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2D and 3D Ablation Front Hydrodynamic Instability Experiments on Nova

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Abstract. Single-mode experiments have been conducted on the Nova laser to examine the effect of perturbation shape on ablation front Rayleigh-Taylor growth. The perturbations investigated had the same magnitude wave vector $k=(k_x^2+k_y^2)^{1/2}$ and the same initial amplitude. The shapes corresponded to 2D $\lambda=50\text{ }\mu\text{m}$, 3D square $k_x=k_y$, and stretched $k_x=3k_y$ perturbations. We observed that the 3D perturbations grew more than the 2D perturbation. Numerical simulations in 2D and 3D are in agreement, showing the most symmetric modes growing the largest.

Understanding the Rayleigh-Taylor (RT) instability is of critical importance to inertial confinement fusion (ICF) because large RT growth on imploding capsules can degrade implosion performance. In direct drive, nonuniformities in laser illumination imprint nonuniformities onto the capsule pusher ablation front. In indirect drive, residual capsule surface imperfections lead to perturbations at the ablation front. In both cases, the ablation front is RT unstable and perturbations grow. In the linear regime, the perturbation growth is exponential,

$$\eta = \eta_0 e^{\gamma t}, \quad (1)$$

where η represents perturbation amplitude and the growth rate γ can be written approximately as (1-3)

$$\gamma = [kg/(1+kL)]^{1/2} - \beta k v_a. \quad (2)$$

Here g is acceleration, $k=2\pi/\lambda$ is perturbation wave vector, L is the density gradient scale length, β is a constant between 1 and 3, and v_a is ablation velocity. When the perturbation spatial amplitude is nonnegligible compared to its wavelength, the RT evolution enters the nonlinear regime. For semi-infinite, incompressible fluids, the bubble approaches its terminal velocity, corresponding to the buoyancy being exactly balanced by kinematic drag (4,5). In this limit the bubble amplitude is just $\eta(t) = \int u_B dt$, with bubble velocity

$$u_B = a(g\lambda)^{1/2}, \quad (3)$$

where $a=0.23$ in 2D and 0.36 in 3D, and we have assumed an Atwood number of 1 for simplicity. Notice that for the same perturbation wavelength (bubble diameter) λ , the bubble velocity is larger in 3D, since the kinematic drag per unit volume is less.

Perturbation growth is sensitive to perturbation shape. The transition to the nonlinear regime occurs approximately when the bubble velocity in the linear regime equals the nonlinear terminal bubble velocity, namely, when $\dot{\eta}_{linear} = \gamma\eta \approx u_B$. Since u_B is larger in 3D than in 2D from Eq. 3, the transition to the nonlinear regime happens later in 3D. Hence, in 3D the linear regime exponential growth phase lasts longer and the asymptotic nonlinear growth rate is higher. Single-mode perturbations therefore are expected to grow larger in 3D than the equivalent perturbation in 2D. This simple qualitative picture is supported by 3rd order perturbation theory (6), recent work with a potential flow model (5), and full numerical simulations (7-9). Until recently, however, experiments in the ICF regime have been lacking due to their complexity. We present here new results of an experimental and computational investigation of 2D versus 3D single-mode perturbation growth at the ablation front in planar, indirectly driven foils (10). Recent advances in target fabrication (11) and diagnostic development (12) have made this experiment possible.

The experimental configuration is shown in Fig. 1a and is described in more detail elsewhere (13). A 750 μm diameter, 60 μm thick CH(Br) planar foil ($\text{C}_{50}\text{H}_{47}\text{Br}_3$, $\rho=1.26 \text{ g/cm}^3$) is mounted across a diagnostic hole on a 3 mm long, 1.6 mm diameter gold cylindrical hohlraum. Eight of the 10 Nova laser beams (14) are used to generate a 3.3 ns low-adiabat, shaped drive, as shown in Fig. 1b. Two 3 ns square beams are delayed relative to the drive and focused onto a Sc backlighter disk to generate 4.3 keV He- α x-rays to back-illuminate the accelerating planar foil. Random phase plates with 5 mm diameter hexagonal elements are inserted as the last optic in the two backlighter lasers to generate a smooth 700 μm diameter x-ray spot. Typical timing of the backlighter lasers relative to the drive lasers is illustrated in Fig. 1b. On each laser shot, two-dimensional gated x-ray images were obtained with a new flexible gated x-ray pinhole camera (12). Four pinhole images are obtained for each strip on the MCP, and the interstrip delay was set to 700 ps. Half of the pinholes on each strip were filtered with 12.5 μm of Ti to eliminate higher energy backlighter x-rays such as from He- β and He- γ transitions in Sc.

The foils were made using a new laser ablation technique to make molds in substrates of either kapton or mylar (11). We prepared perturbed foils all with the same magnitude wave vector $k=(k_x^2+k_y^2)^{1/2}$ and nominally the same amplitude. The "2D" foil (1D wave vector $k=k_x$) was a simple $\lambda=50 \mu\text{m}$ sinusoid with initial amplitude $\eta_0=2.5 \mu\text{m}$. One of the "3D" foils [2D wave vector $k=(k_x, k_y)$] corresponded to a "stretched" $k_x=3k_y$ perturbation, and the other was a square $k_x=k_y$ mode. Characterization of the three foils was done using a contact radiography system, the resulting images of which are shown in Fig. 2a-c, and contact profilometry. The radiographs were converted to spatial amplitudes using

Figure 1. (a) The experimental configuration consists of a Au cylindrical hohlraum with the modulated CH(Br) foil mounted on the wall. The laser beams convert to x rays in the hohlraum, which ablatively accelerate the foil. Two additional laser beams generate backlighter x rays used for in-flight diagnosis of the foil. (b) Power versus time of the eight 0.351 μm wavelength drive laser beams (curves starting at $t=0$) and the two 0.528 μm wavelength backlighter beams (curves starting at $t=2.4$ ns).

Figure 2. Contact radiographs of foils identical to those used in the Nova experiments are shown in (a)-(c). The perturbations correspond to (a) 2D $\lambda=50 \mu\text{m}$, $\eta_0=2.5 \mu\text{m}$, (b) 3D $k_x=3k_y$: $\lambda_x=53 \mu\text{m}$, $\lambda_y=158 \mu\text{m}$, $\eta_0=2.4 \mu\text{m}$, and (c) 3D $k_x=k_y$: $\lambda_x=\lambda_y=71 \mu\text{m}$, $\eta_0=2.7 \mu\text{m}$. The corresponding images from the Nova shots taken at 4.3 ns are shown in (d)-(f).

a step wedge of the same material, CH(Br). Images from the Nova shots at 4.3 ns, which is near peak growth, are shown in Fig. 2d-f. The gated x-ray pinhole camera for these images was run at 8x magnification with 10 μm pinholes, and 150 μm Be filtering. The backlighter was scandium at 4.3 keV.

Each image from the Nova shots is converted to $\ell n(\text{exposure}) \propto -OD = -\int \rho k dz$. Hence, modulations in $\ell n(\text{exposure})$ correspond to modulations in foil areal density. The images are Fourier analyzed, and the amplitudes corresponding to the fundamental mode are extracted. A purely experimental demonstration of the effects of dimensionality on perturbation growth depends upon holding conditions between experiments identical. Two of our shots were done back to back on the same day, where the only change made between shots was the target (2D $\lambda=50 \mu\text{m}$ versus 3D $k_x=3k_y$). The total laser energy for these two shots was close (16.6 vs 15.8 kJ), and the timing and filtering of the diagnostic were identical. The results for the evolution of the fundamental mode for these two shots is shown in Fig. 3a. The 3D $k_x=3k_y$ perturbation has clearly grown larger late in time in the nonlinear regime, as expected.

Shape effects on perturbation evolution can be examined under identical conditions with computer simulations. This is shown in Fig. 3b using the new 3D radiation-hydrodynamics code HYDRA (10). The perturbations, in order of decreasing peak growth, correspond to $k_x=k_y$, $k_x=2k_y$, $k_x=3k_y$, and 2D $\lambda=50 \mu\text{m}$. Our simulations clearly show that the most symmetric perturbations grow the largest, as has been reported by others (6-8). This is qualitatively in agreement with our experimental observations; quantitative comparisons are currently underway.

Figure 3. (a) Results of the evolution of the fundamental mode Fourier amplitude of $\ell n(\text{exposure})$ for the 3D $k_x=3k_y$ (circles) and 2D $\lambda=50 \mu\text{m}$ (squares) perturbations. The connecting lines are meant only to guide the eye. Experimental conditions were kept the same for these two shots to best illustrate the effect of shape on perturbation growth. The diagnostic setup was the same as described in Fig. 2. (b) Predicted Fourier amplitude of $\ell n(\text{exposure})$ from 3D simulations for the evolution of four different perturbation shapes all with the same magnitude $k=(k_x^2+k_y^2)^{1/2}$ wavevector, for drive conditions slightly different from those of (a). The most symmetric ($k_x=k_y$) mode is seen to grow the largest.

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