Radiative shocking and acceleration of polycrystalline slabs for investigation of ablative Rayleigh-Taylor instability triggered by ablator microstructure


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Radiative shocking and acceleration of polycrystalline slabs for investigation of ablative Rayleigh-Taylor instability triggered by ablator microstructure

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NIF ignition capsules are the most unstable imploding systems ever devised by the national inertial fusion program.

Growth rate for ablative Rayleigh-Taylor instability is roughly*

\[ \gamma = \sqrt{kg - \beta k v_a} \]

\( g \) = shell acceleration, \( k \) = perturbation wavenumber, \( \beta \sim 2 \),

\( v_a \) = velocity of ablation front

Number of unstable e-foldings for mode \( m \) during acceleration is

\[ \gamma t \approx \sqrt{m - m/\alpha} \text{ where } m = \text{mode number} = kR_0; R_0 \text{ is initial capsule radius} \]

\[ \alpha = \text{shell compression factor x initial shell aspect ratio} \]

\[ \beta x \text{ fraction of shell ablated} \]

\[ \sim \frac{4 \times 6.25}{2 \times 0.5} \sim 25 \]

Maximum growth \( (\gamma t)_{max} = \alpha/4 \sim 6.3 \) occurs for mode \( m_{max} = \alpha^2/4 \sim 150 \)
6.3 e-foldings implies growth factor \( \sim 540 \)

**Further growth during deceleration leads to total growth factor \( \sim 1000 \)**

Therefore it is vital to identify and control all perturbation sources that could trigger ablative Rayleigh-Taylor instability

- One obvious perturbation “seed” is surface roughness
  - Specification for allowable roughness of NIF ignition capsule* is based on computed perturbation growth, validated by experiments

- But what about internal microstructure of shell materials?
  - Beryllium shells are composed of individual crystalline grains with anisotropic elastic/plastic properties
  - Polymer shells are composed of long molecular chains that might “stack like logs” with a preferred orientation

What happens when shock waves transit anisotropic material? What happens when such material is accelerated by radiation drive? We need a specification for allowable internal anisotropy.

*R.B. Stephens, S.W. Haan, D.C. Wilson, “Characterization Specifications for Baseline Indirect Drive NIF Targets”, internal General Atomics memo

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Recent advances allow computation of fluctuating velocity field behind shock wave in anisotropic material*. This is likely to seed ablative Rayleigh-Taylor instability.

Longitudinal Velocity Fluctuations in Shock Compression of Polycrystalline α-Iron*

\[ V_0 = 150 \text{ m/s} \quad P_s = 5.5 \text{ GPa} \]

\[ \quad -10 \mu \text{m} \]

\[ V_0 = 300 \text{ m/s} \quad P_s = 12 \text{ GPa} \]

\[ V_0 = 1000 \text{ m/s} \quad P_s = 45 \text{ GPa} \]


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How should we go about developing a specification for ablator microstructure?

- **Theoretical/computational approach**
  - Develop models, simulate relevant processes numerically
    -- For example, add radiation to Horie-Yano code, develop 3D Be grain model
  - This was approach used in developing surface-roughness spec
  - Experiments are still necessary to validate models and simulations

- **Empirical approach**
  - Observe behavior of Be/Cu slabs on Omega, Z, early NIF,...
  - Relate behavior (via computed single-mode growth factors) to equivalent surface perturbation
  - Since surface-roughness spec already exists, we thereby reduce microstructure spec to a previously solved problem
  - Computation is still necessary to determine growth factors, and make diagnostic predictions

Either approach must wait for full NIF for final confirmation. Similar experiments must be done in either approach.
We are proceeding with the empirical approach.

- Face-on radiography* of accelerated Be/Cu foils shows growth of unstable perturbations
  - Data consists of time-varying spatial distribution of slab areal density $\int \rho \, dz$
  - Fourier analysis of areal density distribution gives power spectrum $S(k, t)$
  - Computation gives time-dependent linear growth factor spectrum $f(k, t)$
  - Then "equivalent initial surface perturbation" is
    \[ P_{eq}(k, t) = S(k, t)/\rho_0 f(k, t) \]
    where $\rho_0$ is initial slab density.
    -- Perturbation must be linear for this to be valid
    -- If nonlinear saturation occurs, resort to Haan model**
    -- Actual initial surface perturbation $P_0(k, t)$ must be minimized or subtracted
    -- $P_{eq}(k, t)$ is not a unique attribute of a given microstructure, but depends on radiation drive history, drive spectrum, slab thickness, composition, etc.

- We will pursue basic theory and modeling at low level

First experiments at Omega: Radiography of Be/Cu slabs driven by "halfraum"

Diagnostic efforts include:
- **Hohlraum characterization**
  - Experiments require long slowly rising drive to maximize growth factor
  - Diagnostics: Stepped slab, wedge witness plate, DANTE
- **Side-on slab radiography**
  - Slab trajectory, acceleration history
  - Verify drive history
- **Face-on slab radiography**
  - Time-varying spatial distribution of slab areal density $\int \rho dz$

Experiment geometry and parameters:
- **12 to 15 Omega beams on P6-P7 axis**
  - ~190 eV drive is achievable
  - QXI, GXI, FXI gated imaging instruments are available
- **Slabs**
  - Type I: Smoothest possible surface, to emphasize volume microstructure
  - Type II: Intentional sinusoidal surface perturbation
    -- Calibrate growth-factor calculations
Initial computational modeling centers on designing slab/foil and radiation drive history for Omega experiments

- **Goal:** choose drive history, slab thickness to give maximum perturbation growth on Omega laser
  - Modeling approach: calculate single-mode sinusoidal perturbation growth, for variety of candidate slab thicknesses, drive histories, and spectra
  - Use slowly rising pulse to keep slab on low adiabat, minimize preheat
  - Set initial shock pressure to maximize velocity anisotropy for ART seeding

- **Major concern:** Is Omega drive strong enough, and microstructure seed large enough, that microstructure-seeded perturbations become visible?
  - Line VISAR observations of free-surface velocity for shocked beryllium foils* give some information about magnitude of velocity fluctuations
  - Basic theory could give some guidance here, but needs development
  - Meanwhile, simply try to maximize growth factor spectrum with Omega drive

*See poster by Tubbs et al. (this session) for hohlraum designs to produce desired drive histories

Linear stability modeling consists of calculating growth of single-mode sinusoidal surface perturbation

- Although we model surface perturbation, not microstructural perturbation, we can obtain quantitative measure of slab stability: growth factor spectrum of perturbations

Initial mesh for calculation with perturbation wavelength $\lambda = 100 \, \mu m$

Radiation drive incident here

Sinusoidal perturbation on this surface, and on mesh, 0.01-\mu m amplitude
Linear stability modeling computes development of contrast between peak and valley for small-amplitude single-mode perturbation.

Modeling gives time evolution of areal density $\int \rho \, dz$ in spike and bubble.

Density contours

$\lambda = 100 \, \mu m$

t = 14 ns
Trial Omega drive pulse with high-preheat drive spectra gives growth factor $\sim 17$ for $\lambda = 100\ \mu\text{m}$ and 50-$\mu\text{m}$ foil.

$$\Delta \rho z \text{ growth factor (t)} = [(\int \rho dz)_{\text{spike}} - (\int \rho dz)_{\text{bubble}}] / [(\int \rho dz)_{\text{spike}} - (\int \rho dz)_{\text{bubble}}]_{t=0}$$
Current proposed Omega drive pulse with realistic calculated spectra gives growth factor \( \sim 30 \) for \( \lambda = 100 \ \mu \text{m} \) and 50-\( \mu \text{m} \) foil.
Calculations using current proposed Omega drive pulse with 50-μm foil show greatest growth factor occurs for $\lambda = 50 \, \mu m$.

Time-dependent growth factors for 50-μm Be/Cu foil

Curves are labeled with perturbation wavelength $\lambda$. 

**Plot Details:**
- **x-axis:** time (ns) from 0 to 14
- **y-axis:** $\Delta \rho z$ growth factor from 0 to 50
- **Curves:** for 20 μm, 30 μm, 40 μm, 50 μm, 60 μm, 70 μm, 80 μm, and 100 μm
One goal of experiment is to test influence of shock strength on microstructure-seeded perturbations.

- NIF capsules are expected to have first shock pressure in the range 100 - 200 GPa (1 - 2 Mbar)

- Choice of NIF shock pressure is constrained by implosion design considerations: Need to keep shell on low adiabat

- But this is a dangerous range of pressure --- shock at 100 GPa will maximize microstructure-seeded velocity fluctuation

- So in initial Omega experiments we will test effect of shock pressure in seeding instability

- We will vary strength of initial shock from 100 GPa to 200 GPa, thus varying amplitude of seed, while keeping slab instability (growth factor) constant
Greatest velocity fluctuation is induced for ~100 GPa shock, where elastic precursor disappears on \( a \) axis, but not \( c \) axis.

Wave speeds in beryllium

- **shock**
- **sound along c-axis**
- **sound along a-axis**

**Wave speeds in beryllium**

- **bulk sound speed** \( \sqrt{\frac{\partial p}{\partial \rho}} \)

**Graph**

- Wave speeds as a function of pressure (GPa)
- Shock melting point

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Current proposed Omega drive pulse generates first and second shock in range 10 - 30 GPa in first 20 μm of slab.

\[ P(\rho Z) \] for zones in slab at fixed times

1 TPa

100 GPa (1 Mbar)

10 GPa

0.002 0.004 0.006 0.008
\( \rho Z \) (g/cm\(^2\))

1 ns 2 ns 3 ns
Other sources of perturbation include engineering features associated with fabrication: fill tubes, plugs, joints, etc.

- We plan to investigate effect of such “initially nonlinear” perturbations in Omega experiments
  -- Specification for allowable fabrication features will be based on modeling and experiments

- Still other sources of perturbation are associated with microstructure, although not with crystal anisotropy
  -- Oxygen contaminant may accumulate at grain boundaries
  -- Copper dopant may be distributed nonuniformly
Future work:

- Design second pulse shape, giving first shock strong enough to melt Be/Cu grains
- Ensure that pulse shapes can actually be produced at Omega
- Make theoretical predictions of magnitude of velocity fluctuations in Be or Be/Cu that seed ART instability
- Choose concentration of copper dopant