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ABSTRACT

Numerical simulations of laser-driven implosions combined with previously derived scaling laws, both based on classical thermal conduction without any flux limiting, indicate that the absorbed energy required to cause a given implosion, and, therefore, the anticipated nuclear yield ratio should scale approximately inversely with wavelength in the visible and near infrared.

I. INTRODUCTION

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 electron thermal conduction from the surface of critical density, ρ_c, where it is absorbed from the incident laser light, to the surface of the pellet core, or ablation surface. (Recall that the ablation surface essentially separates the blowoff from the dense pellet core which is being compressed.) 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 from which λ, the wavelength, is 1.06 µm, the critical electron density is $n_c = 10^{21}$ cm^{-3}, and in the compressed core, which is at solid densities or higher, $n_c \gtrsim 10^{23}$ cm^{-3}. In Ref. 2 it is shown by a stationary flow model of the thermal conduction and ablation process that, among other things, the absorbed laser power, W, required to provide a given ablation pressure and material ablation rate 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 $W \sim \rho_c^{-\frac{1}{2}}$, and, therefore, since $\rho_c \sim \lambda^{-2}$, that $W \sim \lambda$. The indicated scaling would be very important for laser fusion research and development because a factor of λ would multiply pellet yield ratios, 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 here 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 large λ end of the range of applicability must then be somewhat larger than $\lambda = 10^{-1}$ µm in order for the $W \sim \lambda$ 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 $W \sim \lambda$ scaling, and the approximate location of the large λ end of the range.

II. NUMERICAL PARAMETER STUDY

The simulation parameter study was done with a one-dimensional, spherical, Lagrangian hydrodynamics and heat flow code. 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 electron thermal conduction, $\ln \Lambda = \text{const} \approx 5$. The target is a 10^2 μm radius sphere of $Z = 1$, $A = 2.5$ material of initial density 1 gm/cm^3. The simple 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. Constant power step function pulses of a range of intensities are used. The laser pulse is never shut off in these calculations, but any additional energy supplied to the pellet after peak compression need not be considered. Both more elaborate target and pulse shapes could have been used which would give much larger values ρR (see below). 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 1a shows the peak value of $\int_0^\infty dr\rho$, called ρR, a common figure of merit for spherical compression (see Ref. 1), for a range of pulse powers and for the critical densities $\rho_c = 10^{-1}$, 10^{-2}, and 10^{-3}. Power is given in units of watts/cm^2 at the initial pellet radius. The slight rise of ρR for irradiances above 10^{16} W/cm^2, followed by a drop to the initial time value, occurs when the incident 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 $\rho R \simeq 0.04$ is what one expects from a one-shock implosion, and the effect of changing ρ_c and W is just to alter the shock timing. Figure 1b 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 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 W 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 joules of internal energy and different ρ_c, and three at 8.6 joules, are circled on Fig. 1b, and the same cases are circled on Fig. 1c which is a plot of efficiency, η, of transfer of absorbed energy, W, into internal energy. That is, η is the ratio of the internal energy plotted in Fig. 1c to the total energy absorbed in the pellet up to the time of peak ρR. At 0.33 joules, the ratio of the values of η at $\rho_c = 10^{-2}$ and 10^{-1} (recall that the initial density is 1 gm/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's at 10^{-3} and 10^{-2}, approximately 1.7, is significantly lower. At 8.6 joules, where the mass ablation rate is larger and the stationary ablation model is not expected to be as good, the efficiency is better but the respective ratios; 2.2 and 1.2, are a bit smaller. If the initial density of 1 gm/cm^3 is scaled up to typical outside surface target material densities of about 2 gm/cm^3, then the wavelength corresponding to our highest ρ_c, which becomes 0.2 gm/cm^3, is about 0.15 μm, and that corresponding to the smallest is 1.5 μm. The simulations show that the scaling is weakening considerably at the longer wavelength, which appears to be approximately the large λ end of the range of validity of the $W \sim \lambda$ scaling. Different pulse shapes and target configurations could, by 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 two, but would probably not extend the range as far as 10 μm. We also expect that those pulse shapes which extend the range will give a scaling of W with λ which is closer to W ~ λ than was seen in our parameter study with step function pulses.

III. CONCLUSIONS

Our conclusion from these preliminary calculations is that the efficiency with which absorbed laser energy causes a given spherical implosion in medium to low Z materials should increase by a factor of between three and five if the laser wavelength is decreased from infrared wavelengths between 1 and 10 μm to the blue or near ultraviolet 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 inefficiency at wavelengths as short as 1 μm.[3]

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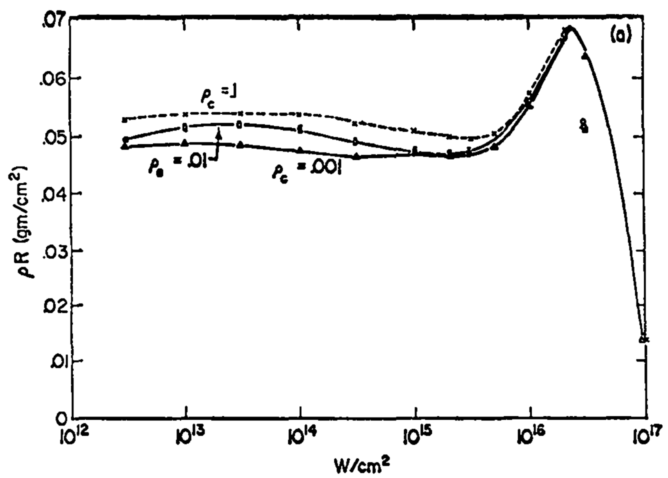

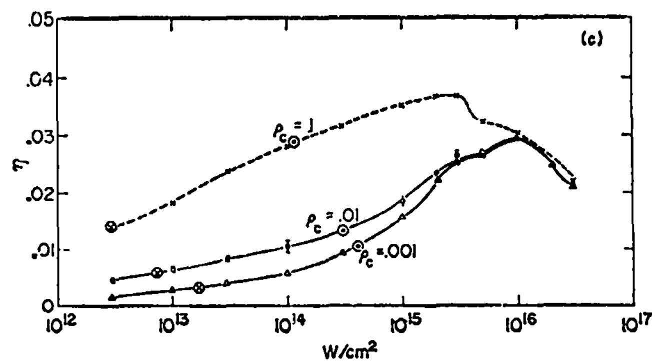

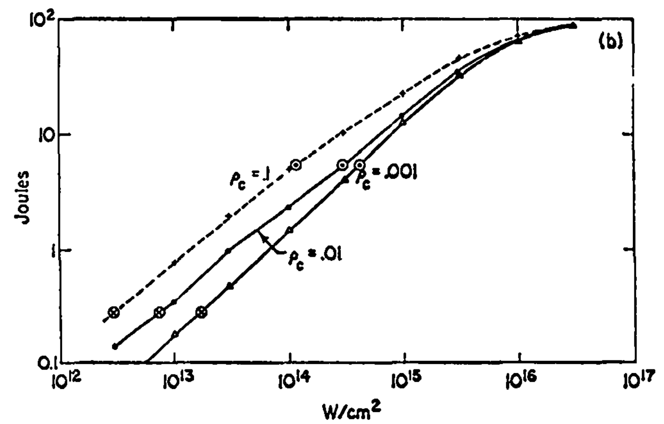

Fig. 1. Results of a numerical simulation parameter study of laser-driven implosion of solid spherical pellets. As a function of power, watts/cm^2 at the initial pellet surface, and critical density, ρ_c, the figures show a) peak values of ρR, b) internal energy in the compressed pellet core at the time of peak ρR, and c) efficiency, η, of transfer of absorbed laser energy into the core energy shown in b).