Numerical Study of Deceleration-Phase Rayleigh–Taylor Instability

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Abstract

Typical ICF targets consist of a solid DT shell filled with DT gas. It is well known that the inner surface of the shell is Rayleigh–Taylor unstable during the final phase of the implosion when the shell is being decelerated by the large central pressure. During the deceleration phase, the inner-surface nonuniformities grow rapidly, causing of the cold-shell material to mix with the hot central plasma, which quenches of the hot-spot ignition process.

We have found that mass ablation on the inner surface of the shell plays an important role in stabilizing short-wavelength modes during the deceleration phase. The ablation process is induced by the heat flux leaving the hot spot and being deposited on the shell's inner surface.

Two-dimensional planar and spherical codes have been developed to study the linear phase of the instability. The single-mode growth rate is compared with the theoretical predictions based on the large-Froude-number model of Ref. 1. It is shown that the mass ablation through the inner-shell surface combined with the finite density-gradient scale length significantly reduces the RT growth rate and suppresses short-wavelength modes.

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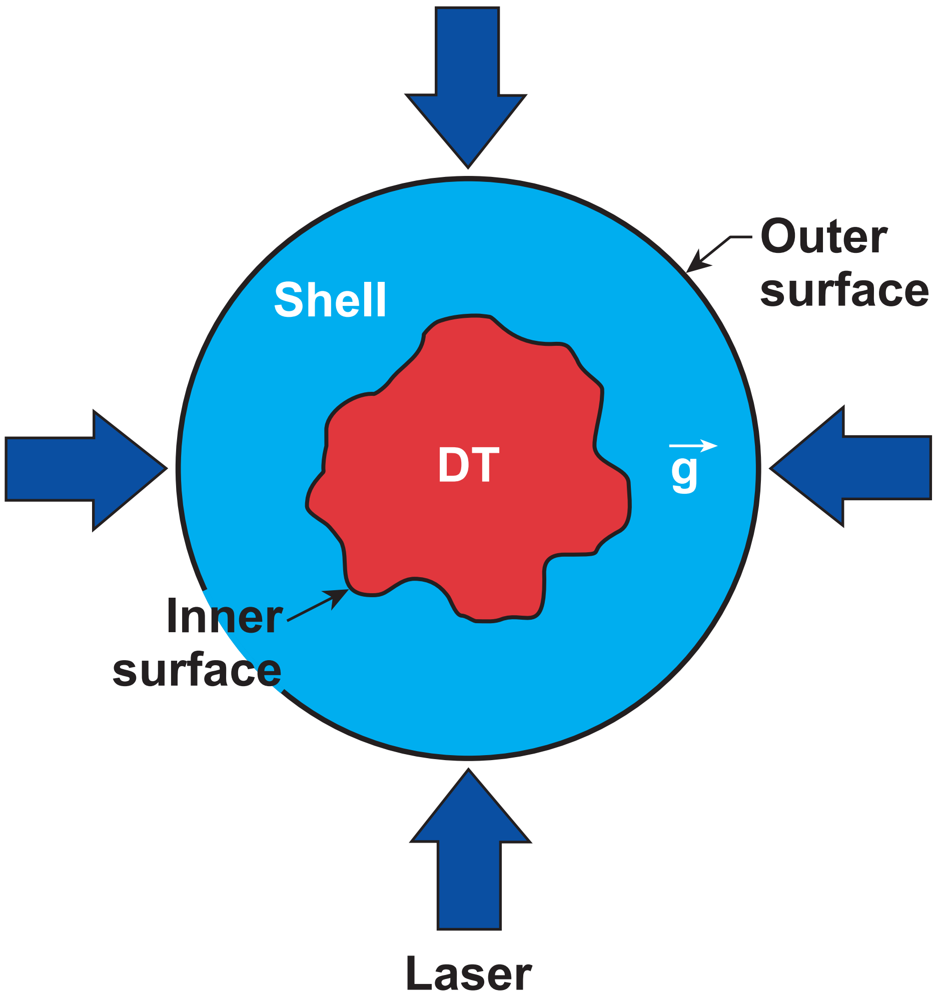
[1] V. Goncharov, R. Betti, R. L. McCrory, P. Sorotokin, and C. P. Verdon, Phys. Plasmas 3, 1402 (1996).

The deceleration-phase instability occurs in the final phase of the implosion



During the deceleration phase, the inner surface of the shell is RT unstable and its perturbations grow exponentially.

TC5357

The deceleration-phase RT growth rates are reduced by ablation and density-gradient scale length

UR LLE

- Mass ablation at the inner shell surface
- Finite density-gradient scale length
- Compression of the shell

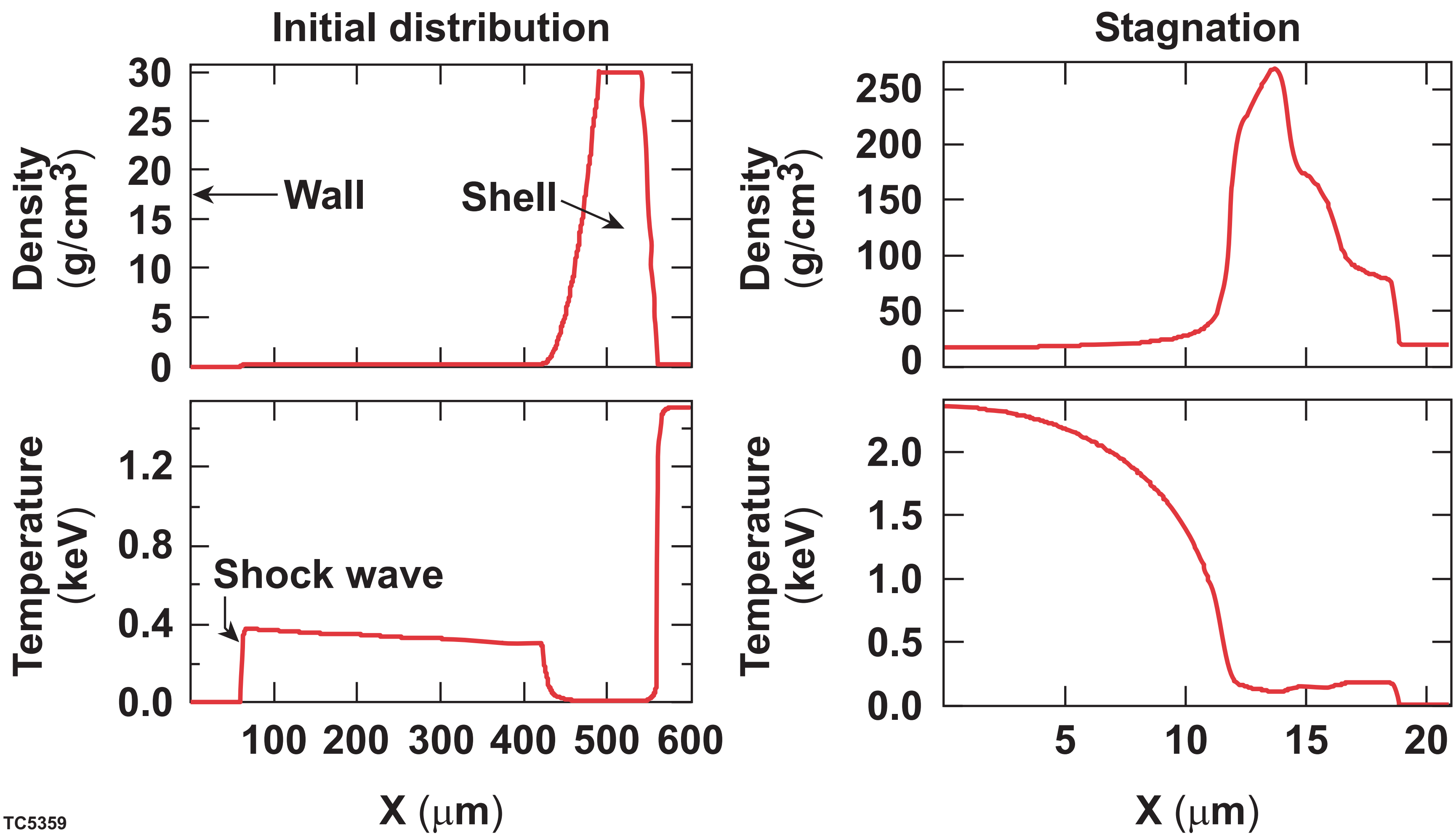
can reduce the RT instability growth

- The results of the study show the significant role of the mass ablation.
- Finite density-gradient scale length is less important than it is typically regarded.
- The compression of the shell has little influence on the instability growth rate.

Planar Model

Planar simulations reproduce the behavior of ICF capsule implosions

- Hot-spot temperature and radius and peak shell density have the same order of magnitude in planar and spherical cases.



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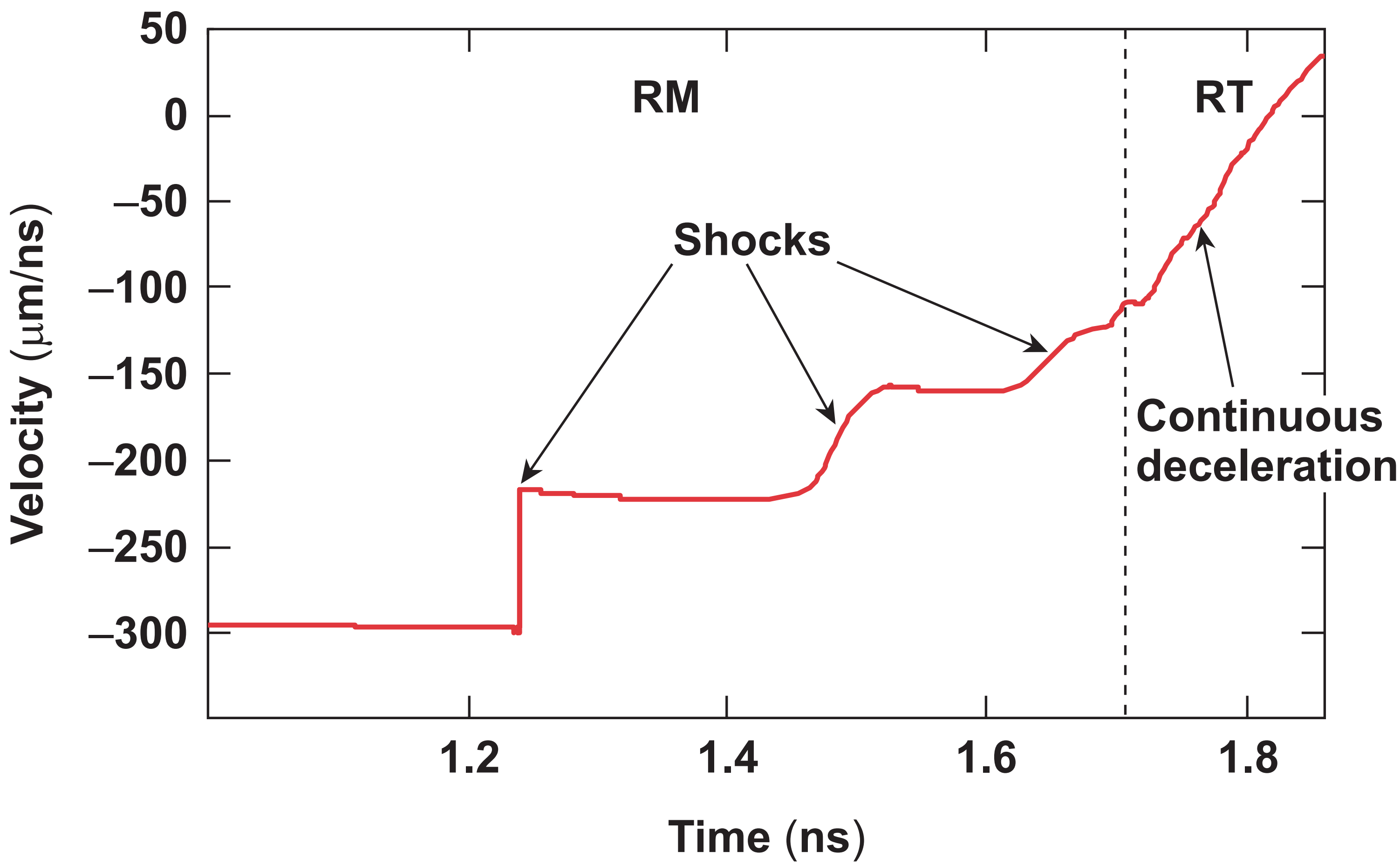
Two stages of the deceleration phase are observed

- Deceleration by a series of shocks t < 1.7 ns
- Continuous deceleration t > 1.7 ns



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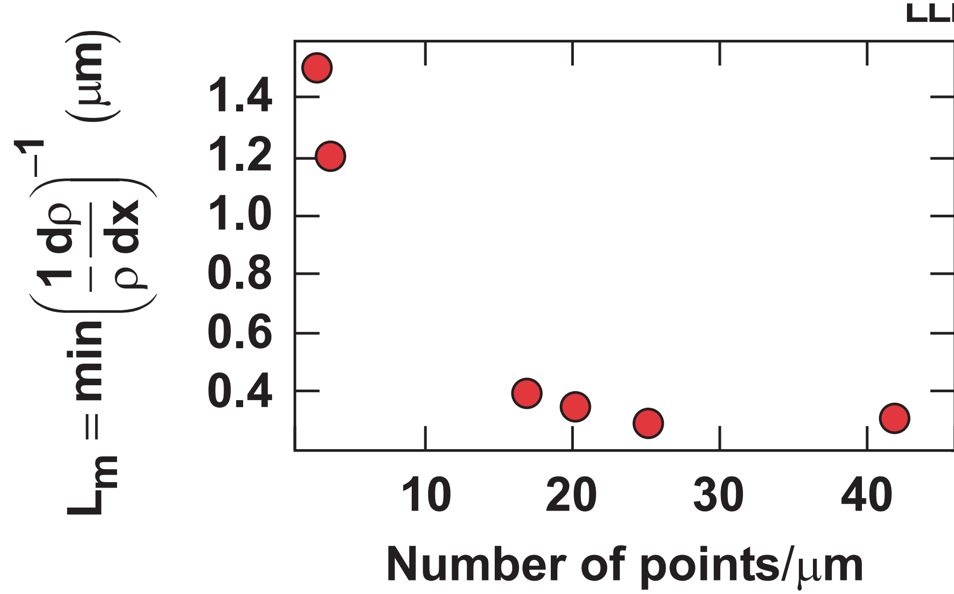
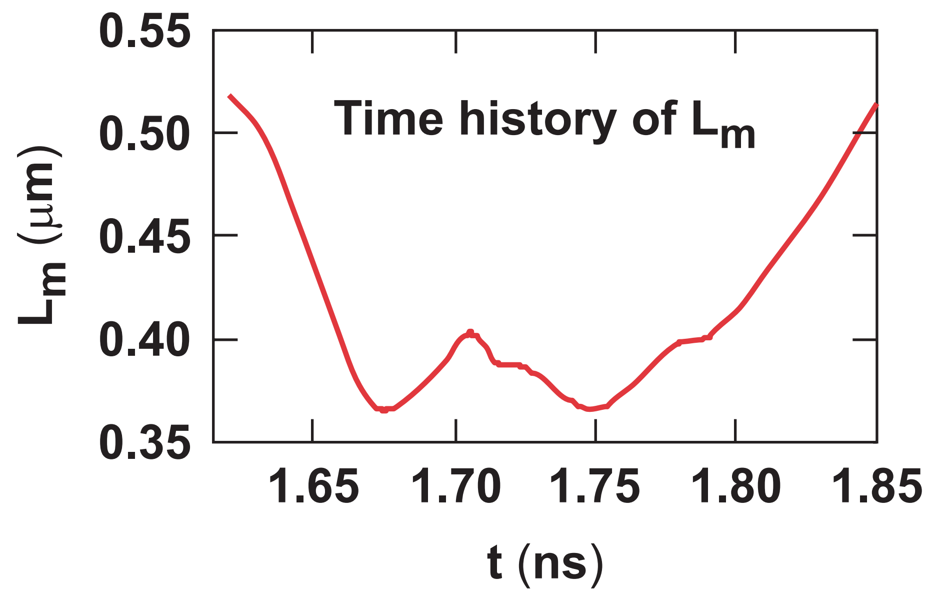
Density-gradient scale length is lower than its standard estimate (20% of the hot-spot radius*)

- A series of 1-D simulations with various spatial resolutions have been performed. In each case L_m was determined at stagnation point.
- Size of domain is 600 μm.
- L_m does not decrease significantly with the grid refinement if $\Delta x < 0.05$ μm.





*J. D. Lindl, Inertial Confinement Fusion, (Springer-Verlag, New York, 1998), Chap. 6.

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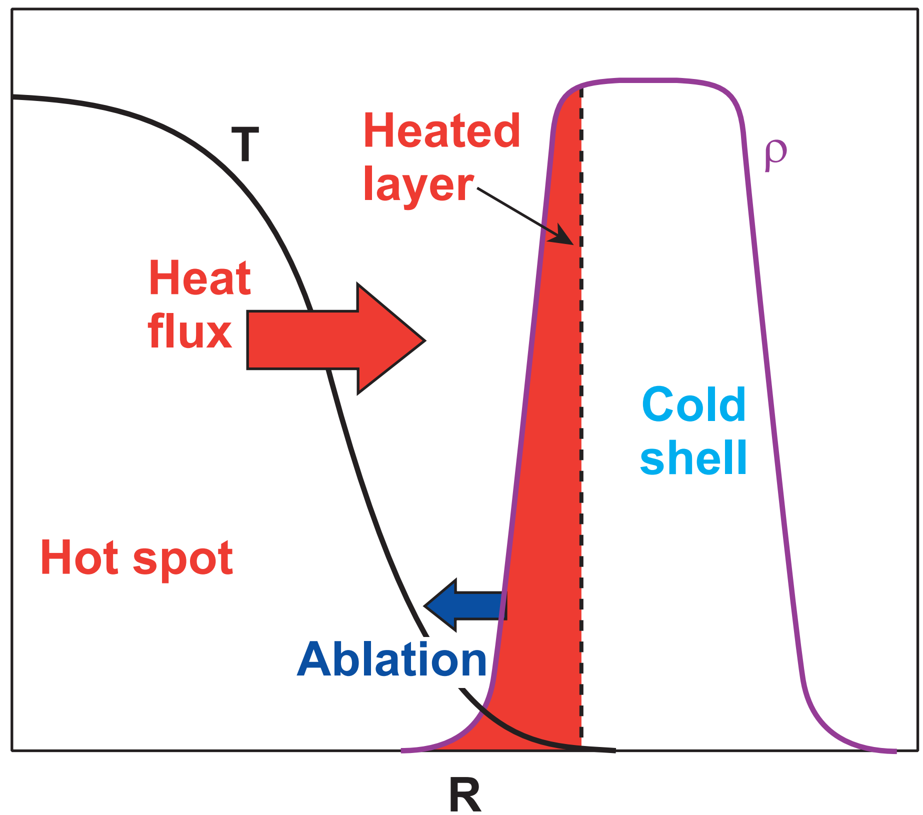
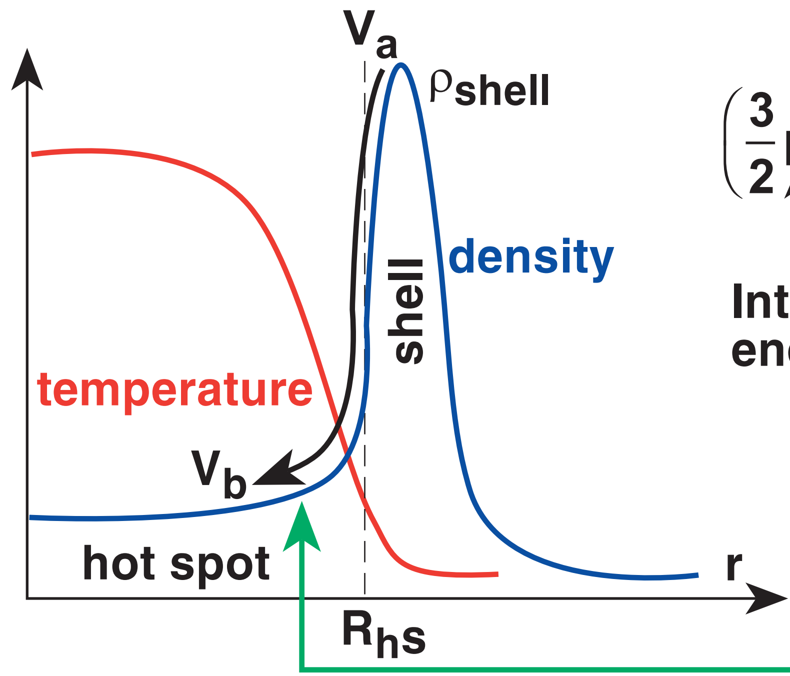
Heat conduction produces mass ablation at the inner shell surface

- The heat flux leaving the hot spot is deposited on the shell's inner surface, causing mass ablation.



The ablation velocity is determined from the energy balance



$$\left(\frac{3}{2}p_b V_b + p_b V_b\right) = \kappa_{Spitz}(T_b)\frac{dT_b}{dR_{hs}}$$

Internal energy flux

pdV work rate

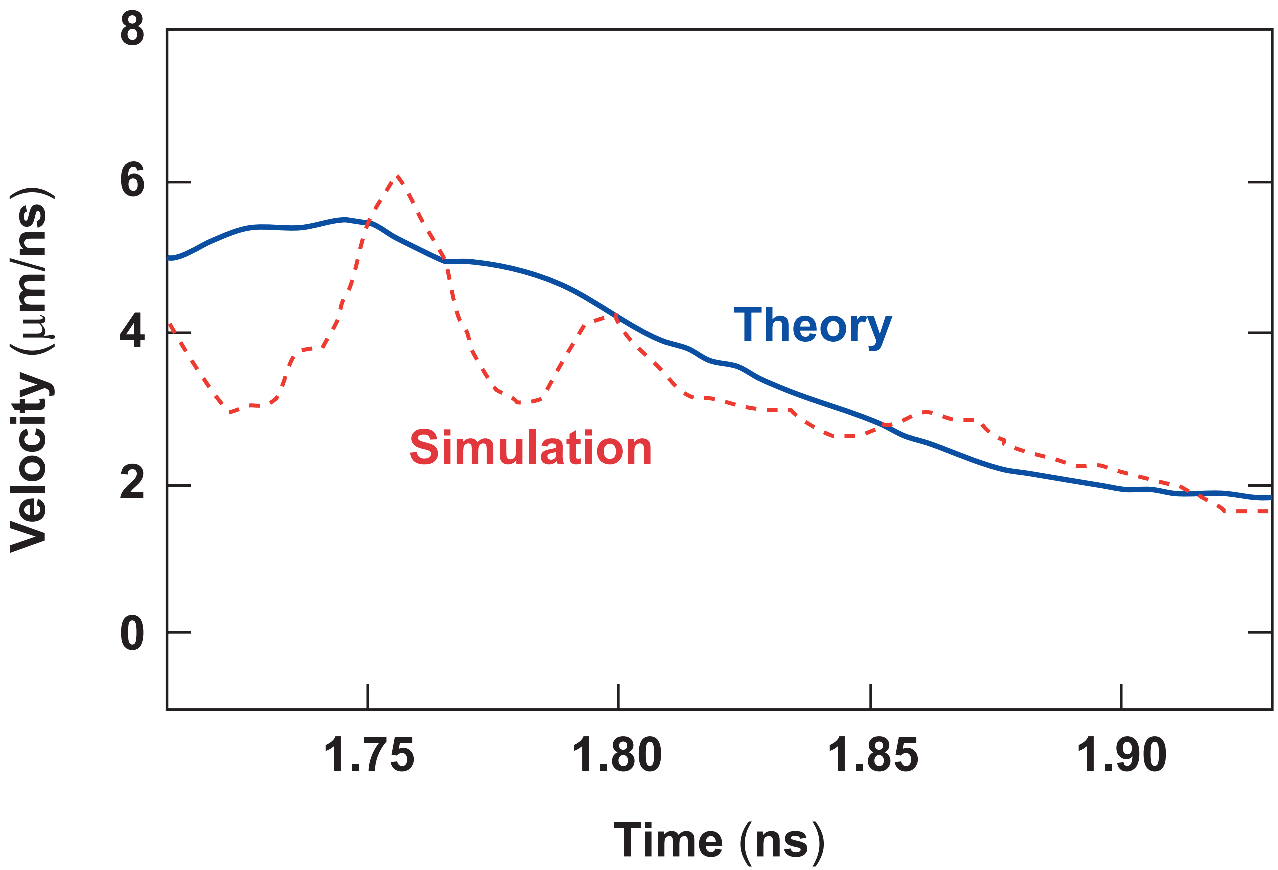
Energy flux balance

- Hot-spot temperature profile: $T_{hs} = T_0\left(1 - \frac{r^2}{R_{hs}^2}\right)^{2/5}$
- Use the EOS: $p_b V_b = 2\rho_b V_b T_b / M_i = 2\dot{m} T_b / M_i$
- Ablation velocity: $V_a = \frac{\dot{m}}{\rho_{shell}} = 0.2\frac{M_i \kappa_{Spitz}(T_0)}{\rho_{shell} R_{hot\ spot}}$

TC5408

Ablation velocity is important during the deceleration phase

$$\text{Theory} \Rightarrow \quad v_a = \frac{2}{5}\frac{\kappa\left(T_{\text{hot spot}}^{\text{max}}\right)}{\rho_{\text{shell}} R_{\text{hot spot}}}$$



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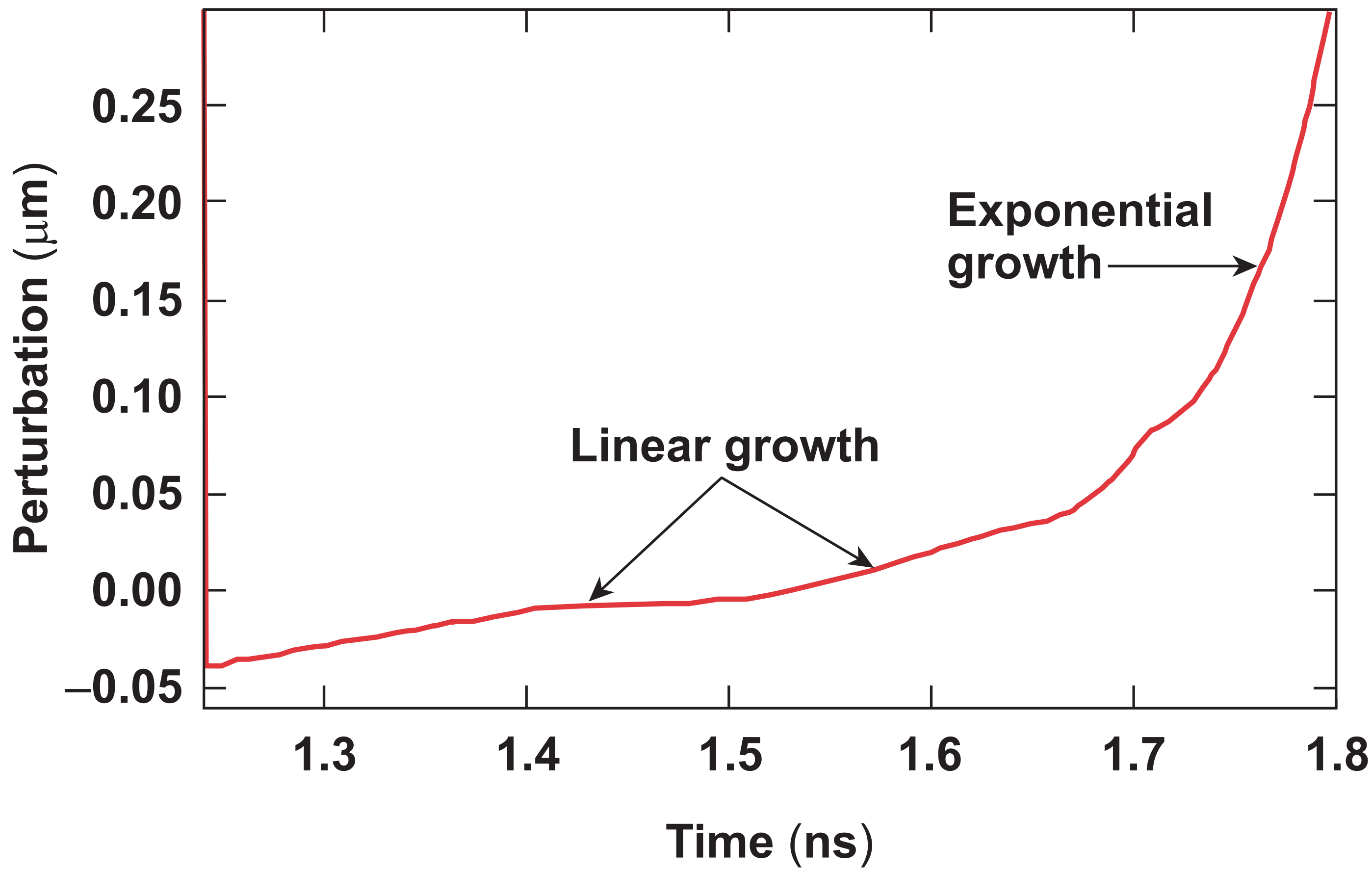
The deceleration-phase instability consists of a RM phase and a RT phase

- Linear RM instability is observed when shocks are coming.
- Exponential RT instability is seen during the continuous deceleration stage.



TC5363

Theoretical predictions of the instability growth are based on a sharp boundary model*

$$\rho \frac{d}{dt}\frac{1}{\rho}\frac{d}{dt}(\rho\eta) + 4k\nu_a\rho\frac{d\eta}{dt} + \eta\left[2k\frac{d}{dt}(\rho\nu_a) + k\rho\left(\frac{2.31k\nu_a^2}{(kL_m)^{2/5}} - \frac{g}{1+kL_m}\right)\right] = 0$$

- Effect of compressibility
- Stabilizing ablation
- Dynamic overpressure is stabilizing.
- Finite density-gradient scale length is a stabilizing factor.

ρ = density
k = wave number
ν_a = ablation velocity
L_m = minimum density-gradient scale length
η = perturbation
g = acceleration

*V. Goncharov, Ph.D. Thesis, University of Rochester (1998).

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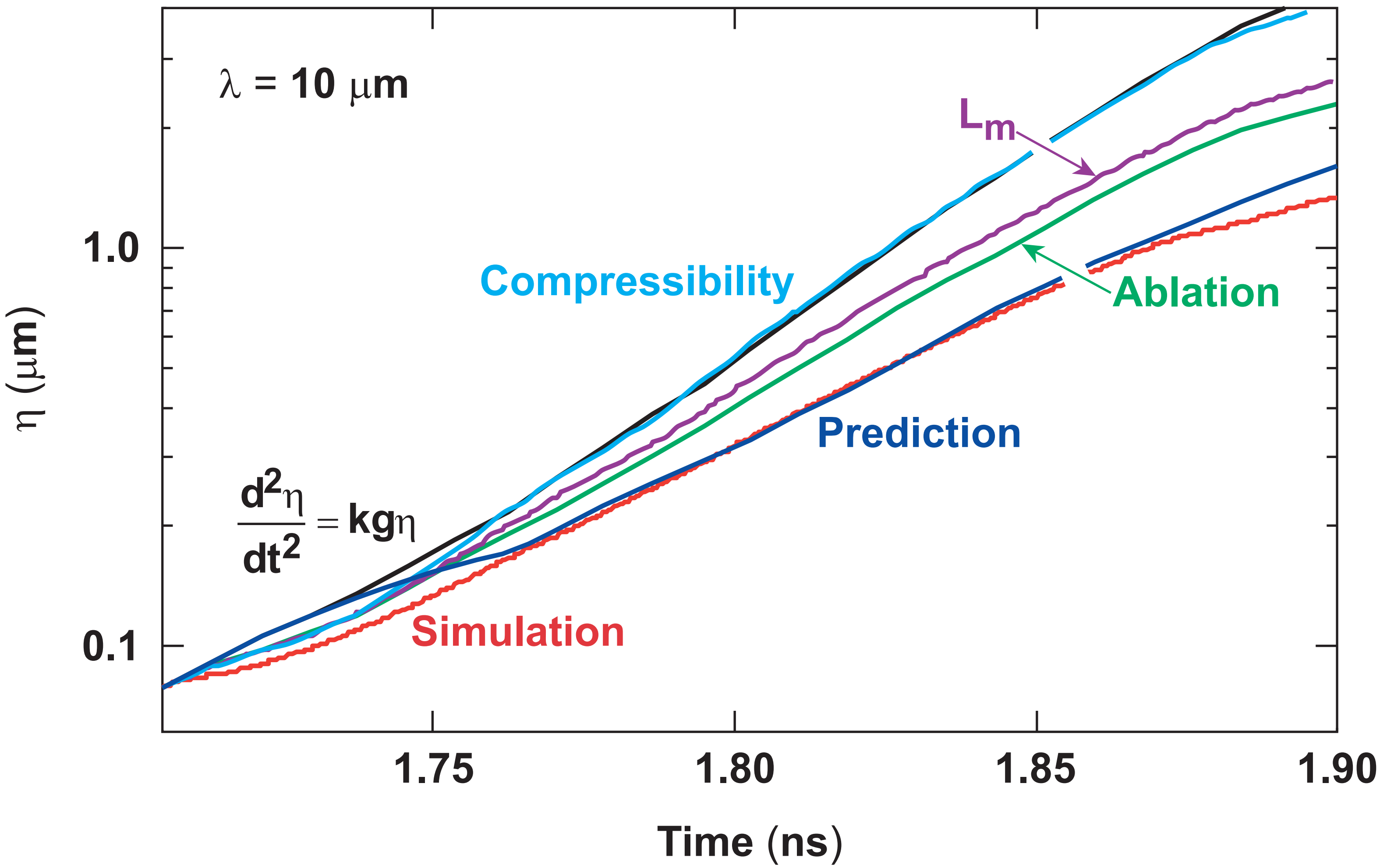
Finite density-gradient scale length and mass ablation have the largest stabilizing effect

- Simple models include only $d^2\eta/dt^2 = kg\eta$, compressibility, ablation, and L_m.



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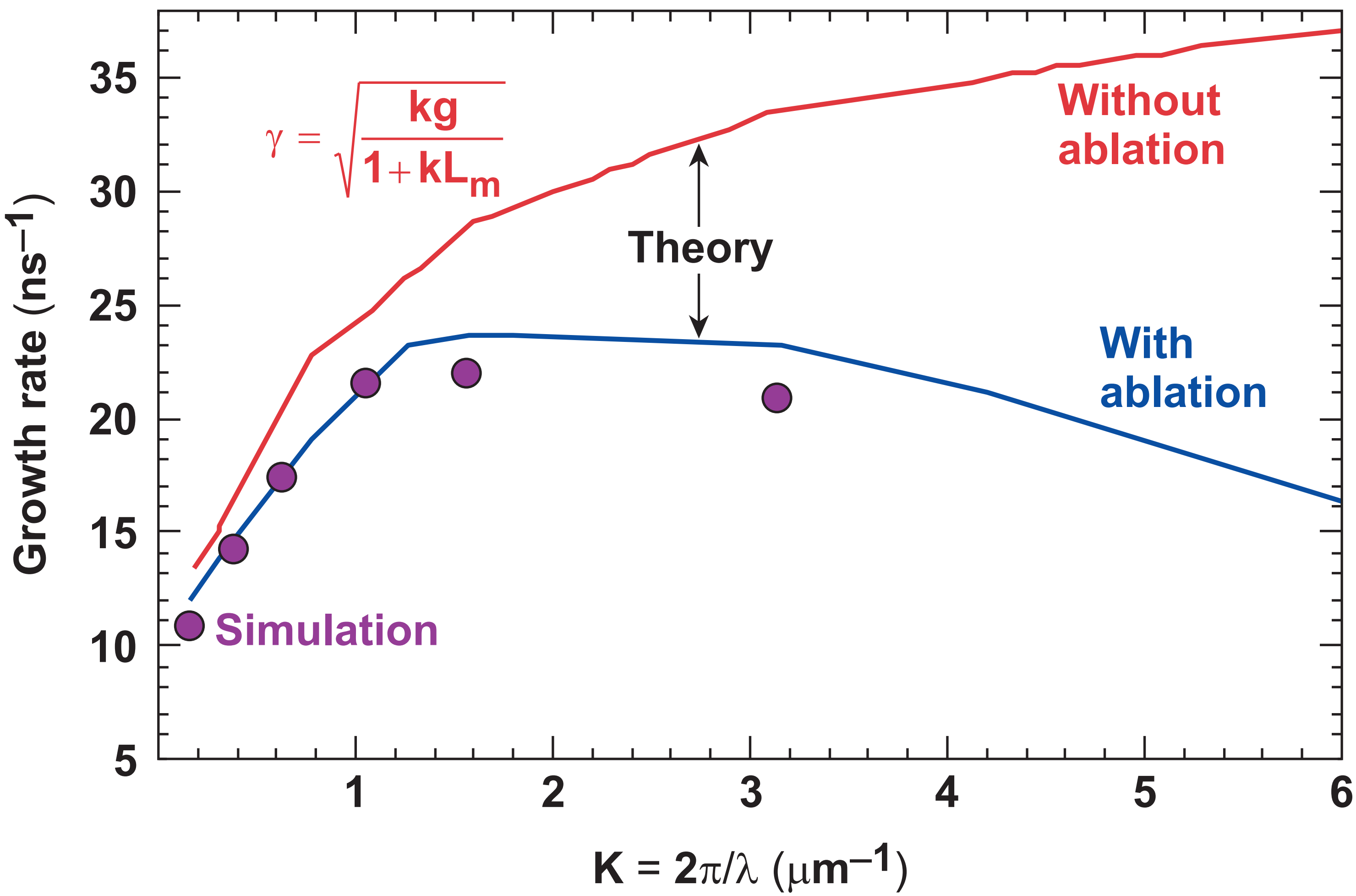
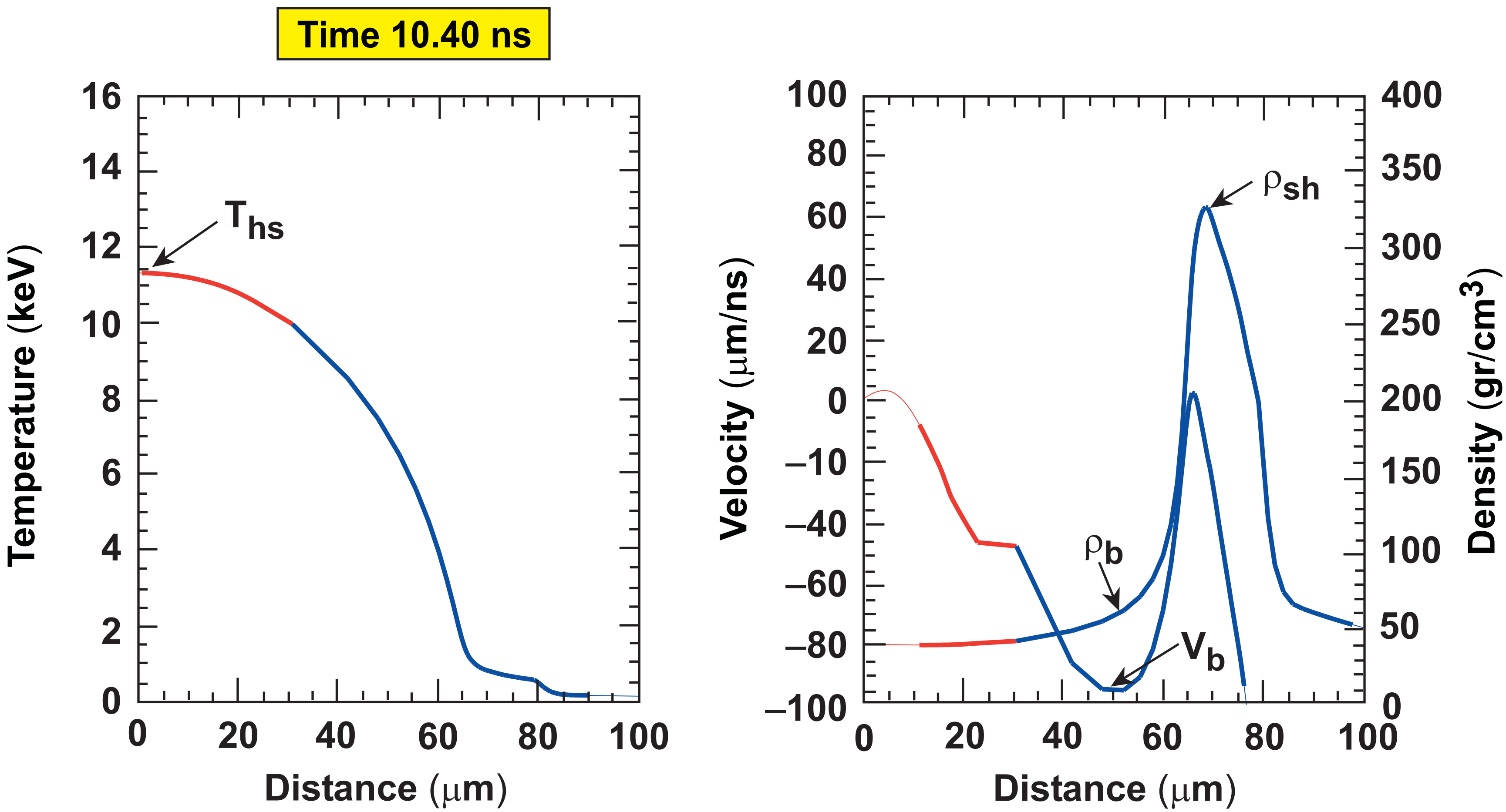
A significant reduction in RT growth rates is due to ablation



TC5366

Ablation velocity in NIF capsules



- From theory using T_{hs} = 11.5 keV, ρ_{sh} = 325 gr/cm^3, R_{hs} = 65 μm → V_a = 25 μm/ns
- From simulations: V_b = 100 μm/ns, ρ_b = 60 gr/cm^3, $V_a = \rho_b$; V_b/ρ_{sh} = 20 μm/ns

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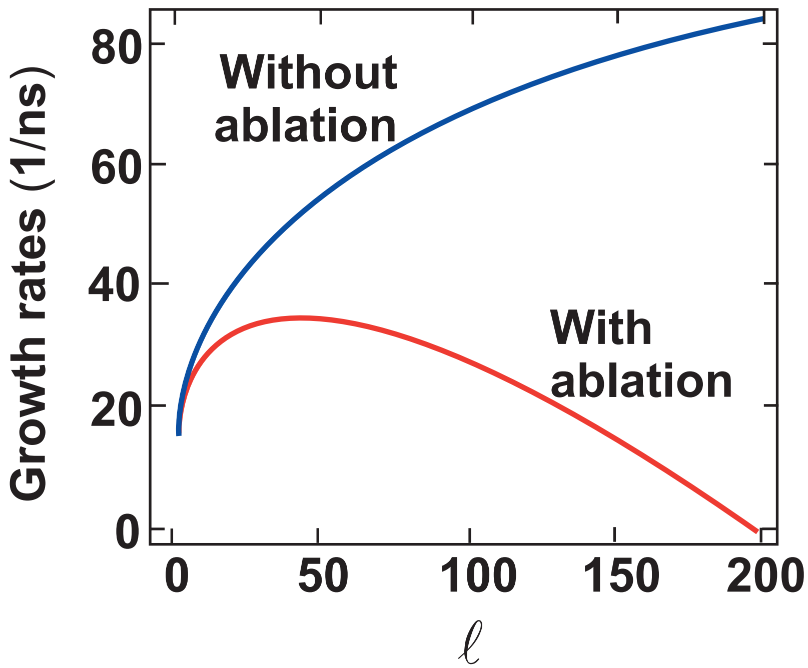
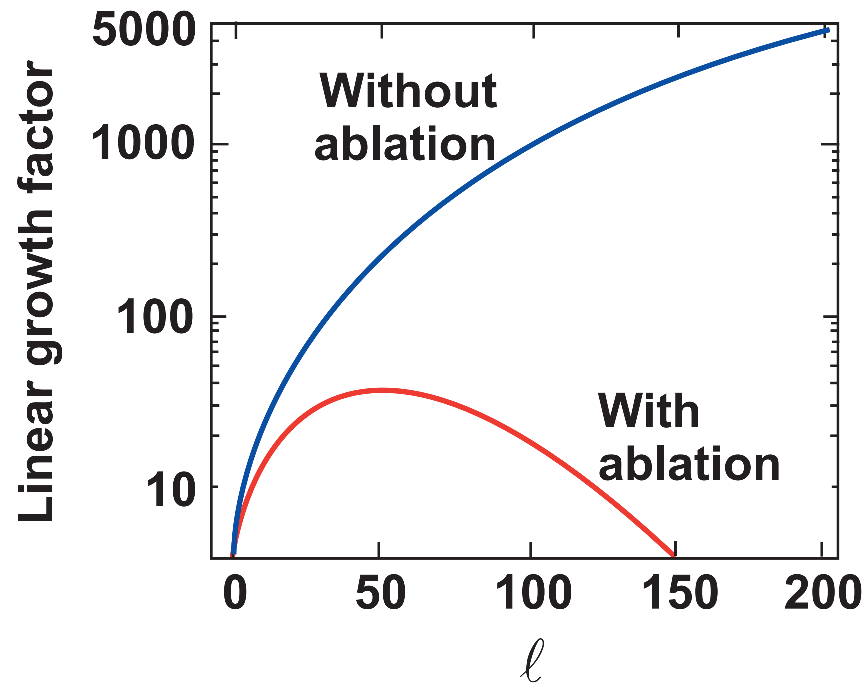
Theoretical NIF linear growth factors are significantly reduced by mass ablation





- Growth rate formula from R. Betti, *et al.*, Phys. Plasma 1998.
- NIF deceleration phase: $g = 10^4$ μm/ns^2, $V_a = 20$ μm/ns, $R_{hs} = 70$ μm, $L_m = 1$ μm.
- Duration of deceleration phase ~ 100 ps.

NIF cutoff: $\ell \approx 190$

TC5411

Conclusions

- Two stages of the deceleration-phase instability are observed: deceleration by a series of shocks and continuous deceleration.
- Mass ablation through the inner surface and finite density-gradient scale length are the most important factors during the RT growth.
- The significant reduction in the RT instability growth rate is due to the mass ablation.