measurement of the group velocity $v_g = \Delta\omega/\Delta k \approx 10^6$ cm/sec in the vicinity of the resonant location. With p_x^{em} from the known incident power and horn radiation pattern, we obtain the reasonable value of 0.2 for the absorption coefficient, a.

The observed field geometry would appear to be inconsistent with a thermoelectric source. Since, at late times, ∇n is monotonic, the sign reversal of B as a function of axial position would require that ∇T reverse sign in one tenth the electron mean free path. Possible effects associated with the ambient magnetic field (measured as 0.4 G in the vertical direction) were ruled out by rotating the microwave horn to establish the independence of the self-generated fields from the ambient field.

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Dependence of Laser-Driven Compression Efficiency on Wavelength

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Efficiency of ablative implosion of laser-heated pellets is estimated from numerical simulations based only on classical thermal conduction. An inverse dependence of overall nuclear-yield ratio on wavelength is indicated in the visible and near-infrared range.

Extensive numerical simulations indicate the possibility of achieving energy breakeven (or better) from laser-driven spherical implosion of pellets containing thermonuclear fusion fuel.[1] Implosion is driven by ablation of material from the surface of a pellet by the absorbed laser energy. This energy is transported by thermal conduction from the surface of critical density, ρ_c, where it is absorbed from the incident laser light, through ablated material to the surface of the compressed pellet core, or ablation surface. For visible or infrared wavelengths λ, ρ_c is much less than the density of the pellet core and occurs in the low-density blowoff. For the Nd laser for which λ is 1.06 μm, the critical electron density is $n_{ce} = 10^{21}$ cm^{-3}, and in the compressed core, which is at solid densities or higher, $n_e \gtrsim 10^{23}$ cm^{-3}. The efficiency of a given laser fusion implosion and burn event may be thought of approximately as a time-ordered product

$$\eta_{LF} = \eta_L \eta_c \eta_H \eta_B, \tag{1}$$

where η_L is the laser efficiency.

We take the view that the power which is effectively absorbed into the pellet from the incident laser light is that power which is transported from the immediate vicinity of the critical surface, after losses through only partial absorption and any subclassical thermal conduction, and into the higher-density ablated material where mass and heat flow are classical. The efficiency of processes near the critical surface which convert incident laser power into this effective absorbed power, P, is η_c. The efficiency with which classical mass and heat flow then convert the absorbed power, P, through the ablation process, into internal energy of the compressed heated pellet core is η_H. The efficiency of conversion of this internal energy into usable energy output by thermonuclear burn in the pellet core is η_B. An overall energy gain, $\eta_{LF} > 1$, requires $\eta_B > 1$, and in general $\eta_B \gg 1$. Most theoretical studies of laser fusion have been concerned with details of the processes represented by η_c, and in particular with the dependence of η_c on λ, or they have assumed an effective absorbed power P, as we do below, and simulated the complete implosion-and-burn process which results. Such simulations, which effectively obtain the product $\eta_H \eta_B$, tend to obscure the role of η_H and its dependence on λ because of the sensitivity of η_B to details of pellet structure and pulse shape. The simulations reported here were done to isolate the dependence of η_H on λ suggested by Gitomer, Morse, and Newberger.[2] In Ref. 2, it is shown by a stationary-flow model of the classical thermal conduction and ablation process that, among other things, the absorbed laser power P required to provide a given ablation pressure and material ablation rate, and therefore a given implosion event, increases with decreasing ρ_c. This result is a consequence of the relatively larger radius of the critical surface when ρ_c is made relatively smaller, which results in a longer region through which the absorbed power must be conducted before reaching the ablation surface. In particular, Ref. 2 finds that, to a good approximation, the required power scales as $P \sim \rho_c^{-1/2}$ and therefore, since $\rho_c \sim \lambda^{-2}$, that $P \sim \lambda$. This is equivalent to $\eta_H \sim \lambda^{-1}$ because the hydrodynamic and heat-flow efficiency is inversely proportional to the effective absorbed power required to cause a given core implosion event. The indicated scaling would be very important for laser fusion research and development because a factor of approximately λ^{-1} would then multiply overall nuclear-yield ratios from laser-compressed pellets, and there are differences of an order of magnitude or more in the wavelengths of the different lasers being considered for this purpose.

We show that this scaling is applicable to a range of values of λ of interest in laser fusion research. The short-wavelength end of the range is simply determined by the requirement that ρ_c be less than the initial solid density of a pellet. Reasons can be given for keeping ρ_c at least a few times smaller than initial solid density. This requires that the critical electron density be less than about 10^{23} cm^{-3} or that $\lambda \gtrsim 10^{-1}$ μm. The larger-λ end of the range of applicability must then be somewhat larger than $\lambda = 10^{-1}$ μm in order for the $\eta_H \sim \lambda^{-1}$ scaling to be important. This end of the range is determined by the validity of the stationary-flow model and occurs, as discussed in Ref. 2, where ρ_c is so small that the time required for material to flow from the ablation surface to the critical surface is no longer small compared to the implosion time. The following time-dependent, numerical simulation parameter study of laser-driven implosions indicates the existence of a range of approximate validity of the $\eta_H \sim \lambda^{-1}$ scaling, and the approximate location of the large-λ end of the range.

The simulation parameter study was done with a one-dimensional, spherical, Lagrangian hydrodynamics and heat-flow code. Absorbed laser energy is deposited at the critical density. This is a common assumption made in models in which hydrodynamics and heat flow leading to implosion are the subjects of interest rather than critical surface phenomena. In order to allow direct comparison to the model of Ref. 2 and to permit scaling the results to a wide range of physical cases, we have used an ideal-gas equation of state, in conjunction with a one-temperature model (for ions and electrons) and, in the expression for electron thermal conduction, we have used $\ln\Lambda = 5$. The target is a 10^2-μm-radius sphere of $Z = 1$, $A = 2.5$ material of initial density 1 g/cm^3. The scaling laws of hydrodynamics and one-temperature heat flow readily transform this case into one of higher or lower initial density and higher Z without changing the calculated efficiencies for a given pulse shape. It can be shown that any particular solution of these equations may be transformed into any other similar solution simply by changing the units (denoted by the customary variable notation with the u subscript) in which the solution is expressed, subject to the constraints

$$C_1 = r_u / V_u t_u, \quad C_2 = (m_A V_u^2 / kT_u) A/(1+z),$$
$$C_3 \equiv \frac{2}{3}\left[(1 \frac{m_A A}{(1+z)kT_0}\right]^{3/2} \frac{\kappa_0}{G(z)}\left(\frac{T_u}{T_0}\right)^2 \frac{T_0}{p_u r_u}, \tag{2}$$

where the electron thermal conductivity, κ, has been put in the form $\kappa = \kappa_0 (T/T_0)^{5/2}$, with κ_0 and T_0 constants, and M_A is the atomic-mass unit. Here, the C's are constants and are calculated for any family of similar solutions by substituting the units of the particular solution from which the others are to be obtained by scaling. The scaling flexibility would be considerably restricted in a mathematical sense by using a model with independent electron and ion temperatures, while the hydrodynamic motion in most cases of interest is very little changed by the two-temperature model.

It is clear that some choices of material, initial dimensions and density, and pulse power which satisfy Eq. (2), will scale any one of our solutions into cases in which other physical phenomena (in particular, collective plasma effects such as instabilities, resonant absorption, and profile modification) are important, while other choices give cases in which such phenomena are unimportant. In those cases in which the absorbed energy input from the laser is effectively modified by collective effects near ρ_c, which are represented by η_c in Eq. (1), our absorbed power P should be taken to be the modified value. In other respects the hydrodynamic and heat-flow efficiency effect which we show below is independent of collective plasma effects.

Constant-absorbed-power step-function pulses of a range of intensities are used. The laser pulse is never shut off in these calculations, but additional energy supplied to the pellet after peak compression is not included in the efficiency. Both more elaborate target and pulse shapes could have been used which would give much larger values of ρR. However, since the object of this study is only to show the dependence of the energy transfer to the imploded part of the pellet on ρ_c, a different, more complex choice of target and pulse shape would, if anything, reduce the generality of the results.

Figure 1(a) shows the peak value of $\int_0^\infty \rho dr$, called ρR, a common figure of a merit for spherical compression (see Ref. 1), for a range of absorbed pulse powers, and for the critical densities $\rho_c = 10^{-1}$, 10^{-2}, and 10^{-3}. Absorbed power P is given in units of watts per centimeter squared at the *initial* pellet radius. The slight rise of ρR for absorbed powers above 10^{16} W/cm^2, followed by a drop to the initial time value, occurs when the power becomes so large that the inward-moving thermal wave front begins to keep up with or outruns the converging shock, viz., the so-called "burn-through" limit. Note that at lower power $\rho R \simeq 0.04$, which is what one expects from a one-shock implosion. Here the effect of changing ρ_c and P is just to alter the shock timing. Figure 1(b) shows the internal energy at the time of peak ρR in that part of the pellet mass responsible for the innermost 80% of ρR. The use of this 80% prescription has been found to be a generally reliable procedure for identifying parameters of the

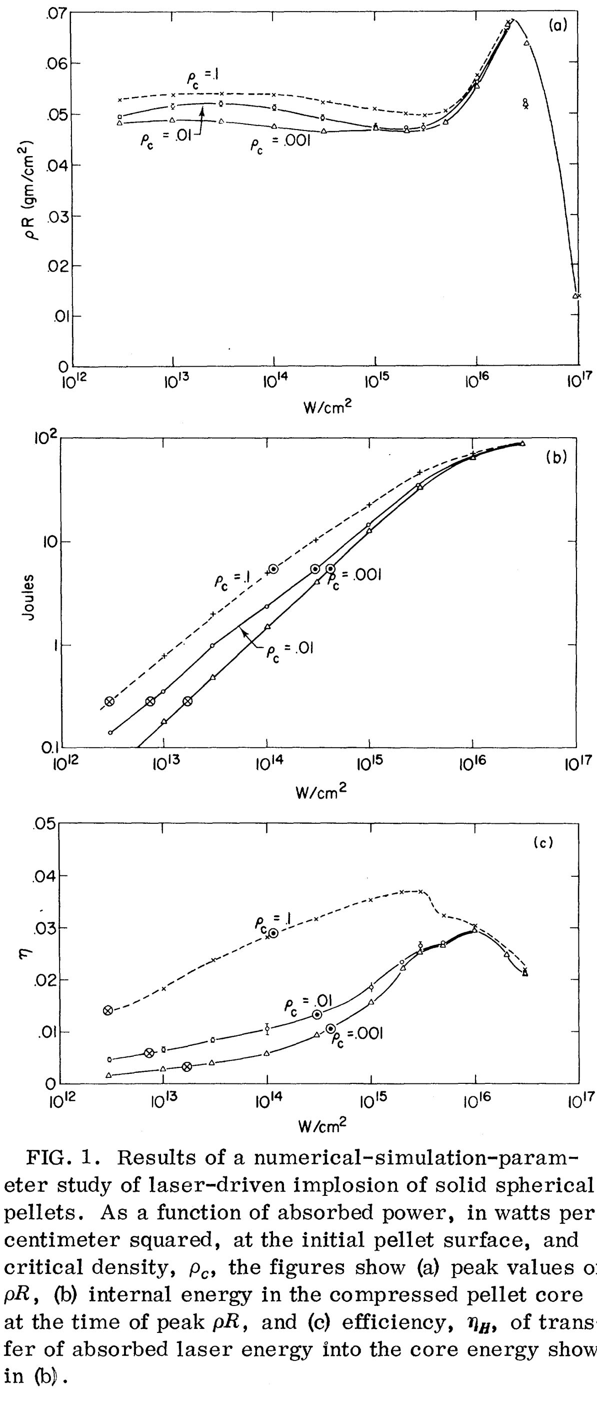

FIG. 1. Results of a numerical-simulation-parameter study of laser-driven implosion of solid spherical pellets. As a function of absorbed power, in watts per centimeter squared, at the initial pellet surface, and critical density, ρ_c, the figures show (a) peak values of ρR, (b) internal energy in the compressed pellet core at the time of peak ρR, and (c) efficiency, η_H, of transfer of absorbed laser energy into the core energy shown in (b).

compressed core, at least for the kind of simple target and pulse considered here. Examination of further details of the simulation results show, as would be expected, that in the lower-power range, where ρR vs P is nearly flat, cases with different ρ_c, which have the same internal energy in the core, are quite similar in all respects inside of the ablation surface. Two sets of such cases, three at 0.33 J of internal energy and different ρ_c, and three at 8.6 J, are circled on Fig. 1(b); and the same cases are circled on Fig. 1(c) which is a plot of the efficiency, η_H, of transfer of absorbed energy into internal energy. That is, η_H is the ratio of the internal energy plotted in Fig. 1(b) to the total energy absorbed in the pellet up to the time of peak ρR. At 0.33 J, the ratio of the values of η_H at $\rho_c = 10^{-1}$ and 10^{-2} (recall that the initial density is 1 g/cm^3 so that these values of ρ_c are numerically the ratio of ρ_c to the pellet density) is about 2.5 or almost the ratio of wavelengths, $\sqrt{10}$, while the ratio of η_H's at 10^{-2} and 10^{-3}, approximately 1.7, is lower. The effect of another decade of decrease of ρ_c (not shown) on η_H is relatively small. At lower P and core energy the accuracy of the stationary model increases. At 8.6 J, where the mass ablation rate is larger and the stationary-ablation model is not expected to be as good, η_H is better but the respective ratios, 2.2 and 1.2, are a bit smaller. If the initial density of 1 g/cm^3 is scaled up to typical outside-surface target-material densities of about 2 g/cm^3, then the wavelength corresponding to our highest ρ_c, which becomes 0.2 g/cm^3, is about 0.15 μm, and that wavelength corresponding to the smallest is 1.5 μm. The same kind of parameter study has been done for ramp pulses ($P \sim t$) with quantitatively very similar results.

The simulations show that the reduction of η_H with increasing λ is weakening considerably at the longest wavelength ($\rho_c = 10^{-3}$). This therefore appears to be the large-λ end of the range of approximate validity of the $\eta_H \sim \lambda^{-1}$ scaling. Different pulse shapes and target configurations could, be changing the time scales of implosions and transients in the ablation flow, change the large-λ end of the range by perhaps a factor of 2, but would probably not extend the range as far as 10 μm. We also expect in general that those pulse shapes which extend the range will give a scaling of η_H with λ which is closer to $\eta_H \sim \lambda^{-1}$ than was seen in our parameter study with step-function pulses.

Our conclusion from these preliminary calculations is that the efficiency with which absorbed laser energy causes a given spherical implosion should increase by a factor of between 3 and 5 if the laser wavelength is decreased from infrared wavelengths between 1 and 10 μm to the blue or near-ultraviolet, which is a large enough factor to have a major effect on the choice of lasers for fusion. A small additional improvement might be gained with some targets by going down into the vacuum ultraviolet, below about 0.2 μm, but at the expense of some increase in experimental difficulty. These calculations, which consider only classical thermal conductivity, indicate that the further loss in efficiency from going to wavelengths as long as 10 μm and longer should be small. This effect should not be confused with nonclassical thermal-flux limiting, which may introduce some further inefficiency at wavelengths as short as 1 μm,[3] in the form of a reduction in the effective absorbed power P for a given incident irradiance.

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