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CONTRASTS IN ONE- AND TWO-DIMENSIONAL HYDROCODE CALCULATIONS OF LASER-GENERATED SHOCKWAVES IN DISK TARGETS*

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ABSTRACT

A comparison is made between 1D and 2D hydrocode calculations and some recent experimental results on laser-driven planar shockwaves in disk targets. A simple model is described which accounts for the trends seen in the calculations and which gives insight into the regime of laser intensity and pulse duration where two-dimensional effects become significant in these experiments.

INTRODUCTION

At Lawrence Livermore National Lab high power laser systems such as Janus and Shiva have been used to generate ultra-high pressure shockwaves in disk targets. To analyze the experiments we have done both one-dimensional (1D) and two-dimensional (2D) simulations using the Lasnex laser-plasma-hydrodynamics computer code. A very great savings in computer time and expense is realized in the 1D calculations, relative to the 2D ones. However, in cases involving long-duration laser pulses and high laser intensities we find that the 1D results are not sufficiently accurate even when

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necessary conditions¹ for generating 1D, i.e., planar, shockwaves are met; see, for example, Figure 1. The reason lies in the two-dimensional nature of the blowoff plasma; the laser-generated shock is quasi-1D with regard to its propagation through the disk when the 1D conditions are satisfied, but 2D effects can still be important in its generation.

SIMPLE MODEL

We can understand the need for 2D computations on the basis of a simple model of the laser-target interaction, sketched in Figure 2. The effective cross sectional area A that the target presents to the laser beam is postulated to be, not the laser spot area A_0 at the original surface of the disk, but rather the area of the critical density surface intercepted by the converging laser rays at the time $t=t_{\text{peak}}$ of peak laser pulse. A exceeds A_0 by a factor $[1 + (\ell_{ac} \sin \theta / R_s)]^2$ (see the caption of Figure 2 for definition of terms) which depends on the laser pulse duration τ_L and nominal peak intensity I_0 through ℓ_{ac} . The effective value of the laser incident intensity is decreased in the ratio A_0/A compared to I_0 , and consequently the peak value of the laser-driven shock pressure, P_s , which scales as I^n , $n \approx 0.7$, is decreased by this two-dimensional effect.

The distance ℓ_{ac} separating the ablation surface and the critical surface is approximately given by the product of the laser pulse duration and the sound speed in the ablating plasma, and thus should vary as $\ell_{ac} \approx \ell_{ac}^{(0)} \tau_L^\beta I_0^\alpha$; from Lasnex calculations for 1.06 μm laser light we find $\beta \approx 0.9$, $\alpha \approx 0.3$. The peak value of the laser shock pressure, corrected for 2D effects, is then predicted by this model to be

$$P_s \approx a I_0^n \left/ \left[1 + \frac{\ell_{ac}^{(0)} \sin \theta}{R_s} \tau_L^{0.9} I_0^{0.3} \right]^{2n} \right. \quad (1)$$

where $n \approx 0.7$, and the coefficient a has a value of about 8 (depending weakly on τ_L and target composition and more strongly on laser wavelength, which we set to 1.06 μm), $\ell_{ac}^{(0)} \approx 120$ for Al vapor and 1.06 μm light, and the units employed are Mbar (1 Mbar = 0.1 TPa) for P_s , 10^{14} W/cm^2 for I_0 , ns for τ_L , and μm for ℓ_{ac} and the spot radius R_s .

Equation (1) has not been exhaustively checked against hydrocode calculations covering a wide range of values for I_0 , τ_L , and R_s , but we offer the following two comparisons. First, Eq. (1) predicts a ratio 3.7 for the 2D vs 1D calculations pertaining to the Shiva experiment² in Figure 1, which is in respectable agreement with the actual value of $90 \text{ Mbar}/149 \text{ Mbar} = 0.6$. Second, in Figure 3 we show 1D and 2D computations of P_s over a wide range of I_0 values for a set of problems involving 0.6-ns Gaussian-shaped laser pulses incident on 72 μm -thick Al disk targets with spot radius $R_s = 256 \mu\text{m}$ and ray convergence angle $\theta = 22^\circ$. Eq. (1) is seen to track the 2D results fairly well over nearly the entire range of

intensity. For such a set of problems (having fixed values of R_s and θ) we can use the model to divide the I_0 - τ_L plane into regions where the 1D and 2D results agree within a certain tolerance, as shown in Figure 4.

CONCLUSION

In conclusion, the simple model provides physical insight and semi-quantitative information regarding the onset of two-dimensional effects in laser shockwave experiments, and allows one to estimate when 1D calculations suffice. We note in passing that the model provides some justification for the often-used calculational expedient of replacing the cylindrically symmetric disk by a spherical cap of suitably chosen radius of curvature.

REFERENCES

1. These conditions are that the laser spot diameter is large compared to the disk thickness, the distribution of laser intensity throughout the spot area is uniform, and the target surfaces are very smooth and flat.
2. D. L. Banner, R. J. Harrach, N. C. Holmes, Y. T. Lee, D. W. Phillion, M. D. Rosen, and R. J. Trainor, "Ultra-high pressure laser-driven shocks in gold," Laser Program Annual Report-1980, Lawrence Livermore Lab report UCRL-50021-80, 1981.

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9

Fig. 1. Comparison of measured (Ref.2) and calculated transit times for laser-driven shockwave in a composite Al/Au gold disk target of thickness (22/50) 72 μm (Al side towards the laser). The peak laser incident intensity and pulse duration are 27 (10^{-4} W/cm²) and 0.60 ns, respectively. The 2D calculation predicts a peak shock pressure of magnitude 90 Mbar just inside the gold layer, decaying to a level of about 32 Mbar after propagating through the target; corresponding numbers for the 1D calculation are 149 Mbar and 54 Mbar. The 2D and 1D calculations required 350 and 29 minutes of CDC 7600 computer time, respectively. By adjusting the amount of laser energy absorbed, the 2D calculation could be brought into close agreement with the two experimental points.

Fig. 2. Schematic diagram of the laser-target interaction, showing the critical surface, where the density of free electrons equals the critical density $n_c(\text{cm}^{-3}) = 10^{21}/[\lambda(\mu\text{m})]^2$, the ablation surface, and the plasma blowing off into the converging incident laser rays. ℓ_{ac} is the distance separating the ablation and critical surfaces. For converging laser rays θ is approximately the ray cone half-angle; for normally incident rays, θ is a more complicated function depending on the amount of beam refraction and the plasma blowoff angle.

Fig. 3. Comparison of predicted values of the peak shock pressure P_s based on 1D and 2D hydrocode calculations and on the simple model result, Eq. (1), for a set of problems involving 0.6-ns Gaussian-shaped pulses incident on 72- μ m-thick Al disk targets with fixed values of the laser spot radius ($R_s = 256$ μ m) and ray convergence half-angle ($\theta = 22^\circ$). The 1D calculations are fit by the dashed line given by $P_s = 8.0 (I_0)^{0.7}$, with P_s in Mbar and I_0 in units 10^{14} W/cm 2 . Our 2D results show large scatter for lower intensities (left side of the graph) for reasons as yet undetermined.

Fig. 4. Diagram of laser incident intensity vs pulse duration corresponding to the results in Figure 3, showing contours within which the 1D and 2D calculations of P_s are expected to agree within a specified amount.