A Model of Laser Imprinting


Laboratory for Laser Energetics, U. of Rochester

The control of laser imprint is of crucial importance for the successful implosion of direct-drive inertial confinement fusion targets. Irradiation nonuniformities generate, or “imprint,” modulations in the ablation pressure that seed the Rayleigh–Taylor (RT) and Bell–Plesset (BP) instabilities, which in turn degrade the symmetry of the implosion and reduce the target performance. To gain physical insight, an analytical model of imprint has been developed. The model takes into account the dynamics of the conduction zone, mass ablation, and the SSD smoothing scheme. The important parameters that characterize laser imprint are found to be the time scale for plasma atmosphere formation, the ablation velocity, and the density-gradient scale length. The first determines the smoothing rate due to thermal transport in the conduction zone, and the last two characterize the dynamic overpressure stabilization described in Ref. [1]. The model has been validated by comparisons to detailed multidimensional hydrocode simulations using a range of ablator materials, perturbation wavelengths, and pulse shapes. The model has been found to be in good agreement with a series of planar-foil imprint experiments performed on the OMEGA laser system at the University of Rochester’s Laboratory for Laser Energetics. Imprint’s effect on NIF and NIF-scaled OMEGA cryogenic targets has been studied. It is has been shown that such targets will remain intact during the implosion when the laser is smoothed with 1 THz 2-D SSD. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority.

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V. N. Goncharov
University of Rochester
Laboratory for Laser Energetics

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University of Rochester
Laboratory for Laser Energetics
Summary

An analytical model is developed to gain physical insight of the laser imprint

• Laser nonuniformities imprint surface modulations that degrade the symmetry of implosion.

• An analytical model has been developed to determine the physical processes contributing to imprint.
  – Hydrodynamic flow is the main imprinting mechanism.
  – Thermal smoothing and the dynamic overpressure are the main processes reducing the imprint.

• Laser imprint, with 1-THz SSD beam smoothing, will not significantly degrade cryogenic-target performance.
Outline

• Laser imprint in direct-drive ICF
• Processes contributing to laser imprint
• Processes reducing laser imprint
• Analytic imprint model
  – comparison with 2-D numerical simulation
  – comparison with imprint experiments
• Effect of imprint upon NIF ignition targets
  – polymer overcoat
  – SSD beam smoothing
  – target gain
In direct-drive target designs developed at LLE, the fuel isentrope is controlled by the shock preheat.

- Direct-drive, $\alpha = 3$, NIF ignition target design

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**Graph:**

- The graph shows the power (in TW) versus time (in ns).
- The power increases sharply after a "Foot" region, indicating the main drive phase.

**Diagram:**

- The diagram illustrates the layers of DT and DT gas with thicknesses of 1.69 mm and 1.35 mm respectively.
- CH layer is shown as the outermost layer.
Laser imprint degrades target performance

At the beginning of the main drive

Surface finish:
\[ \sigma_{\text{inner}} = 1.00 \, \mu m \]
\[ \sigma_{\text{outer}} = 0.08 \, \mu m \]

1-D gain

Maximum compression

Laser

Gain vs. rms imprint (\( \mu m \))
Processes contributing to imprint

- Velocity perturbation due to nonuniform shock propagation
- Acceleration perturbation from the lateral flow in the compressed region
Hydrodynamic flow is the main imprint mechanism: velocity perturbation

- Shock speed depends of the ablation pressure $U_s \sim \sqrt{p_a}$

\[ \frac{d\eta}{dt} = \frac{\delta p_a}{p_a} \]

\[ \eta_{vel} = \tilde{v}t \sim \frac{\delta p_a}{p_a} c_s t \]
Hydrodynamic flow is the main imprint mechanism: acceleration perturbation

- Rippled shock creates lateral mass flow.

\[ \frac{d^2 \eta}{dt^2} = \ddot{a} \propto k \frac{\delta p_a}{\rho} \]

\[ \eta_{ac} \propto k \frac{\delta p_a}{p_a} c_s^2 t^2 \]

\[ \eta = \eta_{vel} + \eta_{ac} \]
Physical mechanisms reducing imprint

- Thermal smoothing
- Dynamic overpressure (rocket effect)
  - ablation-surface oscillation
- Fire polishing, vorticity convection
Thermal smoothing$^1$ suppresses acceleration perturbation

- Laser perturbations decouple from the ablation front when $kD_c \sim 1$

Decoupling time $t_D \propto (kV_c)^{-1}$

Imprint growth is reduced by thermal smoothing

- After decoupling time $t > t_D$, $\tilde{a} = 0$.

\[ \tilde{v}_D \approx \frac{\delta I c_s^2}{I V_c} \]

\[ \eta \propto \tilde{a} t^2 \]

\[ \eta \propto \tilde{v}_D t \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]

\[ \text{kcs} \]

\[ \text{Without thermal smoothing} \]

\[ \text{With thermal smoothing}^1 \]

Late-time imprint growth is stabilized by dynamic overpressure

Thrust force = \( \dot{m}V_{bl} \)

Rate of change of mass

Exhaust velocity

Ablation front

Absorption region

Velocity of blowoff plasma

Mass ablation rate

Dynamic overpressure = \( \dot{m} \Delta V_{bl} \approx \dot{m}V_{bl}k\eta \)
Late-time imprint growth is stabilized by the dynamic overpressure

\[ F = -\nabla(\Delta p_d) = -k^2 \dot{m}V_{bl} \eta \]

Effective spring constant \( k_{bl} \)

Mass-spring system

\[ F = -k_{bl} \eta \]

- Oscillations

Spring \( \omega = \sqrt{\frac{k}{M}} \)

Ablation front \( \omega = \sqrt{\frac{k_{bl}}{\rho}} = k \sqrt{\frac{V_a V_{bl}}{\rho}} \)

TC5277
Imprint amplitude is determined by the decoupling velocity and oscillation frequency

\[ \eta_{\text{max}} = \frac{2 \varepsilon_k}{k_{bl}} = \frac{\tilde{v}_D}{\omega} \]

\[ \varepsilon_k = \rho \tilde{v}_D^2 / 2 \]

\[ \varepsilon_p = k_{bl} \eta^2 / 2 = \rho \omega^2 \eta^2 / 2 \]

\[ \eta_{\text{max}} \propto \frac{\delta I}{I} \frac{c_s^2}{V_c k_{bl} V_a V_{bl}} \]
The most damaging modes oscillate during the shock propagation

- Single-mode imprint ORCHID simulations

![Graph showing shock breakout and amplitude over time]

NIF $\alpha = 3$

Target design

Amplitude (nm)

Time (ns)

Shock breakout

NIF $\alpha = 3$

Target design

Amplitude (nm)

Time (ns)

Shock breakout
Imprint model

- Description of the model
- Results
  - ablation-surface oscillations
  - imprint amplitude
- Comparison with simulations
- Comparison with imprint experiments
The analytic model is based on solution of the sharp boundary model

\[
\partial_t^2 \rho - c_s^2 \partial_x^2 \rho - k^2 \rho = 0
\]

Model is solved by multiple-scale technique.

\[
\tau = k c_s t \quad T = k \sqrt{V_a V_{bl}} t \quad \xi = k V_a t
\]

Oscillations are damped by fire polishing and vorticity convection.
The imprint amplitude is determined by the decoupling velocity and oscillation frequency \( \eta_{\text{max}} = \tilde{v}_D / \omega \)

**Comparison of CH and cryo DT ablators, \( I = 3.0 \times 10^{13} \text{ W/cm}^2 \)**

Decoupling velocity \( \tilde{v}_D \sim c_s^2 / V_c \)

Oscillation frequency \( \omega = k \sqrt{V_a V_{bl}} \)

\( V_a^{\text{CH}} = 1.0 \text{ \( \mu \)m/ns} \quad V_a^{\text{DT}} = 2.5 \text{ \( \mu \)m/ns} \)

\[
\tilde{v}_D^{\text{DT}} \approx 2.5 \\
\tilde{v}_D^{\text{CH}} \approx 2.5 \\
\eta^{\text{DT}} \approx \eta^{\text{CH}} \\
\frac{\omega^{\text{DT}}}{\omega^{\text{CH}}} \approx 2.5
\]
ORCHID simulations confirm the predictions of the model.

Perturbation wavelength $\lambda = 40 \, \mu m$

Front amplitude $(\mu m)/(\delta I/I)$

Time (ns)

\[ DT \approx CH \]

$\eta_{max} \approx \eta_{max}$
The imprint amplitude and oscillation period are reduced by increasing laser intensity.

**Scaling**

\[ \eta \propto \eta_{\text{max}} \sin \omega t \]

\[ \approx \sqrt{V_a V_{bl}} \]

\[ \sim \frac{V_a \sim I}{V_c \sqrt{V_a V_{bl}}} \]

\[ c_s \sim I^{1/3} \]

\[ V_a \sim V_{bl} \sim I^{1/3} \]

\[ h_{\text{max}} \sim I^{-2/3} \]

\[ T_{osc} \sim I^{-1/3} \]

**Detailed model results**

- cryo DT planar foil
- thickness = 345 µm
- flat-top laser pulse

\[ \eta(\mu m)/(\delta I) \]

\[ I = 3.0 \times 10^{13} \text{ W/cm}^2 \]

\[ I = 6.0 \times 10^{13} \text{ W/cm}^2 \]

\[ I = 1.2 \times 10^{14} \text{ W/cm}^2 \]
Simulations confirm that the imprint amplitude and laser oscillation period are reduced by increasing laser intensity.

- Cryo DT planar foil
- Thickness = 345 $\mu$m
- Flat-top laser pulse

$\eta(\mu m)/(\delta I/I) = \begin{cases} 
1.2 \times 10^{14} \text{ W/cm}^2 & \text{for } I = 3.0 \times 10^{13} \text{ W/cm}^2 \\
6.0 \times 10^{13} \text{ W/cm}^2 & \text{for } I = 3.0 \times 10^{13} \text{ W/cm}^2
\end{cases}$

$\xi_{\text{max}} \sim I^{-1.0}$  $T_{\text{osc}} \sim I^{-0.4}$
Shorter-wavelength nonuniformities have lower imprint amplitudes and shorter oscillation periods

- **Model:** \( \eta_{\text{max}} \sim \lambda; \ T_{\text{osc}} \sim \lambda \)

- **ORCHID simulation:** DD, NIF, \( \alpha = 3, \) “all-DT” target design
  - \( I = 3.0 \times 10^{13} \) W/cm\(^2\)
  - thickness = 345 \( \mu \)m

\( \eta_{\text{m}} \sim \lambda^{1.6}; \ T_{\text{osc}} \sim \lambda^{1.1} \)
The model has been tested against planar-foil imprint experiments performed on the OMEGA laser system*.

- 20-μm-thick CH
- Two laser pulse shapes; two perturbation wavelengths
- Nonuniformities were measured using through-foil x-ray radiography.

• Imprint is quantified by the mass equivalence.

\[ A_{EQ} = \frac{A_{\text{imprint}}}{A_{\text{pre}}} A_{\text{pre}}(t = 0) \]

*T. R. Boehly et al., CO2.01, this conference.
The results of the experiments agree with imprint simulations and predictions of models.

Higher intensities and shorter perturbation wavelengths imprint less for modes with $t_D <$ shock breakout time.

<table>
<thead>
<tr>
<th></th>
<th>Experiments</th>
<th>Simulations</th>
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</thead>
<tbody>
<tr>
<td>$\eta_{\text{ramp}}^{60}$</td>
<td>1.7±0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>$\eta_{\text{square}}^{60}$</td>
<td>1.8±0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>$\eta_{\text{square}}^{30}$</td>
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Application of the model: effect of imprint on direct-drive NIF ignition design

- Effect of polymer overcoat
- Effect of SSD
- Target gain
The thin polymer layer required for target fabrication results in enhanced imprint

Rayleigh–Taylor instability

Velocity perturbation

Rarefaction wave

Shock

Ablation front

Pressure

DT CH

Transmitted shock

Ablation front

Shock

Ablation front

Rarefaction wave

g = 0

g > 0

t = t_{rw}
Simulations show increased imprint for polymer overcoated targets

- *ORCHID* simulation; perturbation wavelength $\lambda = 40 \, \mu m$

\[ g_{\text{peak}} \sim \frac{\rho_{\text{CH}} - \rho_{\text{DT}}}{\rho_{\text{CH}d_{\text{CH}}}} \]

\[ \Delta t_{\text{ac}} \sim d_{\text{CH}}/c_{\text{s,CH}} \]

\[ g_{\text{peak}} \sim \frac{\rho_{\text{CH}} - \rho_{\text{DT}}}{\rho_{\text{CH}d_{\text{CH}}}} \]

RT growth factor $\sim \exp\left(\sqrt{kg\Delta t_{\text{ac}}^2}\right) \sim \exp\left(\sqrt{kd_{\text{CH}}}\right)$
Without SSD, thermal smoothing and dynamic overpressure do not reduce imprint to the levels required for high-gain implosions

- NIF direct-drive, $\alpha = 3$ target design
  - mode spectrum from DPP’s and DPR’s; no SSD
  - 40 overlapping beams

Temporal beam smoothing is required.
SSD reduces time-averaged laser nonuniformity

\[ t_c^* = \left[ \Delta \nu \sin \left( k \delta / 2 \right) \right]^{-1} \]

\( \Delta \nu \): bandwidth

\( \delta \): speckle size

\[ \langle \sigma_{\text{rms}} \rangle \sim \sqrt{t_c / \langle t \rangle} \langle \sigma_{\text{rms}}^0 \rangle \]
Imprint amplitude can be reduced by applying SSD smoothing technique (continued)

- **ORCHID simulations**
  For constant-intensity foot pulse \( \langle \delta I \rangle = \delta I^0 \sqrt{t_c/t} \).
  Example: CH foil, \( I = 3 \times 10^{13} \) W/cm\(^2\) laser pulse, \( t_c = 8 \) ps

\[
\eta_{\text{SSD}} \approx \sqrt{\frac{t_c}{t_D}} \quad \frac{\eta_{\text{SSD}}}{\eta_{\text{no SSD}}} \approx \sqrt{\frac{t_c}{t_D}}
\]

\[
\eta_{\text{SSD}} \approx \sqrt{\frac{(\Delta V k \delta)^{-1}}{(kV_c)^{-1}}} = \sqrt{\frac{V_c}{\Delta V \delta}}
\]
2-D SSD with the bandwidth ~1 THz gives sufficient nonuniformity reduction.

Mode spectrum at the beginning of main drive

ORCHID simulations and RT analytic modeling with 3-D saturation

Gain

Bandwidth (THz)

σ_{inner} = 1.00 \, \mu m
σ_{outer} = 0.08 \, \mu m
Summary/Conclusions

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