Title: Two Dimensional Simulation of High
Power Laser-Surface

CONF-980447--

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JUL 31 1998
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Submitted to: SPIE International Symposium,
High-Power Laser Ablation 1998
Santa Fe, NM
April 1998

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Two dimensional simulation of high power laser surface interaction

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ABSTRACT

For laser intensities in the range of 10^8 - 10^9 W/cm², and pulse lengths of order 10μsec or longer, we have modified the inertial confinement fusion code Lasnex to simulate gaseous and some dense material aspects of the laser-matter interaction. The unique aspect of our treatment consists of an ablation model which defines a dense material-vapor interface and then calculates the mass flow across this interface. The model treats the dense material as a rigid two-dimensional mass and heat reservoir suppressing all hydrodynamic motion in the dense material. The computer simulations and additional post-processors provide predictions for measurements including impulse given to the target, pressures at the target interface, electron temperatures and densities in the vapor-plasma plume region, and emission of radiation from the target. We will present an analysis of some relatively well diagnosed experiments which have been useful in developing our modeling. The simulations match experimentally obtained target impulses, pressures at the target surface inside the laser spot, and radiation emission from the target to within about 20%. Hence our simulational technique appears to form a useful basis for further investigation of laser-surface interaction in this intensity, pulse-width range.

Keywords: laser matter interaction, ablation modeling

1. Introduction

The modeling of laser interaction with material has been the subject of intense research activity over the past 25 years in connection with inertial confinement fusion (ICF) research¹. This has resulted in the development of a number of multi-dimensional codes focussing on the problems resulting from the interaction of laser radiation at wavelengths from 0.25 to 10.6 μm and intensity in the range from 10^{13} to 10^{15} W/cm² with targets represented as fluids without material strength². More recently, in connection with such technical areas as material processing, an interest has developed in modeling the laser matter interaction at intensities which are many orders of magnitude lower. Under these conditions material temperatures are, of course, significantly lower, properties depending on the details of atomic levels are likely to be more important, and the issue of material strength and ablation has to be dealt with in detail.

Since there is a wealth of physical modeling available in the inertial fusion codes, we have approached the high power laser surface interaction problem through adaptation of a particular inertial fusion code, Lasnex, to deal with the problems of material strength, ablation, and material opacities at lower temperatures. In Section 2 we present a brief description of the physics within the Lasnex code and the dominant energy couplings in the ICF regime. In Section 3, we indicate the approximations and extensions which we have introduced to allow us to apply Lasnex at lower incident laser intensities. In Section 4, we compare simulational results from the modified code with experimental data. In Section 5, we assess accomplishments of and limitations in our treatment.

2. Description of the physics within the Lasnex code and dominant energy couplings in the ICF regime

Lasnex is a two-dimensional radiation hydrodynamics code written for cylindrical (r,z) geometry. The hydrodynamics is basically Lagrangian, i.e. in the default option, the mesh points defining a quadrilateral zone are transported according to fluid forces with no mass flow in or out of a zone; however

there is a rezoning capability, allowing for a semi-Eulerian, or even Eulerian, flow across zonal boundaries. Pressures and internal energies are determined from Sesame equation of state tables. Energy transport mechanisms include hydrodynamic work through " $p\Delta V$ " terms, multi-group radiation diffusion, and heat flow due to electron and ion thermal conductivities. The material within a given zone is approximated as a single fluid. A variety of models is available for calculation of degrees of ionization and multi-group material opacities. If the material of a particular region is assumed to be in local thermodynamic equilibrium (LTE), these variables can be obtained either from external tables or hydrogenic modeling internal to the code; otherwise (non-LTE) the principal quantum number populations are calculated from rate equations. In addition, there is a post-processing capability for detailed radiation diagnostics. Laser deposition is based on a three-dimensional ray trace imposed on the two-dimensional problem geometry.

The dominant couplings at moderate intensity (neglect of non-thermal laser absorption due to plasma wave processes) are shown in Figure 1. Laser energy enters the problem from above and is transmitted roughly in the negative z -direction through a plasma corona until it is absorbed largely through inverse bremsstrahlung, but also through bound-bound and bound-free transitions, in the plasma in front of the target. The bulk of absorbed laser energy goes first into heating thermal electrons and producing excited ionic states. It can then be reemitted as radiation or it can remain as thermal electron energy, or it can be coupled into ion thermal energy. The radiation can either be transported into the corona to either maintain its temperature or to escape from the problem, or to lower values of z to heat the dense material of the target. The thermal fluid energy can be transported, predominantly through thermal electron motion, into the denser regions of the target at lower z -values. In addition it can drive hydrodynamic motion at all densities. Hence the dense region of the target is heated by a combination of radiation, thermal electron energy transport, and hydrodynamic motion (as through shocks).

Dominant Couplings at Moderate Laser Intensity

Figure 1. Schematic view of conventional Lasnex couplings for laser light incident from $z=+\infty$ in the negative z -direction.

3. Modification of Lasnex to treat the laser matter interaction at lower incident laser intensities

As might be expected, the major difficulty in applying Lasnex at laser intensities significantly below 10^{13} W/cm² lies in dealing with the dense material behavior at lower z -values where the material temperatures are fractions of an electron volt. In this case, the material pressures generated are comparable to material yield strengths and non-ideal fluid modeling is necessary to treat fluid dynamic behavior. (For higher laser intensities there is significant shock heating to greater depths in the target, so that the region of uncertain fluid dynamic behavior due to the sub-eV temperature regime beyond the shock front becomes more remote in space relative to the remainder of the problem, and, in addition, the energy included in this region becomes smaller relative to the total problem energy.)

We have attempted to bypass the difficulties involved in low temperature fluid dynamic behavior by dividing the physical problem space into two regions, a relatively high temperature vapor region treated with the conventional Lasnex fluid modeling and a relatively high density, low temperature region within which the fluid dynamics is suppressed. The two regions are separated by an interface which lies along zonal boundaries at which the material undergoes a liquid-vapor phase transition. Hence the phase transition interface is an ablation front with material passing from the dense region into the vapor region, while energy is transported in the opposite sense. Corresponding to the Eulerian flow of mass across the interface out of the dense region, the interface moves into the dense region so as to maintain its density at a constant value. The conceptual arrangement of couplings is shown in Figure 2.

Dominant couplings for lower intensity, long pulse problems

Figure 2. Schematic view of Lasnex couplings for the ablation model.

The prescription for mass flux across the interface is obtained through a model which includes the zone by zone interaction along the interface of the material in the dense phase with the vapor, characterized by density, flow velocity, and pressure, in the rarefied phase. The transition from liquid to vapor is assumed to take place over each vapor zone bounding the interface and involves two neighboring but spatially separate subregions. Since the size of the total transition region is small compared to the problem size, it is assumed that the variation over each subregion can be analyzed in the steady state and moreover that only one independent spatial variable, z , normal to the local interface surface, is necessary for this.

The geometry is shown schematically in Figure 3. In the region between $z=0$ and $z=z_t$, where z_t is of order the atom-atom mean free path, there is a Knudsen layer transition in which the particle distribution emitted from the dense phase is transformed into a drifting Maxwellian distribution function. In the region between $z=z_t$ and $z=z_c$, with z_c defining the center of the vapor zone, the drifting fluid at $z=z_t$ adjusts to the boundary conditions imposed by the vapor region.

The vapor pressure of the dense phase is obtained as function of the material temperature through the Clausius-Clapeyron relationship, which views the atoms in the dense material as encountering a potential jump at the ablation interface. With reference to Figure 3, this defines a (one-sided) Maxwellian ion distribution, symbolized by "s", for $v_z > 0$ at $z=0$, which provides for fluxes in the positive z -direction. Since this distribution is converted to a drifting Maxwellian, symbolized by "b" at $z=z_t$, it can be characterized by three unknown variables: number density, drift velocity and temperature. The collisional interaction between "s" and "b" within the Knudsen layer determines an additional distribution function "r", which can be specified in terms of the parameters defining "b" and "s", for $v_z < 0$ directed into the dense region at $z=0$. Three equations are provided by the conditions of conservation of mass, momentum, and energy flux between $z=0$ and $z=z_t$. (This modeling for the region with $0 \leq z \leq z_t$ uses the modeling of Anisimov³ and Knight⁴ for the Knudsen layer, with the exception that here "r" is determined self-consistently, whereas the temperature and drift velocity for "r" were assumed to be the same as for "b" in their treatments.)

The transition between $z=z_t$ and $z=z_c$ can be specified by the conditions of conservation of mass flux and momentum flux, which can be expressed as:

$$\begin{aligned} \rho_b u_b &= \rho_c u_c \quad (1), \\ p_b + \rho_b u_b^2 &= p_c + \rho_c u_c^2 \quad (2), \end{aligned}$$

with "b" denoting fluid variables for the Maxwellian at $z=z_t$ and the subscript "c" denoting variables at $z=z_c$. Hence there is a total of five equations from the two sub-regions, and for a unique solution it is necessary to have five unknowns. There are three unknowns in connection with the specification of the drifting Maxwellian "b". Since the normal fluid velocity at the interface is assumed to be zero, it is reasonable to take the function u_c , which defines the normal fluid velocity at the center of the first low density zone, as a fourth unknown, while the variables p_c and ρ_c which can be determined by the full solution of Lasnex for the low density region can be regarded as known. A fifth unknown is obtained if one allows the value of z_t to be determined self-consistently from the set of five equations.

The high intensity limitation of the ablation model can be understood through examination of the equation of state for the ablating material. In Figure 4, we show a commonly used Sesame equation of state for aluminum. The liquid-vapor phase transition is treated through a Maxwellian construction so that the vapor pressure at the phase transition is a definite function of temperature over a extended range of density provided the material pressure is sufficiently low, i.e. below about 0.5 eV. One may readily verify that the phase transition pressures are well approximated by the Clausius-Clapeyron pressure, p_s :

$$p_s = 1.06 \times 10^6 \exp(-L_v/T_i) / \exp(-L_v/T_{b0}) \quad \text{dyne/cm}^2,$$

where L_v ($= 3.0118$ eV) is the latent heat of vaporization for aluminum, T_i is the material temperature of the liquid phase, and T_{b0} ($= 0.2384$ eV) is the temperature at which the aluminum vapor pressure is equal to

Figure 3. Single collision approximation for the Knudsen layer.

Figure 4. Equation of state for Al with Maxwell construction.

atmospheric pressure. Since phase transitions only occur when the pressure is constant over an extended range of density, the maximum possible pressure at a phase transition is approximately 2×10^9 dyne/cm². On the other hand, the pressure in a laser-target interaction problem is usually effectively bounded by the pressure at the ablation front. Hence, for aluminum defined by the 3717 equation of state, the assumption that the ablation front is at a phase transition limits one to problem pressures below approximately 2×10^9 dyne/cm².

Uncertainty in the threshold for plasma initiation in front of the dense target is really present at all laser intensities, but it is more significant at lower laser intensities where the fraction of total energy invested in producing a plasma is a larger part of the total incident energy. The Lasnex modeling provides detailed treatment through opacity tables of the laser interaction with vapor or plasma between the dense target and the laser source, but no fundamental accounting for the direct interaction of the laser with the target. The electromagnetic interaction of the laser light with the dense target is parameterized in terms of a fractional absorption of incident laser energy by the dense material. In addition, as part of the lack of detailed consideration of the direct laser target interaction, the treatment of ablation considers only thermal ablation, not photo-ablation.

In a further approximation, the gaseous state produced by ablation off the dense target is assumed to be composed solely of single atoms and ions. There are neither molecular components, nor clusters of ions and atoms. The default transport of energy in the dense material is also based on single atomic or ionic models.⁵ A metal model based on the properties of copper is available for thermal energy transport, but this is clearly only roughly correct for virtually all other metals.

4. Simulations and comparison with experimental data

We have compared the results of simulations based on the ablation modeling presented above with experiments, performed on the KMS Chroma laser, in which the incident laser energy varied from 1 to 2 kJ at wavelength 1.05 μ m, the laser spot size, d , was of order 1 cm, and the pulse width, τ , was of order 10^{-5} sec. The resultant laser intensities were in the range of 10^9 W/cm², leading to the application of plasma pressures close to, but below, 2 kBar on the ablation interface. For the vapor flow to be one-dimensional, the parameter $\tau' (=c_s \tau/d$, where c_s is the representative speed of sound in the vapor flow) should be of order unity; instead these experiments were strongly two-dimensional with $\tau' \approx 10$. Application of the conventional Lasnex modeling to similar problems had been unsuccessful due to the inability of the code to calculate the two-dimensional dense material fluid dynamic behavior. In addition, it was found useful to apply extensive rezoning to the plasma region for the simulations to proceed smoothly.

The actual targets were flat aluminum targets with background target chamber gas densities of order 10^{-8} g/cm². The laser intensities were sufficiently high that the assumption, consistent with low intensity experimental data, that 0.07 of the laser energy incident on the original dense target was absorbed by the target, led calculationally to the formation of a plasma in front of the dense target at a relatively early time in the laser pulse. Once the plasma had been formed, the incident laser energy was strongly absorbed, predominantly through inverse bremsstrahlung, and did not directly reach the ablation interface, and the plasma temperature and degree of ionization rose rapidly to higher levels.

Results for a simulation with incident laser energy of 1.7 kJ, pulse width of 8 μ sec, and laser spot diameter of 0.69 cm, at a time of 7 μ sec after the onset of the laser pulse, are shown in Figures 5 - 7. These plots provide a perspective on the two-dimensional character of the modeling. The multi-group radiation diffusion treatment was based on using Planck Group Mean opacities, which involve averaging the absorption opacity to the first power over the equilibrium photon energy distribution, in place of Rosseland Group Mean opacities, which involve averaging the reciprocal of the absorption opacity. This choice will be discussed below.

The problem zonal mesh is shown in Figure 5. Dimensions are in cm. The problem grid is defined for $-5.0 \leq z \leq 0.3$ and $0.0 \leq r \leq 5.0$. The dense target is originally specified by the region $0.0 \leq z \leq 0.3$ and $0.0 \leq r \leq 5.0$. The darkened vertical band in the vicinity of $z=0$ is due to a clustering of zones in the

dense material adjacent to the dense material – vapor interface. Laser rays are incident on the mesh from $z = -\infty$ and propagate in the positive z -direction until they are fully absorbed by the plasma in front of the interface. The zoning is significantly finer for $r < 0.4$, i.e within the laser spot radius. Although almost all of the laser energy has been deposited by this time, the only significant zoning changes in comparison to the mesh at $t=0.0$ are in the dense material in the vicinity of the ablation interface, and these are sufficiently small on the scale of the entire problem grid that they can not be seen.

Contours for the logarithm of the density (gm/cm^3) in the gaseous region are shown in Figure 6. The peak density for this region is of order 10^{-3} g/cm^3 ; this value is not unreasonable since one has for the gaseous density, ρ_g , at the interface, $\rho_g = \rho v_{ab} / v_t$, where ρ is the density of the dense phase, v_{ab} is the velocity of the ablation front through the dense material, and v_t is the order of the thermal velocity of atoms at the interface temperature, and $v_{ab}/v_t \ll 1$. The radial spread of the contours is consistent with significant multi-dimensional behavior. For this plot, as well as for Figure 7, the tilt of the contours at large radii for $z \approx 0.0$ appears to be an artifact of the plotting routine.

Contours for the electron temperature (keV) in the gaseous region are shown in Figure 7. The peak temperature of order 9 eV is localized in radius within the laser deposition spot, but there is significant heating, relative to the dense target temperatures of order 0.5 eV, at radii beyond the spot. The peak temperature is at lower z than the ablation interface, corresponding to absorption of the laser beam before it reaches the target.

Figure 5. Zonal mesh at 7.0 μsec .

Figure 6. Contours for the logarithm of the density in the gaseous region at 7.0 μsec .

The experimental data, which were dependent on phenomena, which either occurred in the low density gaseous region between the laser and the dense target, or were directly attributable to its modeling, included:

1. measurements of the ratio of total impulse imparted to the target to the incident laser energy,
2. measurement of the mean pressure applied to a circular section within the laser spot on the target as a function of time,
3. measurement of the photodiode signal produced by radiation from the target on a broad band detector covering photon energies anticipated to cover the peak of the emission spectrum,
4. measurements of holographic interference fringes, which through Abel inversion, could determine the electron density in the gaseous region.

The measurement of total impulse, I , was directly dependent on the area and time integral of the total pressure (static pressure + ram pressure) applied over the target interface. We measured the impulse delivered to targets using a modified ballistic pendulum technique. The mechanical design of the gauge and the Kaman proximeter sensor used to detect displacement time histories were similar to those used for the central target gauge in studies at KMS in 1986⁶. Slight design changes were required to accommodate split Hopkinson bar pressure gauges used on the beam axis during some of the shots. The moving structure to which the targets were mounted was forward loaded against a mechanical stop in the precision linear bearing on which it rode by a slight deliberate tilt in the overall gauge assembly. This defined the initial location of the target. After the laser interaction, the target was free to move 15.7 mm before the structure attached to the bearing contacted the static framework. Motion recorded by the Kaman proximeter sensor provided the initial velocity of the moving structure which together with the known weights of the targets and mounting structure yielded the impulses delivered. As shown in Figure 8, there is reasonable agreement between the calculations and the data. There was no significant difference between Planck and Rosseland Group Mean opacity results.

Figure 7. Contours of the electron temperature in units of keV at 7.0 μ s.

Figure 8. I/E (dyne-sec/Joule) vs beam energy for several laser spot sizes.

The measurement of the time resolved mean pressure (again, static pressure + ram pressure) over an area covering roughly one half of the target area within the laser spot provided a more detailed test of the modeling. We used annular targets to surround (with 0.5 mm clearance to allow free impulse gauge motion) a fixed Hopkinson bar oriented along the motion axis behind the target surface⁷. We placed target material on the end of the Hopkinson bar and located the bar on the axis such that this surface was flush with the rest of the target. Within the minimal gauge motion during the laser pulse and perturbations introduced by the clearance gap, the Hopkinson bar surface then experienced the pressure versus time loading of an ordinary target over that portion of the surface subtended by the bar end. This loading was propagated down the bar and sensed, with an acoustic delay due to the sound speed in the bar, at a thin piezoelectric sensor embedded in the bar. Additional bar length behind the sensor allowed the pressure pulse to continue on without contributing significant interference from acoustic reflections. The sensor pressure history approximates the target surface pressure history except that it is delayed in time and averaged spatially over the bar diameter and temporally over a time corresponding approximately to the acoustic transit time across the diameter of the bar. Hysteresis effects in the piezoelectric sensor also result in a zero shift as the pulse passes through the sensor. Figure 9 shows that the calculated pressures are typically about 20% below the measured pressure, that with the exception of the onset of the pressure, the durations of the main pressure peaks are comparable, and that there is not significant difference between modeling with Rosseland and Planck group mean opacities.

Time resolved broad band radiation output from the target was measured by two detectors consisting of x-ray biplanar diodes with aluminum photocathodes and aluminum filters. The photocathodes was manufactured from 1100 alloy Al and machined to a shiny surface. They were then ultrasonically cleaned, first in solvents and then in deionized water. The defining aperture was 0.59 cm in diameter. The diodes were biased at 2000 volts. The transmission window in the Al-filter absorption profile below the L-edge made the detector sensitive from about 18 eV to 73 eV. The foil thickness was selected to provide good definition of the 18 eV to 73 eV region while not attenuating the signal below useful levels. We typically used 0.8 μm Al filters. The 0.8 μm Al filters are extremely fragile. A large portion of energy in the spectrum was outside the transmission window. Therefore small holes in the filters could cause large errors in the measurement. The filters were inspected for holes before mounting. To guarantee that there were no undetected holes or thin spots in the foils, the two diodes were usually located symmetrically on a given shot, and their signals were compared.

The energy range of significant photon response overlapped substantially with the radiation emission spectrum anticipated from targets with radiation emitting region at an electron temperature somewhat below 10 eV. The data and simulation results are compared in Figure 10. The modeling with Planck group means is significantly closer to the data than the result using a radiation treatment with Rosseland group means.

Figure 9. Mean pressures within the laser spot vs. time. Solid line is experimental data. Dashed line is calculation using Planck Group Mean opacities. Dotted line uses Rosseland Group Mean opacities. Timing of calculated curves translated to agree with experimental fall-off between 35 and 37 μs .

Figure 10. Time resolved X-ray diode output from broad band target radiation normalized to laser energy. Solid lines are experimental data from two detectors. Dashed and dotted lines are for calculation with Planck and Rosseland opacities as in preceding figure. Timing of calculations translated to agree with experimental fall-off.

The electron density (n_e) in the corona was measured using holographic interferometry. Similar applications of this diagnostic at the Chroma laser have been previously described⁸. The system used for these experiments consisted of a single 100 psec, 527 nm probe pulse expanded to cover a 30 mm field of view. A steel ball of known diameter was used as spatial calibration. A cw laser was used to reconstruct the holographic interferograms which were then photographed. In general, the interferograms were symmetric about the laser beam axis. The electron densities were obtained by first defining a symmetry axis on the photographs. A graphics table was then used to manually digitize points along the fringes on one side of the symmetry axis. A surface was fit to the fringe information to obtain fringe shift versus arbitrary image position. Profiles perpendicular to the axis were generated and then Abel inverted to obtain electron density as a function of radius from the symmetry axis and position along the symmetry axis.

Experimental data are compared with simulation results for the Planck opacity model in Figure 11. Closest to the origin, ($r=0$, $z=0$), where the electron densities are greatest, the experimental electron densities are of order 50% higher than the calculated values at the same (r,z) values. The ratio of experimental to simulation volume within the lowest electron density of 10^{18} cm^{-3} is approximately unity, with the experimental contour more extended in z and less extended in r . Hence it appears that experimentally the total electron number is between 1 and 1.5 times the calculated value. The difference between experiment and calculation is at least partially traceable to the occurrence of an additional negative pressure contribution within the simulation due to artificial viscosity along the $r=0$ line. The variation between the Planck and Rosseland opacity models is smaller than between experiment and either model.

Figure 11. Comparison of experimentally based electron density data (right) with simulation results obtained on using Planck Group Mean opacities for the multi-group radiation modeling (left).

5. Assessment of the adequacy of the modeling technique in dealing with the experiments

Since the experimental results depend on both radiation and hydrodynamics treatments, they are reasonably complex in requiring a number of detailed models for description of the interacting physical mechanisms. Hence it is probably not possible to find a unique, most accurate, modeling for them. In particular, adaptation of a code such as Lasnex which has overwhelmingly been concerned with materials at higher energy densities, exposes one to default physics models which have been generated for a somewhat different physical regime. More detailed modeling can in general be found for materials at lower temperatures, as for instance we have employed for the modeling of multi-group opacities, but there is obviously a great deal of complexity likely in description of the atomic *and* molecular state of the matter which is likely to confound the accuracy of derivative models for processes such as energy transport and photo-ablation.

The most marked deviation from experimental data occurs for the total electron number and the electron density contours in the plasma in front of the dense target. These discrepancies may be attributable to a substantial artificial negative viscosity for zones bordering on the cylindrical ($r=0$) axis of the problem. It is a subject for further investigation to determine whether the artificial viscosity can be lowered substantially, whether the calculated depressions in electron density, estimated to be somewhat less than 1/3 of the experimental values, are really due to it, and the ultimate effect on the other measurements.

Nevertheless, the modeling, with its essential assumptions of definition of the ablation front as a phase transition, and simplified atomic and plasma physics, is capable of simulating a variety of radiation-hydrodynamic data with errors of order 15-20%, provided the multi-group radiation diffusion employs photon groups whose opacities are given by their Planck Group Means. It appears that it would be fruitful to apply the same calculational technique to other problems for which the same assumptions are valid, and for which the interest is in the plasma region in front of the dense target and possibly its effects on the dense target.

6. Acknowledgments

This paper is dedicated to the memory of Ronald S. Dingus, who as project leader, provided sustained support and encouragement for the experiments and modeling which it contains.

The idea of approximating the ablation front by a phase change was first encountered in discussions with M. Friedman, S-Cubed, La Jolla, CA, and P. Wu, Physical Sciences Inc., Woburn, MA.

This work was sponsored by the U.S. Department of Energy.

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