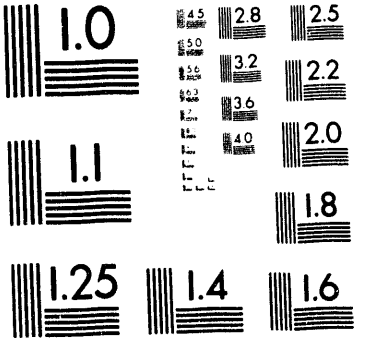
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Hydrodynamic Instability Modeling for ICF*

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The intent of this presentation is to review how we model instability growth in ICF targets, and identify the principal issues. Most of the material has been published in refs. 1-3, but is not familiar to many participants in the meeting.

Hydrodynamic instabilities are a key issue in ICF. Along with laser-plasma instabilities, they determine the regime in which ignition is possible. At higher laser energies, the same issues determines the achievable gain. Quantitative predictions are therefor of the utmost importance to planning the ICF program, as well as to understanding current Nova results.

The key fact that underlies all of our work is the stabilization of short wavelengths. This idea has a long history, going back to Nuckolls' original ICF paper.[4] Recently there has come to be a consensus (from numerical work,[5] with experimental verification[6]) that it is well described by a formula taking into account the ablation velocity (defined as $v_A=(dm/dt)\rho_{max}^{-1}$, where dm/dt is the mass removal rate per square cm) and the scale length L at the ablation front. The growth rate is

$$\gamma=\sqrt{\frac{gk}{1+kL}} - \beta k v_a.$$

where β is a parameter between 1 and 3. This stabilization allows us to arrange our implosions so that the short wavelength growth is not important. Any interfaces with significant density steps (while in-flight) must be carefully avoided. The hydrodynamics is then essentially linear. This is corroborated by multi-mode explicit simulations, as shown in Fig. 1. We present density and temperature isocontours from simulations of an ignition target, shown at the time of ignition. The simulations used realistic initial perturbations in modes 10, 20, ..., 80; the simulation on the right had all modes' amplitudes reduced by a factor of four. It is clear that the final perturbations are nearly linear in initial amplitude. We are also working with Dahlburg and colleagues at NRL on 3D multi-mode ablative instability growth, as reported by Dahlburg at this meeting.

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For arbitrary initial conditions, we use linear analysis based on spherical harmonic analysis (or, in planar geometry, on Fourier analysis). A series of individual code simulations gives growth factor vs. mode number. This can be combined with any initial spectrum of interest. It is important to do code simulations to get the individual modes' growth; analytical formula are not accurate, even to an order of magnitude. An example of this is shown in Table 1.

The onset of nonlinearity, and a model for extension into that regime, is as analyzed in ref. 1. Modes do not become nonlinear when their amplitudes become comparable to their wavelength, except in the special case where no other modes are present. If other modes are present, saturation is local in space. For isotropic, random surfaces, saturation begins when modal amplitudes become comparable to $1/Lk^2$ for planar modes with

perturbed surface $Z(x,y,t)=\sum_k e^{ik.x} Z_k$

and R/l^2 for spherical harmonic modes. Once modes get larger than this, nonlinear effects must be estimated in a way such as we have discussed in Refs. 2 and 3. This particular nonlinear model is not fundamental ICF physics and I will not emphasize it here. For most ICF problems, linear analysis is quite useful: the onset of nonlinear effects can be checked as just described.

Detailed modeling of perturbation growth in 3D remains an area of future work. Direct code simulation is becoming more and more applicable -- see, for example, the presentation by Dahlburg at this meeting. However, we are not yet in a position to simulate directly the growth of realistic 3D perturbations on real ICF targets. Hence effects must be estimated in some other way. Our baseline saturation model is oriented towards 3D perturbations, but it provides only a crude estimate of the 3D nonlinear effects. More detailed calculations are possible for very weakly nonlinear perturbations, using second order RT theory. Work on this will be reported soon.[7] An example is shown in Fig. 2, where we used linear analysis and second order mode coupling theory to predict the size and shape of perturbations on a foil as used in Remington's experiments.[6]

In addition to calculating the size of the perturbations, we must calculate their effects. This can be done in several ways with current code capability: (i) simulations of a single spike on axis in 2D spherical geometry, which is probably the closest to the real 3D situation; (ii) simulations of curtains of material falling in near the waist plane; and (iii) a 1D mix model proposed by G. Zimmerman, in

which an extra thermal diffusivity is incorporated in the mixed region. These various models give fairly consistent results for the problems of interest, giving us confidence in them.

Experimentally testing this modeling requires testing the various ingredients. The most important issue is whether we are correctly calculating the single mode growth, and the reduction by ablation stabilization. This is being tested in the planar experiments by Remington, Glendinning, and Weber (reported on by Remington and Kilkenny at this meeting). Our LANL colleagues are attempting converging geometry single mode experiments.[9] We also must measure perturbations resulting from realistic multi-mode initial surface perturbations. Remington reported here on some planar experiments that are beginning to give data of this sort. Also, the SSD-seeded perturbations done by Glendinning and Weber (described by Kilkenny here) show the growth of fully three dimensional randomly seeded perturbations, and will be a challenging test of our modeling capability. Implosion experiments are also being done, using spectroscopic trace emission as a diagnostic of the perturbation size in the imploded configuration. Modeling of some of these experiments requires extending our analysis into the nonlinear regime, using our saturation model from ref. 1.

Direct drive and indirect drive instability growth are qualitatively similar, although the different ablation velocities and scale lengths make for important quantitative differences. In direct drive we have the additional problem of laser-seeded irregularities, both the early time speckle and the long-time residual modulations. These can be modeled with either linear analysis or direct simulation (in full detail in 2D, and with a growing amount of detail in 3D). Conceptually, the modeling approaches and issues are very similar whether the drive is direct or indirect.

We have made remarkable progress in ICF instability modeling in the last few years. Modern code capability, along with the realization that the perturbations are nearly linear, have made the instability growth problem quite tractible, compared to a few years ago when most workers in the field regarded it as a black art. Experimental tests of the modeling are coming along very well: although they have not yet definitively verified our understanding of all the relevant issues, results are continually very encouraging and we are optimistic that definitive verification will be in hand soon.

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4. J. Nuckolls, L. Wood, A. R. Thiessen, and G. Zimmerman, "Laser Compression of Matter to Super-High Densities: Thermonuclear Applications," *Nature* 239, 139 (1972).

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6. S. G. Glendinning et al. *Phys. Rev. Lett.* 69, 1201 (1992). B. A. Remington et al., Large Growth Planar Rayleigh-Taylor Experiments on Nova, *Phys. Fluids* B 4, 967 (1992). Also reported in this proceedings, by Remington and Kilkenny.

7. M. J. Dunning and S. W. Haan, to be published.

8. W. Hsing, private communication.

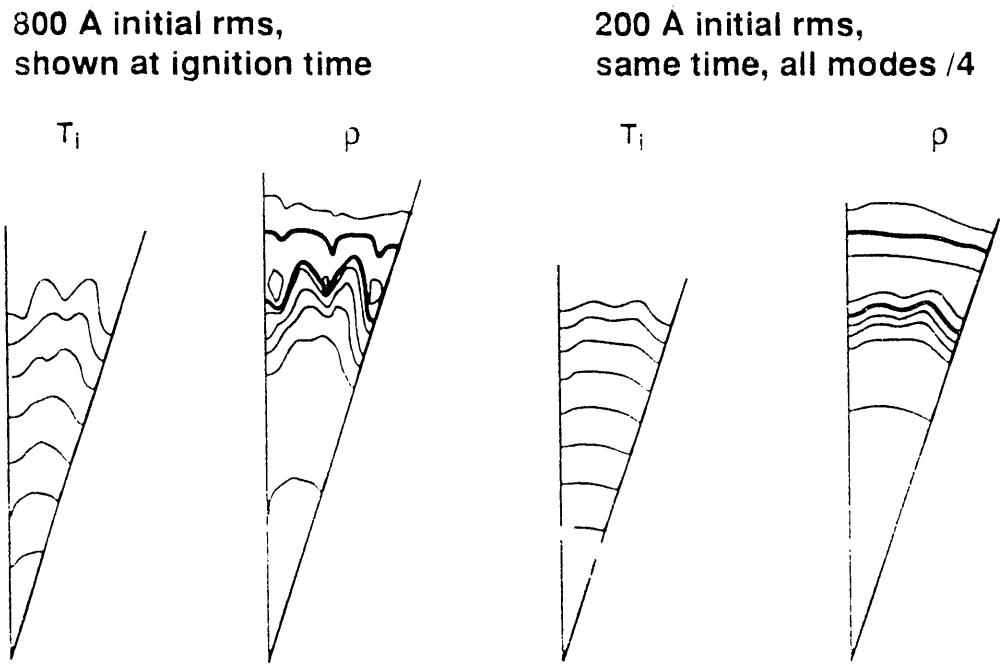
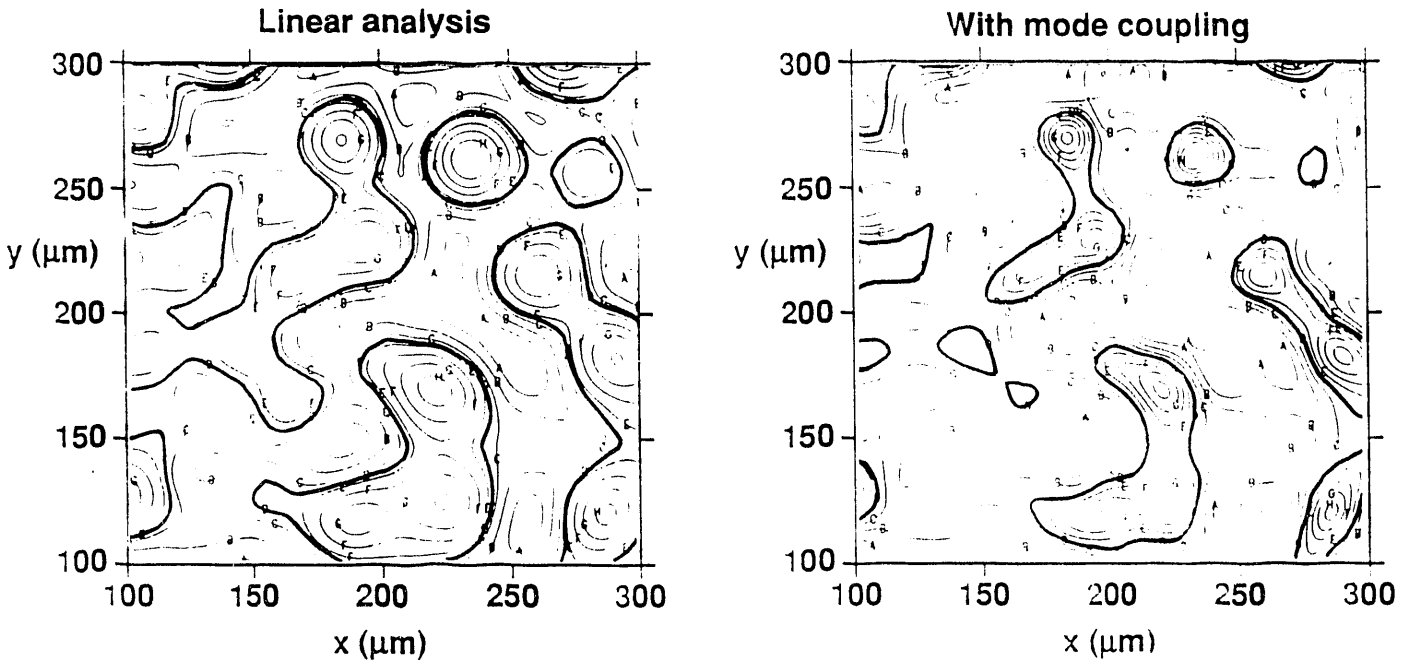


Figure 1. Density and temperature isocontours at igntion time for an ignition target, as calculated in a simulation with a multi-mode initial perturbation on the outside of the shell. Results from two perturbations are shown, which differ by a factor of four in all modes. The resulting perturbations are virtually linear. The perturbations shown on the left are marginally acceptable, with an 800 Å rms equivalent initial 3D perturbation. The perturbations shown on the right are certainly acceptable, and the initial perturbation is similar to perturbations currently measured on Nova-scale target surfaces.

"Weakly nonlinear" is t ~3-4 ns for 0.45 μm initial rms
Contours of $\rho r = \delta(\bar{x})$ at 3.6ns ⊗ MTF, half max contour highlighted



Equally spaced contours: 0 - 14 x 10^{-4} g/cm^2

Equally spaced contours: 0 - 16 x 10^{-4} g/cm^2

Figure 2. The effect of second order mode coupling on the shape of perturbations growing on an ablatively accelerated foil. These are contours of $\int \rho dz$ vs. x and y, for a perturbation that has grown out of a random array of bumps. The left-hand plot shows the prediction of linear analysis, with modal growth factors calculated with 2D simulations. The right-hand plot shows the effect of second order mode couling, in that the spikes are made narrower and the bubbles broader. The half-max contour is highlighted to emphasize the spike-narrowing produced by second-order effects.

$L/\Delta R$	$v_A t/\Delta R$	$\gamma\tau$	$e^{\gamma\tau}$
0.3	0.6	4.3	75
0.2	0.4	6.6	750
0.4	0.75	2.6	14

Table 1. Predicted growth factors obtained from the ablation-stabilization formula, for various values of the ablation scale length and velocity. The wavelength is taken to be ΔR, the shell thickness, and the distance moved to be 15 ΔR. The scale length and velocity, relative to ΔR, are taken to be as indicated. Since the parameters cannot be estimated to better accuracy than about 25%, it is impossible to make meaningful predictions from the formula alone. Full-code simulations, with experimental verification, must be used to estimate perturbation growth.

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