Richtmyer-Meshkov jet formation and areal mass oscillations triggered by HED shock waves

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For many years we at NRL have studied seeding of the RT growth in laser fusion targets.

\[ \delta m_l = A_l \times \exp(\Gamma t) \]

Laser imprint and beam imbalance

Outer surface roughness

Interface roughness

Inner surface roughness

Early-time perturbation processing

Seed for exponential RT growth

J. Lindl, E. Moses et al., *Status and Plans of the National Ignition Campaign*, May 31, 2012:
Planar experiments to evaluate Richtmyer-Meshkov growth during the early phase of an ignition pulse.
Fundamental strongly nonlinear motions of compressible fluids

- Compression: shock waves (Rankine, 1870; Hugoniot, 1887)
- Expansion: centered rarefaction/expansion waves (Riemann and Earnshow, 1858)
- Stability/response to small perturbation analysis
  - Reveals basic properties of any physical system (spectra, characteristic velocities, general behavior)
  - For shock waves, the stability studies started together with nuclear weapons development in the mid-1940s
  - For rarefaction/expansion waves stability studies stimulated by ICF/HEDP started in the 1980s


Shock front stability

Planar shock waves can be unstable in various ways but shock waves in ideal gas are superstable for any $\gamma$

Small oscillations

Small-amplitude theory. The shock wave propagates into a thick plastic target, driven by constant-strength ablative piston.

Decays as $(k c_s t)^{-3/2}$
Everyone who studied compressible gas dynamics has heard or read about centered expansion waves.


Expansion wave stability

Small-amplitude theory, ideal gas.
Why does the areal mass in a rippled expansion wave oscillate?

Laser or hohlraum radiation drive

Planar shock wave propagates toward the rippled rear side of the target

After shock breakout, reflection of the rippled expansion wave starts from the valleys

Rippled rarefaction wave is fully formed. When it breaks out at the front surface of the target, its acceleration begins

Can we make the areal mass oscillations stronger?
Yes, if gas $\gamma$ is low

Asymptotic formula for oscillatory growth at $\gamma \ll 1$

$$\delta m(\tau) \approx \cos \tau - \left(\frac{\gamma - 1}{2}\right)^{1/2} \tau \sin \tau,$$

where $\tau = kc_s t$

Peak amplitude estimate

$$\delta m_{\text{max}} \approx \frac{2^{5/4}}{(\gamma - 1)^{1/2}}$$

Are these predictions supported by numerical simulations?
Yes, and the theory provides a challenging verification test. ICF codes are supposed to handle small perturbations well.

\[ \gamma = \frac{5}{3} \]

\[ k \eta_0 = 0.1 \]
Shock speed \(10^7\) cm/s, ripple wavelength 15 \(\mu\)m

\[ \gamma = 1.05 \]

\[ k \eta_0 = 2 \times 10^{-6} \]

Can the large areal mass oscillations in a rippled expansion wave be observed?
Possible but difficult with a finite-thickness target

- First phase reversal: \( L/\lambda > 0.9 \)
- First negative minimum: \( L/\lambda > 2.7 \)

\( \gamma = 5/3 \)

RT growth starts early
Earlier experiments

Thick target: $L/\lambda = 1.7$
One phase reversal observed.

Thin target: $L/\lambda = 0.65$.
No phase reversals.

Put the ripples on the front side of the target and turn off the laser early.

Rippled front surface: Theory predicts strong oscillations
Both areal mass and shock ripple amplitude oscillate

Small-amplitude perturbation analysis for \( \gamma = 7/5 \).
This prediction is supported by numerical simulations

Simulation:

- Rippled plastic target
  \( \lambda = 30 \, \mu m, \; \eta_0 = 5 \, \mu m \)
  53 or 100 \( \mu m \) thick
- KrF \( \lambda_L = 248 \, nm \) pulse
  peak \( 2.3 \times 10^{14} \, W/cm^2 \)
- Truncated Gaussian pulse
  FWHM 0.350 ns
The strong oscillations observed experimentally on Nike

Two successive Nike shots, similar CH targets rippled on the front
\[ \lambda = 30 \, \mu\text{m}, \, \eta_0 = 5 \, \mu\text{m} \]
100 \, \mu\text{m} thick

**Blue**: strong areal mass oscillations produced by impulsive loading
FWHM 0.45 ns
peak \(2.1 \times 10^{14} \, \text{W/cm}^2\)

**Green**: a single oscillation due to ablative RM instability
FWHM 4 ns
peak \(0.9 \times 10^{14} \, \text{W/cm}^2\)

Arrows mark phase reversals of areal mass
Lines: Fourier-transformed monochromatic x-ray face-on streak records

Phase reversals are seen with a naked eye

Three observed phase reversals

\[ \lambda = 45 \, \mu m, \ \eta_0 = 5 \, \mu m \]

125 \, \mu m thick

FWHM 0.45 ns

peak \(1.9 \times 10^{14} \, \text{W/cm}^2\)

Black solid line: experiment

Red dotted line: simulation

Density map: streak image

broadband filtering

22 to 50 \, \mu m

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Y. Aglitskiy et al., PRL 109, 085001 (2012).
What about the Richtmyer-Meshkov instability at Atwood# = -1 predicted by incompressible theory?

Shaped charge effect – RM-related jet production

Widely used by bad guys: Nazis starting from 1943, Faustpatrone + Ofenrohr, Iranians now.

The low velocity of the grenade does not lessen its effectiveness, because of the hollow-charge principle.
Source: Tactical and Technical Trends, No. 51, October 1944.
Large \( \gamma \) – approaching incompressibility

Theory predicts secular growth of perturbations in a perturbed expansion wave instead of decaying oscillations.

Instability is predicted for \( \gamma > 3 \).

Power-law growth

\[
\frac{\delta m}{\delta m_0} \propto (k c_s t)^{(\gamma-3)/(\gamma-1)}
\]

In the incompressible limit

\( \gamma \to \infty \) linear classical

Richtmyer-Meshkov growth is recovered:

\[
\eta(t) = \eta_0 - \left(1 + \frac{1}{\sqrt{2}}\right) k \eta_0 U t
\]

Low drive intensity => low shock pressure
=> low compressibility => high gamma

CH target rippled on the rear side
\[ \lambda = 46 \, \mu m, \eta_0 = 7.5 \, \mu m \]
53 \, \mu m thick
Single Nike beam
FWHM 4 ns
peak 1.4 \times 10^{12} \, W/cm^2
pressure \approx 0.7 \, Mbar
Side-on monochromatic x-ray image taken at 15 ns
pre-shot and driven images aligned and overlapped
jets 500 \, \mu m wide along the line of sight

@ this conference, Y. Aglitskiy’s talk TO4.00014 on Thursday, Nov. 1, Room 551B, 12:06 pm
Slightly increase the drive intensity and the RT instability comes into play

Flat top $\Phi 400 \mu m$

$\text{t}=16.5 \text{ ns}$

Oscillations

Driven image

Pre-shot

RT growth at the ablation front starts from formation of the front-surface bubbles aligned with rear-surface valleys

$3$ overlapped Nike beams
peaks $4 \times 10^{12} \text{ W/cm}^2$
pressure $1.4 \text{ Mbar}$
acceleration starts shortly before the end of the laser pulse
Full Nike power, strong RT growth

- **Flat top** \( \phi 400 \mu m \) at \( t=15ns \)
- **t=3.8 ns**
- **t=1.4 ns**
- **Undriven target**

**Late-time:** all mass rests in spikes, no phase reversals

- **36 overlapped Nike beams**
- **Peak** \( 5 \times 10^{13} \) W/cm²
- **Pressure** 8 Mbar
- **Acceleration starts at** \( \sim 1 \) ns