ic parameters by varying the field strengths; in fact, if the driving-field frequencies are resonant, respectively, with the transition frequencies, and the two Rabi frequencies are *equal*, the mathematical problem becomes similar to that of a spin-1 system driven on resonance. It should be noted, however, that such a phenomenon is different from the one considered presently. In the present instance of a single (monochromatic) driving field, the ratio of the two Rabi frequencies is determined solely by the atomic parameters; if the two transition frequencies are different, spin-1-type Rabi oscillation can be achieved only if the two Rabi frequencies are *unequal*, since the frequency shift from two-photon resonance required to produce this oscillation depends inversely on the parameter α, which vanishes for equal Rabi frequencies.

Rayleigh-Taylor Instabilities in Laser-Accelerated Targets

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Numerical studies of the ablation-driven Rayleigh-Taylor instability in laser-accelerated targets show growth rates typically within a factor of 2 of the classical growth rate. The appearance of the "Kelvin-Helmholtz" instability depends on the form of the initial perturbation and also on the laser irradiance. Perturbations of the target surface and laser irradiation are simulated and compared.

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The achievement of inertially confined thermonuclear fusion in laser driven pellets requires that a hollow shell be symmetrically imploded to less than one tenth of its initial radius in order to generate the high densities needed for significant thermonuclear burn.[1] The use of a hollow rather than solid pellet reduces the peak power requirement from the laser which decreases as the ratio of shell radius to thickness, $\alpha = R/\Delta R$, is increased. Unfortunately the hollow shell targets are hydrodynamically unstable in the ablation region where the pressure and density gradients are of opposite sign, i.e., $\nabla p \cdot \nabla \rho < 0$. The instability in this region is similar to the classical Rayleigh-Taylor (RT) instability of two incompressible fluids[2] but is complicated by the finite density and temperature scale lengths, heat conduction, compressibility, and flow of the ablating material. Various analytic approximations have been made to estimate the growth rates of the instability,[3,4] and numerical simulation with use of both Eulerian and Lagrangian formulations have also been employed.[5-7]

The simulation data consistently show growth rates γ reduced by a factor of 2 or 3 below the classical growth rate for an Attwood number $\gamma = (ka)^{1/2}$ of unity, where k is the wave number and a the effective acceleration.

There is a qualitative difference between the results of McCrory *et al.*[6] and those of Emery, Gardner, and Boris[7] regarding the appearance of a Kelvin-Helmholtz (KH) type of instability as evidenced by a broadening of the tips of the RT "spikes" as they fall into the less dense medium. These differences have at times been attributed to the numerical differences of the Eulerian and Lagrangian formulations, and particularly to a supposed "stiffness" of the triangular Lagrangian mesh induced by the von Neumann artificial viscosity used in all Lagrangian codes. We report here the results of simulations performed with an Eulerian code (which does not use an artificial viscosity) which show that the appearance of the "KH" features is dependent on the initial conditions of the problem and cast some doubt as to whether it is indeed a KH instability. Our results agree well with both Emery, Gardner, and Boris and McCrory *et al.* for the rather dissimilar cases that they considered.

The simulations are performed with an Eulerian formulation in cylindrical (r, z) geometry. The code includes laser absorption by inverse bremsstrahlung, and electron and ion energy transport by flux-limited thermal conduction and fluid motion through the flux-corrected transport algorithms of Boris and Book.[8] The equation of state used is that of a fully ionized perfect gas since experience in one-dimensional simulations has shown that real equation-of-state effects are not important if the initial shock pressure is greater than about 3 Mbar, which is the case for all the simulations presented here. A full description of the code including also magnetohydrodynamic calculations is given by Pert[9]; however, the magnetic field subroutines are omitted from the calculations described here.

In performing the simulations it is necessary to "seed" the instability by introducing a perturbation into the target mass distribution or the laser irradiance or by introducing a divergence-free velocity perturbation in the fluid flow. The advantage of this latter method is that a form for the velocity perturbation may be taken which approximates to the eigenfunction of the instability. Exponential growth is then seen almost immediately, whereas if the mass distribution is perturbed it is necessary to wait until the nongrowing components of the perturbation have been overtaken by the unstable modes.

Since one of the aims of this work is to make a quantitative estimate of the breakup of a target due to RT instabilities, we have chosen to perturb the initial mass distribution despite the disadvantages outlined above. The overriding benefit is that immediate comparison can be made with targets actually used for laser acceleration and implosion experiments. The initial conditions of the simulation are shown in Fig. 1. A flat foil of thickness 2.5 μm is irradiated from the right of the figure with a uniform beam of laser light at a wavelength $\lambda = 0.53$ μm. The target is "corrugated" as shown with a square wave of amplitude 0.125 μm and wavelength $\lambda_\perp = 2.5$ μm deliberately chosen to approximate the most damaging mode. The simulation mesh is 5 μm by 10 μm and is made up of 50×80 intervals.

Simulations have been performed for laser irradiances of 2×10^{13}, 10^{14}, and 5×10^{14} W cm^{-2}. For the simple incompressible RT instability with a constant acceleration the integrated growth exponent $\int\gamma\, dt = (4\pi z/\lambda_\perp)^{1/2}$ depends only on z. Thus it is a sensible comparison to show the simulation results for different irradiances at the same distance traveled. In order to keep the ablated mass fraction constant for a given distance traveled we have increased the initial mass density to compensate. In Fig. 2 we show the comparison of the three irradiances at a distance traveled of about 9.5 μm. Clearly the spatial growth rate is somewhat reduced at the increased irradiance. There are two notable features in the simulations; first, the high spatial frequencies appearing at 2×10^{13} W cm^{-2} are progressively reduced at higher irradiances, and second, the KH "mushroom" features (i.e., a broadening of the spikes) also diminish as the irradiance is in-

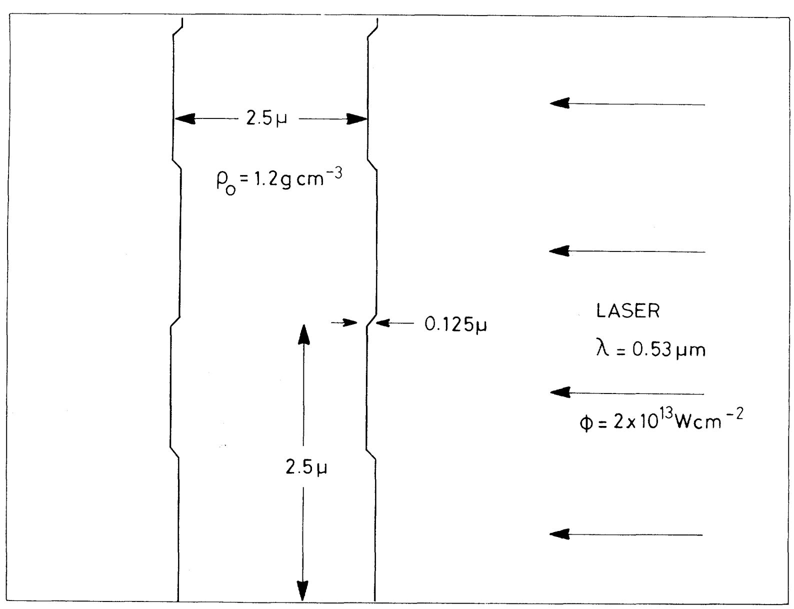

FIG. 1. Density contours at $\rho = 1$ g cm^{-3} for the initial "square-wave" corrugated target.

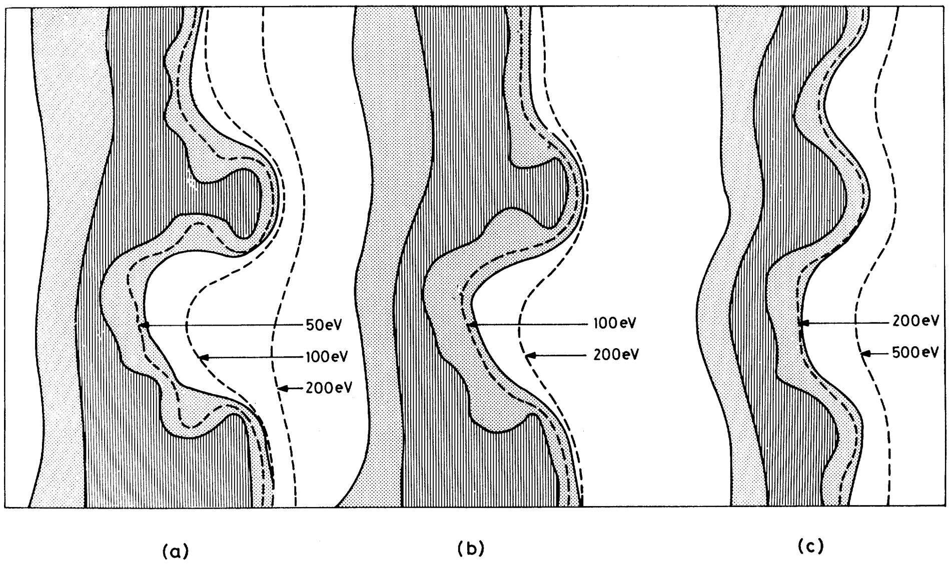

FIG. 2. Density contours, $\rho > 0.5$ g cm^{-3} (dotted) and $\rho > 1.0$ g cm^{-3} (hatched), and temperature contours at $z = 9.5$ μm. Laser irradiances (a) 2×10^{13} W cm^{-2}, (b) 10^{14} W cm^{-2}, (c) 5×10^{14} W cm^{-2}. The scale is the same as Fig. 1.

creased.

Our simulations at 2×10^{13} W cm^{-2} are qualitatively similar to those of Emery, Gardner, and Boris at 10^{13} W cm^{-2} with prominent KH features, while at 5×10^{14} W cm^{-2} our results are similar to the McCrory *et al.* simulations at 10^{15} W cm^{-2}. It is tempting to attribute the disappearance of the KH features to the increased plasma temperature at the higher irradiances. This increases the thermal conductivity, changes the density and temperature scale lengths, and tends to reduce the growth rate of short-wavelength modes.

However, the KH features are also removed at an irradiance of 2×10^{13} W cm^{-2} if the form of the initial perturbation is changed. In Fig. 3 we show the result of a sinusoidal rather than square-wave initial modulation of the target surface. Although this is still not an eigenmode of the RT instability, the content of the higher spatial harmonics is reduced and the density profiles show no evidence of KH growth.

We propose that these effects are not due to a true KH instability but are the result of vorticity being generated at high spatial frequencies as a result of the form of the initial perturbation. This vorticity is advected into the spikes by the fluid flow and appears eventually as a broadening of the tips.

We have also investigated the seeding of the RT instability by a small-scale modulation of the laser intensity,

$$I = I_0\{1 + 0.2\sin[2\pi r/(2.5\ \mu\mathrm{m})]\}.$$

This spatial scale length is so small that in the steady state the intensity perturbation is strongly smoothed by lateral thermal conduction between critical and ablation surfaces.[10] However, in the initial transient phase there is a modulation of the shock velocity through the foil and

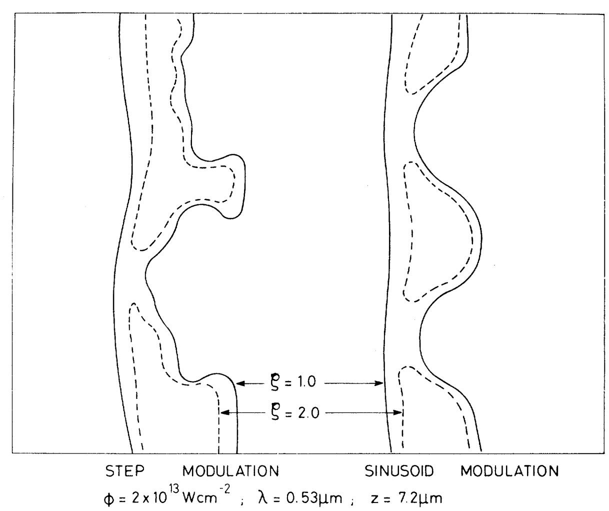

FIG. 3. Comparison of density contours at $z = 7.2$ μm for "square-wave" and "sine-wave" corrugations of the initial target surface.

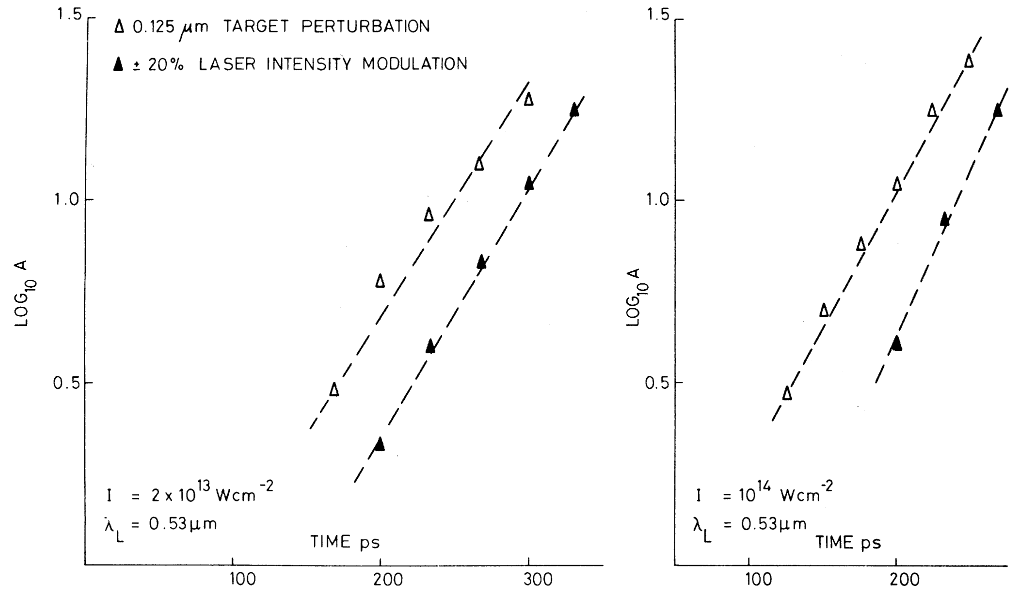

FIG. 4. Amplitude of the RT instability as a function of time for modulation of the target and of the laser beam.

vorticity is introduced into the fluid flow. In Fig. 4 we show the comparison of modulated laser intensity and modulated target at an irradiance of 2×10^{13} W cm^{-2}. In the portion of exponential growth the amplitude of the irradiance-induced instability is about one half of the target-induced instability. Thus it is reasonable to say that the 20% laser modulation is equivalent to a target perturbation of 0.06 μm. As the laser intensity and wavelength are varied the effectiveness of transient thermal smoothing and the seeding of vorticity both change. In Fig. 5 we have plotted the instability amplitude versus distance traveled for four different simulations. The change of laser wavelength from 0.53 to 0.265 μm requires about a factor of 5 increase in laser intensity to recover the same degree of transient smoothing, giving a scaling with $I\lambda^{2.3}$, compared with a scaling of $I\lambda^{3.8}$ in the steady state as found by Gardner and Bodner.[10]

From these results it is clear that small-scale uniformity of target finish and of laser illumination will be crucial for the successful implosion of laser fusion targets. Even when adequate steady-state thermal smoothing exists the transient imprint of illumination nonuniformities can be an effective source of RT instability.

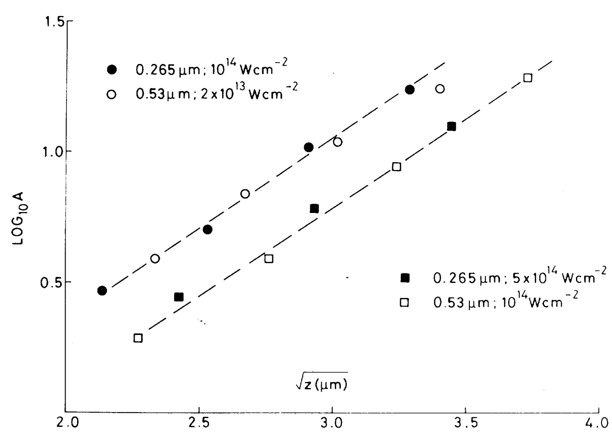

FIG. 5. Amplitude of the RT instability as a function of distance traveled for different laser wavelengths and intensities.

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