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LASER-DRIVEN SHOCKWAVE EXPERIMENTS AT EXTREME HIGH PRESSURES*

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ABSTRACT

Laser-driven shockwave experiments have been proposed for accurate determination of equation of state data in the multi-megabar pressure range. This paper gives a quantitative analysis of the prospects for such experiments.

In order to unambiguously interpret shockwave data, one requires a clean shock--that is, a planar, steady shock wave entering cold material (without significant preheat perturbation). We examine the problems of attaining sufficiently clean shocks at high pressure and develop scaling relations which relate the pressure achieved to laser intensity, pulse energy, etc. It is shown that significantly higher pressures can be achieved when structured (layered) targets are used.

1. INTRODUCTION

High power pulsed laser irradiation of small targets appears capable of generating remarkably high pressures. Experiments recently conducted at the JANUS laser system in Livermore find shock velocities compatible with pressures of 20 Mbar (2 TPa).¹ Calculations predict that larger lasers can generate shockwave pressures up to 100 Mbar (10 TPa)--extending by two orders of magnitude the range of pressure (and temperature) now available in the scientific laboratory.^{2,3}

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How far can the laser technique extend? Can a laser generate steady shock waves or is there a limitation to impulsive blast waves? How harmful is fast-electron preheat? Can one usefully exploit the preheat for novel types of hydrodynamic experiments? Does the generation of steady shocks (without preheat) require unreasonable laser energies?

This paper reports a parameter study aimed at answering these questions.⁴ The objective is to develop quantitative information to assist in planning experiments, designing shock-wave targets and selecting priorities for laser development.

To be successful, a laser-driven shockwave experiment must achieve (1) a high pressure, (2) a good contrast between the shock itself and any preheat from fast electrons generated by the laser, and (3) a steady shock which moves at constant velocity. These objectives conflict, and therefore it is necessary to examine them closely to identify favorable compromises. In every case, greater laser energy yields better results although this may not represent a practical solution in the immediate future. Additional constraints are imposed on laser-shock experiments by the need to accurately measure both shock and particle speeds; however, this paper will concentrate on the fundamental physical limitations involved in production of clean shocks by laser irradiation.

There is little doubt that lasers can generate high pressures. Heavily diagnosed laser fusion implosion experiments performed on the JANUS laser (including space- and time-resolved x-ray detectors, x-ray spectra, alpha particle and neutron counters and plasma calorimetry) show good agreement with computer calculations which indicate pressures of ~ 200 Mbar (20 TPa) in the imploded DT fuel.⁵ Larger lasers built in recent years (ARGUS, SHIVA) can achieve still higher pressures; however, the spherical implosion geometry does not lend itself to accurate measurement of material properties.

A survey of available equation-of-state theories shows that experiments must have accuracies of 15% or better to produce useful information.⁶ With few exceptions,^{7,8} the existing experiments are confined to a pressure range below 5 Mbar. Thus it appears entirely reasonable to compromise on the peak pressure in order to achieve conditions better suited to accurate measurement.

The most serious problem for laser-generated shock studies is caused by hot electron preheat. Laser absorption, especially at high intensities, leads to copious production of superthermal electrons having energies of 1-100 keV.⁹ These electrons traverse a thin target much faster than a shock-wave and deposit

their energy as hot electron preheat in the material ahead of the shock. This preheat interferes with the standard Hugoniot measurement technique which determines the thermodynamic state of the shocked material by measuring the particle (material) and shock (wave) speeds.¹⁰ The Hugoniot analysis assumes that both temperature and density are known for the (cold) material ahead of the shock. Experiments of this type can be analyzed with confidence only if the hot electron preheat temperature is small. Therefore, a large part of our work is aimed at quantifying the preheat and locating conditions in which it will be negligible or unimportant.

The calculation of laser-matter interaction is so complicated that it contains substantial uncertainties. It is very important to understand that the uncertainties do not imply correspondingly large error-bars in an equation-of-state experiment. If a shockwave is traversing cold material (of known temperature and density), and if the shock speed and particle speed are accurately measured, then the pressure, density and energy of the heated material are uniquely determined by conservation laws.¹⁰ The error or uncertainty in the inferred pressure and energy is controlled exclusively by uncertainties in the measured velocities or in the initial density and temperature. The calculation of laser-matter interaction can be used to design an experiment but is not used in the data-reduction. The direct and simple interpretation of shock-wave data is the best reason for choosing Hugoniot experiments as the first step of a general attack on high pressure physics with lasers.

2. CALCULATIONAL MODEL

The calculations reported here are performed with several elaborate computer codes developed by George Zimmerman and his collaborators.⁴ Our calculations use a tabular theoretical equation of state; at very high pressures this is based mainly on the Thomas-Fermi-Kirzhnits model.^{11,12}

The computational model contains several empirical parameters which provide flexible description of otherwise difficult physical processes. We have selected parameter settings typical of recent laser fusion target calculations while recognizing that the laser-shock experiments may lead to refinement of these parameter choices.

The laser absorption process is calculated as follows: an incident laser ray is traced by geometrical optics up to the critical density surface, and its intensity is reduced by inverse bremsstrahlung absorption which heats the thermal electrons.⁴ Near the critical surface, a fixed fraction (30% in our calculations) of the energy is deposited with generation of

PLANAR LASER-SHOCK EXPERIMENT HAS FOUR MAIN VARIABLES:

- Laser intensity I
- Pulse duration τ
- Depth to observation point d
- Target material, structure

Fig. 1 There are four main design variables in a planar shock-wave experiment. Representative values are intensity $I = 2 \times 10^{14}$ watt/cm, pulse length $\tau = 300$ psec, target thickness $d = 25 \mu\text{m}$, target material = aluminum foil.

superthermal electrons. The remainder of the laser light is reflected and again attenuated by inverse bremsstrahlung. It is necessary to emphasize the arbitrariness of this prescription, because it predicts an absorption of $\sim 60\%$ at 10^{14} watt/cm². The experimental absorption is more likely to be 40-50%. We have not altered the absorption model because the discrepancy mainly involves energy absorbed to inverse bremsstrahlung which plays a comparatively weak role in shock generation and preheat formation.

The energy absorbed by superthermal electrons is assumed to generate a Maxwellian electron spectrum with temperature¹³

$$kT_{\text{TOT}} = 2.6 \text{ keV} (I/2)^{0.425}$$

where I is the laser intensity (units of 10^{14} watt/cm²) and λ the laser wavelength in microns (fixed at unity). The formula actually employed also includes a weak dependence on the thermal electron temperature.

Thermal electron transport is inhibited by a model which invokes ion turbulence limiting the electron heat current to flow with a drift velocity proportional to the ion sound speed.¹⁴ It is this transport inhibition which reduces the importance of the inverse bremsstrahlung absorption fraction.

We have performed a series of calculations which alter zoning, electron and photon group structure and other parameters; typically these changes produce less than a 10% alteration in the computed results. However, the superthermal electron generation and transport constitute the most uncertain aspect of our calculations, and we look forward to early experimental test of the preheat predictions.

The atomic ionization state is calculated by a method based on the Saha equation; this predicts excessive recombination at densities above the solid state.¹⁵ We have adjusted the minimum electron temperature used by the Saha equation to force reasonable initial ionization of the cold solid target material.

3. AN EXAMPLE AT 10 MBar (1 TPa)

Laser-driven shock experiments may be characterized by four design variables (Figure 1):

- a. The peak laser intensity I in the focal spot (a value of 2×10^{14} watts/cm² will be taken as typical of recent experiments on the Livermore JANUS laser).

EXAMPLE SHOWS 10 Mbar SHOCK IN ALUMINUM

ENERGY TRANSFERS IN LASER-TARGET INTERACTION

Fig. 2 (a) Calculated pressure versus time at 25 μ m depth in aluminum foil irradiated as described in Fig. 1. The time is in units of 10^{-8} sec so that the shock arrives at 1 nsec. (b) Temperature (units are 10^{-4} keV) versus time; the 1/2 eV early signal is preheat which appears during the laser pulse. (c) Energy transfers which occur during the calculation; numerical values are indicated in the text.

- b. The pulse duration τ (300 psec for recent experiments at JANUS). For short pulse calculations, the laser intensity is assumed to rise linearly to its peak in 300 psec and then to decline to zero in another 300 psec (this will be referred to as a 300 psec pulse). For longer pulse lengths, the laser pulse is held constant at the peak power from 300 psec to time τ , and drops to zero at $\tau + 300$ psec.
- c. The depth d to the observation point on the rear surface of the target (typically, $d = 25$ microns). To prevent rear-surface perturbation by evaporation caused by preheat, the computational targets are usually more than 25 microns thick (e.g., 35 μ).
- d. The target material (typically aluminum foil).

We are free to adjust these variables to achieve favorable shock pressure, preheat contrast and shock steadiness.

A sample calculation is given in Figures 2a, b which show pressure and temperature at a depth $d = 25 \mu$ in an aluminum foil target irradiated by a 300 psec pulse at $I = 2 \times 10^{14}$ watt/cm². The shock arrives at $\tau = 1.05$ nsec and reaches a pressure of 10 Mbar and temperature of 5.4 eV. These conditions represent a significant extension of the pressure range available in the laboratory.

Unfortunately, the calculated preheat temperature is about 1/2 eV, corresponding to a 10% perturbation of the shock state, and the pressure relaxes rapidly after the shock has passed, implying that a rarefaction has overtaken the shock.

For these reasons, the conditions reached in the calculation are not quite satisfactory for a scientific measurement at high precision.

We have examined the calculated energy transfers in this example, in order to learn which interactions are most important (Figure 2c). With the absorption model described in section 2, some 35 Joules of energy are absorbed by the target. Of this, 14 Joules are directly absorbed by superthermal electrons, 21 by the thermal electrons. During the calculation, 11 Joules are transferred from superthermals to thermals. Smaller amounts of energy are transferred from superthermals to ion thermal energy (1.5 J), hydrodynamic motion (this is an electrostatic coupling, which transfers 0.8 J) and radiation (0.006 J).

The thermal electrons lose approximately 5.5 Joules to recombination radiation and transfer about 21.2 Joules to the hydrodynamic kinetic energy. The electrons continuously share energy with the ion thermal distribution.

At the end of the calculation, the thermal ion energy is 1/2 Joule, the electron energy is 6.4 Joules, and 22.8 Joules have been converted to hydrodynamic energy. Most of this hydrodynamic energy resides in a small number of ions expanding toward the laser at high velocities.

The hydrodynamic efficiency of shock generation can be defined as the final kinetic energy of the rear quarter of the target divided by the total laser energy. Defined in this manner, the hydrodynamic efficiency is approximately one percent.

Similar percentage efficiencies were inferred from laser implosion experiments by Pelah, et al.¹⁶ The reason for the low efficiency is largely the unfavorable partition of energy between the small number of high-energy blowoff ions and the remainder of the target. Because of momentum conservation, it would be very useful to reduce the velocities of the ablated ions.¹⁷ This idea is investigated in section 7. below.

4. DEPENDENCE ON LASER PULSE CONDITIONS

This section will describe a series of calculations done at various laser pulse lengths and focal spot intensities. In order to directly compare these different cases, pressure and temperature are examined at a fixed depth of 25 μm below the front (laser) surface. The target is 35 μm thick so that rear-surface release does not affect the conditions reached at the 25 μm depth.

As is evident from figures (3a, b) and (4a, b), the preheat is very severe for high laser intensities. For this reason, the 25 micron position is much too close to the laser absorption region for meaningful Hugoniot experiments at high intensities (i.e., beyond 5×10^{14} watt/cm²). Even though these conditions are not suitable for principal Hugoniot measurements, it is interesting to examine these calculations for the following reasons:

- a) It is desirable to perform experiments on thin targets in which the preheat temperature is observed in order to verify or correct the computer calculation of preheat. The preheat temperatures calculated here are large enough (at high laser intensity) to produce easily visible signals in an optical streak camera. Experiments of this type, which observe and resolve

SHOCK-TO-PREHEAT RATIO IS DEPENDENT ON LASER PULSE LENGTH

Fig. 3 (a) Shock and preheat temperature as functions of laser pulse length τ for fixed intensity ($I = 2 \times 10^{14} \text{ watt/cm}^2$) and fixed depth ($d = 25 \mu\text{m}$). (b) Shock and preheat pressures as functions of laser pulse length τ .

SHOCK AND PREHEAT AT 25 μ IN ALUMINUM

Fig. 4 (a) Shock and preheat pressure as functions of the laser intensity for fixed pulse length ($\tau = 300 \text{ psec}$) and fixed target thickness ($l = 25 \text{ }\mu\text{m}$). The dots are the pressures attained in long-pulse irradiation. (b) Shock and preheat temperatures.

preheat and shock luminosity on the same shot, have recently been performed at LLL by N. C. Holmes and R. J. Trainor.¹⁸

- b) The calculations give guidance for design of preheat hydrodynamic experiments in which hot electrons give rapid isochoric (constant-volume) heating of a thin target. The subsequent expansion can be observed and compared with hydrodynamic calculations.
- c) Even if a thick target is selected to avoid hot electron preheat of the rear surface, we want to understand conditions in the front portion of the target, because that is where the shock wave is generated.

Figures 3a, b show the shock temperature (pressure) and preheat temperature (pressure) as a function of laser pulse length for fixed laser intensity ($I = 2 \times 10^{14}$ watt/cm²) and fixed depth (25 μ) in an aluminum target.

For long pulses, the shock pressure achieved at the 25 micron position (~ 16 Mbars in Figure 3b) is about 60% higher than the pressure produced in short-pulse calculations. A close examination of the short-pulse case shows that an equally high pressure was generated near the front surface, but that the high pressure is attenuated by $\sim 60\%$ during propagation to the 25 μ m position. This attenuation occurs because a release wave rapidly overtakes the shock in the short-pulse calculations.

After examining many calculations like those plotted in Figure 3b one can extract the useful approximate scaling law

$$P_{\max} = 8.6 I^{.82} \quad (1)$$

where $P_{\max}$ is the pressure (Mbars) generated in long pulse irradiation and I is the laser intensity divided by 10^{14} watts/cm². This scaling law gives the pressure at 25 microns for long pulse cases; the same equation gives the maximum pressure (produced near the front surface) for shorter pulses. Equation (1) differs only slightly from an analytic result obtained by Kidder.¹⁹

The hot electron preheat temperature, shown in Figure 3a, rises in time proportional to the absorbed laser energy until one reaches long pulse conditions ($\tau \geq 0.9$ nsec). This preheat temperature is defined as the temperature existing at the 25 μ m position just before the shock wave arrives. The preheat temperature does not increase for pulses longer than 0.9 nsec because that is the shock arrival time under long-pulse conditions.

It is clear from Figures 3a, b that the ratio of shock and preheat temperatures is more favorable for short pulses. However, in the short pulse case, a release wave overtakes the shock before it crosses the sample. This means there is a conflict between the goals of a steady shock and a preheat-free target environment.

Figures 4a, b show the dependence of shock conditions on laser intensity (I) for fixed depth (25 microns) for a 300 psec pulse. These curves clearly illustrate the difficulty of doing clean experiments at very high pressures.

Figure 4a shows that good contrast between shock and preheat is obtained for laser intensities below 2×10^{14} W/cm², corresponding to pressures less than 15 Mbars. (The dots in Figure 4a indicate the shock pressure achieved in long pulse irradiation.)

Figures 4a, b show that pressures up to 100 Mbar are obtained with laser intensities greater than 10^{15} watts/cm², but that these pressures are generated in the presence of severe preheat. For $I \geq 10^{15}$ W/cm², the preheat temperature is 50% of the shock temperature. In this case, the shock is a weak probe of the preheated material.

Experiments at these conditions would be interesting integral hydrodynamic experiments but could not be analyzed through the usual Hugoniot technique without a direct, specific measurement of the preheat temperature.

It is useful to develop a quantitative measure of the importance of preheat. Comparison of Figures 4a, b shows that the temperature ratio (shock to preheat) provides a more conservative criterion than the pressure ratio. The next section gives an analytic formula for the perturbation of the Hugoniot adiabat produced by a specified level of preheat.

5. CONSTRAINTS ON LASER SHOCK EXPERIMENT

This section identifies the constraints on target thickness, area and laser pulse length which assure generation of a steady shock entering cold material. The combined effect of these constraints is to limit the range of pressures accessible for a given laser energy.

A first constraint is required to assure that edge rarefactions do not interfere with the high pressure region in the shock front (see Figure 5). If one wishes to observe a uniform shock wave arriving over an area $A_0 = \pi R_0^2$ on the rear surface of the target, it is necessary that the laser light

AVOID RAREFACTION FROM
EDGES BY SELECTING LARGE FOCAL SPOT

Fig. 5 It is necessary to select a large focal spot area in order to prevent edge rarefactions from reducing the shock pressure observed on the target rear surface.

RAREFACTION BEHIND SHOCK

- Short pulse allows pressure release
- Possible decoupling of critical surface
- Prepulse can destroy front surface
- Energy loss to sides weakens shock

Fig. 6 When the laser pulse ends, a release wave (dotted) is launched; it rapidly moves to overtake the shock and reduces the pressure. If the critical-density surface becomes decoupled from the ablation region, this problem might occur during the laser pulse.

cover a larger area $A = \pi (d+R_g)^2$ on the front surface. (This estimate assumes that the edge rarefaction enters at an angle of approximately 45° , but whatever the angle the focal spot area A is proportional to d^2 for thick targets.) If this condition is met, edge rarefactions do not perturb the pressure in the central part of the shock wave.

This condition becomes a difficult constraint for thick targets because it requires coverage of a large focal spot. In addition, it is necessary that the laser beam give spatially uniform irradiation over the focal spot in order to produce a planar shock.²⁰ Thermal conduction in the laser absorption region is able to reduce modest spatial variations of the laser intensity.

The second constraint is required to obtain a steady shock whose velocity remains constant as it traverses the sample. The space-time graph of Figure 6 shows the trajectory of the release wave (rarefaction) which begins at the front surface when the laser intensity drops. This rarefaction travels at the sound speed in the shocked material; i.e., faster than the shock. Once it overtakes the shock, the peak pressure begins to decline resulting in an unsteady shock. An accurate measurement of the shock speed is only possible if the rarefaction does not overtake the shock before it reaches the rear surface of the sample.

A simple estimate (including the particle velocity of the shocked material) shows that the release wave does not overtake the shock at depth d if the driving pressure persists for a time $\tau > d/2D$. For strong shocks, the shock speed D is approximately proportional to the square root of the pressure P . The inequality $\tau > d/2D$ requires a long laser pulse for a thick target.

There may be problems in achieving a continuous (steady) driving pressure even if the laser is able to produce a long pulse. Potential troubles include fluctuations (spiking) in the laser output, decoupling of the critical surface, and other energy loss mechanisms which may remove energy from the focal spot during the laser pulse.

The third constraint, most difficult of all, is imposed by the need to avoid hot electron preheat and its deleterious effects (Figure 7). The hot electrons are generated in the process of laser absorption with energies between 2 keV and 200 keV. A fraction of these electrons penetrate into the sample at speeds much greater than the shock speed. These electrons raise the sample temperature almost simultaneously with the rise of the laser pulse; at any point in the sample the preheat temperature is proportional to the total laser energy absorbed. The manner in which the preheat temperature decreases with depth

HOT ELECTRON PREHEAT AHEAD OF SHOCK:

- Hugoniot displaced by $\Delta T, \Delta \rho$
- Average shock speed is reduced slightly
- Shock traversing preheat is not steady
- Rear surface destroyed (thin target)
- Preheat launches precursor shock (thick target)

Fig. 7 Space-time plot showing region ahead of shock which is affected by hot-electron preheat. In a very thick target, there is the possibility of a precursor shock launched by preheat.

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into the sample is controlled by the range-energy relation for the superthermal electrons.

It is useful to set a criterion for the severity of preheat. One might be tempted to compare the preheat temperature with the initial temperature of the sample, but this condition is much too severe. It is shown below that the correct criterion is obtained from the ratio $T_{\text{preheat}}/T_{\text{shock}}$ of preheat temperature to shock temperature.

The problems produced by preheat include the following:

- a. The preheat displaces the Hugoniot locus; i.e., the density and pressure produced differ from those expected from a shock of the same pressure entering cold material. An approximate formula for this displacement is given below.
- b. The speed of a shock traversing preheated material is different from that of a shock (at the same pressure) traversing cold material. However, this velocity change is small; i.e., second order in the temperature ratio $T_{\text{preheat}}/T_{\text{shock}}$.
- c. The preheat is formed with a spatial variation arising from the energy loss of the original hot electrons. The shock traverses this spatially non-uniform layer and leaves behind material with corresponding non-uniform density and temperature. The material behind the shock oscillates until its inhomogeneities are smoothed. If these oscillations are severe, they interfere with generation of a steady shock.
- d. For relatively thin targets, the preheat temperature may exceed the melting temperature of the target material. The rear surface of the target is then subject to hydrodynamic disassembly. If the rear surface expands, the observed shock may have properties (arrival time, temperature, or pressure) significantly different from those it had in the bulk.
- e. For experiments at very high pressures (~ 100 Mbar), where thick targets are necessary to avoid major preheat perturbation, the preheated material is raised to a high temperature (~ 50 - 100 eV) and can launch a precursor shock ahead of the main shock wave.

In a well-designed experiment, conditions are adjusted so that preheat is a small perturbation on the Hugoniot measurement. The size of the perturbation resulting from a specified

level of preheat can be estimated as follows: assume that preheat raises the temperature of the target without changing its density, and assume further that the shock pressure is fixed. It is straightforward to apply the Hugoniot relations to connect the final (shocked) density or energy to the preheat temperature. The relation which results is (see Figure 8)

$$\frac{\Delta E}{\Delta E_0} = \frac{1 + \frac{1}{2}(\rho - \rho_0) (\partial P / \partial E)_0 / (\rho_0 \rho)}{1 + \frac{1}{2}(p_s + p_0) (\partial P / \partial E) / (\rho^2 \partial P / \partial c)} \quad (2)$$

where ΔE is the change in final state energy (with respect to a shock of the same pressure entering cold material) and ΔE_0 is the energy per gram associated with the preheat; p and p_0 are the shocked and initial pressures. The righthand side of this equation is 1.5 - 2 for tabular equations of state or for ideal gases. In effect, 1/2 eV of preheat simply raises the shock wave temperature by 1/2 eV. In order to perform experiments with an accuracy of a few percent at pressures above 10 Mbars, the preheat must be kept below about 1/10 of an eV. If this condition is satisfied, rear surface disassembly is also reduced to a minor problem.

The computer code⁴ provides numerical calculation of hot electron generation, transport energy loss and heating of the target. The code also simulates the hydrodynamic disruption (d. or e. above) produced by the preheat. It is useful to extract crude analytic formulas in order to establish the trends which govern shock-wave target performance. For this purpose, we can combine the computed scaling of hot electron temperature with well-known range-energy relations (Fig. 9).

The hot electron temperature T_{hot} (keV) for laser intensity I (in units of 10^{14} watts per cm^2) may be written (the expression given applies to Nd-glass laser radiation):

$$T_{hot} \approx (2.6 \text{ keV}) (I)^{.425} \quad (3)$$

While the hot electron temperature is given by the above equation, the hot electrons responsible for the preheat in the rear portion of the target have energies about $5 kT_{hot}$. (This conclusion follows from numerical analysis of the preheat.) The calculated preheat is approximately described by an equation for the preheat temperature T_e

$$T_e = \eta \frac{I \cdot t}{C_v} \phi(x) \quad (4)$$

where η is the hot electron production efficiency, I is the peak laser intensity, t is the time that the laser has been on, C_v is a material specific heat (constant density) and $\phi(x)$ is approximately

PREHEAT DISPLACEMENT OF HUGONIOT LOCUS

Assume: Fixed initial density ρ_0
 Fixed shock pressure p_s
 $p = p(\rho, E)$

$$\frac{\Delta E}{\Delta E_0} = \frac{1 + \frac{1}{2}(\rho - \rho_0) \left(\frac{\partial p}{\partial E_0} \right) / \rho_0 \rho}{1 + \frac{1}{2}(p_s + p_0) \left(\frac{\partial p}{\partial E} \right) / \left(\rho^2 \frac{\partial p}{\partial \rho} \right)}$$

≈ 2 for ideal gas

≈ 1.5 for aluminum tabular EOS

$\frac{1}{2}$ eV of preheat raises T_s by $\frac{1}{2}$ eV

Fig. 8 Equation for final specific energy with (ΔE) and without (ΔE_0) preheat.

$$p(x) \sim e^{-x/R}$$

The range R extracted from the computer calculations is then approximately the range of electrons having energy $\sim 5 kT_{\text{hot}}$. Close to the front surface, the typical hot electron energy is smaller ($\sim kT_{\text{hot}}$), and at greater depths in the sample, very low preheat temperatures are produced by the few electrons having still higher energies.

In the next section this scaling of preheat is combined with other constraints to identify the laser energy requirement for strong shock experiments.

6. SCALING LAWS FOR HOMOGENEOUS TARGETS

We have seen that three interrelated problems must be overcome to generate clean, strong shocks. In each case a solution is possible by raising laser energy.

Hot electron preheat preceding the shock causes the measured Hugoniot to be displaced from the desired principal Hugoniot. The straightforward solution to this problem is to absorb the preheat in a thicker target. The required target thickness d must exceed $R(E)$, the hot electron range, for electron energies $E \sim 5kT_{\text{hot}}$. The range-energy relation,²¹ combined with the dependence of T_{hot} on laser intensity I then results in

$$d \gg R(E) \sim T_{\text{hot}}^2 \sim I^{0.85} \sim p \quad (5)$$

where the last proportionality is deduced from the observed scaling of peak pressure with laser intensity (section 3). In order to avoid preheat, the target thickness must rise proportional to the desired pressure.

The second problem is the release wave which begins at the end of the laser pulse and moves to overtake the shock wave. The straightforward solution to this problem is to require the laser pulse length τ to be long enough so that

$$\tau \geq d/2D \quad (6)$$

where d is the target thickness and D is the shock speed, proportional to the square root of the pressure. For high pressures, d is large and Eq. (6) requires a long pulse and therefore a large laser energy.

Finally, the focal spot area A must increase (proportional to d^2) in order to prevent edge rarefactions from reducing the pressure.

The total energy the laser must supply is determined by the peak intensity I , area A and pulse length τ according to

$$E = I \cdot A \cdot \tau \quad (7)$$

Combining the above scalings, one finds (Fig. 10)

$$E \propto p^4 \quad (8)$$

To produce twice the pressure, one requires 16 times the laser energy. This is not the energy required to produce the high pressure per se; the scaling law gives the energy required to produce the pressure in the form of a clean, steady shock wave entering cold material.

Although three successive LLL lasers have delivered energies 10 times larger than their predecessors, the scaling expressed by the relation (8) shows that even the largest laser cannot freely explore the realm of very high pressures when used with homogeneous targets. (See section 7 below.)

Figure 11 shows a calculation for a thick target (50 μm of aluminum) which supports the conclusions drawn above. The quantity plotted is the temperature as a function of time for 9 positions in the target (the positions are initially 5 μm apart). The laser remains at an intensity of 2×10^{14} W/cm^2 for the time interval from 300 psec to 900 psec; the laser intensity has dropped to zero at 120 nsec.

It is easy to distinguish the linear temperature rise caused by preheat in the first few zones ($x < 25$ μm) from the sharp temperature rise associated with the shock itself. Two features are immediately apparent:

- 1) The contrast between shock and preheat is much better at the 45 μm position near the rear surface, and
- 2) The shock jump is roughly constant as it rides over the preheat, so that the post-shock temperature is the sum of the preheat temperature and this constant. (This illustrates the rule of thumb given in section 5.)

It is interesting to observe that the temperature continues to rise for the forward zones ($x < 25$ μm) even after the shock has passed. This temperature rise can be described as "post-heat", i.e., deposition of energy by superthermal electrons generated after the shock passes the zone in question. The rear zones do not experience post-heating because the laser intensity falls after 900 psec.

SCALING OF HOT ELECTRON PREHEAT

Range $R(E) \approx 0.6 \mu (E/10 \text{ keV})^2$ for 10-100 keV

Hot electron temp $T_{\text{HOT}} \sim 2.6 \text{ keV} (I\lambda^2)^{.425}$

Preheat temp $T_e = \eta \frac{I \cdot t}{C_v} \phi(x)$

η = hot electron production efficiency

$\phi(x)$ is larger than $\exp(-x/R(T_{\text{HOT}}))$

Fig. 9 Simple approximate formulas for scaling of hot-electron preheat produced by a laser pulse of constant intensity I which has been applied for a time t .

DIRECT APPROACH REQUIRES LONG PULSE, LARGE LASER

Energy = $I \cdot A \cdot \tau$
 Intensity $\uparrow$ Area $\uparrow$ Pulse length $\nwarrow$

$$\begin{cases} I \sim p^{1.22} \\ A \gtrsim d^2 \\ \tau \gtrsim d/2D \quad D \sim \sqrt{p} \\ d \gtrsim R(E) \sim T_{\text{hot}}^2 \sim 1.85 \sim p \end{cases}$$

Gives $E \sim p^4$

Additional problem at high pressure from precursor shock launched by preheat

Fig. 10 The energy required to produce a clean steady shock, without preheat perturbation, rises proportional to the fourth power of the shock pressure.

GOOD CONTRAST OF SHOCK AND PREHEAT OBTAINED IN THICK TARGET

Fig. 11 Time-dependent temperature in zones which are 5, 10, ..., 40 and 45 microns into a 50 μ aluminum target. For the rear surface zones, the preheat perturbation is relatively small.

STRUCTURED TARGET OFFERS ADVANTAGES:

- Impedes preheat penetration.
- Acts as pusher to maintain shock
- Could reduce temperature near critical density
- Could increase hydrodynamic efficiency
- Thinner target implies smaller spot size and shorter pulse

Fig. 12 Conceptual design for a structured laser shock-wave target.

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Detailed inspection of this calculation shows that the rear part of the target experiences a 15 Mbar shock with less than 1/2 eV of preheat. These conditions appear to be comparatively favorable.

7. RESULTS WITH STRUCTURED TARGETS

In this section we examine the results obtained with a more elaborate target (Fig. 12). It will be shown that the presence of a tungsten layer leads to a dramatic improvement in target performance. Our initial examination of targets of this type was based on the hope of raising the hydrodynamic efficiency by ablating heavier material; in the final analysis, that is not the most important advantage of layered targets.

The targets considered here consist of thick aluminum foils. The side facing the laser has a thin layer (3 microns) of tungsten, covered with another two microns of aluminum. The outer layer is present in order to have the laser impinge on aluminum, for which the hot-electron generation is comparatively well-understood.

The computational analysis of targets in this category shows:

- The tungsten layer significantly reduces hot-electron preheat penetration.
- The massive tungsten acquires enough momentum to sustain the shock pressure for several hundred picoseconds after the end of the laser pulse. Energy deposition in the tungsten causes it to expand and exert pressure on the aluminum even after the first rarefaction enters the tungsten.
- One expects that material having so many electrons per atom will remain colder than aluminum and thereby cool the critical surface. This effect would (presumably) enhance the inverse bremsstrahlung absorption; however, no temperature difference is actually observed in the calculations.²²
- It is also a plausible conjecture that the heavier atoms ablate at lower velocities which should raise the hydrodynamic efficiency. This gain could not be detected in the computer output, probably because of the aluminum overlayer.
- The most significant result is that the target with a tungsten pusher achieves good shock-to-preheat contrast

in about half the thickness of the all-aluminum target. The implication of this result, according to Eqs. (5, 8) is a dramatic reduction in the energy required to achieve a given shock pressure.

To expand on this point, we observe that a factor of two reduction in target thickness d significantly reduces both the required pulse length and focal-spot area, and this leads to almost an order-of-magnitude reduction in the required laser energy.

This gain has been obtained mainly because the tungsten layer impedes penetration of hot electrons. However the tungsten also functions as a very effective pulse-stretcher; the computed shock pressures are extremely stable for as much as a nanosecond after the shock enters the aluminum. This is presumably caused by momentum storage in the tungsten as well as by the high pressure generated in the tungsten by electron energy deposition.

It is our belief that future laser-driven shock-wave experiments will find the advantages of layered targets to be irresistible.²³ However, there are significant practical difficulties in bonding flat thin layers of material with the exceptional tolerances required to conduct accurate measurements on the scale of tens of microns and tens of picoseconds. More generally, a high level of technical artistry is obviously necessary to perform accurate scientific studies of tiny specks of matter which have been heated to astrophysical conditions.

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REFERENCES

1. R. J. Trainor, J. W. Shaner, J. M. Auerbach and N. C. Holmes, Phys. Rev. Letters 42, 1154 (1979); L. Veaser and J. Solem, Phys. Rev. Lett. 40, 1391 (1978).
2. Portions of this work have previously appeared in Bull. A.P.S. 24, 720 (1979).
3. As a personal note, I recall that informal discussions on the use of large lasers for shockwave experiments occurred here in Rochester as early as 1975 (M. Lubin, E. Goldman, L. Goldman, E. Thorsos and R. More). Then as now, the critical question was the feasibility of obtaining accurate scientific data from laser experiments.
4. The calculations reported here were performed with several computer codes developed by G. Zimmerman and his collaborators. Partial description of these codes is given in the Laser Program Annual Reports for 1975 through 1978 (Lawrence Livermore Laboratory Rept. UCF-50021-75, UCRL-50021-76, etc.) See also G. B. Zimmerman and W. L. Kruer, Comments on Plasma Physics 2, 51 (1975).
5. J. Larsen, unpublished.
6. R. M. More, Phys. Rev. A 19, 1234 (1979).
7. C. E. Ragan III, M. G. Silbert, and B. C. Diven, J. Appl. Phys. 48, 2860 (1977) and more recent work (unpublished).
8. L. V. Al'tshuler, B. N. Moiseev, L. V. Popov, G. V. Simakov, and R. P. Trunin, Soviet Physics JETP 27, 420 (1968).
9. H. G. Ahlstrom, Lawrence Livermore Laboratory Rept. UCRL-79819 (1977) gives a thorough review of laser absorption phenomena.
10. G. E. Duvall, in Physics of High Energy Density, edited by P. Caldirola, Academic Press, New York, 1971.
11. S. I. McCarthy, Lawrence Livermore Laboratory Rept. UCRL-19364 (unpublished).
12. N. N. Kalitkin, Soviet Physics JETP 11, 1106 (1960).
13. Lawrence Livermore Laboratory Rept. UCRL-50021-77 (page 6-18) (1978).
14. Lawrence Livermore Laboratory Rept. UCRL-50021-76 (section 4-7.3) (1977).
15. G. B. Zimmerman and R. M. More, Lawrence Livermore Laboratory Rept. UCRL-81336 (1978).
16. I. Pelah, E. Thorsos and E. Goldman, unpublished.
17. Dr. C. Cranfill drew the author's attention to this possibility (private communication).
18. N. C. Holmes, R. J. Trainor and R. M. More, to be presented at the APS Plasma Physics meeting in November 1979.
19. R. Kidder, in Physics of High Energy Density, edited by P. Caldirola, Academic Press, New York, 1971.
20. Failure to achieve sufficient spatial homogeneity can drastically reduce the shock pressure attained (R. Schultz and L. Veaser, personal communication).

21. R. D. Evans, The Atomic Nucleus (Mc-Graw-Hill Book Co., New York, 1955), p. 624.
22. This idea was suggested to the author by M. Rosen.
23. Efforts to fabricate layered targets are underway in E-Division at the Lawrence Livermore Laboratory.

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