plasma turbulence and heating at the critical density, a pronounced steepening of the density profile results in this region. In effect, one is pushing on an otherwise freely expanding plasma at a preferred point — i.e., where the density is nearly critical. Hence, density piles up behind this region.
forming a sharp step. This pronounced profile modification has been directly observed in experiments using microwaves in low-density plasmas. The modification has also been inferred from some recent laser-plasma experiments.

The nonlinear steepening of the density profile has several important consequences for light absorption. First, the critical density is more accessible to obliquely incident radiation. This makes resonant absorption effective for larger angles of incidence than

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**Fig. 11.** Two-dimensional FLUID-code calculation of contours of constant density in a plasma (at less than the critical density) through which laser light with an intensity of \(5 \times 10^{15}\) W/cm\(^2\) is propagating (from the bottom). Vertically through the center of the plot a filament has formed that propagates the light into the plasma, thus improving the coupling of the laser-light energy to the plasma.
would be expected on the basis of unsteepened density profiles. Also, the suprathermal electrons produced by the resonantly excited plasma waves are much reduced in energy, because these waves have a shorter wavelength and smaller phase velocity when the density profile is steep. This is very important for reducing preheat and decoupling. Finally, the efficiency of the parametric instabilities, which occur above the critical density and are driven by the laser-light field, is reduced by the steepening. The simulations indicate that the instabilities in the steepened profile will absorb no more than 20% of the laser-light energy. On the other hand, for optimum angles of incidence and polarization, we have calculated that the plasma can absorb about 60% of the laser-light energy by resonant absorption.

More complicated models of light absorption are also under study. These complications include intensity variations in the incident light due to hot spots or filaments and the possibility that part of the light is scattered in the plasma before critical density is reached. We have developed several codes in addition to ZOHAR to explore such reflective processes in an underdense plasma. For example, OREMP, a one-dimensional electromagnetic-field and relativistic-particle code, can study direct backscatter or laser light; FLUID, a two-dimensional code, solves for the electromagnetic fields but describes the plasma as a simple fluid. We are using FLUID to study the long-term competition between back- and sidescatter and filamentation.

Figure 10 shows some typical results for light reflection in the underdense plasma. This is a plot of the back-reflection due to the Brillouin instability (which occurs below the critical density) as a function of laser-light intensity. In this example, the reflection strongly onsets for an intensity about $2 \times 10^{15}$ W/cm$^2$ and has reached 50% at an intensity of $10^{16}$ W/cm$^2$. These results are averaged over an interval that is many instability-growth-times long but is short compared with hydrodynamic time scales. However, recent experiments$^{11}$ indicate that a strong reflection may persist for as long as 50 to 100 ps.

Clearly, it is important to understand how to limit such reflection and under what conditions it persists. Several limitation mechanisms are under study, including energy transfer to the ions and filamentation, in which the light pushes the plasma aside and forms channels through which it propagates. Figure 11 shows an example of this filament formation as calculated with FLUID. This is a two-dimensional plot of density surfaces in an underdense plasma through which intense laser light ($5 \times 10^{15}$ W/cm$^2$) is propagated. Note that the light (incident from the bottom of the figure) has dug out a density channel (vertically through the center of the plot) through which it then propagates. The formation of these channels reduces the nonlinearly induced reflection by reducing the amount of underdense plasma in contact with the light. Further study is under way to determine the conditions under which such filaments form.

Key Words: laser-plasma coupling; absorption; instabilities; calculations; ZOHAR; FLUID; OREMP.