Although our understanding of the later energy-flow processes has been largely empirical, much of our understanding of the initial absorption processes has been theoretical (see “The Tools of High-Energy Laser-Plasma Physics”). This is so because, at the 10-µm wavelength, there are only a li number of unambiguous experimental signatures that define *specific* absorption processes rather than reflecting an overall effect. As a result. most of the information on absorption comes from computer simulations and analytic theory that have been iterated to reproduce macroscopic experimental data, such as the hot-electron energy spectrum or total absorption. As a result, the analysis has, in fact, been a difficult problem. Fortunately, we have been very successful in putting together a detailed picture of specific absorption mechanisms. What are the main elements of this picture’?

The Critical Density. Initially, the laser light arrives at the target in a near vacuum with the intensity adjusted to achieve nearly uniform illumination. Such uniformity is difficult to maintain, however, because as the target heats up, hot plasma is blown off. and the propagation of light is altered by the changing density of the plasma. In fact, at a certain density called the *critical density* n_c, light does not penetrate further.

In more mathematical terms the index of refraction n of a plasma is given by

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2}, \tag{1}$$

where w is the laser frequency and w_p is the natural frequency of oscillation of electrons in the plasma. This latter frequency, called the local plasma frequency, is given by

$$\omega_p^2 = 4\pi \frac{n_e e^2}{m} \tag{2}$$

where n_e, e, and m are the electron density. charge, and mass. respectively.

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The Tools of High-Energy Laser-Plasma Physics

The laser fusion program has considerable strength in both theory and experiment, The complexity of the physics has kept the program at the forefront *in* developing new theoretical tools, experimental techniques, and diagnostics. For example, it is experimentally taxing to measure phenomena on a time scale of picosecond when the entire experimcnt occurs in about a nanosecond and to resolve phenomena spatially at the 1 wavelength of CO_2 light when targets may be as large as millimeters.

In addition, many of the phenomena on the submicromcter, subpicosccond scale—the truly microscopic-strongly influence the macroscopic behavior but can’t be readily measured. Computer simulation is then heavily relied on to couple microscopic phenomena to macroscopic observables.

Theoretical Tools

Three codes—WAVE, VENUS, and LASNEX-are used to simulate laser fusion phenomena. As depictcd in the figure, each code simulates phenomena occurring within different ranges of density, time, and space.

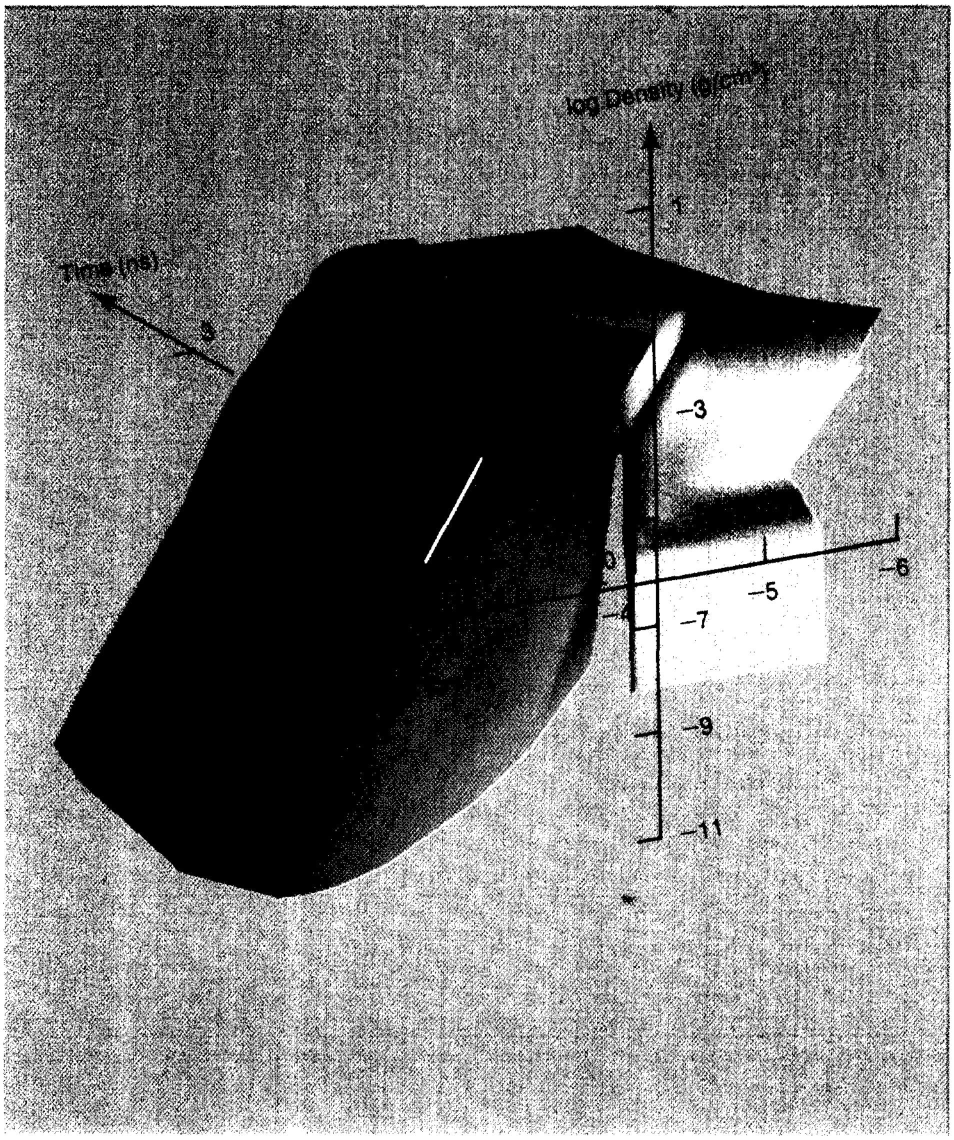
WAVE. The code that deals with the most microscopic aspects of energy absorption and transport in the target is WAVE. a 2-dimensional particle simulation code. WAVE is an explicit code that does a first-principles calculation; that is, it solves, in a self-consistent manner. Maxwell’s equations and the relativistic Newton’s laws for particles in 3-component electric and magnetic fields. WAVE typically advances 10^6 particles on a grid of 10^5 cells for 10^4 time steps.

only a portion of the absorption problem can be modeled by WAVE because the time step must be limited to a small fraction of the period of oscillation of the laser light (that is. a small fraction of about 0.03 picosecond). Thus WAVE can cover only a few picoseconds in a given problem, even with the immense power of the Los Alamos computing facilities. In turn. the grid size of one cell is limited to the distance light travels in one time step. As a result. the code is used primarily to study the details of absorption in the region between the underdense plasma of the corona and the overdense plasma close to the surface of the imploding target. At the very low densities of the underdense plasma, absorption lengths become too long; the code cannot both have the required cells per wavelength of’ light and still span the absorption length. In the overdense plasma the time and space scales are so short that it is impractical to resolve them with WAVE.

Because of such limits to the time and space scales, the initial conditions and the boundary conditions for the fields and particles are unknown and must be put into the calculation separately. Much of the skill in using the code involves estimating these conditions correctly: they should be consistent with themselves, with hydrodynamic calculations, and with experiment.

Why not expand the time scale by increasing the time step? WAVE calculations arc performed by alternately advancing the particles and then the fields. If the time step becomes much larger than a natural frequency in the problem, the calculations can become unstable, The problem is avoided by estimating what the particles *are going to be doing* and then plugging these estimates into the step that advances the fields. This type of code is called *implicit* and forms the basis of our second theoretical tool.

VENUS. Use of the implicit code. VENUS, allows the time and grid size to be increased by about a factor of fifty). Although the increase is obtained by neglecting some high-frequency phenomena. it allows us to handle the spatial scales needed for the study of collective phenomena. In particular, VENUS has been able to verify a model in which very strong self-generated magnetic fields play an important role in electron transport. These magnetic fields also provide the mechanism for copious fast-ion emission, that is, for the ion jets that have been observed streaming from targets. Because of their success with the ICF program, a new generation of implicit codes is rapidly being adopted by the magnetic fusion and space physics communities.



This figure depicts the approximate range of parameters dealt with by each of the computer codes WAVE, VENUS, and LASNEX in typical simulations of laser fusion. The entire surface is a LASNEX calculation, whereas the thin black line on the red surface represents the range of a VENUS calculation, and the even thinner white line represents the range of a WAVE calculation. For ***example, while the LASNEX calculation can span a range of time from O to several nanoseconds, VENUS is confined to a range of only 0.1 nanosecond and WAVE to a range of 0.01 nanosecond.***

Although quantum mechanics and atomic physics are not included in the implicit codes, the fully developed strong turbulence that can occur in laser-plasma interactions is still described accurately. Such descriptions are limited only by the computer resources. In the last decade the scale of accessible problems has increased by a couple of orders of magnitude because of improvements in both computer hardware speed and the numerical algorithms employed in the implicit codes. This increase has greatly broadened our understanding of the physical processes.

LASNEX. The code that deals with phenomena on the largest time and space scales is called LASNEX. This code is a 2-dimensional radiation flow and hydrodynamics code. LASNEX is used to model electron transport. radiation flow, hydrodynamics of’ implosion. and possible thermonuclear burn in the target. However. the models in this code are phenomenological, and the simulation is of relatively macroscopic phenomena.

We can see how these three codes mesh by summarizing the various steps for modeling the production of hot electrons. WAVE generates the initial models for such things as the distribution and energies of the hot electrons, but only in the limited region between the overdense and the underdense plasma. To predict large-scale behavior of the plasma. a model generated by WAVE is used in LASNEX and adjusted to fit macroscopic data. However, the time scale of typical LASNEX calculations is too coarse to resolve electron flow in the underdense plasma with its accompanying generation of magnetic fields, AS a result, the model is incorporated into VENUS to study these important collective phenomena.

The insight gained from using WAVE and VENUS to simulate and verify models has led to two important improvements for LASNEX. The various physics packages used in the code have been improved, and a better choice of input conditions to the code is possible.

Experimental Tools

A wide variety of experimental techniques have provided the basic data against which the theoretical models must be compared.

Absorption and Energy Flow. We obtain the overall energy delivered to a target in one of’ two ways. The scattered 10-yin light not absorbed by the target can be measured directly with in infrared-sensitive detectors and subtracted from the incident energy. Or all of the ion, electron, and x-ray energy emitted from the target can be measured using calorimeters that are gold-coated to reflect, and therefore reject, scattered CO_2 radiation.

To determine the ho-electron temperature and the amount of hot-electron energy, we can measure either electron or x-ray spectra. Although hot electrons from the target can be detected with magnetic electron spectrometers, only a few electrons actually manage to escape. Therefore, the bulk of the electron energy is studied by measuring the bremsstrahlung radiation resulting from collisions of hot electrons with atoms in the solid parts of’ the target. We measure these hard x rays with a multichannel broadband x-ray spectrometer that uses an array of filtered scintillators coupled to visible light photodiodes. The measurement covers the spectrum from about 30 kiloelectron volts (keV) to large fractions of an MeV with nanosecond resolution. One detector that responds to x rays of energies greater than 100 keV is used to study the time history of the hot-electron energy with subnanosecond resolution.

The target. heated by hot electrons, emits soft x rays (below 1 keV). This radiation is detected with separate multichannel spectrometers that have filtered vacuum photodiodes sensitive to soft x-ray illumination. The diodes are electrically designed for fast response and are coupled to ultrafast oscilloscopes (developed in the nuclear weapons program), providing a time resolution of better than 300 picoseconds.

Spatial details of the intensity or energy of the x rays from the surface of the target are resolved with multichannel x-ray collimators that restrict the field of view of’ the diodes. Although such collimators are simple in principle, the small targets used in the laser fusion program require that the collimating pinholes be machined and positioned precisely. To achieve the required 25-pm accuracy, the pinholes, only 150 µm in diameter, are aligned with respect to the target and to each other with optical techniques.

The total absorbed energy measured with ion calorimeters, the fast-ion energy obtained with filtered calorimeters, the energy deposited in the target as determined from the hard x-ray bremsstrahlung emission, and the target surface temperature obtained from soft x-ray measurements, all help reveal the overall energy flow, in the experiment. The comparison of these related measurements has provided considerable information about the basic physics of plasmas created by CO_2 lasers. However, considerably more detailed information is required if the physics is to be understood on a more fundamental, microscopic basis.

High-Resolution Imaging and Spectroscopy. Optical and x-ray emission can be imaged, with simple optical or pinhole cameras, to map the distribution either of hot electrons in the target or of the beating of the corona. These techniques can identify nonuniformities in energy deposition due to imperfections in the laser beam or to plasma effects. By using film and filter combinations to compare images of x rays at fractions of a keV with images of x rays in excess of tens of keV, a picture of the hot-electron flow can be built.

Crystal or grating spectrographs are used to obtain high-resolution x-ray and vacuum ultraviolet spectra that offer a wealth of information on the details of the atomic physics of the plasma, as well as on the plasma conditions themselves. For example, we can identify plasma parameters, such as temperature and density, by selecting specific x-ray transitions from elements in the target and then examining the relative intensities of x-ray lines from different ionization states, as well as for lines from a single ionization state. Spectral line broadening and detailed lineshapes relate to the density of the plasma surrounding the emitting atom. Particularly in the case of extreme conditions far from thermodynamic equilibrium, line intensities and lineshapes must be compared to detailed atomic physics codes to yield accurate temperature and density information. Such information is very useful for evaluating the conditions of the imploding fuel.

Specific characteristic x rays can give us further important information. For example. hot electrons have enough energy to create inner electron shell vacancies, giving rise to K-line x rays, but thermal background electrons do not have enough energy. Therefore, we can image the target in K-line radiation and track the flow of hot-electron energy. We can do this by using two pinholes in a single pinhole camera with specially matched filters: one passes the light of the K line and one does not. By subtracting one image from the other, we can build. in effect, a single-wavelength image of the target. A more attractive, state-of-the-art solution is to use the so-called layered synthetic microstructure (LSM). The LSM acts like a crystal in that it reflects, in accordance with its designed lattice spacing and Bragg's law, only selected frequencies. Placed between the pinhole and the film, the appropriate LSM can be used to reflect only the transition of interest.

Microfabrication techniques can be used to place materials at strategic locations in the target, for example, in a spot on the target surface or as a thin layer on or beneath the surface. The x-ray emission from these materials then serves as a tracer, allowing us to determine the amount or the time of energy flow to these locations by observing the spectral lines characteristic of the tracer material. This technique also allows us to examine in detail the plasma conditions of a well-defined region; we don't have to be content with averages over all densities and temperatures in the plasma.

In addition, both images and spectra can be time resolved to less than ten picosecond with optical or x-ray streak cameras, enabling us to follow the evolution of the plasma as the experiment proceeds. For example, optical streak cameras, filtered to record only one of the high harmonic frequencies of the CO_2 light, can determine if the conditions producing such harmonics are present throughout the nanosecond experiment. On the other hand, infrared optical emission (for example second harmonic emission from the steep density gradient, light reflected from the critical-density surface in the plasma, light that is Brillouin scattered near 10 μm, or light that is Raman scattered at longer wavelengths) must be measured with fast infrared sensors and spectrometers. Because there is nothing equivalent to a streak camera sensitive to these low-energy photons, it is difficult to examine, in the detail we would like, the evolution of these signatures of the absorption process.

Many of these instruments-particularly the x-ray pinhole cameras, spectrographs, and collimators—must be close to the target and must survive the blast of particle debris and intense x-rays from each shot. In a typical Antares shot hundreds of gigawatts of hard x rays and gigawatts of microwaves are emitted. Heroic measures are required to shield detectors, film, and electronics sufficiently to make the necessary measurements.

The wide range of measurement techniques we have used in this hostile environment, combined with our ability to modify target design in a microscopic manner, has allowed us to develop a detailed empirical base against which the theoretical picture can be compared.

Comparison with Experiment

The code that provides the most direct link with experimental data is, of course, LASNEX. With its post processing packages, LASNEX can simulate directly the outputs of such diagnostic records as pinhole photographs and streak camera images, as well as bremsstrahlung, ion emission. and soft x-ray emission spectra.

The code also calculates the source spectra and so can be used to help deconvolute experimental data. For example, it can extract the electron temperature from the hard x-ray bremsstrahlung spectrum or extract the compressed fuel properties from the x-ray pinhole images and x-ray spectra. Using the code to model a variety of phenomena simultaneously on a given target shot greatly enhances our confidence that we understand the target behavior.

Matching the experimental data frequently requires an iteration in the input conditions to LASNEX, and often the search for a specific signature of a phenomenon predicted by the code leads to suggestions for modifying existing diagnostic techniques or developing new ones. From this interplay between theory and experiment new target concepts are developed that might better use the energy flow. ■