A Model of Laser Imprinting

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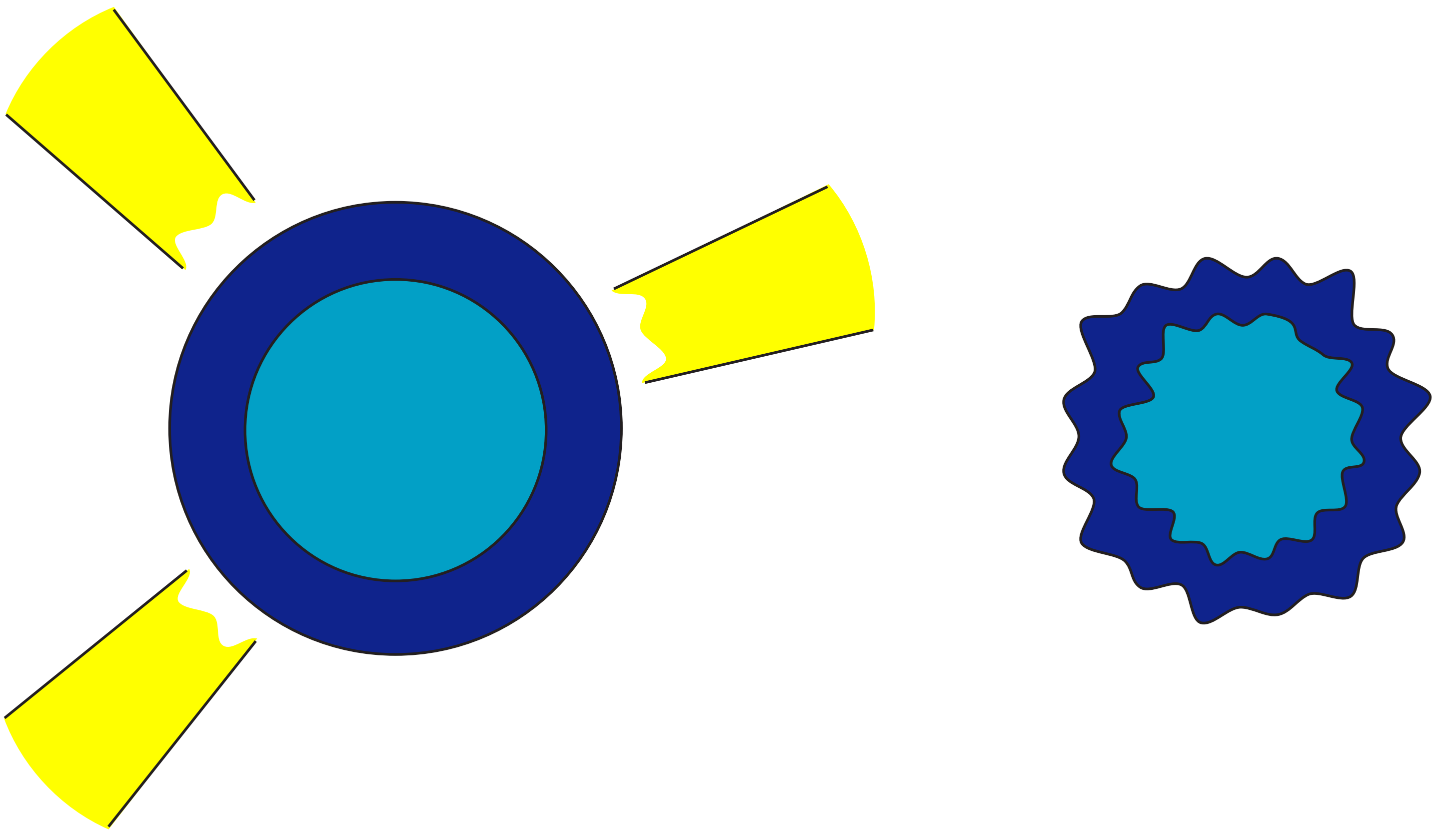
The control of laser imprint is of crucial importance for the successful implosion of direct-drive inertial confinement fusion targets. Irradiation nonuniformities generate, or "imprint," modulations in the ablation pressure that seed the Rayleigh–Taylor (RT) and Bell–Plesset (BP) instabilities, which 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.

[1] V. N. Goncharov, Phys. Rev. Lett. **82**, 2091 (1999).

A Model of Laser Imprinting



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Summary

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

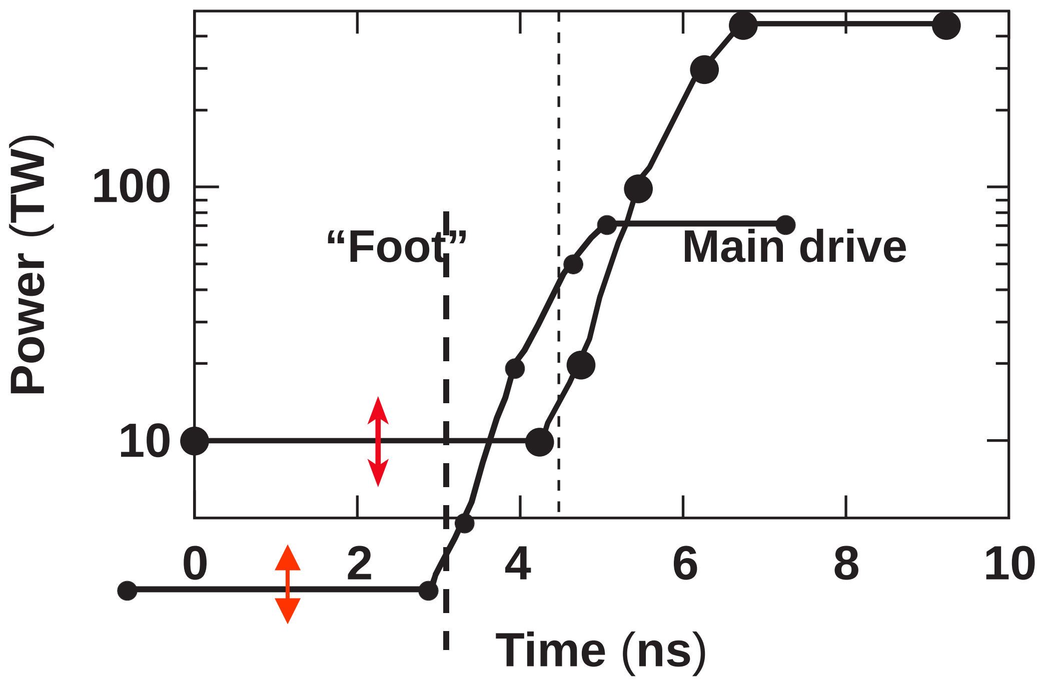
- Laser nonuniformities imprint surface modulations that degrade the symmetry of implosion.
- An analytical model has been developed to determine the physical processes contributing to imprint.
    - – Hydrodynamic flow is the main imprinting mechanism.
    - – Thermal smooting and the dynamic overpressure are the main processes reducing the imprint.
- Laser imprint, with 1-THz SSD beam smoothing, will not significantly degrade cryogenic-target performance.

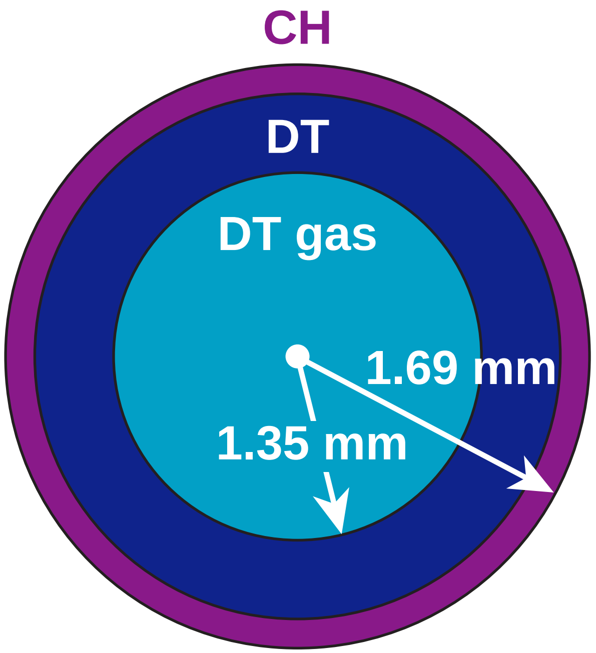
Outline

- 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

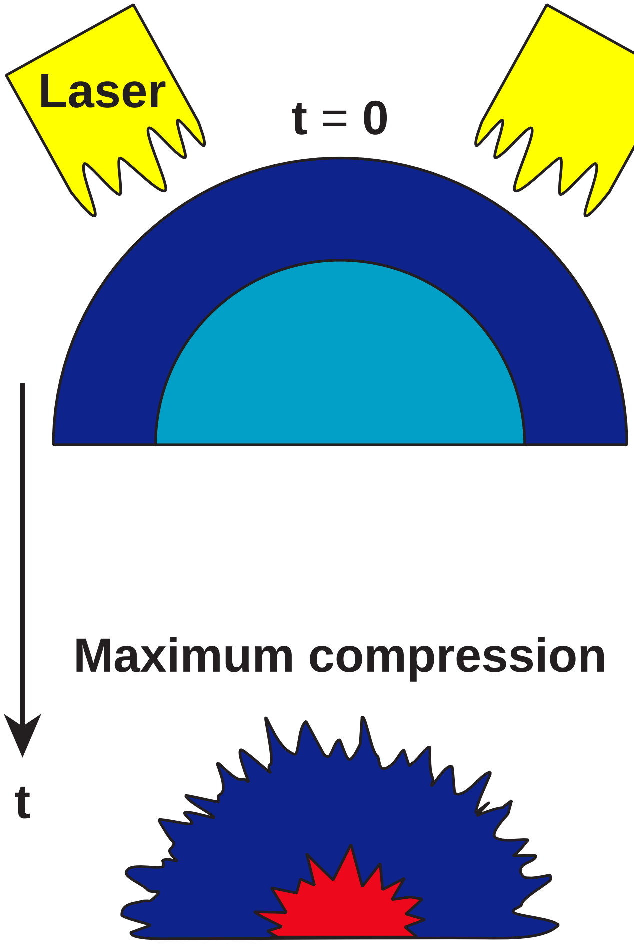
In direct-drive target designs developed at LLE, the fuel isentrope is controlled by the shock preheat

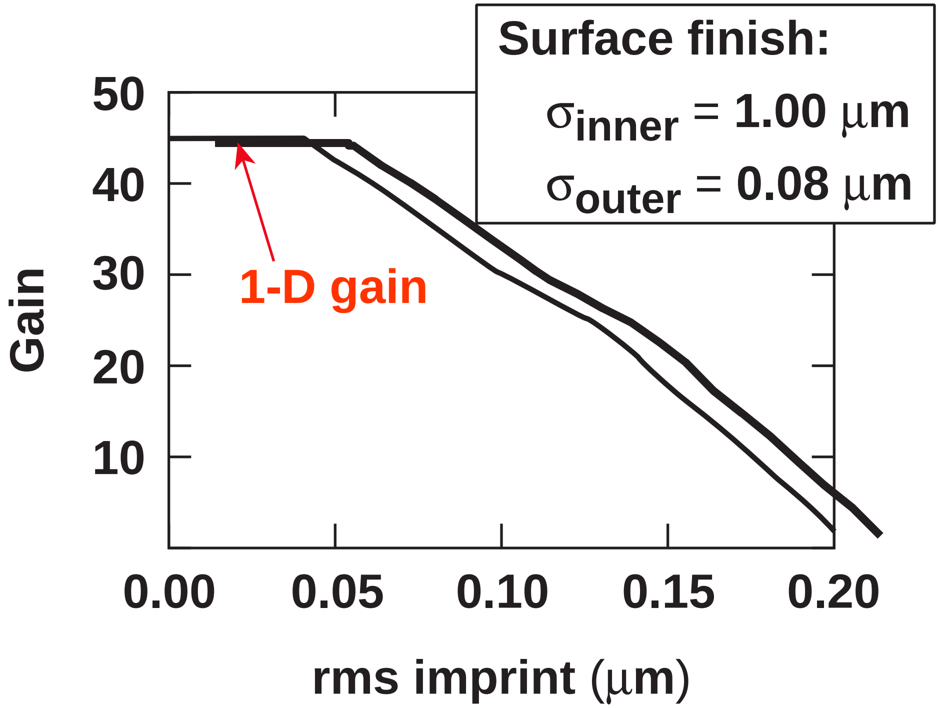
- **Direct-drive, α = 3, NIF ignition target design**





Laser imprint degrades target performance





At the beginning
of the main drive

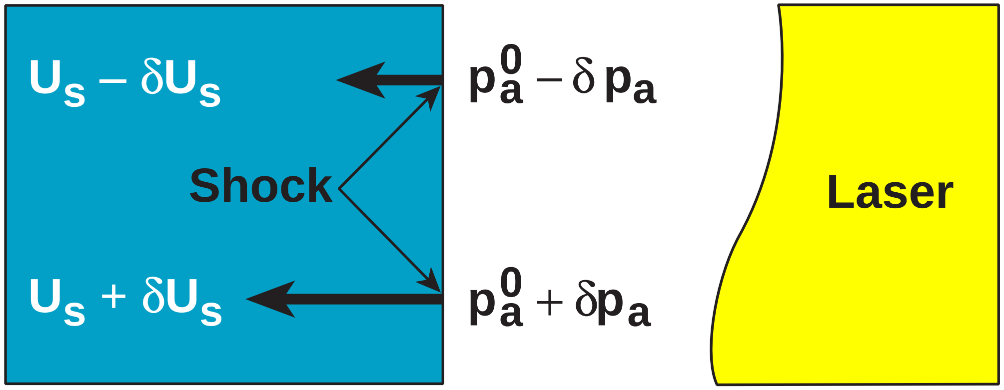
Processes contributing to imprint

- Velocity pertubation due
  to nonuniform shock propagation

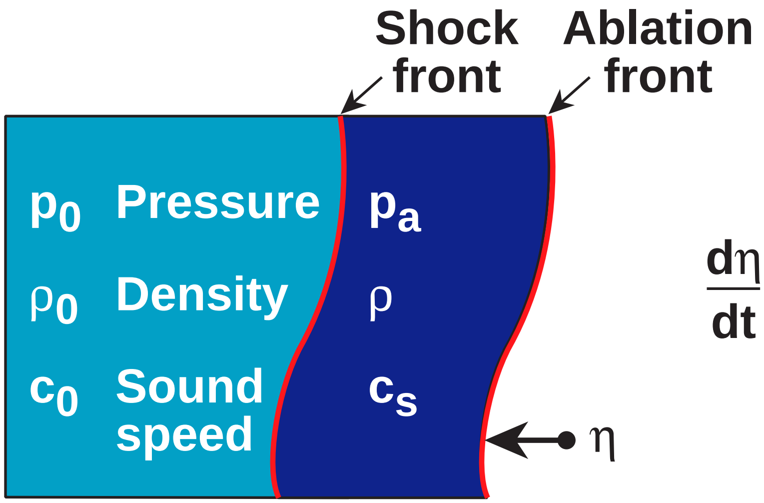
- Acceleration perturbation from the lateral
  flow in the compressed region

Hydrodynamic flow is the main imprint mechanism: velocity perturbation

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



$$\tilde{v} \sim \delta U_s \sim \frac{1}{2} U_s \frac{\delta p_a}{p_a^0}$$



$$\frac{d\eta}{dt} = \tilde{v} \sim U_s \frac{\delta p_a}{p_a}$$

$$\boxed{\eta_{vel} = \tilde{v}t \sim \frac{\delta p_a}{p_a} c_s t}$$

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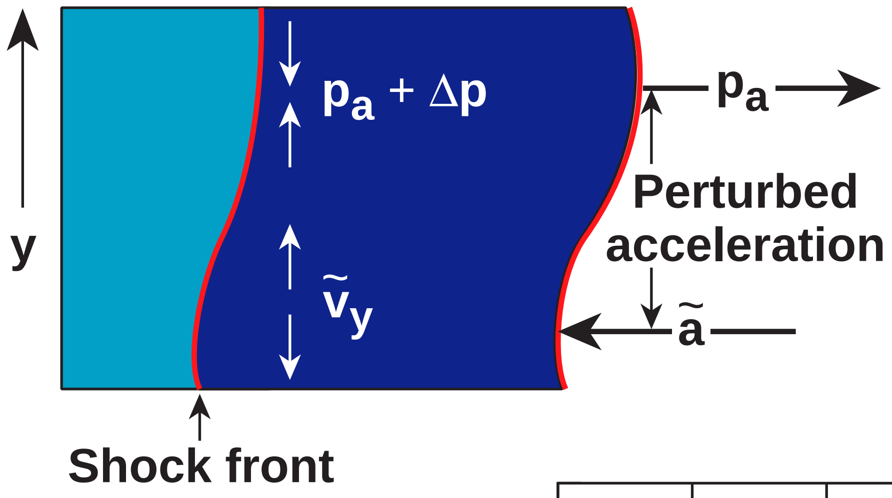
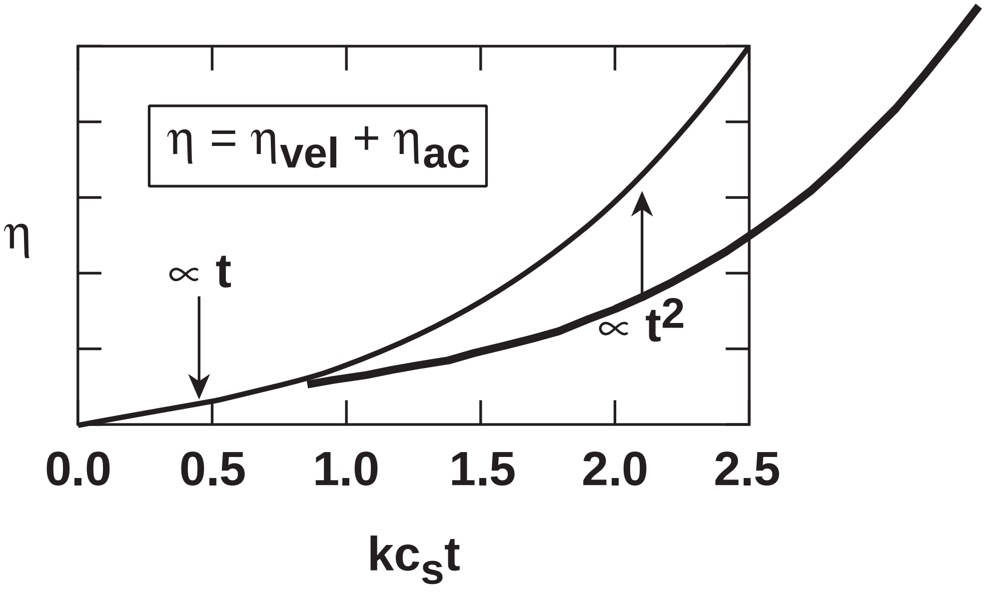
Hydrodynamic flow is the main imprint mechanism: acceleration perturbation

- Rippled shock creates lateral mass flow.



$$\frac{d^2\eta}{dt^2} = \tilde{a} \propto k\frac{\delta p_a}{\rho}$$

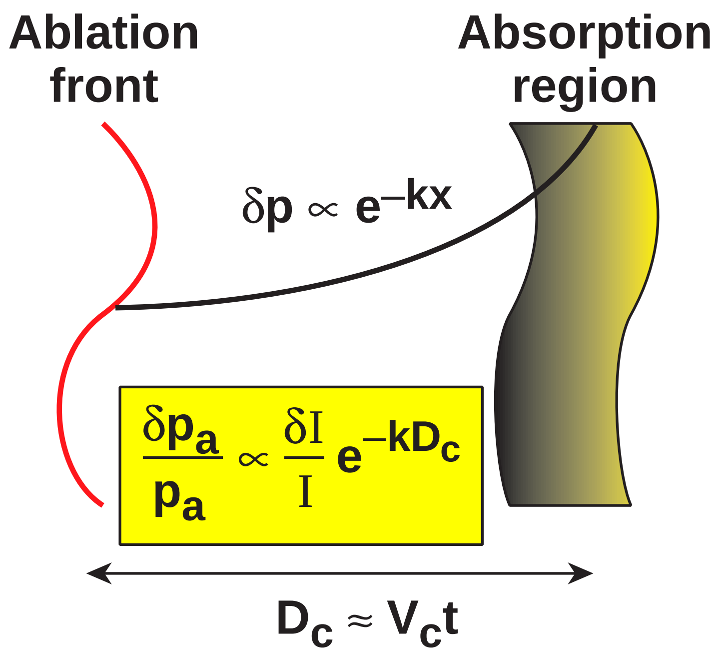
$$\boxed{\eta_{ac} \propto k\frac{\delta p_a}{p_a} c_s^2 t^2}$$



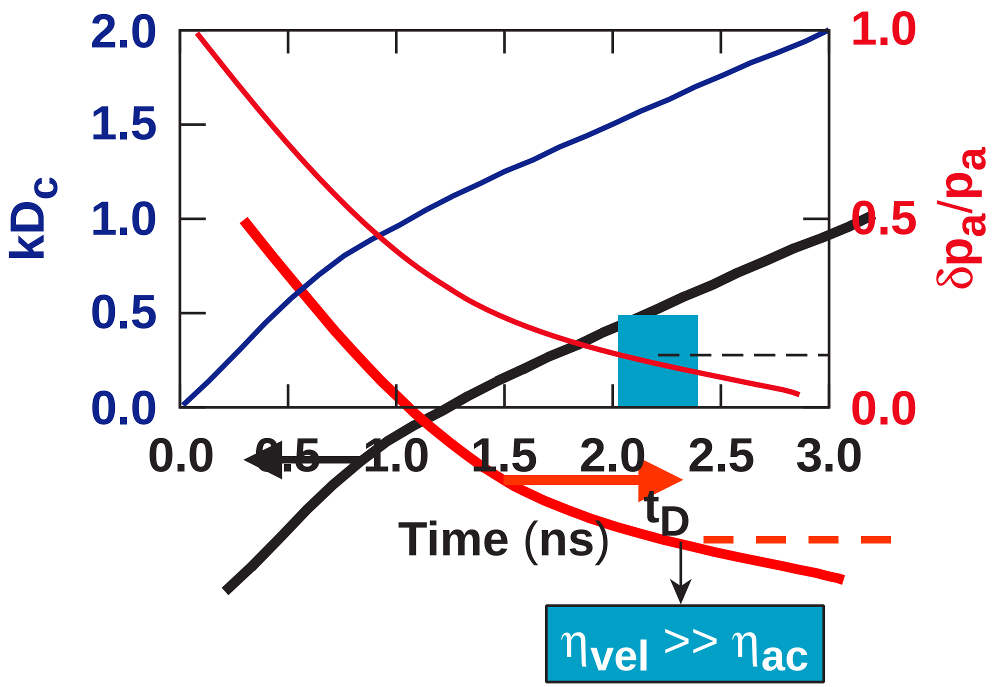
Physical mechanisms reducing imprint

- Thermal smoothing
- Dynamic overpressure (rocket effect)
  - ablation-surface oscillation
- Fire polishing, vorticity convection

Thermal smoothing[1] suppresses acceleration perturbation



$$\frac{\delta p_a}{p_a} \propto \frac{\delta I}{I} e^{-kD_c}$$



$\eta_{vel} >> \eta_{ac}$

- Laser perturbations decouple from the ablation front when kD_c ~1

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

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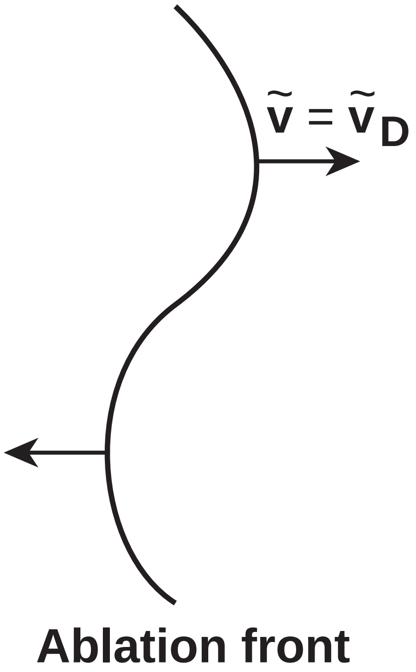
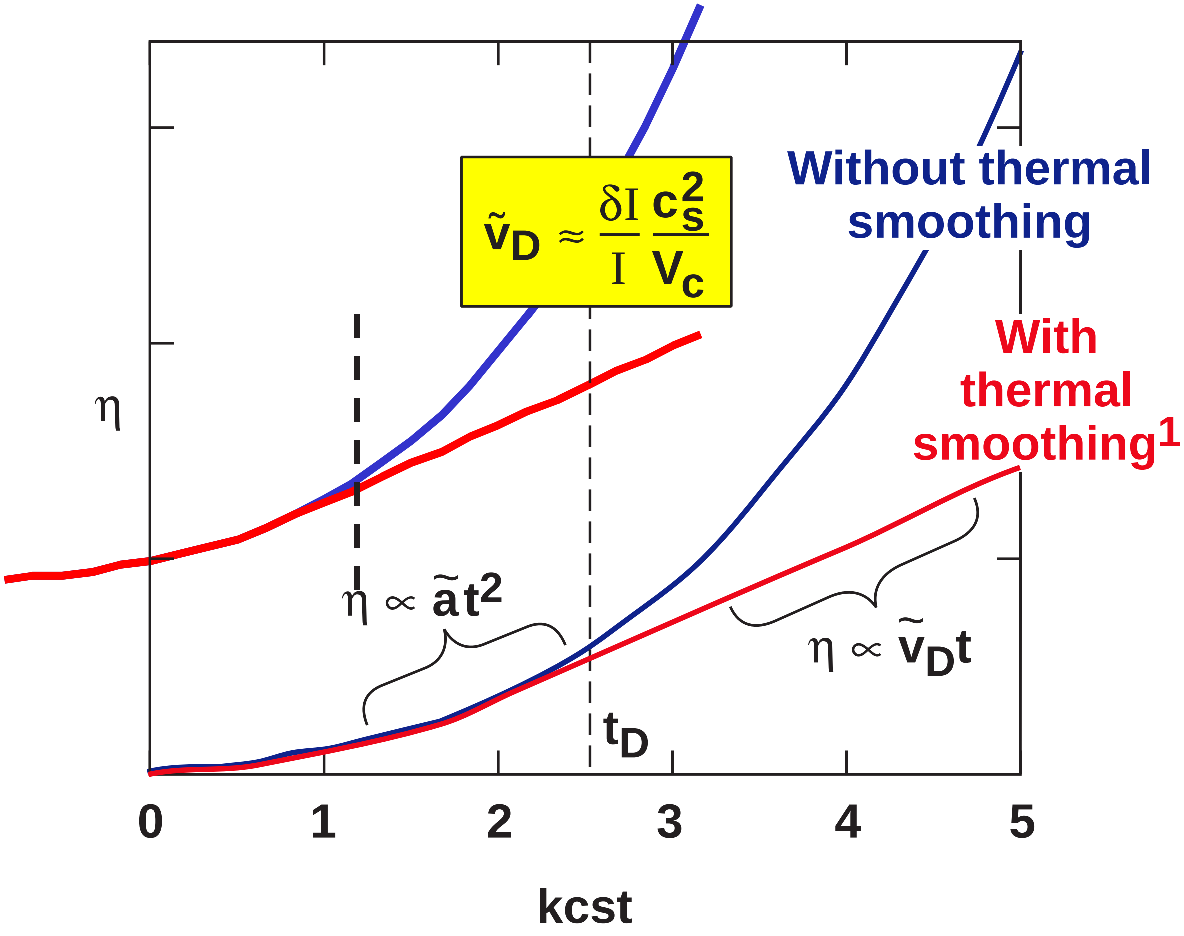
[1] K. A. Brueckner and S. Jorna, Rev. Mod. Phys. 46, 325 (1974).

Imprint growth is reduced by thermal smoothing

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





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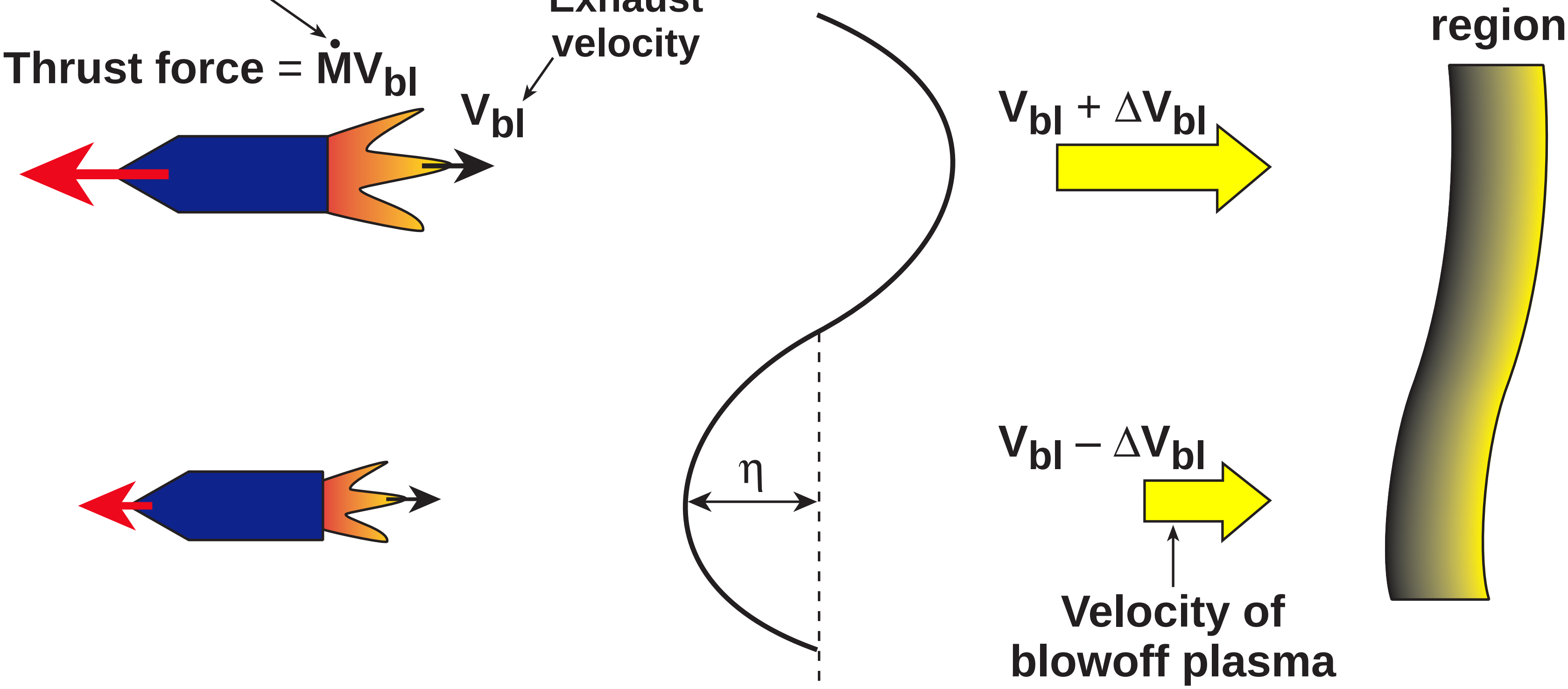
[1] A. Velikovich *et al.*, Phys. Plasmas 5, 1491 (1998).

Late-time imprint growth is stabilized by dynamic overpressure



Rate of change of mass

Thrust force = $\dot{M}V_{bl}$

Exhaust velocity

V_{bl}

η

Ablation front

$V_{bl} + \Delta V_{bl}$

$V_{bl} - \Delta V_{bl}$

Velocity of blowoff plasma

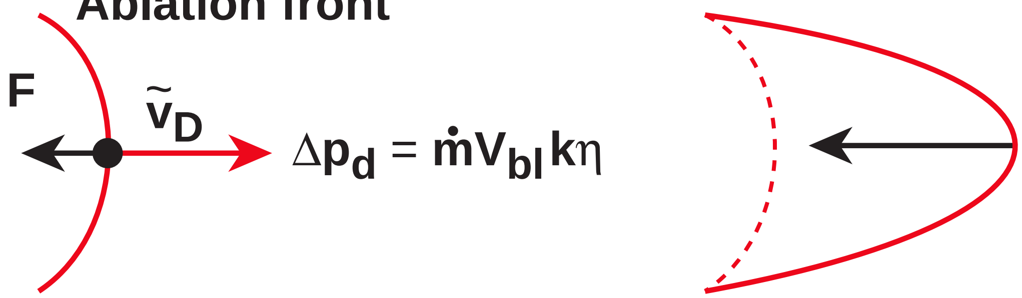
Absorption region

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

Ablation front



$\Delta p_d = \dot{m} V_{bl} k \eta$

$F = -\nabla(\Delta p_d) = -\boxed{k^2 \dot{m} V_{bl}}\,\eta$

Effective spring constant k_{bl}

$\boxed{F = -k_{bl}\eta}$

Mass-spring system

- **Oscillations**

Spring $\omega = \sqrt{K/M}$

Ablation front $\omega = \sqrt{k_{bl}/\rho} = k\sqrt{V_a V_{bl}}$

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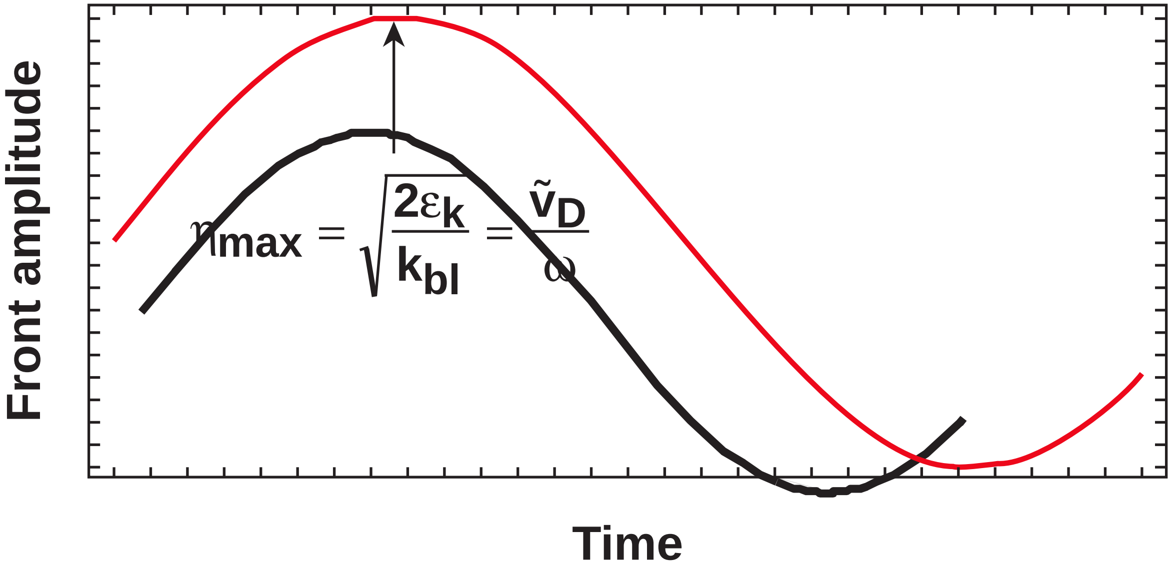
Imprint amplitude is determined by the decoupling velocity and oscillation frequency

Kinetic energy εk → **Potential energy εp**

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

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

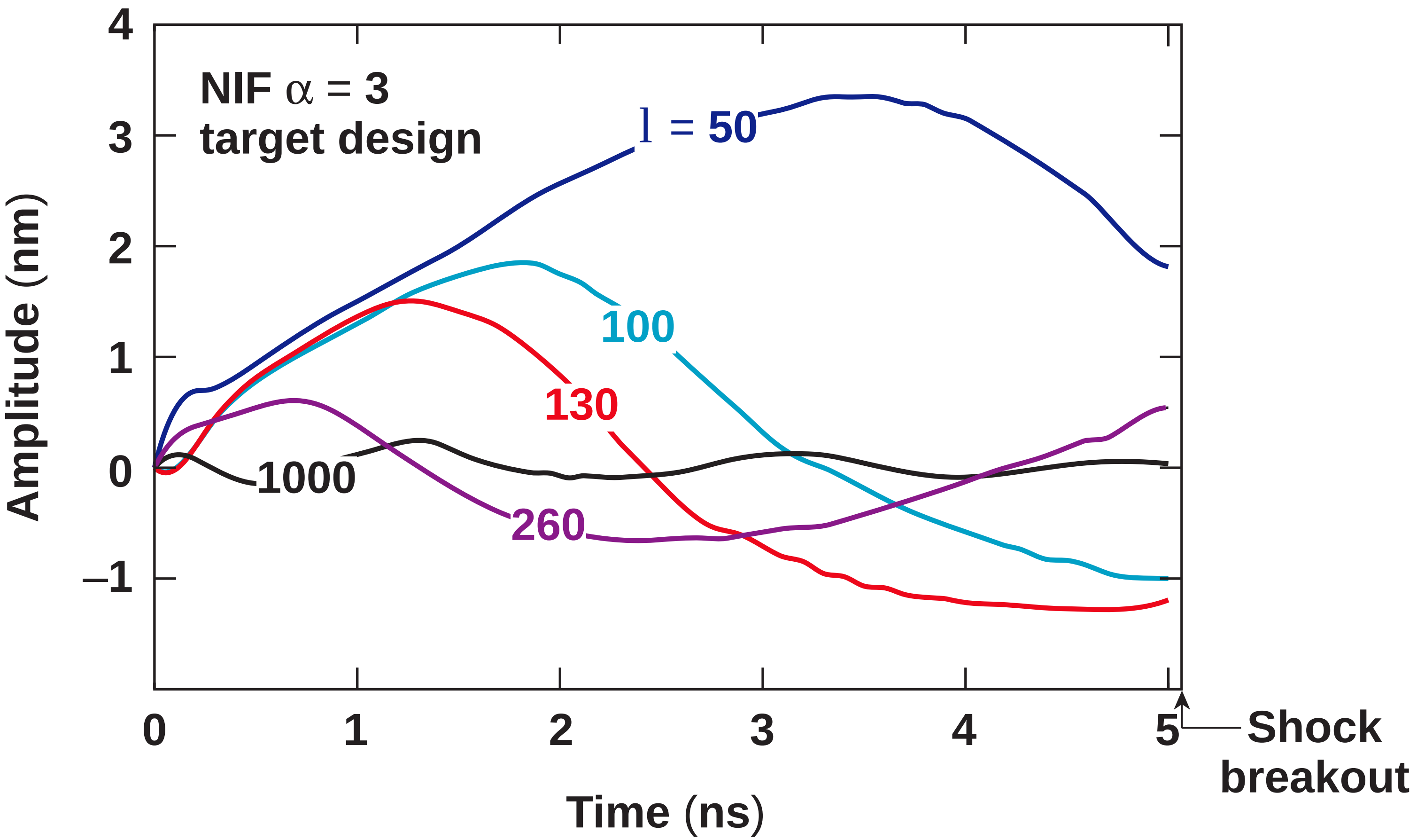


$$\eta_{max} = \sqrt{\frac{2\varepsilon_k}{k_{bl}}} = \frac{\tilde{v}_D}{\omega}$$

$$\boxed{\eta_{max} \propto \frac{\delta I}{I} \frac{c_s^2}{V_c k \sqrt{V_a V_{bl}}}}$$

The most damaging modes oscillate during the shock propagation

- Single-mode imprint *ORCHID* simulations



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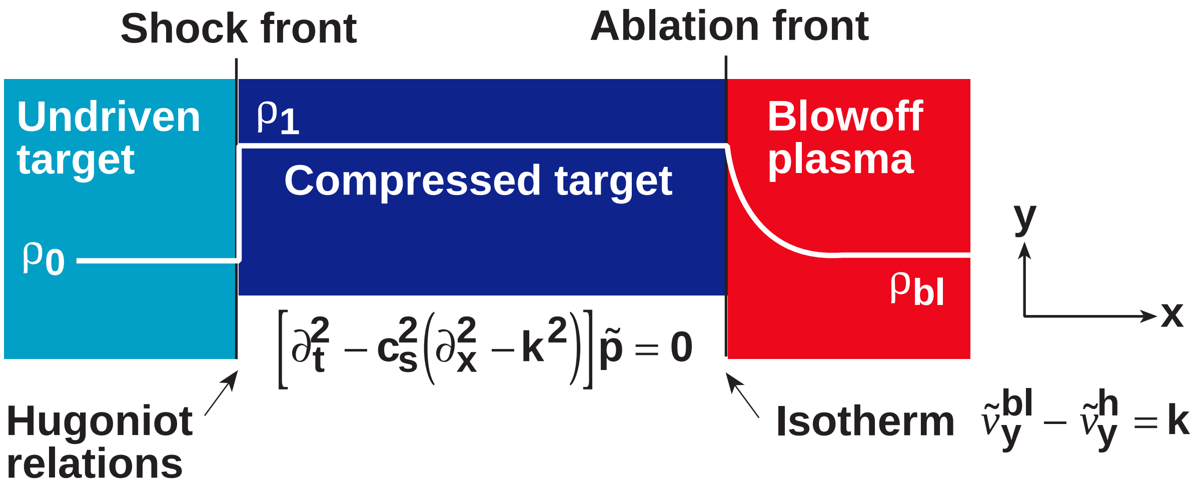
Imprint model

- 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



$$\left[\partial_t^2 - c_s^2\left(\partial_x^2 - k^2\right)\right]\tilde{p} = 0$$

Isotherm $\tilde{v}_y^{bl} - \tilde{v}_y^{h} = k\,\eta_a\left(V_{bl} - V_a\right)$

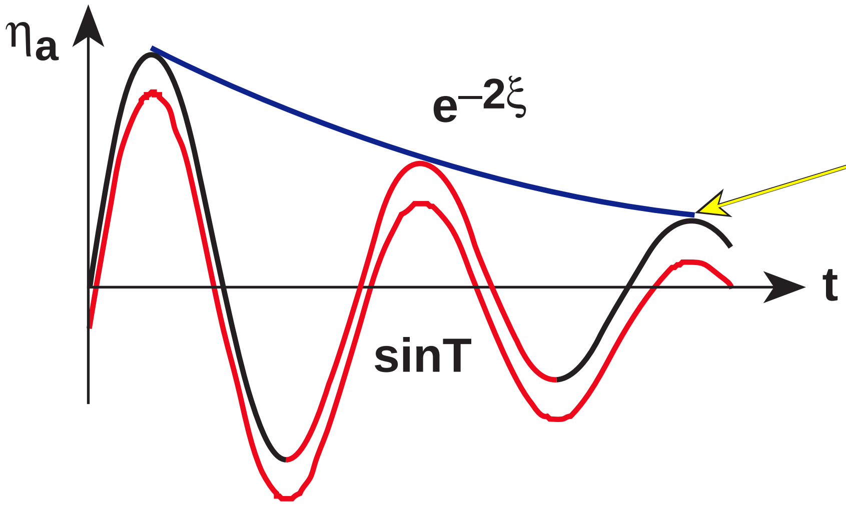
Assumptions

$\frac{V_a}{C_s} \ll 1 \qquad \frac{V_{b1}}{Cs} \sim 1$

$D_c = V_c t$

- Model is solved by multiple-scale technique.

$\tau = k\,c_s t \qquad T = k\sqrt{V_a V_{bl}}\,t \qquad \xi = k\,V_a t$

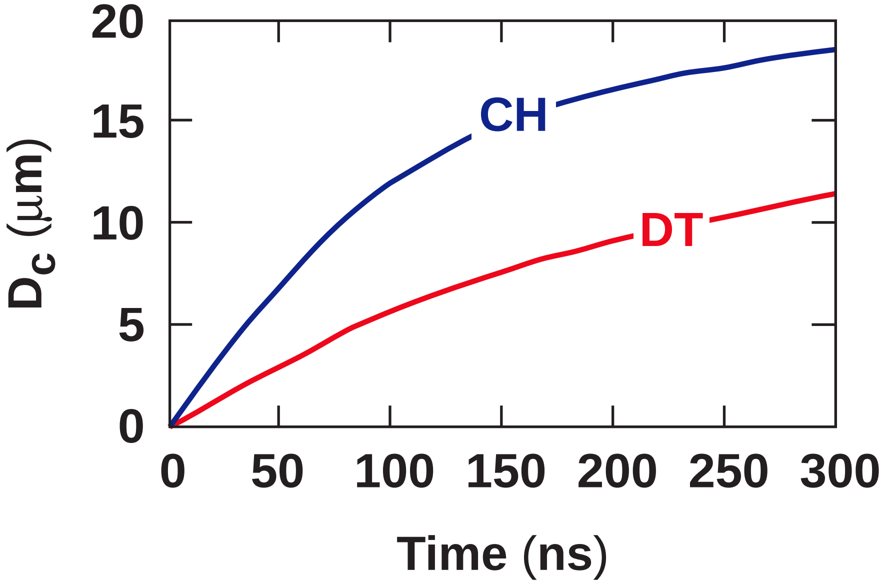


Oscillations are damped by fire polishing and vorticity convection.

The imprint amplitude is determined by the decoupling velocity and oscillation frequency $(\eta_{\text{max}} = \tilde{v}_D/\omega)$

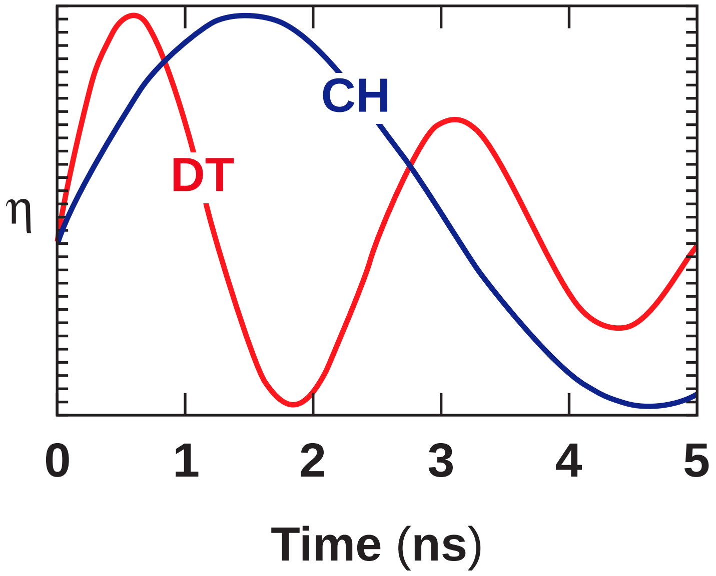
Comparison of CH and cryo DT ablators, $I = 3.0 \times 10^{13}$ W/cm^2

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



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

$V_a^{CH} = 1.0$ μm/ns $V_a^{DT} = 2.5$ μm/ns

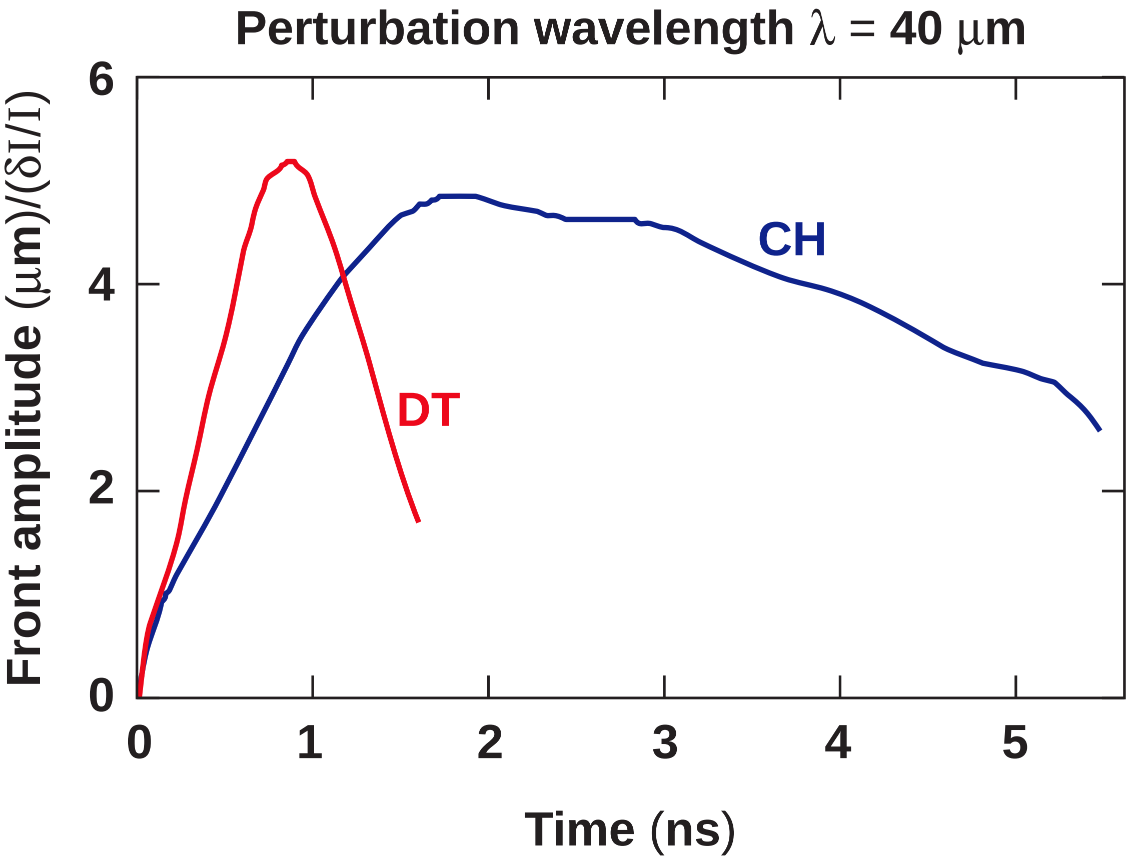


$$\frac{\tilde{v}_D^{DT}}{\tilde{v}_D^{CH}} \approx 2.5$$

$$\eta_{\text{max}}^{DT} \approx \eta_{\text{max}}^{CH}$$

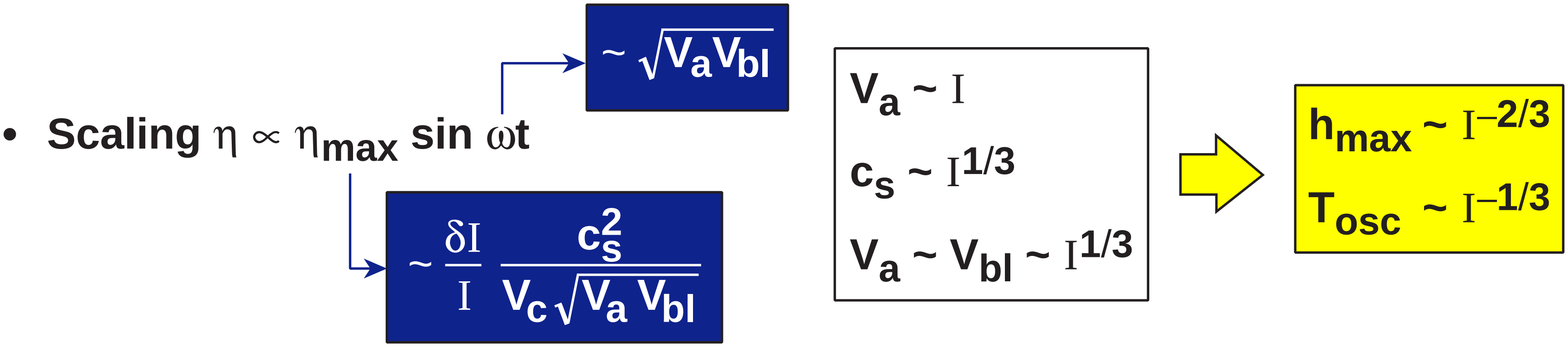
$$\frac{\omega^{DT}}{\omega^{CH}} \approx 2.5$$

ORCHID simulations confirm the predictions of the model



$$\eta_{\max}^{DT} \approx \eta_{\max}^{CH}$$

The imprint amplitude and oscillation period are reduced by increasing laser intensity



- Scaling $\eta \propto \eta_{max} \sin \omega t$

$\sim \sqrt{V_a V_{bl}}$

$\sim \frac{\delta I}{I} \frac{c_s^2}{V_c \sqrt{V_a V_{bl}}}$

$V_a \sim I$

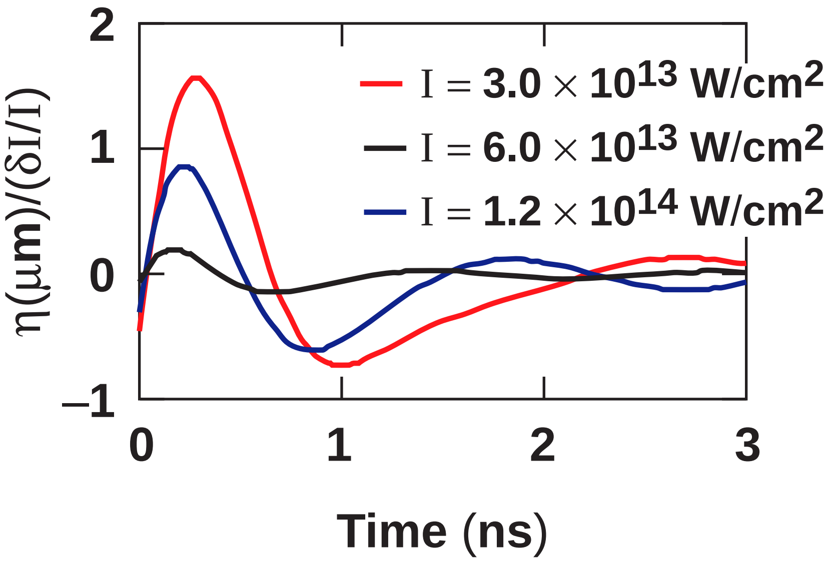
$c_s \sim I^{1/3}$

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

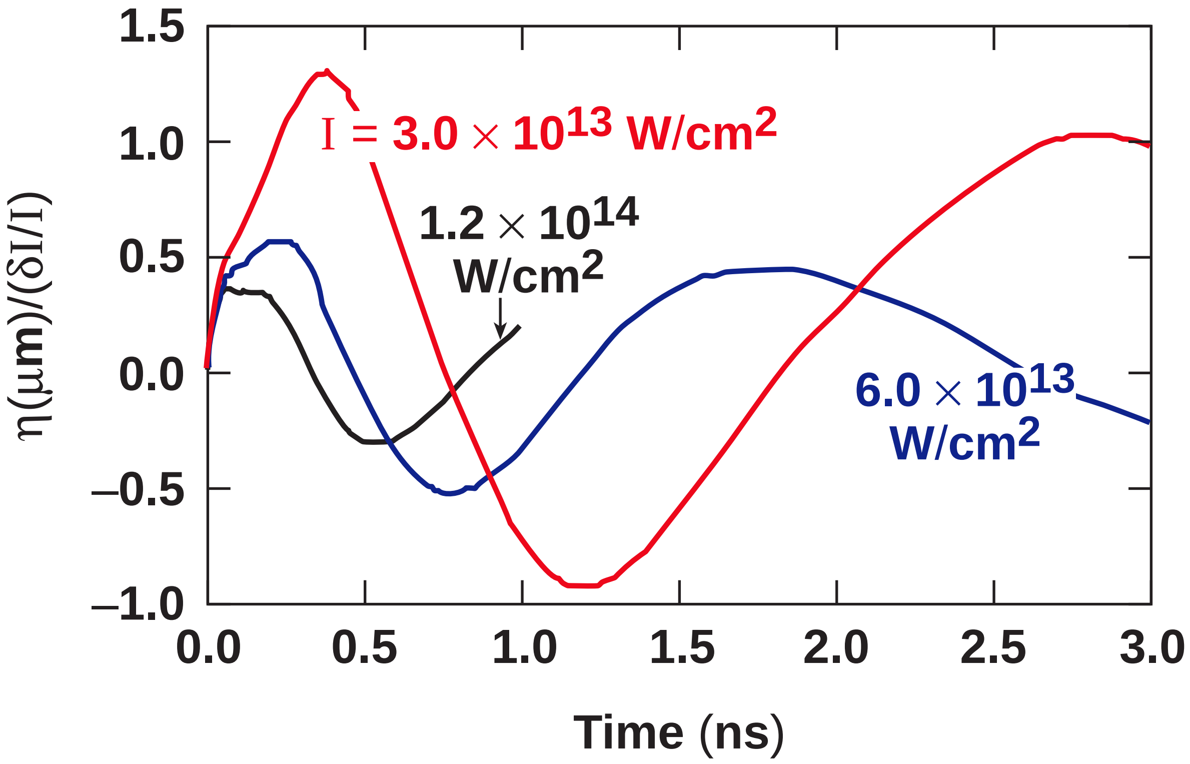
$h_{max} \sim I^{-2/3}$

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

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



Simulations confirm that the imprint amplitude and laser oscillation period are reduced by increasing laser intensity



- Cryo DT planar foil
- Thickness = 345 μm
- Flat-top laser pulse

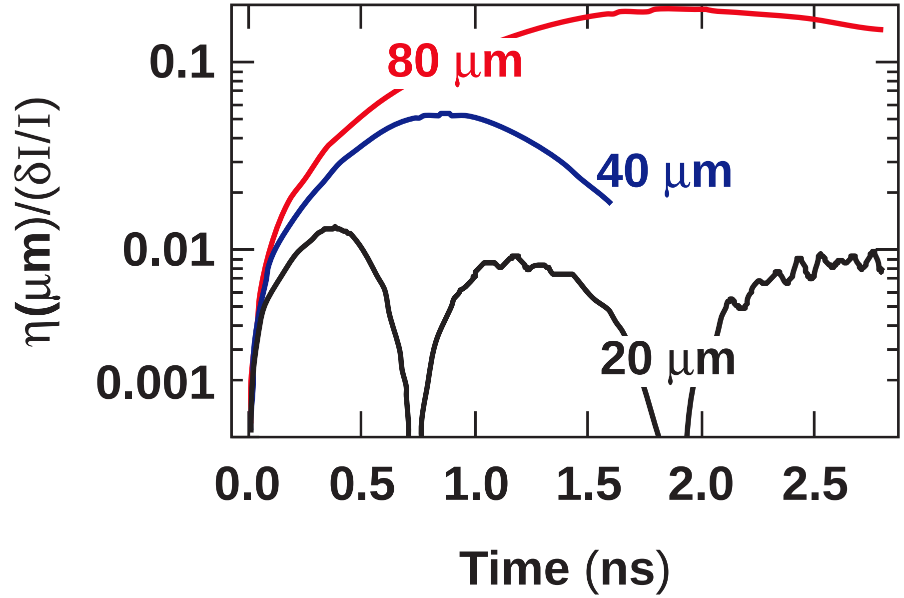
$\text{ç}_{max} \sim I^{-1.0}$ $\qquad$ $T_{osc} \sim I^{-0.4}$

Shorter-wavelength nonuniformities have lower imprint amplitudes and shorter oscillation periods

- **Model:** $\eta_{\max} \sim \lambda; \; T_{osc} \sim \lambda$

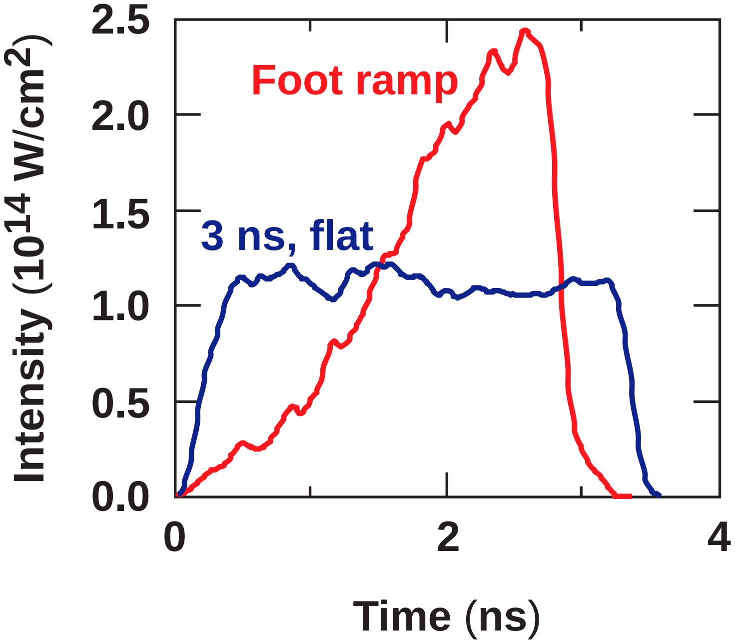
- ***ORCHID*** **simulation: DD, NIF, $\alpha = 3$, "all-DT" target design**
  - $I = 3.0 \times 10^{13}$ W/cm^2
  - thickness = 345 μm

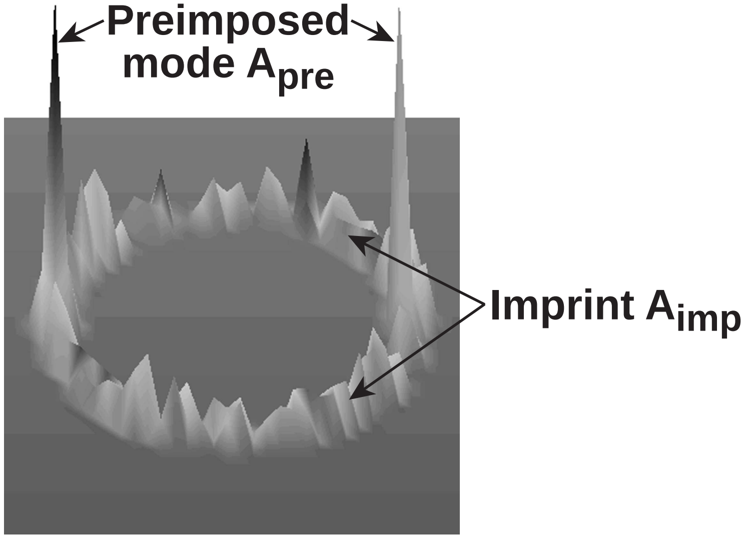
$\eta_m \sim \lambda^{1.6}; \quad T_{osc} \sim \lambda^{1.1}$



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.

$$A_{EQ} = \frac{A_{imprint}}{A_{pre}} A_{pre}(t = 0)$$

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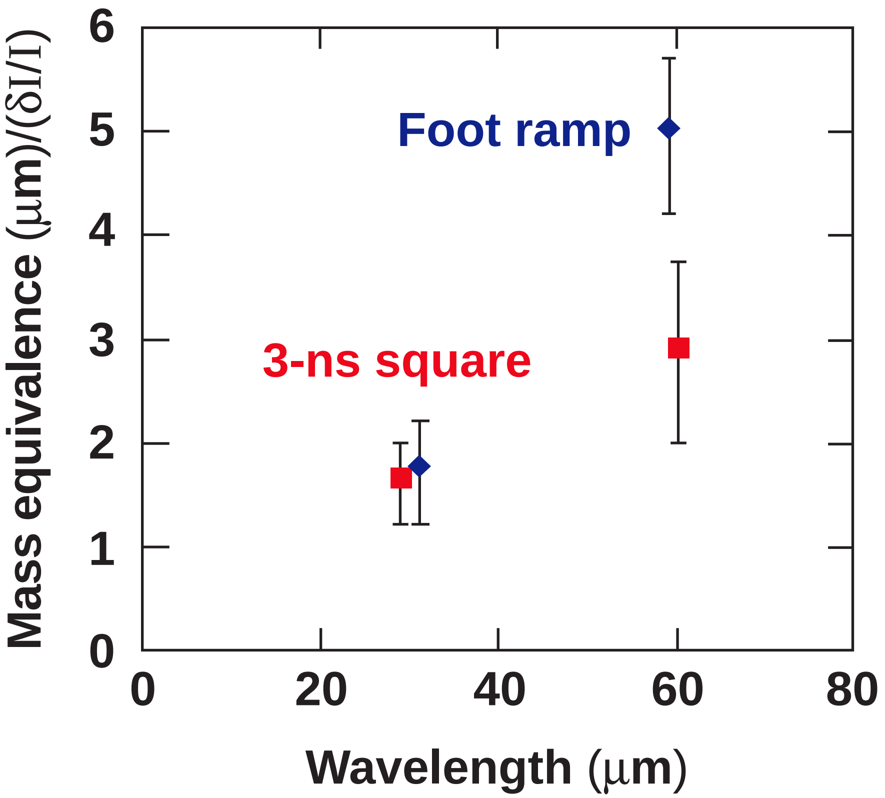
*T. R. Boehly *et al.*, CO2.01, this conference.

The results of the experiments agree with imprint simulations and predictions of models



	Experiments	Simulations
$\frac{\eta^{60}_{ramp}}{\eta^{60}_{square}}$	1.7±0.5	1.6
$\frac{\eta^{60}_{square}}{\eta^{30}_{square}}$	1.8±0.6	1.5

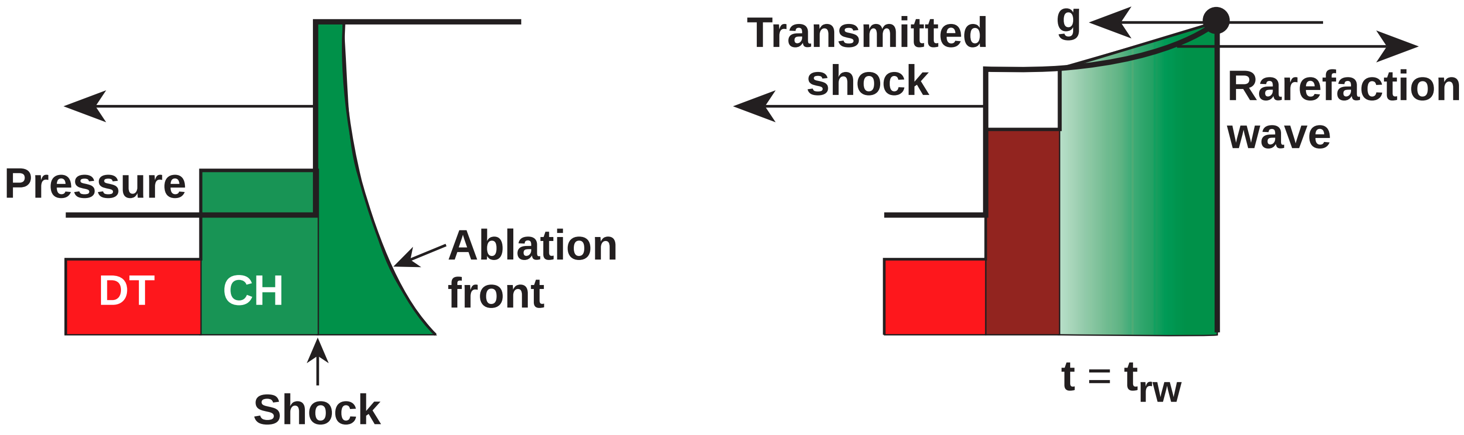
Higher intensities and shorter perturbation wavelengths imprint less for modes with t_D < shock breakout time

Application of the model: effect of imprint on direct-drive NIF ignition design

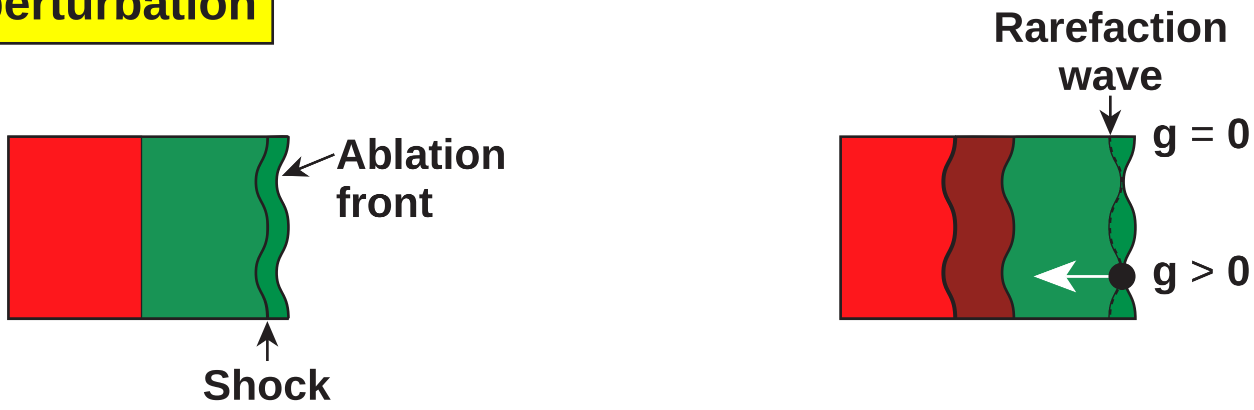
- Effect of polymer overcoat
- Effect of SSD
- Target gain

The thin polymer layer required for target fabrication results in enhanced imprint

Rayleigh–Taylor instability

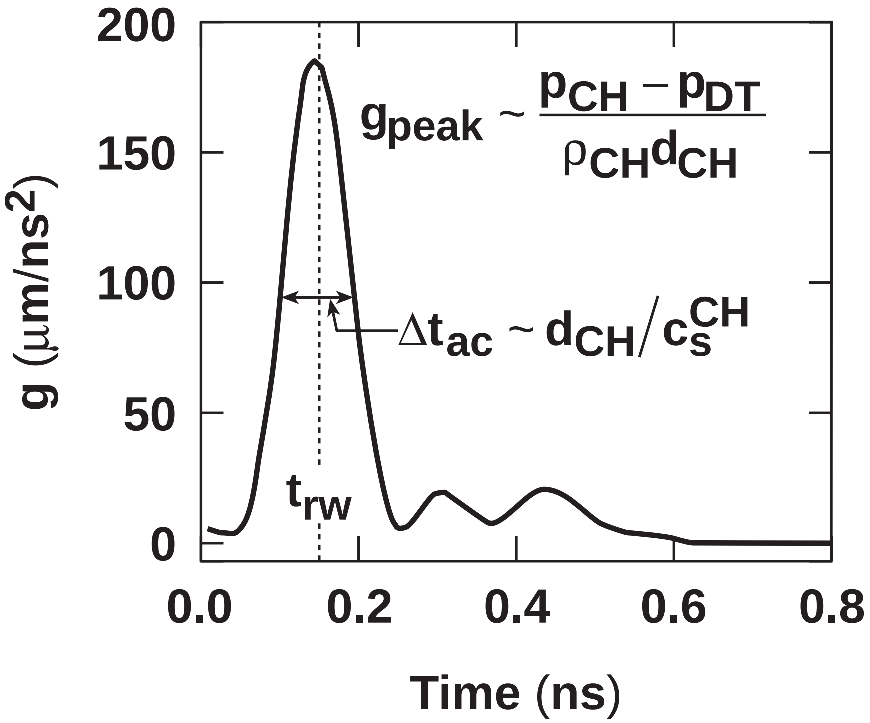


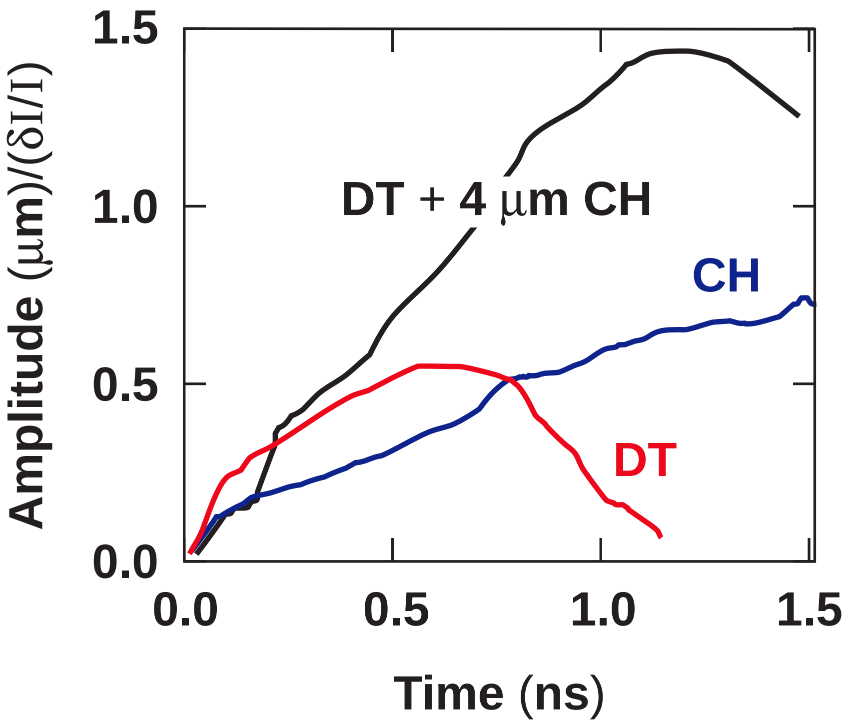
Velocity perturbation



Simulations show increased imprint for polymer overcoated targets

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



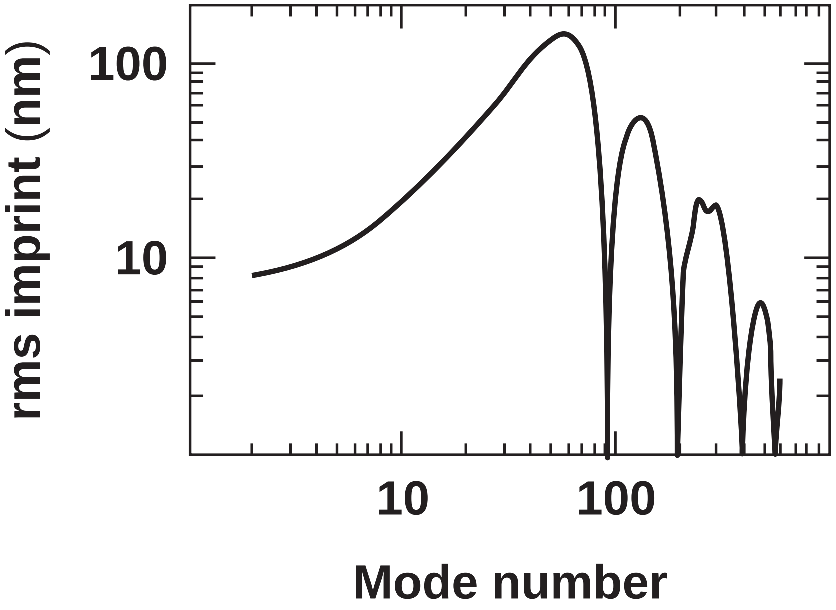


RT growth factor $\sim \exp\left(\sqrt{kg\Delta t_{ac}^2}\right) \sim \exp\left(\sqrt{kd_{CH}}\right)$

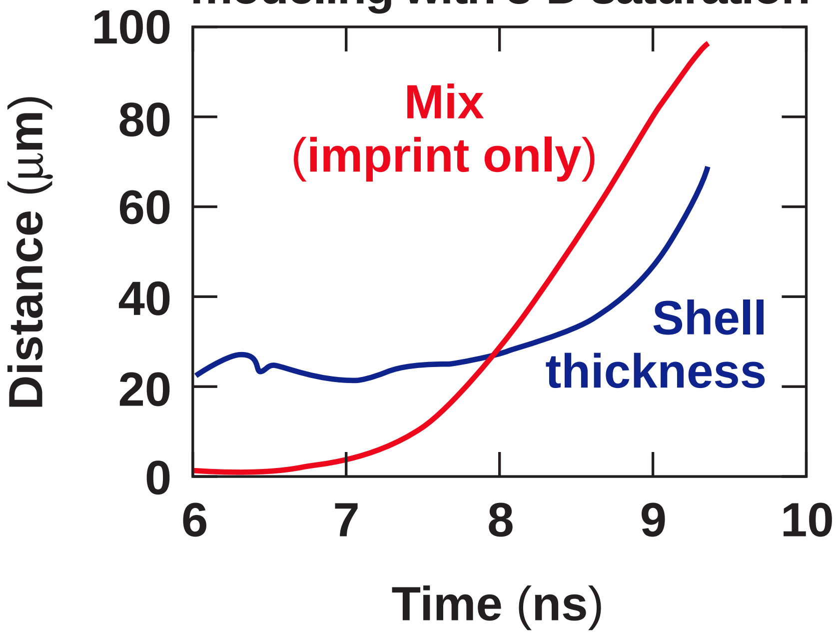
Without SSD, thermal smoothing and dynamic overpressure do not reduce imprint to the levels required for high-gain implosions

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

Beginning of main drive pulse

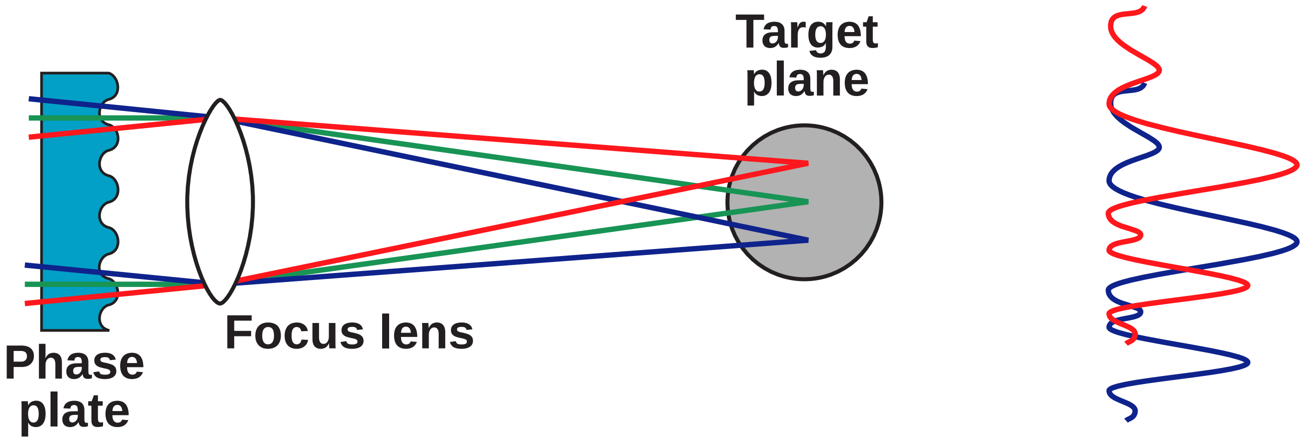


ORCHID simulation and RT modeling with 3-D saturation

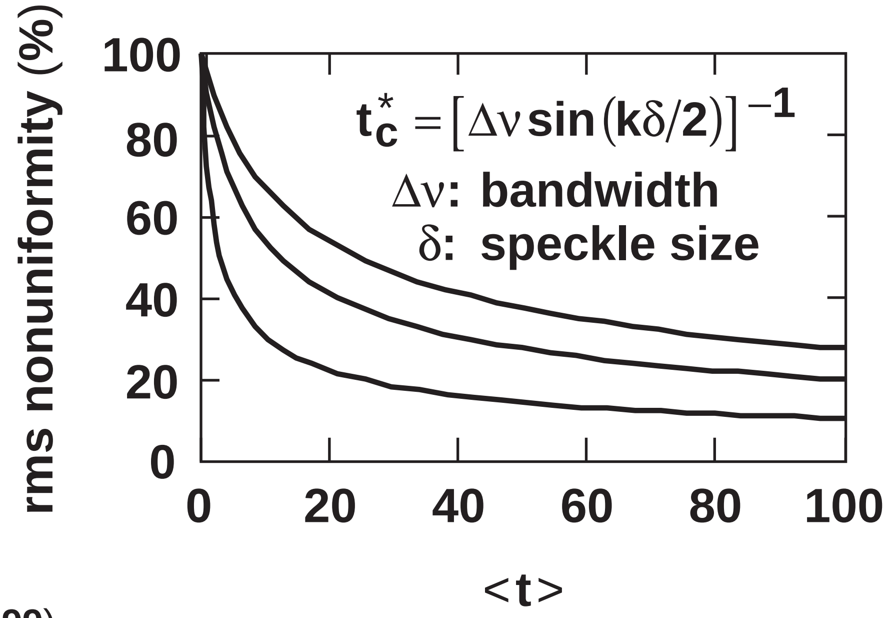


Temporal beam smoothing is required.

SSD reduces time-averaged laser nonuniformity



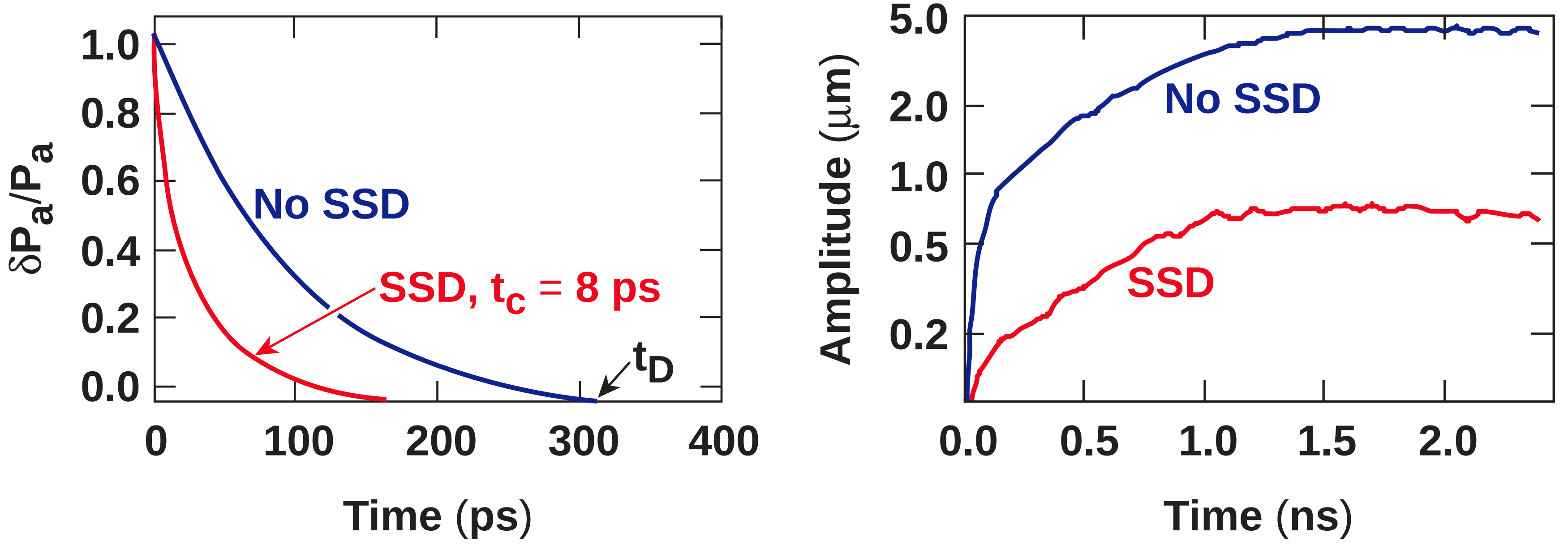
$$\langle\sigma_{rms}\rangle \sim \boxed{\sqrt{t_c/\langle t\rangle}}\,\langle\sigma^0_{rms}\rangle$$



*S. Skupsky, Phys. Plasmas 6, 2157 (1999).

Imprint amplitude can be reduced by applying SSD smoothing technique (continued)

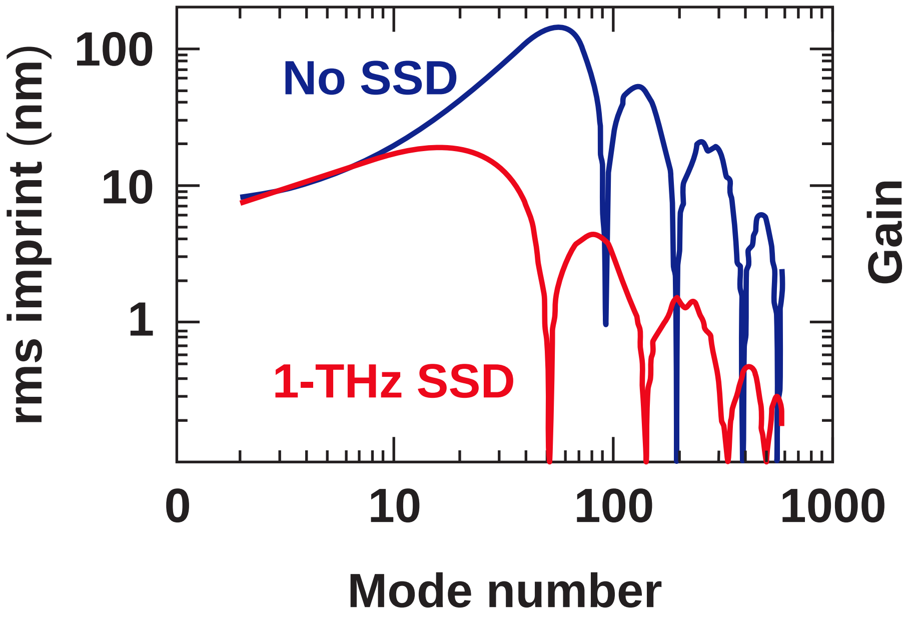
- *ORCHID* simulations
  For constant-intensity foot pulse $\langle \delta I \rangle = \delta I^{0} \sqrt{t_c / \langle t \rangle}$.
  Example: CH foil, $I = 3 \times 10^{13}$ W/cm^2 laser pulse, $t_c = 8$ ps



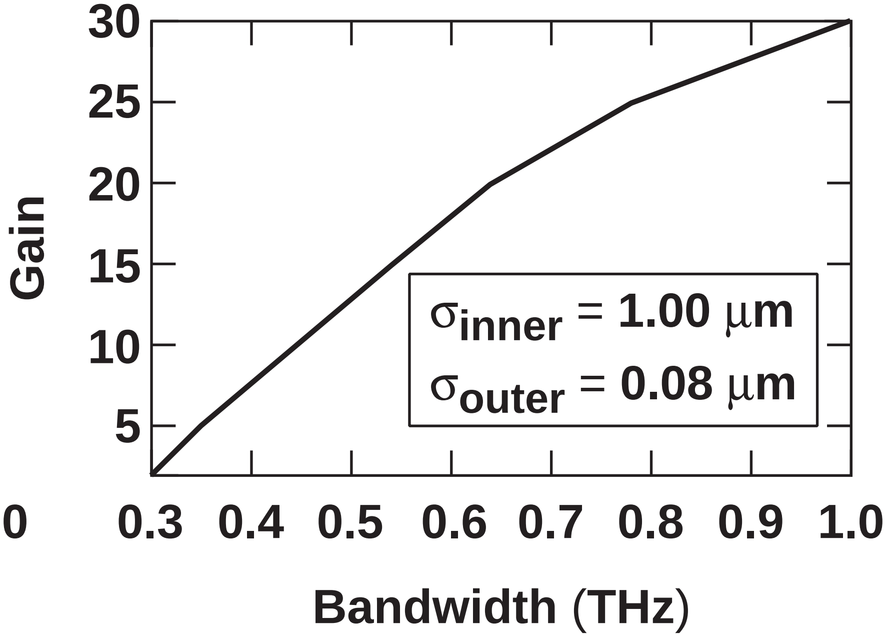
$$\frac{\eta^{\mathrm{SSD}}}{\eta^{\mathrm{no\,SSD}}} \sim \sqrt{\frac{t_c}{t_D}} \approx \sqrt{\frac{(\Delta\nu\, k\delta)^{-1}}{(kV_c)^{-1}}} = \sqrt{\frac{V_c}{\Delta\nu\,\delta}}$$

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**



Summary/Conclusions

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.