LA-5444-MS

INFORMAL REPORT

Symmetry of Laser Driven Implosions

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $4.00; Microfiche $1.45

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

LA-5444-MS
Informal Report
UC-20
ISSUED: October 1973

Symmetry of Laser Driven Implosions

by

D. B. Henderson
R. L. Morse

SYMMETRY OF LASER DRIVEN IMPLOSIONS

by

D. B. Henderson and R. L. Morse

ABSTRACT

The achievement of significant nuclear energy yields from laser heated pellets of thermonuclear fuel requires that the fuel be compressed to at least several orders of magnitude above initial density. Such compressions can be attained by spherical implosions, but because of the large compression ratios required, these implosions must be highly symmetrical. Calculations of the behavior of imploding spheres and shells by a spherical harmonic perturbation method, and by two dimensional hydrodynamic codes within their limitations, have shown the importance of electron thermal conduction in the low density ablation cloud of a pellet in bringing about the required symmetry. These calculations show that at early time in the heating of a pellet when the ablation cloud is relatively small and cold, the symmetry requirements are most severe and call for as many as four laser beams. However, symmetry requirements at later times, when most of the laser energy must be deposited, may be met by as few as one beam.

I. INTRODUCTION

It has been shown by one-dimensional, spherically symmetric numerical simulations that spheres[1,2] or shells[2] of thermonuclear fuel heated by laser pulses with as little as one kilo-joule of absorbed energy may return more than this amount of nuclear energy if the laser pulse compresses the fuel to 10^3 or 10^4 times solid density. These large compression ratios are made to occur by timing the deposition of laser energy onto the outside of the spherical pellet of fuel in such a way as to cause sufficient ablation pressure to drive a strong spherical implosion. Electron thermal conduction is the process by which most of the absorbed laser energy is transported from near the critical surface in the ablated or "blow off" region, where it is absorbed, to the surface of the high density core of the pellet where ablation occurs. In order that full use be made of the advantages of the converging character of the implosion, the ablation pressure at the surface of the high density core must be sufficiently spherically symmetric. This, in turn, places symmetry requirements on the irradiation of the outer surface of the pellet. To analyze these requirements, as well as to anticipate some hydrodynamic instability problems which can occur during implosions, we have developed a linear perturbation method and have applied it to representative laser driven implosions.

II. PERTURBATION EQUATIONS

The unperturbed, or zero order, flow is a purely radial, angle independent flow. The method, though constructed to work in concert with zero-order Lagrangian computations, is fundamentally Eulerian in the sense that first order quantities are defined at zero order positions, i.e., on unperturbed trajectories. It is, however, useful to introduce the perturbed displacement, $\bar{\xi}$, defined through

$$\frac{d\bar{\xi}}{dt} - (\bar{\xi}\cdot\bar{\nabla})\,\bar{v}_o = \bar{v}_1 \qquad (1)$$

where $\bar{v}_o(\bar{r},t)$ and $\bar{v}_1(\bar{r},t)$ are zero and first order velocity, respectively. Linearizing Euler's equation with respect to pressure, density, and velocity gives

$$\frac{d\bar{v}_1}{dt} + (\bar{v}_1\cdot\bar{\nabla})\,\bar{v}_o = -\frac{\rho_1}{\rho_o}\frac{d\bar{v}_o}{dt} - \frac{\bar{\nabla}p_1}{\rho_o} \equiv \bar{a}_1 \,. \qquad (2)$$

The perturbed density is then

$$\rho_1 = -\vec{\xi}\cdot\bar{\nabla}\rho_o - \rho_o\bar{\nabla}\cdot\vec{\xi} + \frac{\rho_o}{\rho_{oI}}\rho_{1I} \equiv \rho_{1C} + \rho_{1L}, \tag{3}$$

and perturbed pressure, temperature, and other auxiliary state variables are given by expressions of the form

$$p_1 = -\vec{\xi}\cdot\bar{\nabla}p_o + \rho_{1L}\left(\frac{\partial p}{\partial \rho}\right)_s + S_{1L}\left(\frac{\partial p}{\partial S}\right)_\rho \equiv p_{1C} + p_{1L} \tag{4}$$

$$T_1 = -\vec{\xi}\cdot\bar{\nabla}T_o + \rho_{1L}\left(\frac{\partial T}{\partial \rho}\right)_s + S_{1L}\left(\frac{\partial T}{\partial S}\right)_\rho \equiv T_{1C} + T_{1L}$$

where I, C, and L denote initial, convective, and local parts, respectively. The specific entropy, S, and the density, ρ, are taken to be the independent state variables. The local entropy, S_{1L}, is then advanced according to

$$\frac{dS_{1L}}{dt} = \frac{1}{\rho_o T_o}\left[\frac{dQ_1}{dt} - \left(\frac{\rho_{1L}}{\rho_o} + \frac{T_{1L}}{T_o}\right)\frac{dQ_o}{dt}\right] \tag{5}$$

where Q_1 is obtained from the perturbed viscous dissipation, external heat sources, and heat flow, the last being described by

$$\frac{dQ_{1\kappa}}{dt} = \bar{\nabla}\cdot(\kappa_1\bar{\nabla}T_o + \kappa_o\bar{\nabla}T_1). \tag{6}$$

The Landshoff-Spitzer[3] κ and the ideal gas equation of state are used in the calculations below.

When all first order quantities are assumed to have the form $\rho_1(\bar{r},t) = \rho_1(r,t)Y_{\ell,m}(\Omega)$, Eq. 2 can, after some integrating, be put in the form

$$\frac{dA}{dt} = a_1\Big/\left(\frac{dr_I}{dr}\right),\ v_{r1} = \left(\frac{dr_I}{dr}\right)A \tag{7}$$

$$\frac{dB}{dt} = \left(\frac{dr_I}{dr}\right)^2 A,\ \xi_r = B\Big/\left(\frac{dr_I}{dr}\right)$$

$$\frac{dC}{dt} = \ell(\ell+1)p_1/\rho_o\ ,\ C = r^2(\bar{\nabla}\cdot\bar{v}_1)_\Omega$$

$$\frac{dD}{dt} = C/r^2\ ,\ D = (\bar{\nabla}\cdot\vec{\xi})_\Omega\ ,$$

Eq. 6 becomes

$$\frac{dQ_{1\kappa}}{dt} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(\kappa_1\frac{\partial T_o}{\partial r} + \kappa_o\frac{\partial T_1}{\partial r}\right)\right] - \frac{\kappa_o}{r^2}\ell(\ell+1)T_1, \tag{8}$$

and Eqs. 3, 4, and 5 are unchanged except that now all first order quantities are coefficients of a particular $Y_\ell^m(\Omega)$. We have found, therefore, that if the viscosity and thermal conductivity are scalar, the equations of motion for different ℓ's decouple and are degenerate with respect to m, with obvious important advantages for computation and interpretation.[4,5,6] A three-dimensional analysis, not two-dimensional as in (r,z) hydro-codes, is obtained with about the complexity and computational cost of a one-dimensional calculation. The scalar assumption requires that we be justified in ignoring thermoelectric effects and off-diagonal viscous stress tensor elements, assumptions which seem reasonable in many cases of interest. It is noteworthy that taking only the angular thermal relaxation term from Eq. 8 and the assumed form $T_1 \sim e^{-t/\tau}$ gives an angular symmetrising time

$$\tau = \frac{3}{2}\ \frac{k(n_e + n_i)r^2}{\ell(\ell+1)\ \kappa_o} = \frac{3.2\times 10^{-10}\ (n_e + n_i)\ r^2\ \ell\ \Lambda_{ei}}{T(ev)^{5/2}\ \ell(\ell+1)} \tag{9}$$

which can be as small as 10^{-12} sec/$\ell(\ell+1)$ for some situations which arise in laser fusion work. A computer code has been written which integrates the above equations selfconsistently with the zero order equations.

III. ABLATION PRESSURE SYMMETRY

In this letter the equations derived above are used to show the important result that electron thermal conduction in angular directions can have a very powerful effect in making ablation surface pressures, and thus implosions, much more symmetrical than the deposition of laser energy at the critical surface. Whether a pellet starts as a sphere or shell, ablation pressure forms a shell of higher than initial density and somewhat smaller thickness than radius, just inside the ablation surface. If the pressure is assymetric, then parts of this shell will reach the center ahead of others and may prevent the achievement of the necessary high densities. It is then necessary that the distortion, $\delta_{R,\ell}$,

$$\delta_{R,\ell} \equiv \frac{\int_0^{t_{final}} dt \; v_{r1,\ell}(r_s)}{\int_0^{t_{final}} dt \; v_{ro}(r_s)} \approx \frac{1}{r_{sI}} \int_0^{r_{sI}} dr_s \, \frac{v_{r1,\ell}(r_s)}{v_{ro}(r_s)}, \qquad (10)$$

be sufficiently small for all ℓ-numbers. The dr integration is in the sense that $dt = dr_s/v_{ro}(r_s)$ and r_s is the instantaneous radius of the shell. The distortion represents the ratio of the perturbed motion of the shell to the initial shell radius, r_{sI}. The allowed distortions may be as large as 0.1 for pellets (spheres or shells) which are not to be too highly compressed. But for shells of large aspect ratio (radius to thickness) they must be much smaller. It is impossible to be more precise without considering cases individually, but it will be clear that important general conclusions can be reached from simply requiring $\delta_R \lesssim 0.1$.

An impulse approximation is now applied in which various idealized sets of $\rho_o(r)$, $T_o(r)$ profiles of Deuterium-Tritium mixtures are assumed and held fixed in time, on the grounds that they do not change significantly during the time of interest for the required first-order calculations. (Calculations with self consistent zero order flows have shown the important additional result that the ablation process is itself positively stable.)

The four zero order cases used here are the two forms, I and II in Fig. 1,* with two different

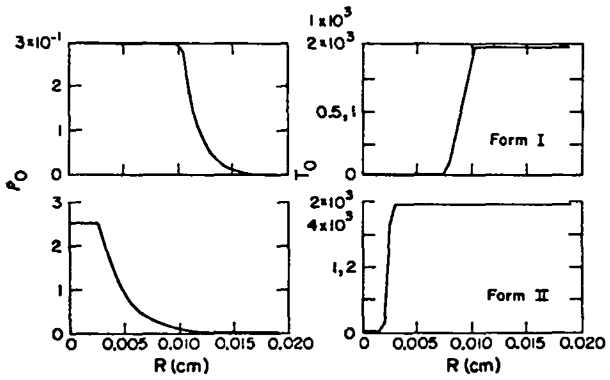

Fig. 1. Zero order density, temperature profiles. Note two temperature scales for each form.

*The units throughout are c.g.s.; temperatures are in ev.

temperature scales each. In both $r_{crit} = 2 \times 10^{-2}$ cm (where $\rho_{crit} = 5 \times 10^{-3}$ g/cm^{-3}). In I the ratio of ablation to critical surface radii is seen to be two, typical of earlier times; in II the ratio is eight. These density profiles have filled centers but are thought of for present purposes, which do not directly involve the center, as representing a variety of more or less hollow profiles. The temperature is then given the same initial perturbation, $T_1(r,t = 0)$, localized near r_{crit} for all ℓ. This perturbation corresponds for $\ell = 0$ to an increment of the zero order absorbed energy and for $\ell > 0$ to an asymmetry of the absorbed energy which is equal in amplitude, i.e., where the $Y_\ell^m(\Omega)$'s $= \pm 1$, to the $\ell = 0$ increment. The contribution of the absorbed energy input asymmetry at the time represented by the chosen ρ_o, T_o profiles to the asymmetry of the system at a given ℓ can be estimated by taking the ratio of the $\ell(>0)$ and $\ell = 0$ linear responses of the system for the given $T_1(r,t = 0)$ to be the asymmetry resulting from 100% input asymmetry at that ℓ. In particular the ratio $v_{r1,\ell}/v_{ro}$ in Eq. 10 is taken to be the value of $v_{r1,\ell}/v_{r1,0}$ at the shell, obtained after the impulse contributions of $T_1(r,t = 0)$ to the ablation driven implosion has occurred. The asymmetry caused by smaller input modulations is then scaled down from this value. Note that $Y_\ell^m(\Omega)$ has ℓ or more maxima, depending on m, which may indicate the correspondence to the number of incident beams.

A large number of overlapping focal spots may give quite small absorbed energy modulation, depending on the spot size and nonnormal absorption efficiency. However, as the number of beams and dominant ℓ number are reduced to four or less, it will be difficult to reduce the modulation very much below 50% without the equivalent of rather unconventional optics.

Figures 2 and 3 show $\ell = 0$ and 4 responses of the Form II, $T_{o\,max} = 2$ keV, profiles to the $T_1(r,t = 0)$ shown in Fig. 1. Figure 2 shows a thermal wave propagating rapidly inward, giving increasing ρ_1 as it reaches regions of larger ρ_o, and causing only a small acoustic response until it reaches the ablation front and makes it's contribution to ablation by launching strong acoustic waves inward (implosion) and outward (blow-off recoil), at about $t = 4.0 \times 10^{-11}$ sec. The $\ell = 4$

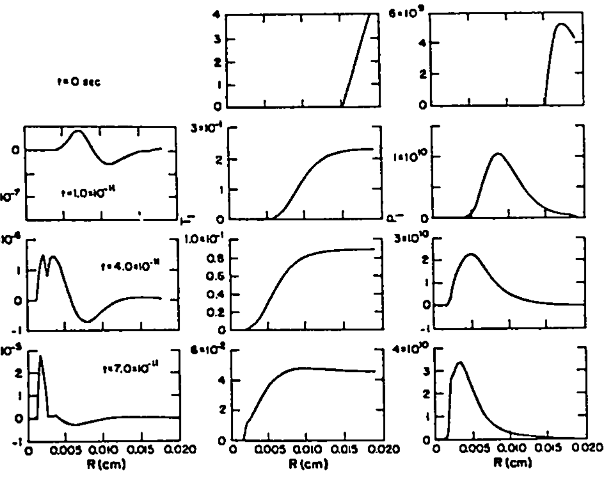

Fig. 2. Time sequences of first order quantities from Form II, 2 keV, ℓ = 0 calculation.

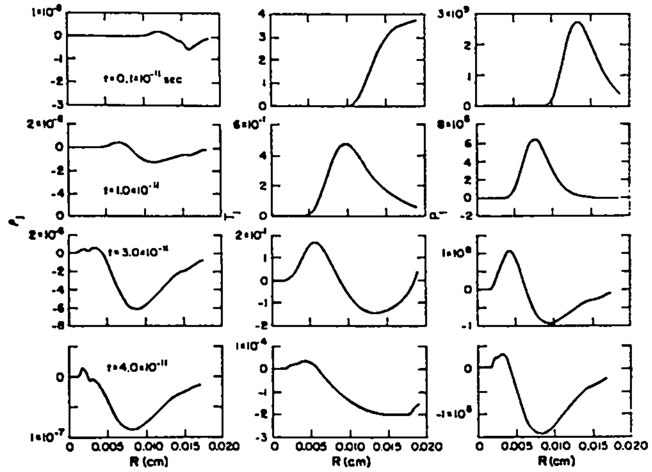

Fig. 3. Time sequences of first order quantities from Form II, 2 keV, ℓ = 4 calculation.

response, Fig. 3, shows the thermal and pressure wave being attenuated very strongly by angular thermal conduction, and to some extent by the angular acoustic response, the cause of large negative T_1's and p_1's being mostly acoustic. Figures 4 and 5 show the maxima over r of the $p_1(r)$ and $v_{r1}(r)$'s as a function of time for all four zero order profiles and assorted ℓ's. Figure 6 shows the history of positions of these negative maxima of the $v_{1r}(r)$'s for ℓ = 0 (the $\ell > 0$ curves are quite similar) from which one can see when the thermal wave reaches the ablation front and makes its essentially impulsive contribution to v_{r1} of the shell.

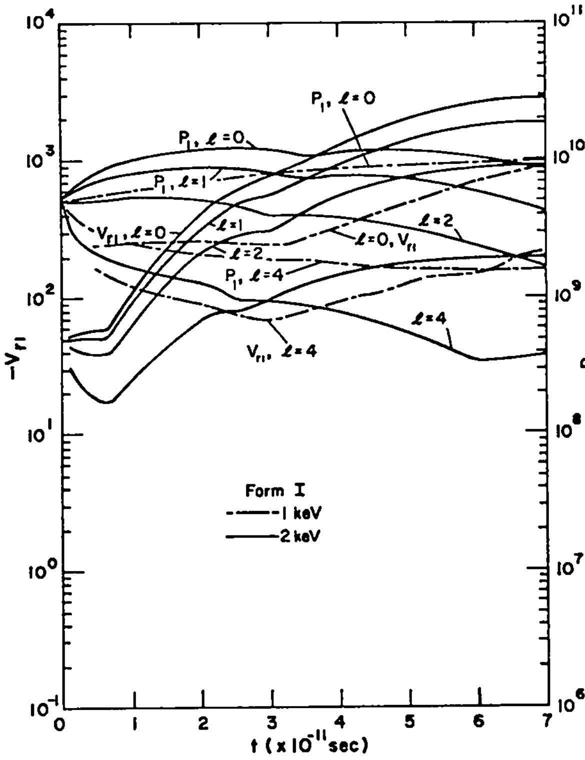

Fig. 4. Time histories of p, and v_{r1} maxima for Form I calculations.

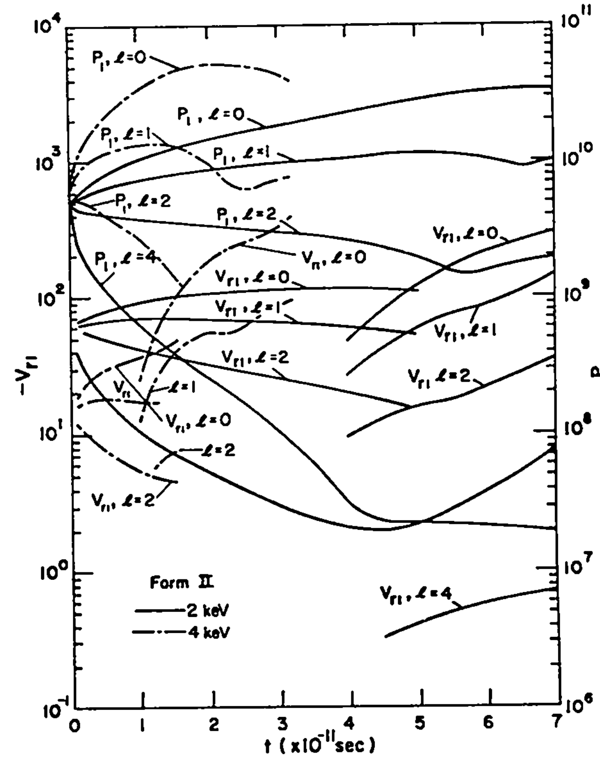

Fig. 5. Time histories of p, and v_{r1} maxima for Form II calculations.

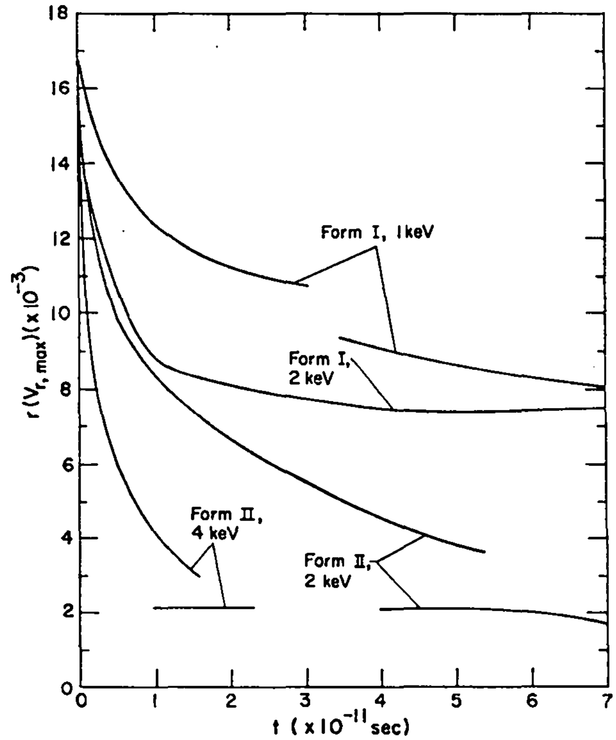

Fig. 6. Histories of radial positions of v_{r1} maxima from ℓ = 0 calculations; $\ell > 0$ positions are very similar.

From Figs. 4,5 and 6 one can see a general improvement in implosion symmetry in going to higher temperatures and larger ratios of ablation to critical surface radii, both associated with latter times in a given implosion. The improvement with increasing critical radius also strongly favors larger laser light wavelengths.

More particularly it is seen from Fig. 4 that energy absorption with 100% angular modulation is sufficiently smoothed by thermal conduction at early implosion times to give a contribution to the dr integration in Eq. 10 of 0.1 or less, only if ℓ = 4 or larger, whereas at later times and higher temperatures Fig. 5, ℓ = 2 symmetry is sufficient if not ℓ = 1. Moreover, ℓ = 1 perturbations are not in all cases disruptive since they may only shift the implosion center. Hence, within the limitations of this perturbation treatment and impulse approximation, we conclude that while the equivalent of four or more evenly spaced beams may be required to initiate an adequately symmetric implosion, the subsequent, and more intense, irradiation may be carried by as few as one beam.

REFERENCES

1. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature (London) 239, 139 (1972).

2. J. S. Clarke, H. N. Fisher and R. J. Mason, Phys. Rev. Lett. 30, 89 (1973), and 30, 249 (1973).

3. Rolf Landshoff, Transport Phenomena in a Mixture of Electrons and Nuclei, Los Alamos Report LA-334, July 23, 1945 (Reclassified Feb. 1962) (this is the earliest definitive work on electron thermal conduction); Phys. Rev. 76, 904 (1949); Phys. Rev. 82, 442 (1951); L. Spitzer, Physics of Fully Ionized Gases (Interscience, New York, 1956), Chap. V.

4. This method and preliminary results showing Taylor instabilities of time dependent zero order implosions were first presented to the laser fusion community at the January 4-5, 1973 AEC Laser Fusion Coordinating Committee Meeting at LLL, and appear in various internal LASL reports in November and December 1972.

5. The results given here were first presented at the Washington, D. C. APS Meeting, D. B. Henderson and R. L. Morse, Bull. Am. Phys. Soc. Ser. II. 18, 684 (1973).

6. This report is the text of talks to be presented at the Philadelphia APS Meeting, D. B. Henderson and R. L. Morse, Bull. Am. Phys. Soc. Ser. II 18, 1360 (1973) and R. L. Morse, Bull. Am. Phys. Soc. Ser. II. 18, 1359 (1973).

CM:344(120)