Title
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Permalink
https://escholarship.org/uc/item/0xh2x8gn

Journal
Proceedings of the National Academy of Sciences of the United States of America, 116(37)

ISSN
0027-8424

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Publication Date
2019-09-01

DOI
10.1073/pnas.1717236115

Peer reviewed
Rayleigh–Taylor instabilities in high-energy density settings on the National Ignition Facility

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Edited by William A. Goddard III, California Institute of Technology, Pasadena, CA, and approved May 10, 2018 (received for review September 30, 2017)

The Rayleigh–Taylor (RT) instability occurs at an interface between two fluids of differing density during an acceleration. These instabilities can occur in very diverse settings, from inertial confinement fusion (ICF) implosions over spatial scales of ~10^{-3} – 10^{-1} cm (10–1,000 μm) to supernova explosions at spatial scales of ~10^{12} cm and larger. We describe experiments and techniques for reducing (“stabilizing”) RT growth in high-energy density (HED) settings on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. Three unique regimes of stabilization are described: (i) at an ablation front, (ii) behind a radiative shock, and (iii) due to material strength. For comparison, we also show results from nonstabilized “classical” RT instability evolution in HED regimes on the NIF. Examples from experiments on the NIF in each regime are given. These phenomena also occur in several astrophysical scenarios and planetary science (Drake R (2005) Plasma Phys Controlled Fusion 47:B419–B440; Dahl TW, Stevenson DJ (2010) Earth Planet Sci Lett 295:177–186).

Rayleigh–Taylor instability | high-energy density experiments | National Ignition Facility

High-energy density (HED) experiments, typically defined as experiments requiring energy densities > ~10^{14} erg/cm^2 or pressures > ~100 GPa to be possible, offer unique opportunities to study phenomena that typically can be found only in high-energy astrophysics and astronomy. Examples include the study of the properties of stellar and planetary interiors (3, 4), supernovas (7, 8), gamma-ray bursts (9), galactic mergers (10), and inertial confinement fusion (ICF) implosions (11–13). Aspects of these phenomena can be accessed in the laboratory using high-energy, high-power lasers, such as the National Ignition Facility (NIF) laser at Lawrence Livermore National Laboratory (LLNL) (14, 15) and the Omega laser (16) at the University of Rochester. An example of ICF research on the NIF is illustrated in Fig. 4, which shows results from a 3D simulation of an ICF implosion (13). The red region in the center of the image on the left is the central hot spot just before the time of peak nuclear yield (“bang time”). The predicted peak temperature in the hot spot is 3–4 keV. Fig. 1B shows output from the same 3D simulation, but 170 ps later, at bang time. Note that the hot spot is cooler, due to mixing of shell material into the deuterium–tritium (DT) hot spot and conduction losses, but is considerably denser, having reached peak convergence (13). Fig. 1C shows experimentally measured neutron yields from an extensive series of cryogenic layered DT capsule implosions on the NIF, at four different peak laser powers (17). The results are plotted as a function of experimentally inferred mix mass, that is, the amount of CH(Si) capsule shell material that is mixed deep enough into the central hot spot that it radiates in the soft X-ray regime, enhancing the observed X-ray emission, cooling the hot spot, and lowering the nuclear yield. When the mix mass into the hot spot exceeds ~100 ng, the nuclear yield drops by an order of magnitude or more. The results shown in Fig. 1D are similar to Fig. 1C except that the horizontal axis corresponds to the X-ray enhancement factor, that is, the increase in X-ray emission over what is expected from an unmixed (“clean”) hot spot (17). In Fig. 1D, the blue symbols correspond to the low-adiabat, high-compression four-shock “low-foot” drive, whereas the green symbols correspond to the “high-foot” higher-adiabat three-shock drive, which reduces the hot-spot mass considerably, albeit at lower fuel areal density (17).

Two of the dominant sources of this hot-spot mix are ablation-front Rayleigh–Taylor (RT) and Richtmyer–Meshkov (RM) instabilities, which amplify preexisting defects and other perturbations. Predictions of RT growth and its effects in ICF and HED experiments use large-scale 2D and 3D radiation hydrodynamics simulations, which can also include models of material strength, which can act like an effective lattice viscosity. For HED plasmas, assuming that viscosity and surface tension are negligible, we can write a simple heuristic equation to approximate linear regime, ablation-front RT growth rate, γ_{RT}, namely

\[ \gamma_{RT} = \alpha \left[ \frac{A k_0}{1 + k L} \right] - \beta v_w, \]  

whereby perturbations of initial amplitude η_0 grow as η = η_0 e^{γ t}, provided γ t/λ ≪ 0.1 (18–33). Here α and β are fitting parameters, k = 2π/λ is the perturbation wave number, q is the acceleration of the RT unstable interface, L = ρ/(∇ρ) is the density gradient scale length at the ablation front, v_w = (d\rho_m/dt)/\rho_{max}

Significance

We present research results on the Rayleigh–Taylor (RT) instability at an unstable interface under high-energy density conditions using the National Ignition Facility at Lawrence Livermore National Laboratory. We can reach pressures in the 100-TPa regime on the Hugoniot, or ~500-GPa regime along a quasi-isentrope, allowing the sample under study to remain solid, at planetary interior pressures. We observe RT stabilization (i) at an ablation front; (ii) in the presence of a strongly radiative shock; and (iii) in a unique regime of quasi-isentropic, high pressure, solid-state material flow, where the material strength significantly affects the evolution of a hydrodynamically unstable interface.

Author contributions: H.-S.P., R.M.C., D.S.C., A.R.M., and K.S.R. designed research; B.A.R., H.-S.P., D.T.C., C.M.H., C.C.K., S.R.N., and V.A.S. performed research; H.-S.P., D.T.C., and K.S.R. contributed new experimental and simulation tools; H.-S.P., D.T.C., C.M.H., C.C.K., S.R.N., and V.A.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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Published online June 26, 2018.
Ablation Front, Spherical Hydrodynamic Instability Experiments

A wide variety of experiments are being performed on the NIF to study the hydrodynamics of ICF to study the hydrodynamics of ICF to study the hydrodynamics of ICF to study the hydrodynamics of ICF to study the hydrodynamics of ICF to study the hydrodynamics of ICF. At the ablation front, instability growth of preimposed modulations was measured with in-flight, time-resolved, face-on, X-ray radiography (35, 36, 39, 46, 47). Perturbation growth of “native roughness” modulations and engineering features such as fill tubes and capsule support membranes was also measured (37, 42, 48), as was instability growth at the ablator–ice interface (41). In the deceleration phase of implosions, RT growth from low-mode asymmetries and high-mode perturbations was measured near peak compression with X-ray and nuclear techniques. In one technique, the self-emission from the hot spot was enhanced with 1% argon dopant to “self-backlight” the shell in flight (40), and “adiabat-shaping” techniques were developed (49) to control hot-spot mix in cryogenic layered DT implosions (36, 50, 51).

We show in Fig. 2A the experimental configuration where a hollow Au cylindrical cavity (“hohlraum”) is irradiated on the inside by 192 NIF laser beams, generating an ~250- to 300-eV peak hot-spot ion temperature at this time shown is slightly over 4 keV. The peak hot-spot ion temperature is also indicated by the arrow on the lower right side (13). (B) Similar to A except at bang time (the moment of peak nuclear yield). Note that the hot-spot peak temperature is slightly lower than in A but the peak density is significantly higher (13). (C) Experimental results of total neutron yield vs. hot-spot mix mass (nanograms) from a set of cryogenic layered DT implosions on the NIF, showing the monotonic decrease in yield as mix mass increases (17). The different-colored symbols correspond to different peak powers in terawatts (TW) of the NIF drive laser. (D) Similar to C except the horizontal axis corresponds to the X-ray enhancement factor, which is proportional to increasing mix mass (main text). Here, the blue symbols correspond to the low-adiabat four-shock drive, whereas the green symbols correspond to the high-foot higher-adiabat three-shock drive, which reduces the hot-spot mix mass considerably, albeit at lower fuel areal density (17). (A and B) Reproduced from ref. 13, with permission of AIP Publishing. (C and D) Reproduced from ref. 17, with permission of AIP Publishing.

In the following, we present four areas of HED research on the NIF: (i) ablatively stabilized, spherically converging hydrodynamic instability experiments, measuring RT growth factor vs. perturbation mode number; (ii) a set of planar embedded interface, “classical” (nonstabilized) hydrodynamic instability experiments; (iii) radiative shock stabilized, hydrodynamic instability results in planar geometry; and (iv) a material strength stabilized hydrodynamic instability experiment. We then summarize and conclude.
radiation drive for the "hydro-growth radiography" (HGR) platform (35, 45). This radiation drive ablatively implodes a hollow spherical capsule of 1-mm initial radius and 150–200 μm initial shell thickness, which consists of doped and undoped layers of plastic. Various dopant layers, such as CH(I), CH(Ge), and CH(Si), are used to block hard X-ray preheat generated at the ablation front. An example inflight X-ray radiograph from a preimposed ripple pattern on the ablation front of an imploding capsule is shown in Fig. 2B, inset and measured RT dispersion curves for low-foot vs. high-foot drives are shown as growth factor vs. mode number in Fig. 2B.

The high-foot drive has a stronger leading shock, and three total shocks instead of four, to increase the entropy, decrease the shell and hot-spot compression and reduce the amount of shell mass mixing into the hot spot. This is done by reducing the steepness of the density profile (increasing the density gradient scale length) at the ablation front and the shell–hot-spot interfaces. Also, the stronger leading shock leads to favorable changes in the RM phase of instability growth due to the RM oscillations at the ablation front described earlier (36), albeit at a lower fuel and hot-spot areal density. We see in Fig. 2B that the peak in the ablation-front growth factor curves is at a Legendre mode number of 60–70 and there is an ablative cutoff at approximately mode 160. Very similar values are found in the simulation (solid curve) and the experiment (symbols with error bars). We observe an ablation-front RT peak growth factor of ~1,000 for the low-foot drive vs. ~200 for the high-foot drive. It is clear that the high-foot drive generates conditions that are more hydrodynamically stable, compared with the low-foot drive. The image in Fig. 2B, inset shows an example inflight backlight X-ray radiograph of a capsule implosion with a preimposed perturbation with mode numbers of l = 60 (left-hand side) and 90 (right-hand side), near peak growth for the low-foot drive, and the raw data lineout is shown in Fig. 2B, bottom (35, 39).

Profiles of density and temperature vs. radius at bang time from simulations are shown in Fig. 2C for the low-foot (low-adiabat) drive (17). Fig. 2C, inset shows the capsule configuration. This 20-ns drive was developed to minimize the entropy created by shock heating, thereby maximizing the peak compression for cryogenic layered DT implosions. For enhanced diagnostic access, surrogate implosions are performed with an extra layer of ablator material to replace the normally cryogenic DT fuel layer and filled with gas. The simulation results given in Fig. 2C show that the CH shell (initial density of 1 g/cm³) has been compressed to nearly 150 g/cm³, corresponding to an increase in density of over a factor of 100 (blue curve in Fig. 2C). The peak temperature in the hot-spot DT gas fuel in this simulation was 4 keV, which leads to the predicted nuclear burn profile of 14-MeV DT neutrons/cm³ vs. radius shown by the gray curve in Fig. 2C.

To complete this sequence of experiments, we show in Fig. 2D the results from experiments to infer the amount of atomic mix ending up in the hot spot at peak burn from a smooth capsule without a preimposed perturbation on the outer surface. A deuterated layer of CD is put at or near the shell–hot-spot interface in the CH(Si) capsule, with a pure tritium (T₂) gas fill, as illustrated in Fig. 2D, inset. If there is atomic mix from the CD layer in the shell into the T₂ hot spot, there will be DT nuclear reactions, generating 14-MeV neutrons. The experimental yield of these 14-MeV DT neutrons vs. the recession depth of the CD layer is plotted in Fig. 2D. We see the expected trend: As the recession depth of the CD layer is increased, the amount of DT yield (mix) decreases monotonically (43, 45). This allowed the extent of original shell material that mixed into the hot spot by peak compression (bang time) to be determined, giving a mix width value of hmix ≈ 2–3 μm. Using the same methodologies validated in HGR experiments, detailed modeling of cryogenic layered, DT implosions on the NIF, such as those shown in Fig. 1A and B and described in ref. 13, approximately match the measured integrated implosion observables (neutron yield, total compression, hot-spot temperature, and ablator–hot-spot mixing). These simulations used the measured capsule surface roughness and account for other known perturbation sources, such as the support tent, fill tube, and hohlraum drive asymmetries.

### Embedded Interface, Planar Hydrodynamic Instability Experiments

We also developed and carried out a series of planar experiments in HED plasmas where a RT unstable region was formed at an embedded interface, which would not be significantly affected by the stabilizing effects of ablation, viscosity, or material strength. The experimental configuration is shown in Fig. 3A, where half of the NIF beams enter a hollow Au radiation cavity (hohlraum) and convert to a T₂ ~ 190 eV radiation drive of 5–7 ns duration which ablatively accelerates the sample under study. The planar physics package that is accelerated is shown in Fig. 3B. It consists of a CH(3%) ablator that is glued to an undoped polyamide–imide (PAI) layer, which is approximately transparent to the 9.0-keV Zn He-α backlighter X-rays used to radiograph the evolving interface from a side-on view. On the back side of the PAI layer, a square cross-section “trench” is machined into the PAI, and a CH(I) sample is precision fitted into this trench. Hence the front (driven side) and back sides of the physics package have CH(I) regions which are optically opaque, whereas the
middle part of the target is undoped polyamide–imide, which is nearly transparent to the high-energy backlit X-rays. This allows the side-on radiography experiments to measure 1D compression and decompression, which are needed to interpret the 2D side-on radiographs, so that the simple “accordion-like” 1D decompression is not mistaken for RT growth.

When the laser drive turned off, this physics package then decelerated for tens of nanoseconds, during which time the plastic-foam rippled interface was RT unstable. The resulting RT growth was measured at 40 ns after the laser drive turned on, with pulsed, side-on X-ray radiography. The radiograph in Fig. 3C shows the RT growth, including the spike tip formation at 40 ns from a $\lambda = 200\,\mu m$ perturbation with two different initial amplitudes, $\eta_B = 2.5\,\mu m$ and $10\,\mu m$. Later in time at 46 ns, for a $\lambda = 120\,\mu m$, $\eta_B = 6\,\mu m$ perturbation, the data exhibit the beginning stages of a transition to the advanced stages of RT evolution, showing the RT bubble and spike shape and spike tip Kelvin–Helmholtz roll-ups, as illustrated in Fig. 3D (44, 49).

Radiative Shock Stabilization of Planar Hydrodynamic Instabilities

Fig. 4 shows a planar, RT experimental design whereby a strong shock is launched into a doped plastic ablator of density 1.4 g/cm$^3$ and then enters a low-density 0.2 g/cm$^3$ SiO$_2$ aerogel foam tamper region of the target, where the shock becomes radiative (Fig. 4A). This creates a strong source of radiation from the radiative shock in the SiO$_2$ foam which can reduce the perturbation growth at the plastic–foam interface by ablative stabilization (52–54). A radiation cavity (hohlraum, 4 mm diameter $\times$ 3 mm long, shown in Fig. 4A, Left) converts the blue light from the NIF laser to a soft X-ray source of radiation at temperatures ranging from 200 eV to 350 eV (as shown in Fig. 4B), which in turn ablatively launches a strong shock into the CH ablator. Note that the peak in the radiation drive occurs during peak laser intensity around 3–5 ns, but the radiation does not immediately drop to zero when the optical laser turns off around 5 ns. There is a radiation afterglow that continues for 20 ns or longer.

In Fig. 4C, we show the 2D radiation-hydrodynamics simulations (55) of the perturbation growth at the RT unstable polyimide (PI)–foam interface, as a function of the hohlraum drive strength ranging from $T_R \sim 200\,eV$ to 350 eV. These 2D simulations assume a preimposed single-mode sinusoidal perturbation at the PAI–foam interface of wavelength $\lambda = 120\,\mu m$ and amplitude $\eta_B = 6\,\mu m$. Interestingly, the RT growth for the hohlraum drive cases is lower than that for the low-drive simulations. Analysis of these 2D simulations shows that the shock in the SiO$_2$ foam for the high-drive simulations is sufficiently hot and radiative that this radiation and heat conduction ablatively stabilizes the RT growth at the PI–foam interface. Conversely, for the low-drive case, the resulting shock in the foam is not sufficiently radiative and the shocked foam is not hot enough to stabilize the RT growth. Hence, the predicted RT growth is close to classical and, at the same interface distance traveled, is 40% larger than that of the high-drive case. Preliminary experiments on the NIF laser are shown in Fig. 4D and exhibit a similar effect (54). In both the simulations and experiments, the mix width increases monotonically with time, as expected from basic instability theory (56–58). Quantitative dependence of the growth rate of RT instability on radiation temperature and spectrum is a challenging problem worthy of additional investigation.

Material Strength Stabilized Hydrodynamic Instability Experiments

Finally, we describe a set of planar experiments on the NIF where the ductile metal sample under study is taken to high pressure but kept in the solid state. A variety of materials are being studied on the NIF in this effort; we discuss the tantalum (Ta) experiments here (59). To reach high pressure but keep the physics package solid requires a ramped compression wave, low-adiabat drive that can maintain an acceleration for many tens of nanoseconds. One approach to generating such a ramped drive is a reservoir–gap–sample configuration developed by Barnes et al. (60) in the 1970s and adapted to our HED laser experiments as shown in Fig. 5A (61). A strong shock is launched through a plastic “reservoir,” which in this experiment is a planar CH ablator attached over a window (hole) in the side of the hohlraum wall. The X-ray radiation from the hohlraum launches a strong shock through the plastic reservoir. When the shock breaks out the back side of the reservoir, the resulting releasing plasma sweeps across a vacuum
gap and stagnates on the heat shield (thin CH layer) glued onto the rippled Ta physics package. This drive accelerates the sample (physics package), while keeping it at high pressure and in the solid state. An example time-resolved radiograph for Ta at late time, t = 60 ns, is shown in Fig. 5B. The corresponding pressure vs. time on the sample, P(t), is shown in Fig. 5C, with P_{\text{max}} \sim 350 \text{ GPa}. Note that the sample is at pressure and accelerating for \( > \sim 30 \text{ ns} \). Fig. 5D shows \( \frac{T_{\text{sample}}}{T_{\text{melt}}} \leq 1 \) for the simulations, which predict that the physics sample remains more than a factor of 2 below the melt curve for the useful duration of the experiment.

The interface between the stagnating plasma reservoir and the rippled Ta payload is RT unstable during this acceleration. Preimposed ripples in the Ta tend to grow due to the RT instability, but the rate of growth is reduced by the high-pressure (100–500 GPa), high-strain rate (\( 10^6–10^7 \text{ s}^{-1} \)) material strength of the solid-state Ta. The sensitivity of the RT growth factors to the material strength stabilization is shown in Fig. 5E for peak pressure of 350 GPa and for different strength models: Preston–Tonks–Wallace (PTW) (62), Steinberg–Guinan (SG) (63), Steinberg–Lund (SL) (64), LLNL multiscale (LMS) (65), SG multiplied by a factor of 2 at all conditions and all times (2 \times SG), and SG multiplied by a factor of 5 (5 \times SG).

One of the simplest strength models is the SG model (63), where the material strength, \( \sigma \), of the sample increases with pressure and strain (\( \epsilon \)) decreases with temperature and is independent of strain rate,

\[
\sigma_{\text{SG}} = \sigma_0 f( \epsilon ) \left[ G(P, T) / G_0 \right] \tag{2}
\]

and

\[
G(P, T) = G_0 \left[ 1 + G'_P \frac{P}{G_0} \eta^{1/3} + G'_T \frac{T - 300}{G_0} \right], \tag{3}
\]

where \( G \) is the material shear modulus; \( G'_P = dG/dP; G'_T = dG/dT; \eta = \rho / \rho_0 \) is compression; and \( f(\epsilon) = [1 + b(\epsilon_i + \epsilon)]^n \) is the work hardening factor as a function of plastic strain \( \epsilon \) and any initial strain, \( \epsilon_i \), before the start of the dynamic experiment. Inspection of Eqs. 2 and 3 suggests that solids can become very strong at high pressure.

The PTW model (62) is a more sophisticated strength model which includes strain rates and has been applied favorably to experiments at the high strain rates of laser experiments (66). The LMS strength model adds yet another level of sophistication, by tying the components of the model to ab initio theory and direct numerical simulations, based on quantum-based interatomic potentials and dislocation mobilities (65). The Steinberg-Lund, PTW, and LMS models all predict that strength increases monotonically with strain rate. The net result of our laser experiments at high pressures and strain rates is that the Ta sample is predicted to be very strong, as shown in Fig. 5F, based on the LMS model, which reproduces reasonably well the RT experimental results shown in Fig. 5E. The inferred peak flow stress (strength) of the Ta physics sample is \( \sim 10 \text{ GPa at } P_{\text{max}} \sim 350 \text{ GPa}, and } \frac{d \sigma}{dP} \sim 10^7 \text{ Pa s}^{-1} \), while keeping the sample solid. \( T_{\text{sample}} \leq T_{\text{melt}} \). These strength levels (flow stress) at this extreme condition are large and it remains to be explored in future experiments whether the strength continues to rise monotonically with increasing pressure.

Conclusion

We developed experiments on the NIF to study the RT instability and advanced stages of RT evolution at a wide variety of extreme conditions, from hot, dense plasmas and burning hot spots to relatively cool, high-pressure materials undergoing solid-state, plastic flow at high strain and strain rate. We carried out experiments in HED regimes at an ablation front and at an embedded interface with or without the presence of a strongly radiative shock. These experiments were conducted in either planar or spherical geometry. HED conditions with and without strong radiative effects were shown. The solid-state plastic flow experiments shown in Fig. 5 allow us to study material response at pressures of 100–500 GPa and high strain rates, \( 10^6–10^7 \text{ s}^{-1} \). We found that the material strength in these-high pressure, high-strain rate plastic flow experiments is large and can significantly reduce the RT growth rates compared with classical values. For these high-pressure, high-strain rate, short-timescale conditions, there seems to be little sensitivity to sample initial microstructure. These results are relevant to planetary formation dynamics at high pressures (67). We find that widely used models for high-pressure strength differ significantly from one another at these extreme conditions of solid-state plastic flow. An intriguing consideration is the possibility of using these findings to enhance resistance to hydrodynamic instabilities in advanced designs of ICF capsule implosions.
ACKNOWLEDGMENTS. We gratefully acknowledge the insightful discussions and input from Dr. Stephen MacLaren from LLNL in the early stages of writing this manuscript. We appreciate the critical reading and useful suggestions of the referees. This work was performed under the auspices of the US Department of Energy by LLNL under Contract DE-AC52-07NA27344. We gratefully acknowledge the access to the NIF facility for the basic science experiments described in several of the figures, which was through the NIF Discovery Science program, which issues an annual call for proposals for basic science experiments on NIF.

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