Ablative Rayleigh-Taylor Instability at Short Wavelengths

Moire Interferometry

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Penumbral Imaging

Fresnel Phase Zone Plate
Primary obstacle of IFE is Rayleigh-Taylor instability.

Typical wavelength = several tens µm
Time scale = ns
High resolution advanced diagnostics are required.

X-ray Moire interferometry
Fresnel phase zone plate
Penumbral imaging

Ablative Rayleigh-Taylor instabilities

Eagle nebula

Type Ia supernovae

Laser exp't

Astrophysics of exploding objects
Lecture notes by Serguei Blinnikov

Perturbation amplitude \( a = a_0 e^{\gamma t} \)

\[ \gamma = \sqrt{\frac{kg}{1+kL} - \beta k v_a} \]

\( v_a \) = fluid velocity across the unstable surface

\( \beta \) = depends on the ablation structure.
**Motivation**

New method is needed for the measurement of short wavelength Rayleigh-Taylor (RT) Growth.

It is necessary to measure short wavelength RT growth in order to understand the mechanism of the ablative stabilization.

**Dispersion curve of the Rayleigh-Taylor instability**

- Short wavelength RT Moire interferometry
- Independent test Penumbral imaging Fresnel phase zone plate
Moire interferometry / short wavelength Rayleigh-Taylor
Experimental procedure

Schematic view of the experimental setup

Setup

Backlight Laser
Target (Cu)
Filter (Mg)

Grid
Mask (Ta)

X-ray Imager

Laser
Drive

X-ray

Shield (Mg)

Experimental condition
Laser intensity: $7 \times 10^{13} \text{ W/cm}^2$
Laser wavelength: $0.53 \mu\text{m}$
Target: CH 16$\mu$m

Corrugated polystyrene foil

0.3 mm
Moiré interferometry is very useful for measurements of the RT instability at short wavelength.

**Principle**

**Perturbation wavelength**

\[ \lambda_{\text{Perturb.}} = 12 \text{ \(\mu\text{m}\)} \]

\[ \lambda_{\text{Grid}} = 10 \text{ \(\mu\text{m}\)} \]

\[ \lambda_{\text{Moiré}} = 60 \text{ \(\mu\text{m}\)} \]

\[ k_{\text{Moiré}} = |k_{\text{Perturb.}} \pm k_{\text{Grid}}| \]

Due to the moiré interference, the short wavelength perturbation is converted to longer wavelength perturbation.

Experimental results

Raw data of Rayleigh-Taylor instability observed with moiré interferometry

\[ \lambda = 12 \mu m \quad a_0 = 0.1 \mu m \]

\[ \lambda = 8.5 \mu m \quad a_0 = 0.1 \mu m \]

\[ \lambda = 4.7 \mu m \quad a_0 = 0.05 \mu m \]

\[ \lambda_M = \frac{\lambda_1 + \lambda_2}{\lambda_1 - \lambda_2} \text{ sensitive to } \Delta \lambda \]
Large Rayleigh-Taylor growth was observed up to 5-µm wavelength.

- This exp’t suggests that nonlocal heat transport plays a role in ablative stabilization.
- However, for unambiguous clarification, we need to make independent observation.
Reduction of the target density with nonlocal heat transport

Density profile at 1.3 ns

- Spitzer-Härm (SH)
  - Local heat transport:
    - Diffusion approximation of electron thermal conduction

- Fokker-Planck (FP)
  - Nonlocal heat transport:
    - High-energy electrons in the tail of Maxwellian distribution penetrate into the target and preheat it.

\[ \dot{m} = \rho_a v_a \approx \text{const} \]

Density profile was obtained from the x-ray backlighting image of the planar target.

\[
\mathcal{T} = \exp(-\mu \rho l)
\]

\(\mathcal{T}\) : Transmission, \(\mu\) : mass absorption coeff.

\(l\) : material thickness, \(\rho\) : density
Fresnel phase zone plate / density profile
The principle of the FPZP imaging

Advantage
- High spatial resolution 2.2 µm
- Hard x-ray imaging 4.7 keV

Disadvantage
- Chromatic aberration
- Background

FPZP
When x rays transmit through the material zones of the FPZP, the phase of x ray increases by π.

Point source
Diffraction
x rays
Screen
Spatial resolution test of FZP

Ta grid mask
10.0 µm pitch
Thickness: 2.2 µm

The wavelength at which the MTF becomes 5% is 2.2 µm.

CCD camera MTF is removed by Calculation.

The wavelength at which the MTF becomes 5% is 2.2 µm.
Ablation density profile

Obtained data

Spectrum breadth 2~3 %
Target thickness 2~3 %
The target bend negligible
Intensity profile of the probe x rays <1 %

Contribution of the background <20 %

Experiment (disagreement)

Simulation+Smear

$\text{t= 1.3 ns: the early phase of acceleration}$

$\text{t= 2.2 ns: the late phase of acceleration}$
Penumbral Imaging / density profile
The proper density profile of the laser-undriven polystyrene target was obtained with penumbral imaging coupled with a side-on x-ray backlighting.

ILE OSAKA
The density profiles in target plasmas driven by the HIPER laser were observed from shock transit to target acceleration.

Density measurement with penumbral imaging

S. Fujioka
(ILE. Osaka)

The origin of the time is set to be the time when the shock breaks out at a target rear surface.

Spatial resolution: 3 - 5 µm
Temporal resolution: 140 - 160 ps
Kinetic effects on electron energy transport are not negligible even in the case of relatively low intensity blue laser irradiation ($I_L = 0.7 \times 10^{14}$ W/cm$^2$, $\lambda_L = 0.35 \mu$m).

Density measurement with penumbral imaging

S. Fujioka
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$L_m = 2.6 \mu$m (Experiment)

$\rho_a = 2.1^{+0.2}_{-0.3}$ g/cm$^3$ (Experiment)
$\rho_a = 2.1$ g/cm$^3$ (Kinetic)
$\rho_a = 2.5$ g/cm$^3$ (Diffusive)

Motion blurring were cleared away by a deconvolution process with measured temporal history of backlight x-rays and velocity of targets.
summary

With advanced diagnostic techniques, we are approaching to better understanding of the Rayleiu-Taylor instability.

• Rayleigh-Taylor (RT) is the critical physics for high-gain IFE

• Energy transport can modify the RT growth at short wavelengths.

• Moire interferometry first observed the short wavelength RT growth.

• The observed RT growth suggests that nonlocal transport plays a role in ablative stabilization. But there is some ambiguity due to saturation.

• For independent test of the transport effect, we are measuring the ablation density with high-resolution imaging techniques.

• Initial test result is supportive to the nonlocal transport.

Our strategy is to measure all necessary quantities ($\gamma, k, g, m, \rho_a, L$) to test various RT theories.