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In An Air Environment

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A THEORETICAL DESCRIPTION OF PULSED LASER-TARGET INTERACTION
IN AN AIR ENVIRONMENT*

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Abstract

A comprehensive treatment of pulsed laser target interaction in an air environment is described. Included in the treatment is target heating and vaporization, nonequilibrium effects and two-dimensional hydrodynamics, radiative transfer, and thermal conduction. A description of damage effects arising from LSD waves is also given.

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A realistic assessment of the effects of a high power laser pulse on a target in an air environment requires a comprehensive model including the following effects:

1. target heating and vaporization
2. absorption wave ignition and propagation
3. nonequilibrium effects
4. two-dimensional hydrodynamics.

Since our understanding of the first and third categories is far from complete, the success of the model as a whole must be judged by how well it fits experiment.

The difficulties in constructing an accurate absorption model for a metal are obvious. The model must be capable of spanning target conditions ranging from low temperature and high density, when Drude's classical theory of a metal can be assumed to apply, and absorption is governed by the complex permittivity

$$\epsilon = 1 - \frac{4\pi N e^2}{m(\omega^2 + i\nu_c \omega)}$$

to a condition of high temperature and low density when the metal becomes an ionized atomic vapor and absorption takes place by inverse bremsstrahlung. The transition between these two conditions is known as a "Mott transition" and is not well understood. In addition, the constants to be used in the Drude theory at ambient temperature require adjustment in order to account for the properties of imperfect surfaces. Fortunately calculational results do not seem to be sensitive to the details of the assumed model. What appears to be important is that parameters are chosen so that vaporization or blow-off can take place in an experimentally observed time.

The inclusion of nonequilibrium effects is essential for a correct description of absorption wave phenomena, although it does not appear necessary to include a precise description of the electron cascade to obtain good agreement with experiment. One requirement of a nonequilibrium treatment is that it should be able to give the right behavior in the equilibrium limit. Otherwise, heating rates and pressures will be incorrect. This is difficult to achieve unless the nonequilibrium model is extremely complex. A practical solution is to utilize detailed equilibrium data as much as possible within the framework of a 2-temperature model. The LASNEX nonequilibrium scheme is built around a three temperature model and takes maximum advantage of existing equilibrium equation of state tables. The three temperatures are T_e , the electron temperature, T_i , the ion or heavy particle temperature, and T_r , the radiation temperature, which is not of great importance at low temperatures. The ion and heavy particle temperatures are coupled together through the equation

$$\frac{dT_e}{dt} = - \frac{T_e - T_I}{\tau_{ei}} \quad ,$$

where the coupling constant

$$\tau_{ei}^{-1} = \tau_{en}^{-1} + \tau_{ec}^{-1}$$

is made up of contributions from electron-neutral and electron-ion scattering. The electron cascade is treated approximately in the following manner. For $T_e < T_p$, where T_p is the temperature at which molecular dissociation is essentially complete, the electron energy density is assumed to be given by

$$E_e = n_e(T_e) \left[3/2 kT_e + \bar{I} \right] \quad ,$$

where $\bar{I}$ is the average ionization potential for air, and n_e is assumed to be a function of T_e . Differentiating this expression with respect to T_e we obtain an expression for the electron specific heat

$$C_V^e(T_e) = \frac{\partial E_e}{\partial T_e} = \frac{3}{2} n + \frac{\partial n_e}{\partial T_e} \left(\frac{3}{2} k + \bar{I} \right), \quad T_e < T_p \quad .$$

An expression for $\partial n_e / \partial T_e$ can be gotten by further assuming n_e is governed by the Saha equation at temperature T_e . The heavy particle specific heat can in turn be gotten from an equilibrium table through

$$C_V^I(T_I) = C_V^{TABLE}(T_I) - C_V^e(T_I) \quad , \text{ if } T_I < T_p \quad ,$$

which involves subtracting off the electron contribution to the specific heat from the tabular value. If $T_I > T_p$, the ion specific heat is assumed to be given by

$$C_V^I(T_I) = 3/2 n_I k \quad T_I > T_p$$

and the electron specific heat is gotten from the equilibrium table by the relation

$$C_V^e(T_e) = C_V^{TABLE}(T_e) - 3/2 n_I k \quad T_e > T_p \quad .$$

The above procedure insures that for T_e below the temperature T_p the molecular binding energy is assigned to the molecules. For T_e above T_p ionization energy is assigned to the electrons, as it should be.

Pressures are also obtained from equilibrium tables by a similar scheme, namely:

$$p_e = n_e k T_e \quad T_e < T_p$$

$$p_i = p^{\text{TABLE}}(T_i) - p_e(T_i) \quad T_i < T_p$$

$$p_e = p^{\text{Tab}}(T_e) - n_i k T_e \quad T_e > T_p$$

$$p_i = n_i k T_e \quad T_i > T_p$$

The internal energy of air as a function of temperature is shown in Fig. 1 along with the temperature T_p at which the change in table use is made. The curve E_i is made up of translation kinetic energy of heavy particles along with molecular binding energy. Clearly molecular binding energy dominates below 1 ev and any calculation which neglects this fact will be in error.

Figure 2 shows the numerical representation of Craig Walters¹ pulse giving a peak intensity of 7×10^7 watts/cm². Figure 3 shows the complete failure of a one-temperature equilibrium calculation to give ignition of an absorption wave. Plotted are the temperatures of the aluminum surface and of the air a short distance away from the surface. Vaporization takes place at 50 μ sec followed by a steadily rising metal temperature which rises to 4 volts. Notice that the shock heated air never rises above .6 ev, which is too low a temperature to produce the ionization necessary for an absorption wave. There is, however, sufficient ionization at .6 ev for some laser absorption, which would result in still further ionization if the energy absorbed were not going primarily to molecular dissociation. Other calculations have shown the impossibility of even maintaining an LSD wave which has already been assumed to have been initiated, for intensities of the order of 5×10^7 w/cm² or less. The reason is again the high thermal barrier imposed by molecular dissociation. Figures 4a and 4b show results of two temperature calculations for the same metal surface and air temperatures. The two figures appear almost identical. The first is for a high density ($\rho = 1$) Mott transition while the second is for a low ($\rho = .1$) density Mott transition, illustrating the lack of sensitivity of results to heating model. Note the characteristic electron temperature runaway in both metal and air with the steeply rising electron temperature going to over 2 volts in the air then dropping, eventually to equilibrate with the ion temperature. The same effects are shown as functions of position in Fig. 5, where the electron and ion temperatures are plotted as functions of position at times $t = 80$ nsec and 140 nsec. Thus the front travels 4.1×10^{-2} cm in 60 nsec giving a detonation speed of just under .7 cm/ μ sec which is in good agreement with Walters' measurements of peak LSD velocity.¹ Note that at the detonation front the ion temperature rises first due to shock heating, followed by the

heating of the electrons. Thus shock heating is what propagates the laser supported detonation wave in this model. Somewhat more general results are shown in Fig. 6 which indicates detonation velocity as a function of constant intensity for a one-dimensional geometry and a $10.6 \mu\text{m}$ wavelength. In these calculations the LSD waves are initiated by first irradiating and blowing off an aluminum surface. Notice how well the Raizer² formula $D = [2(\gamma^2 - 1)I/\rho_0]^{1/3}$ is obeyed at STP from just under 10^7 watts/cm^2 up to $2 \times 10^9 \text{ watts/cm}^2$. The value of γ is determined to be a constant 1.18 even though the calculation is a two-temperature calculation, and the medium, air, is not a constant γ gas. The value 1.18 is close to the value $\gamma = 1.17$ which has become used by Hall et al. to fit measurements of LSD wave front positions to Raizer's theory.³ Note that at an intensity of the order of $5 \times 10^6 \text{ w/cm}^2$ the calculation begins to dip below the Raizer line due to the fact that the wave front has become transparent and allows radiation to get through to the aluminum piston. At an intensity about $2 \times 10^6 \text{ watts/cm}^2$ a significant fraction of the laser energy is able to penetrate through to the target surface. This behavior indicates a one-dimensional threshold for the degeneration of a true LSD wave into some form of more spatially extended absorption wave. Similar thresholds have been reported by the various experimenters at just below 10^7 watts/cm^2 . Figure 7 shows similar behavior for a $1.06 \mu\text{m}$ wavelength. (Note that the $\gamma = 1.18$ value seems to be universal constant for STP air.) The indicated LSD threshold in this case is about $2 \times 10^8 \text{ w/cm}^2$ which compares with a value of about $1 \times 10^8 \text{ watts/cm}^2$ quoted by Rudder et al⁴ for an LSD maintenance threshold at $1.06 \mu\text{m}$.

Figure 8 shows the detailed pulse shape for Hall's³ laser as it is used in the LASNEX calculation. Total time encompassed is 10 μsec . For the calculational run to be described the total energy output was 17 joules. Figure 9 shows the evolution of the Lagrangian grid at successive times. The initial grid is arranged so that the actual focusing of the laser is accounted for, since each horizontal row in the grid carries constant power. The clock begins at .82 μsec which is the calculated time required to vaporize the target surface and initiate the LSD wave. The pattern of the Lagrange grid zones indicates the distribution of mass and creates patterns very similar to the experimental interferogram patterns.³ For example the location of the shocks is easily identifiable by the compressed zones.

Figure 10 shows a comparison between a calculated and the measured curve of detonation front position as a function of time. The 0 in time begins from the calculated time of LSD wave initiation. The agreement is surprisingly good. It should be remembered that the detailed temporal pulse shape as well as the beam focusing have been folded into the calculation.

Figure 11 shows a comparison between calculated and measured arrival times for the radial shock waves at different radii on the target. It is seen that the agreement is quite good, indicating the correctness of the calculated radial flow.

Figure 12 shows a comparison between LASNEX peak pressures and Hall's measured pressures as a function of radius. Again agreement is good.

At this point a set of computer movies were shown which dealt with the generation of LSD waves in Hall's³ and Walters'¹ experiments. In the modeling of the Hall experiment the two dimensional phase of the calculation was started using initial conditions on temperature and material velocity obtained in a one-dimensional calculation. In the modeling of Walters' experiment the LSD wave is initiated by the two dimensional blowoff of the target.

The LASNEX results discussed so far have applied to existing experimental lasers which put out on the order of 10's of joules. It is of interest to use the LASNEX code as an extrapolation tool to predict the effects of much higher power lasers, when LSD waves are present and, in particular, to assess the damage capabilities of such lasers. The interesting variable will of course be pressure on the target surface as a function of radius and time.

We turn our attention first to the one dimensional case in which a surface is irradiated by a constant intensity laser. Figure 13 shows the pressures calculated for the aluminum surface and in the air a fraction of a cm away, as functions of time. In both cases an initial transient relaxes to a steady pressure. The height and shape of the transients are characteristics of the basic structure of the detonation wave. The height of the peak is determined by the rate of heating, the rate of expansion of the heated zones, and by the self-shielding of material upstream from the point under consideration.

The steady pressure in the air right next to the aluminum surface for sea level air is shown in Fig. 14. It is seen to have an $I^{2/3}$ dependence as does the pressure behind the detonation front in Raizer's LSD wave theory.² Raizer gives for the pressure behind the front

$$p_D = \frac{p_0}{\gamma+1} D^2 \sim I^{2/3},$$

where D is the detonation speed, whereas Pirri⁵ and Holmes⁶ have independently derived an expression for the pressure at the target surface due to a propagating LSD wave which is

$$p = \left[\frac{\gamma+1}{2\gamma} \right]^{2\gamma/(\gamma-1)} \left(\frac{p_0 D^2}{\gamma+1} \right) \sim I^{2/3}.$$

If the value $\gamma = 1.18$ obtained from the calculated detonation front velocity is applied to the above formula, one obtains $p = 6.9 \times 10^{-4} I^{2/3}$ bars whereas the LASNEX calculations give $p = 6.35 \times 10^{-4} I^{2/3}$ bars. Thus the Pirri-Holmes surface pressure formula and the LASNEX calculations are in quite good agreement.

The significance of the pressures in Fig. 14 is that when multiplied by the hydrodynamic relaxation time $\tau = R/c$, R being the beam radius, they give a lower limit to the impulse intensity at the target surface and at the center of the original beam spot. It is seen that the pressures are not notably high. In fact a beam intensity of 2×10^9 watts/cm² is required to produce a pressure of only 1 Kilobar. There are, however, several effects which will tend to increase the target surface loading. First of all, there is an initial pressure transient. There is some question as to how accurately this transient can be calculated. Secondly, the pressure at the surface under the original spot is sustained after the hydrodynamic relaxation time due to the existence of an expanding blast wave. Pressure equilibrium thus takes place after a much longer time than the hydrodynamic relaxation time. In addition, the expanding blast wave can load the target surface outside the original beam area. In order to assess all of the above effects together, it is necessary to carry out a LASNEX calculation to get the correct surface pressure loading and then apply the resulting pressures to an elastic plastic code such as HEMP⁷ to ascertain damage capabilities.

Figure 15 shows the results of shining a high power laser with intensity 3×10^9 watts/cm², pulse duration 5.7 μ sec, and energy 336 Kilojoules, on a spot 10 cm in diameter. The problem was run for a wavelength of 10.6 μ m although it would be equally valid for the DF frequency 3.8 μ m, for which the given intensity would be well below the clean air breakdown threshold. Figure 15 shows the condition of the air at $t = 5.7$ μ sec or just as the laser is switched off. The higher temperatures lead to greater electron conduction and radiative transfer which prevents the formation of a strong shock front.

Figure 16 shows the shape of the pressure peak on target at the on-axis position. A peak of 5 Kilobars is reached after which the pressure rapidly declines. In Fig. 17 the impulse intensity accumulated up to 25 μ sec is plotted as a function of radius and compared with SRI results⁶ for explosively simulated LSD waves (ESD's) for the same intensity. The shape of the computer simulated wave does not show as much concentration in the originally irradiated spot as do the ESD's. The peak impulse intensity for the LSD is also lower. Since most of the impulse has already been delivered to the center in the calculation, the difference can be accounted for by the fact that the detonation speed is faster for the LSD and consequently less laser energy is deposited during a hydrodynamic relaxation time than is the case for the ESD's. The hydrodynamic relaxation time may also be longer for the ESD's due to a lower sound speed for high explosive than for air.⁸

The total impulse delivered to the target as a function of target radius is shown in Fig. 16. The value saturates at roughly 10^6 dyne-sec. This gives a coupling constant of 3 dyne-sec/joule which must be considered conservative since not all of the momentum is deposited by 25 μ sec.

In order to assess the damage capabilities of such a pulse it is necessary to apply the surface pressure loading as input to the HEMP code. The following table indicates the resulting damage to two sizes of 1mm thick

aluminum plate. The boundary conditions consist of holding the boundary rim of the plate fixed, and are referred to as "stonewall" boundary conditions.

Table I
Failure of 1.5mm Aluminum Plate

Plate Radius	Time to Plastic Deformation on Back Surface	Time to Fracture Back Surface
15 cm	135 μ sec	140 μ sec
3 cm	40 μ sec	40 μ sec

The failure occurs at a single point, namely the center of the plate, and the failure results in subsequent tearing and crack propagation. Failure is determined by a criterion involving the fractional number

$$f = 1 - \frac{(\gamma - \gamma^*)}{\gamma_0}$$

where γ is the index of plastic deformation. When γ attains the value γ^* the material undergoes irreversible damage or plastic deformation. When the irreversible damage exceeds a critical value determined by γ_0 , the material is assumed to have failed. If failure occurs at a radius greater than zero a plug is assumed to have formed, whereas failure at $r = 0$ must be assumed to lead to tearing. Whenever $f = 0$ first, for $r = 0$, the continuation of the problem is not wholly meaningful since following the ensuing cracks would require a three-dimensional calculation. The exact values of γ_0 and γ^* are determined by comparing code runs with actual dynamic and static failure tests.

Plastic deformation and failure occur first on the back side of the plate for the obvious reason that tension is greater there. The fact that failure occurs sooner for the smaller radius plate is interesting for two reasons. First, it is indicative of the fact that failure can be expected to occur sooner if the beam impact is close to a structural support. Secondly, the smaller sized plate is actually subjected to less total force and momentum than is the larger plate. In fact, the smaller plate has an area approximately equal to the area of the beam spot itself. Thus it is not a simple matter to decide how effective the additional momentum supplied by an expanding blast wave is in creating damage. In short it must inevitably depend on the details of the target.

Figures 19a, b, c show the 3 cm plate configurations at times $t = 0$, $t = 50 \mu\text{sec}$ (after failure has already taken place) and $t = 100 \mu\text{sec}$ as calculated by HEMP. The triangular formation at $r = 0$ in Fig. 19c is due to pressures having been set equal to 0 in the central zone. This feature is always a tell-tale sign that failure has occurred at the center. Figures 20a, b, c show the mesh configuration at times $t = 0$, $t = 150 \mu\text{sec}$ and $t = 300 \mu\text{sec}$ for the 30 cm plate.

A variety of other HEMP results for various laser beams are summarized in the table below.

Table II

Failure of Aluminum Plates due to a Variety of Laser Pulses

Laser Description	Plate Description	Time to Failure
10^8 w/cm^2 , 5 cm diam, 10 μsec , 10 μm , 20 Kilojoules	15 cm radius 1.5mm thick	Never exceeds elastic limit
10^9 w/cm^2 , 5 cm diam, 1 μsec , 3.8 μm , 20 Kilojoules	15 cm radius 1.5mm thick	Never exceeds elastic limit
$2 \times 10^9 \text{ w/cm}^2$, 25 cm diam, 3.58 μsec , 3.8 μm , $3.8 \times 10^6 \text{ joules}$,	15 cm thick 1.5mm thick	40 μsec
SAME	15 cm radius 3mm thick	85 μsec
SAME	15 cm radius 5mm thick	Never exceeds elastic limit

The various results obtained on the pressure effects of LSD waves may be summarized as follows:

1. High pressures and high impulse intensities are difficult to achieve.
2. Damage depends on the target, e.g. proximity to support can make a large difference. Momentum is not the sole criterion for damage, and the effectiveness of blast is still ambiguous.
3. Failure tends to occur at the center of the irradiated area leading to ripping or tearing.
4. Very substantial pulse energies are required to cause damage in aluminum targets with thicknesses of 1.5mm or greater.

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Fig. 1

Fig. 2

TEMPERATURE VS TIME AL SURFACE

Fig. 3

TEMPERATURE VS TIME

Fig. 4a

Fig. 4b

TEMPERATURE VS POSITION

6

Fig. 5

Fig. 6

Fig. 7

Fig. 8.

+0. = ZO AIR RECORD = +2.0
 +0. = RO CYCLE = +.0
 +3.0000E+000 = ZMAX TIME = +.82

+0. = ZO AIR RECORD = +38.0
 +0. = RO CYCLE = +.0
 +3.0000E+000 = ZMAX TIME = +3.0

+0. = ZO AIR RECORD = +59.0
 +0. = RO CYCLE = +.0
 +3.0000E+000 = ZMAX TIME = +5.0

+0. = ZO AIR RECORD = +123.0
 +0. = RO CYCLE = +.0
 +3.0000E+000 = ZMAX TIME = +9.9

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19a

TIME
50.01357

CYCLE
1255

TEMP
DISK

Fig. 19b

TIME
100.03617

CYCLE
2429

HEMP
DISK5

Fig. 19c

TIME
0.01000

CYCLE

HEMP
DISK

Fig. 20a

TIME
200.00511

CYCLE
1555

TEMP
0.525

Fig. 20b

HEMP
DISK5

CYCLE
7192

TIME
300.0154

Fig. 20c