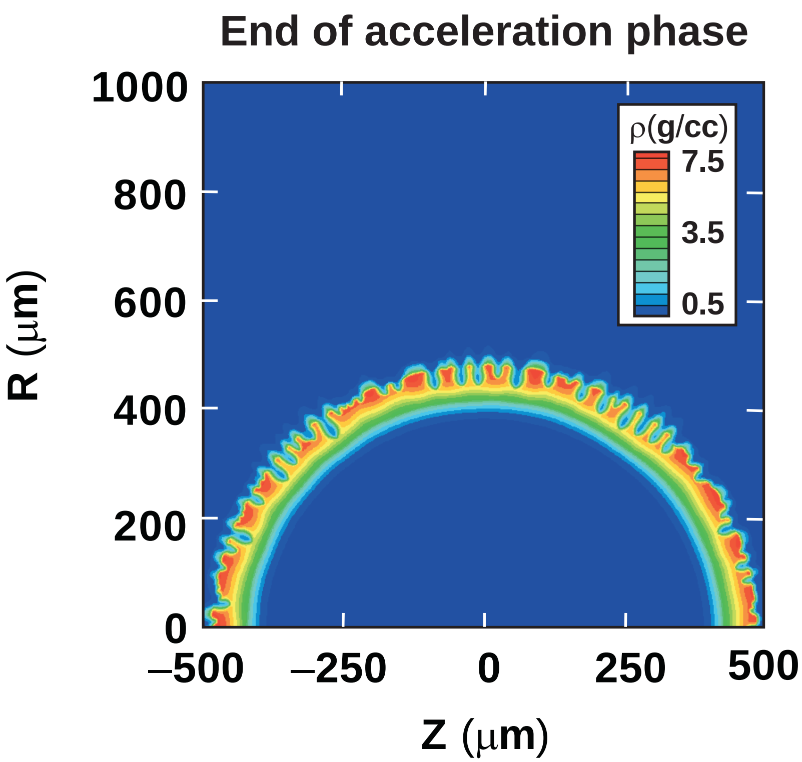
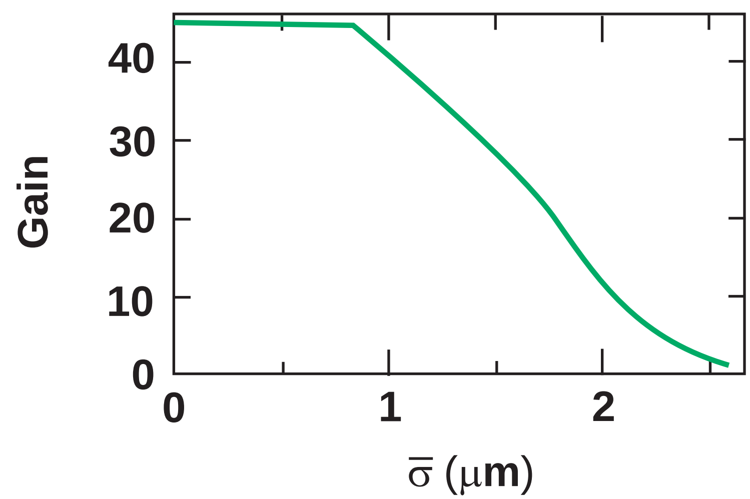
Analysis of a Direct-Drive Ignition Capsule Design for the National Ignition Facility





$$\bar{\sigma}^2 = 0.06\,\sigma_{1-9}^2 + \sigma_{>10}^2$$

P. W. McKenty *et al.*
University of Rochester
Laboratory for Laser Energetics

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Analysis of a Direct-Drive Ignition Capsule Designed for the NIF

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The current direct-drive ignition capsule design planned by the University of Rochester's Laboratory for Laser Energetics to be fielded on the National Ignition Facility (NIF) will be reviewed in this paper. The direct-drive requirements to establish a propagating thermonuclear burn on the NIF will be discussed in terms of the constraints on laser-irradiation uniformity and target surface roughness. The ignition design[1,2] consists of a cryogenic DT shell (~350 μm thick and ~3 mm in diameter) contained within a very thin (~2-μm) CH shell. To maintain stability during the implosion, the target is placed on an isentrope approximately three times that of Fermi-degenerate DT (α = 3). One-dimensional hydrodynamic studies using *LILAC* show that the ignition design is robust to uncertainties in laser power history and fuel composition. The two-dimensional hydrodynamics code *ORCHID* is used to examine the target performance under the influence of the main sources of nonuniformity: laser imprint, power imbalance, and inner- and outer-target-surface roughness. Results from these studies indicate that the reduction in target gain from all sources of nonuniformity can be described in terms of a single parameter related to the resultant inner-surface deformation at the end of the acceleration stage of the implosion. This parameter is constructed from a spectral decomposition of the surface deformation by giving different weights to the long and short wavelengths of nonuniformity. The physical reason for the difference in weighting is discussed in terms of the mechanisms for ignition failure. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.

1. C. P. Verdon, Bull. Am. Phys. Soc. **38**, 2010 (1993).
2. S. E. Bodner *et al.*, Phys. Plasmas **5**, 1901 (1998).

Collaborators

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Summary

Scaling target gain with $\overline{\sigma}$ provides the basis for developing a global nonuniformity budget for the NIF direct-drive point design

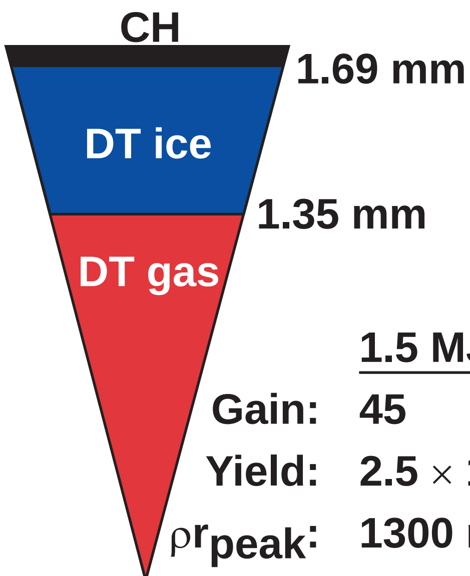
- Results from the nonuniformity budget, accounting for all four sources of nonuniformities, indicate that direct-drive targets can achieve gains in excess of 30 using current NIF specifications and the deployment of SSD with two color cycles.
- Outer surface roughness does not make a significant contribution to the nonuniformity budget.
- Distortions at stagnation are dominated by low order modes, however, high order modes cannot be neglected.
- Gain reduction is caused by target nonuniformities delaying the onset of ignition thereby wasting margin of the stagnating fuel layer.

Outline

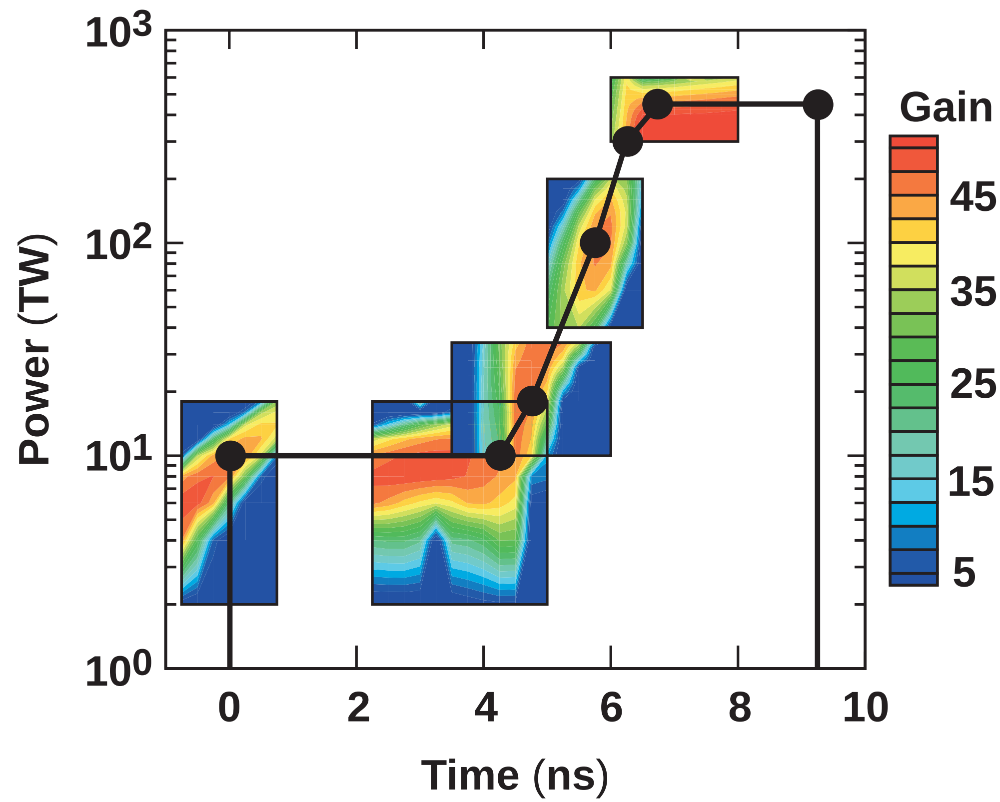
- Point design
- Numerical modeling
- Sources of implosion nonuniformities
  - power balance
  - ice/vapor surface roughness
  - outer surface roughness
  - laser imprint
- Failure analysis
- Nonuniformity budget
- Summary

Point design

The "all-DT" direct-drive target is a thick DT-ice layer enclosed by a thin CH shell



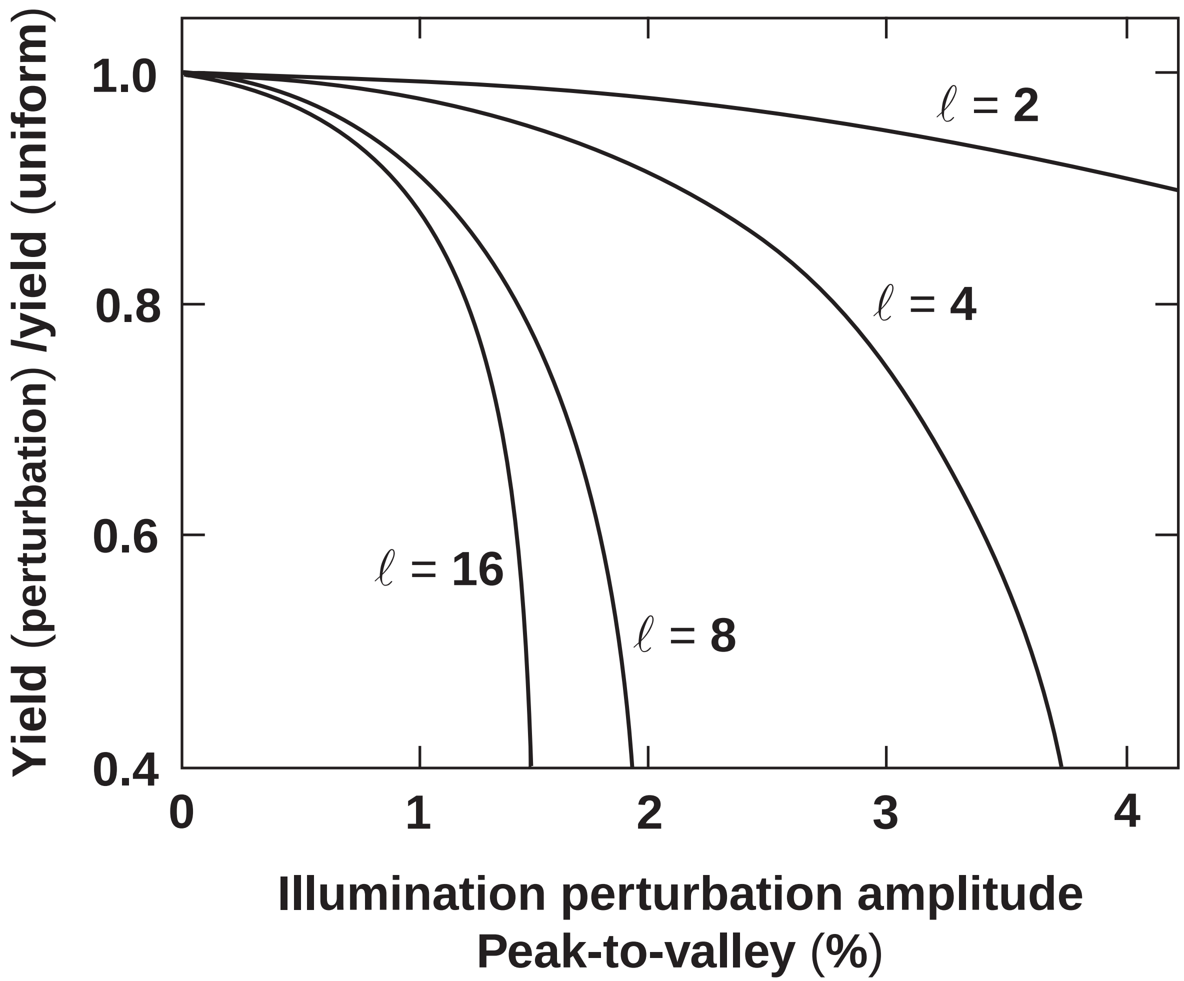
1.5 MJ, α = 3	
Gain:	45
Yield:	2.5×10^{19}
ρr_{peak}:	1300 mg/cm^2
$\langle T_i \rangle_n$:	30 keV
Hot spot CR:	29
Peak IFAR:	60



R. Town, LLE Review, 79, 121 (1999).

Numerical modeling

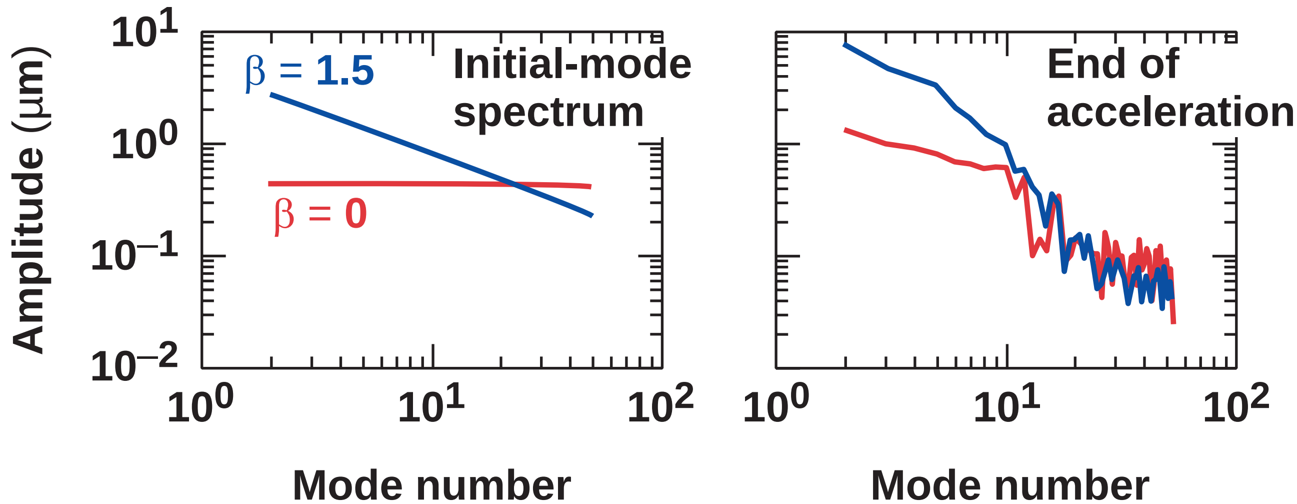
Simulations show that low-order modes can reduce high-gain capsule performance if the perturbation amplitudes are large



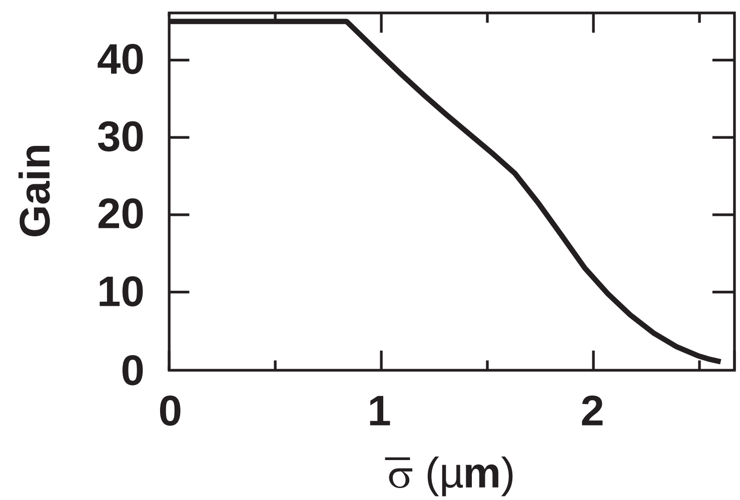
TC2802a

To relate the gain reduction to the mode spectrum, a series of 2-D *ORCHID* simulations with perturbed inner DT-ice interface has been performed

- $\sigma_\ell = \frac{\sigma_0}{\ell^\beta}$



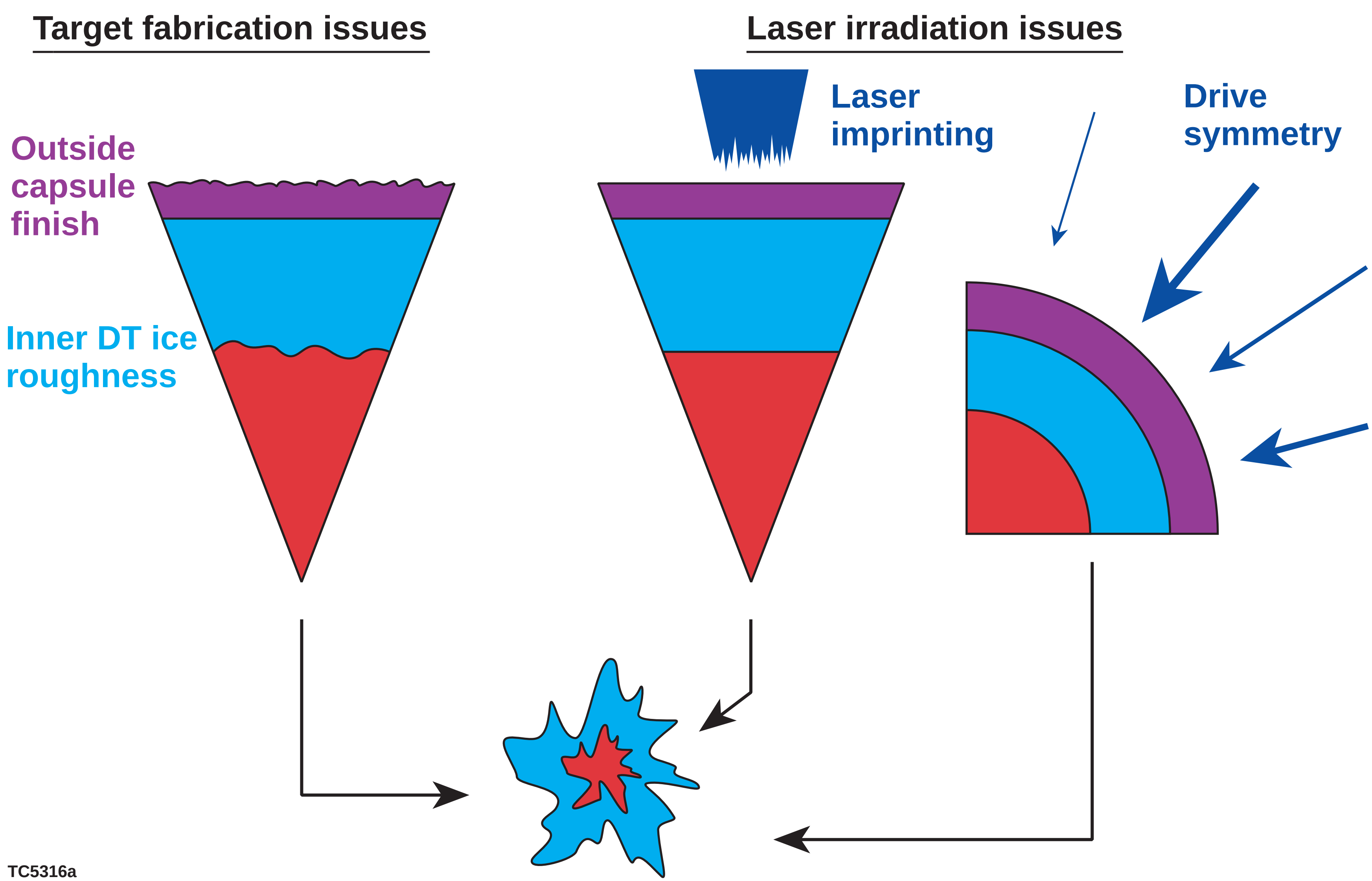
$$\bar{\sigma}^2 = 0.06\,\sigma^2_{1-9} + \sigma^2_{>10}$$



TC5137

Sources of implosion nonuniformities

There are four sources of perturbations a direct-drive capsule must tolerate to ignite and burn



TC5316a

Heuristically, there are four sources of perturbations a direct-drive capsule must tolerate to ignite and burn

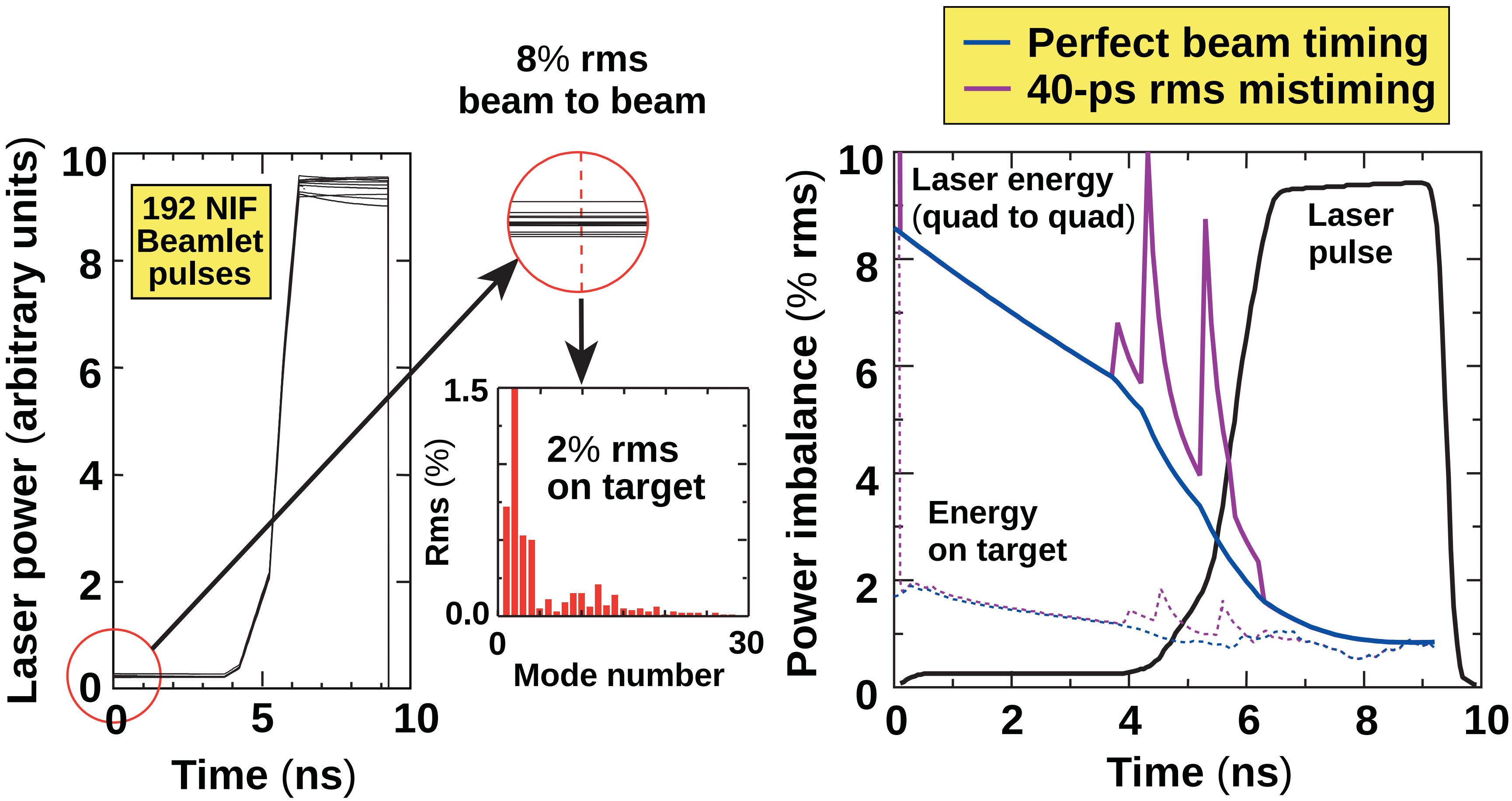
$$\left(\frac{\sigma_{rms_{\text{drive symmetry}}}}{\text{Max allowed value}_{\text{drive symmetry}}}\right)^2 + \left(\frac{\sigma_{rms_{\text{laser imprinting}}}}{\text{Max allowed value}_{\text{laser imprinting}}}\right)^2$$

$$+ \left(\frac{\sigma_{rms_{\text{DT ice}}}}{\text{Max allowed value}_{\text{DT ice}}}\right)^2 + \left(\frac{\sigma_{rms_{\text{outside capsule finish}}}}{\text{Max allowed value}_{\text{outside capsule finish}}}\right)^2 < 1$$

- Laser-irradiation-related issues (red)
- Target-fabrication-related issues (yellow)

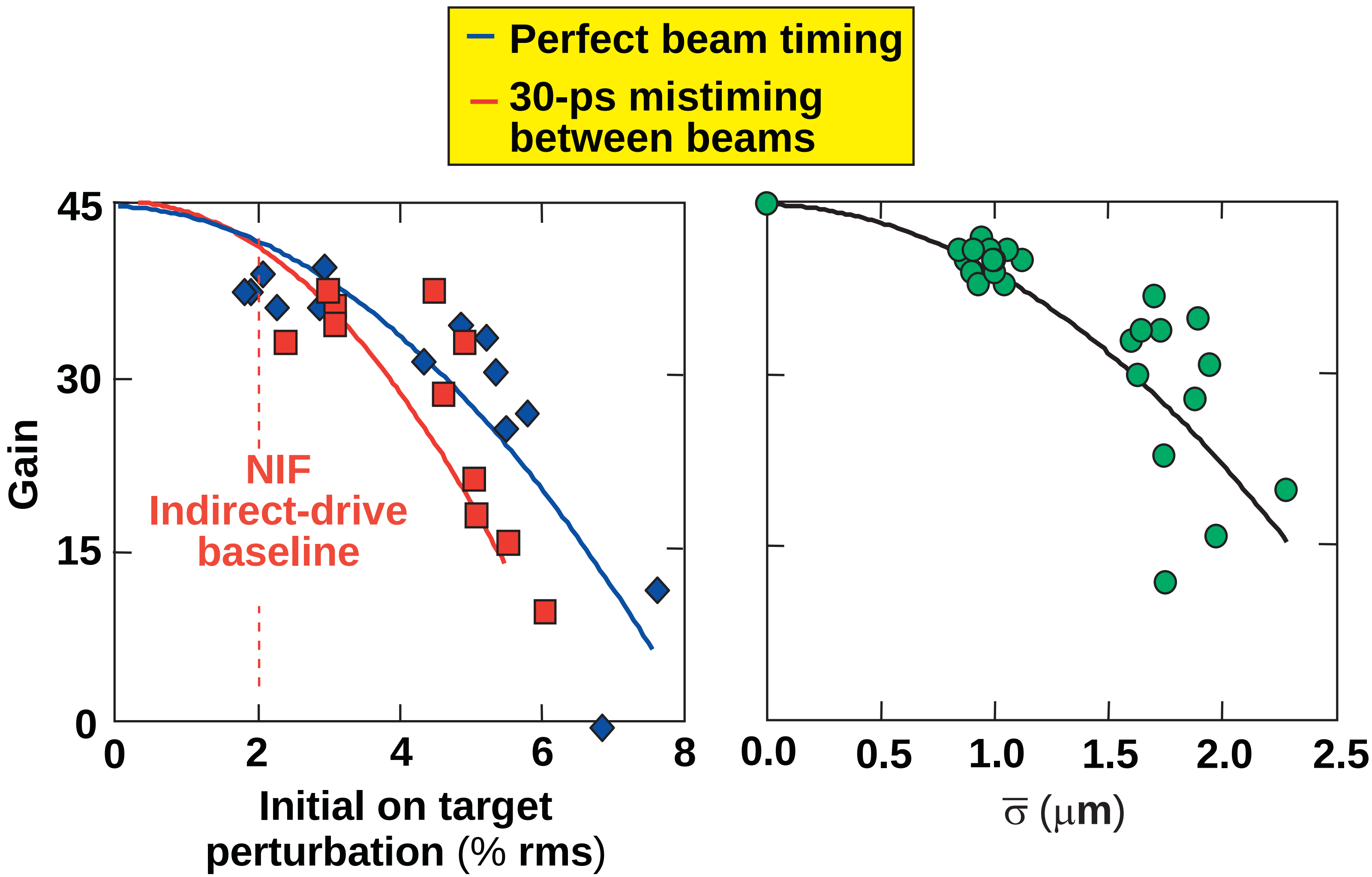
TC4113f

NIF temporal power histories are mapped to target and spherically decomposed for input into *ORCHID*



NIF laser power histories provided by Ogden Jones (LLNL)

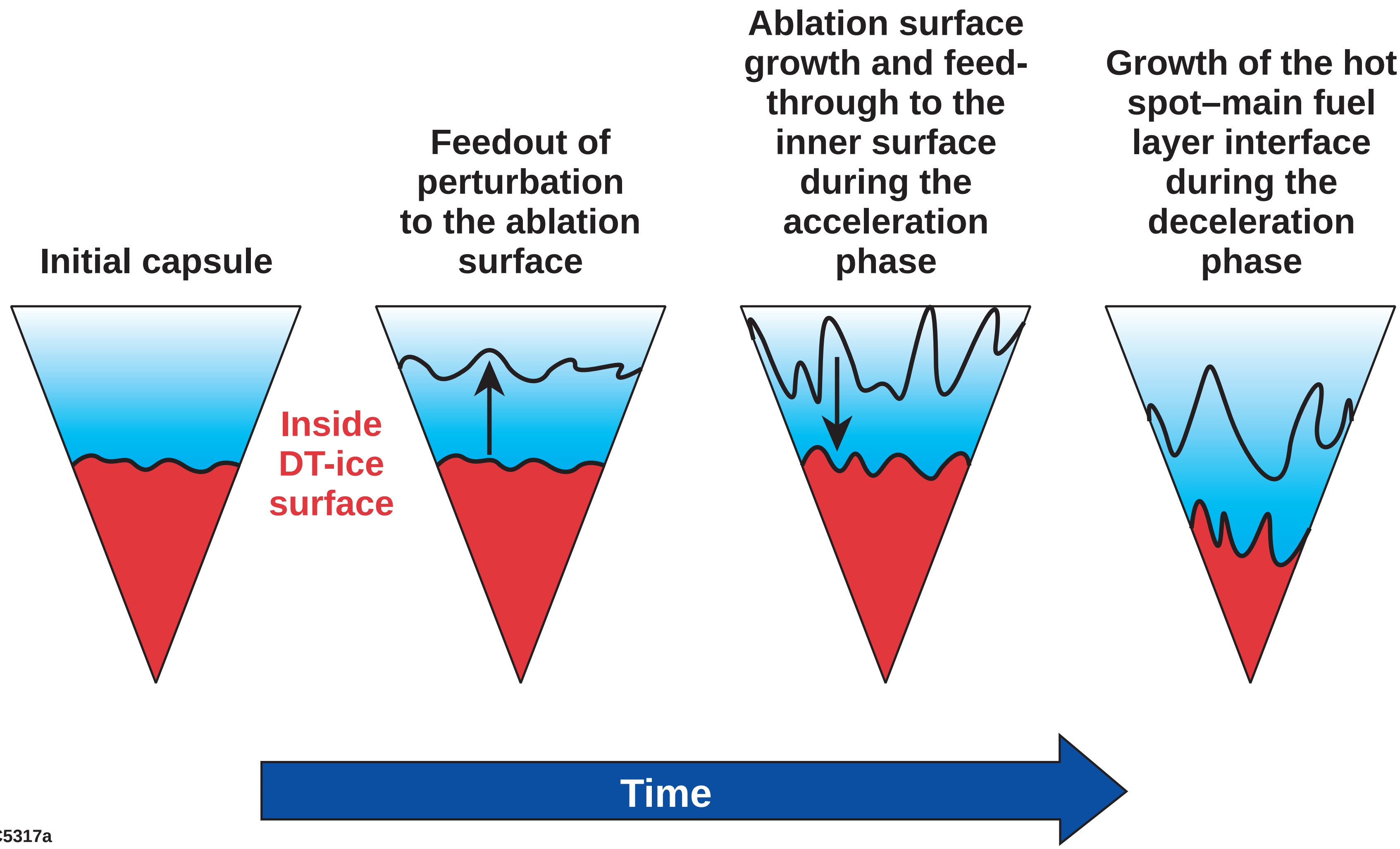
Results of *ORCHID* calculations have validated the direct-drive base-line power imbalance specifications



TC5563

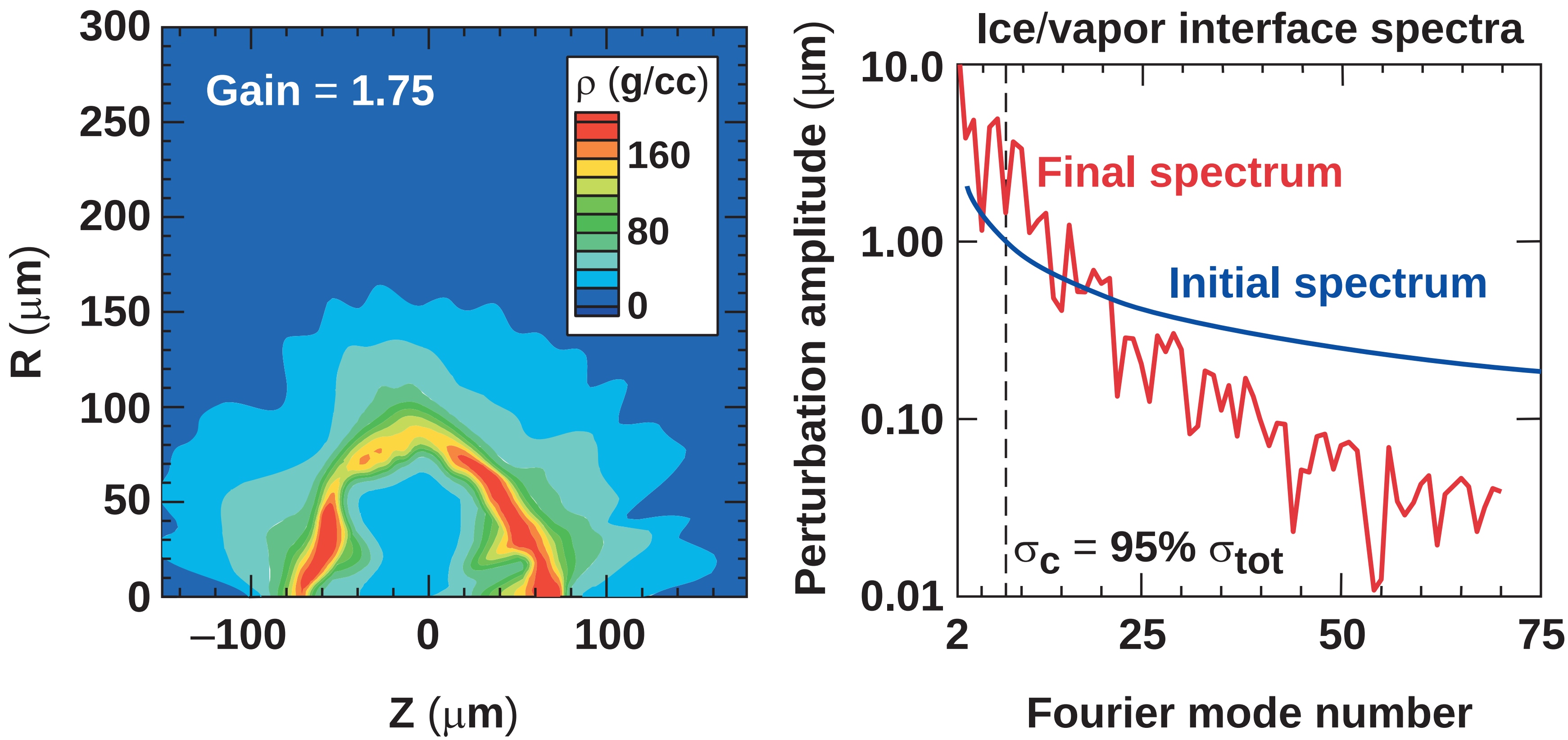
Ice/vapor surface roughness

Perturbations located initially on the inside DT-ice surface affects the capsule implosion during both the acceleration and deceleration phases



TC5317a

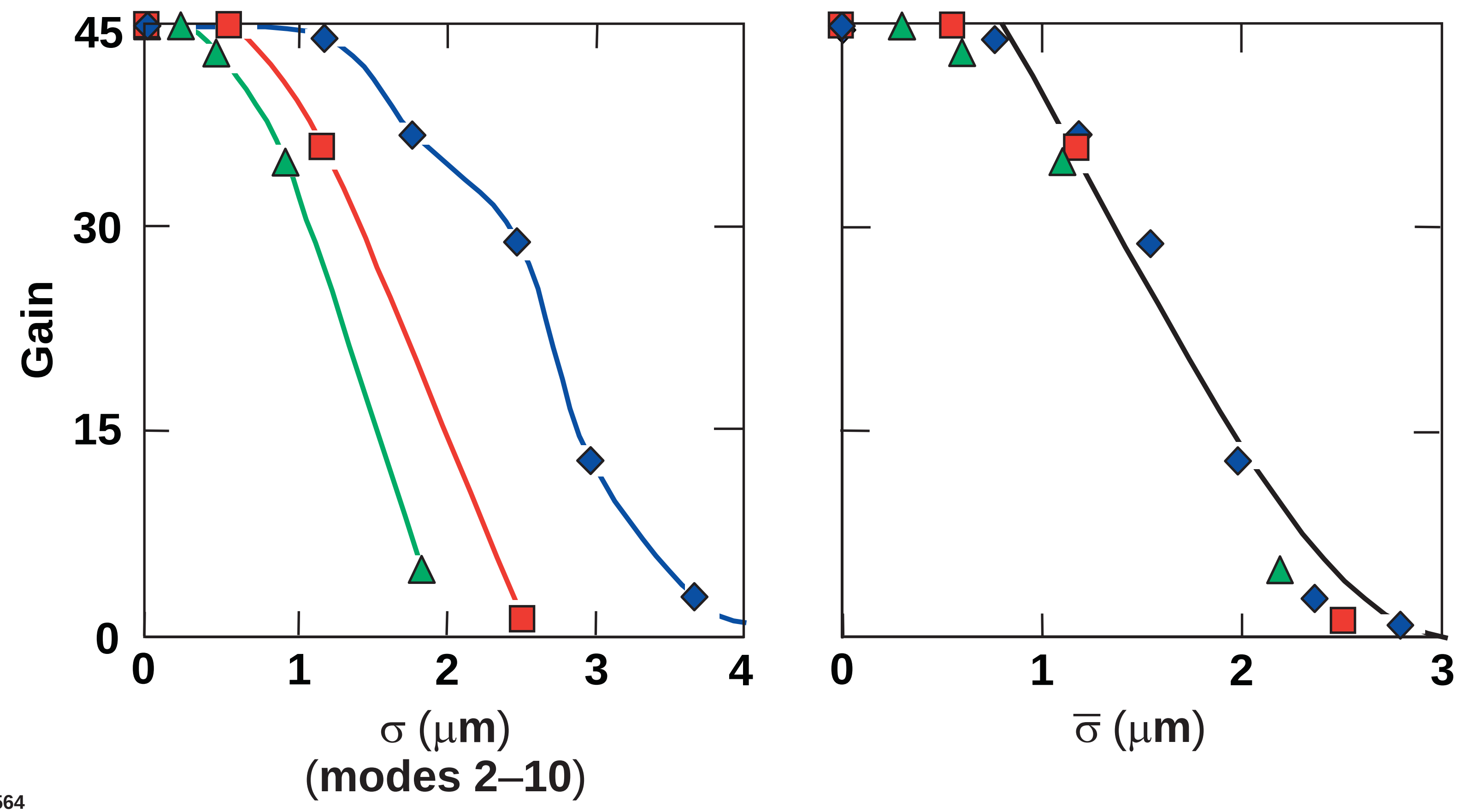
ORCHID simulations indicate that target gain depends strongly on the development of the low-order modes



TC5211

Scaling target gain with $\overline{\sigma}$ correctly balances the individual contributions of the low and high order modes during the implosion.

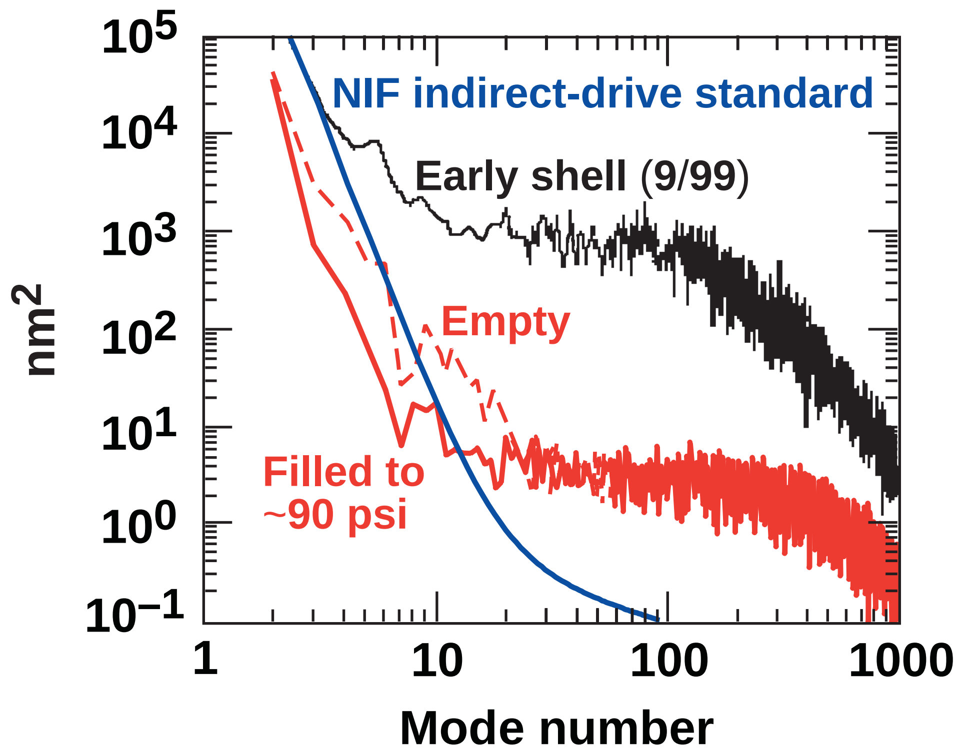
$a = a_0/l^{\beta}$, β = 0(▲), 0.75(■), and 1.50(◆)



TC5564

Outer surface roughness

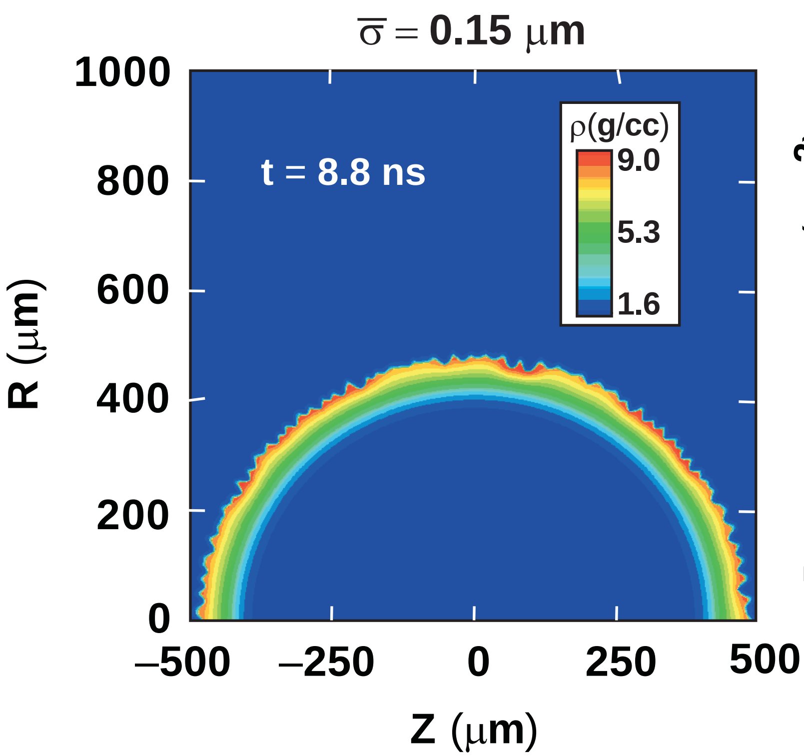
The smoothness and concentricity of thin-wall polyimide targets (1.5 to 2.0 μm) have been improved

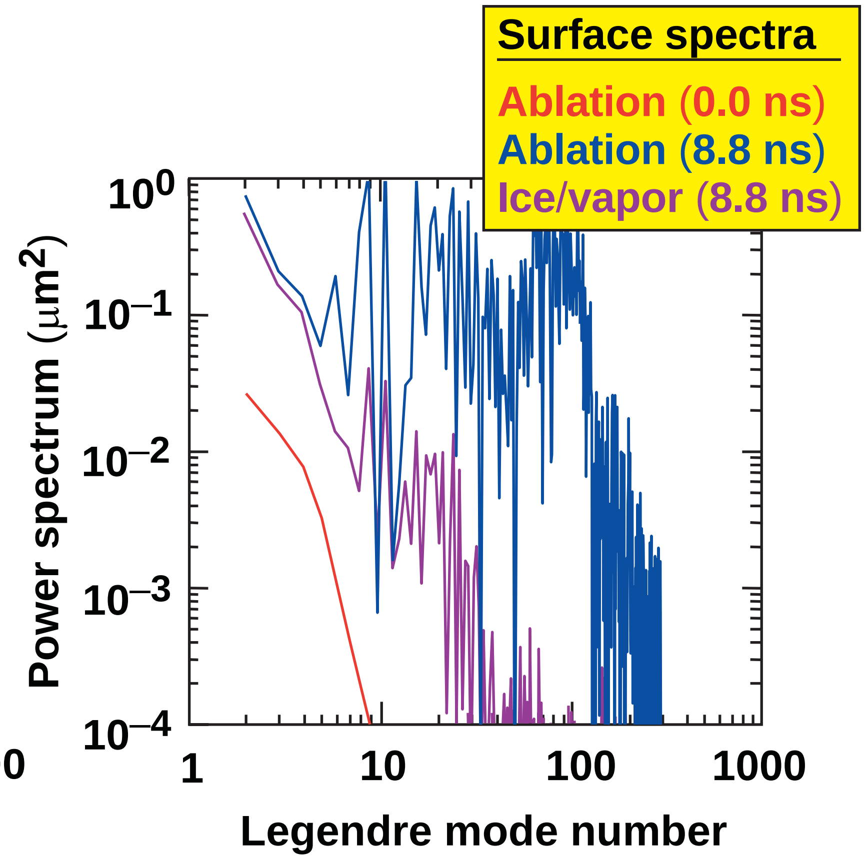


- High-frequency roughness is a consequence of the coating process; the rms value $\ell > 100$ is < 40 nm.
- Low-frequency roughness is caused by weak shells deforming to accommodate the bending moments that develop during processing.
- Inflating the shell reduces the low-frequecy roughness.

TC5565

Twice the NIF standard specification (~165 nm) for outer surface roughness does not result in any significant disruption of the ice/vapor interface



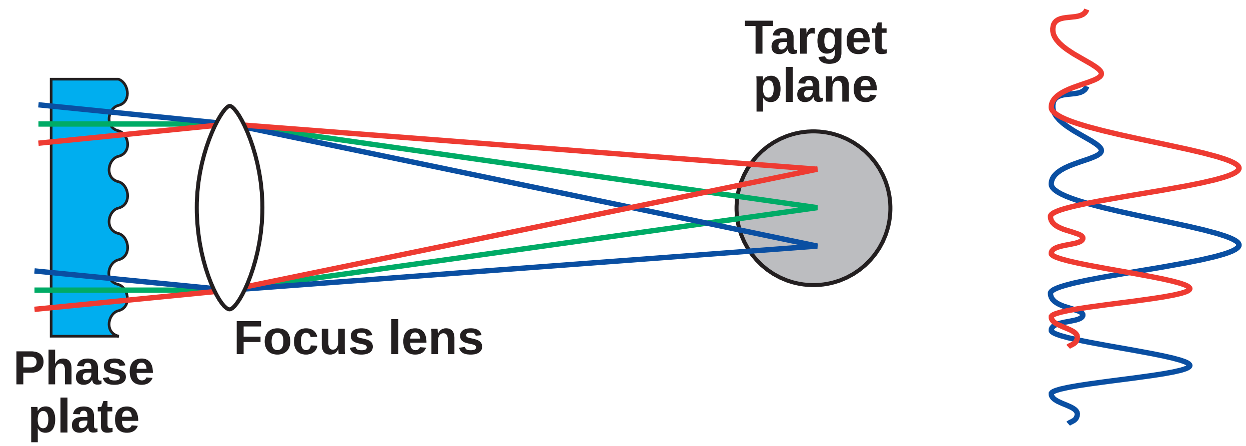


TC5455

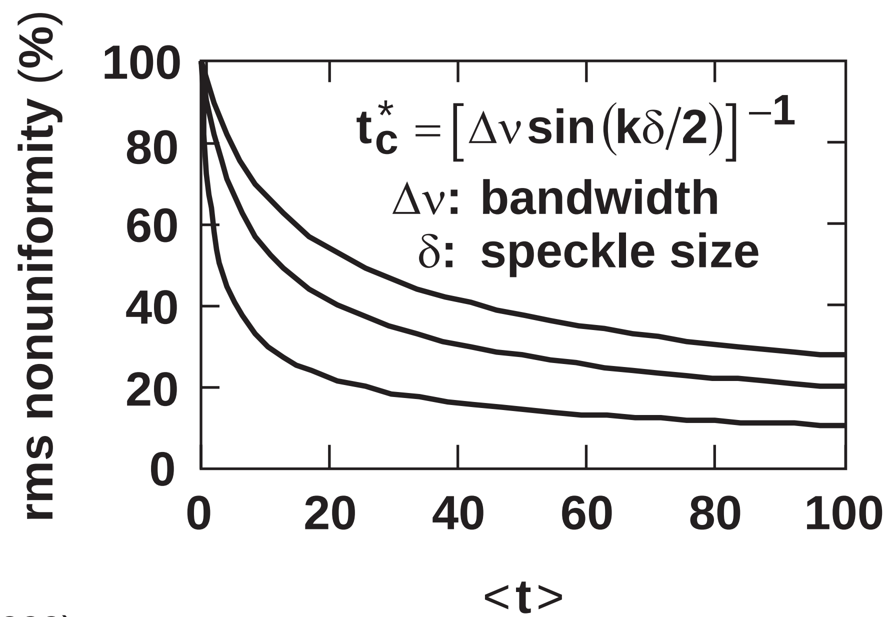
Laser imprint

SSD reduces time-averaged laser nonuniformity

- DPP spectrum
- Beam Overlay
- PS

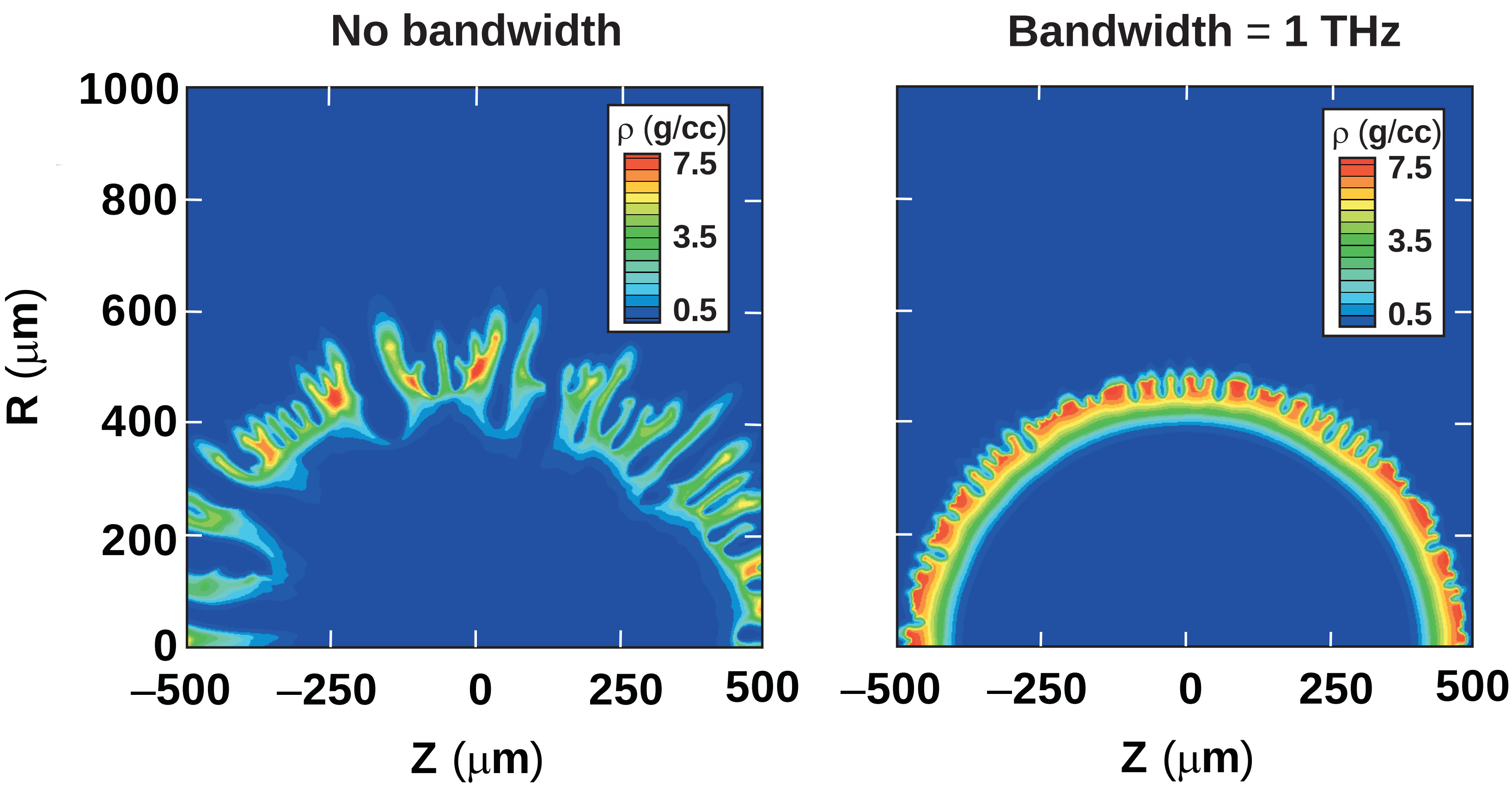


$$\langle\sigma_{rms}\rangle \sim \sqrt{t_c/\langle t\rangle}\,\langle\sigma^0_{rms}\rangle$$



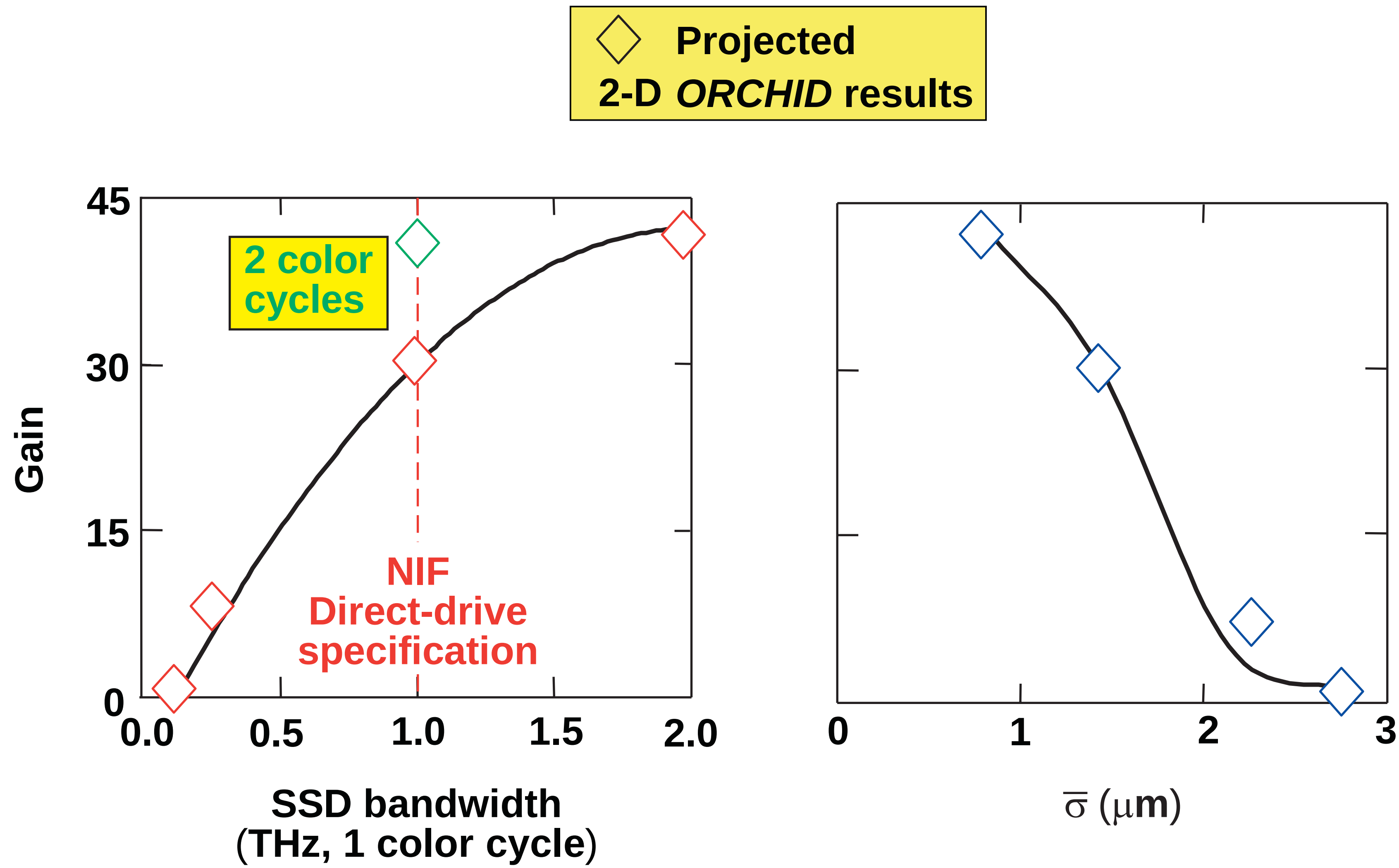
TC5220a *S. Skupsky, Phys. Plasmas 6, 2157 (1999).

Application of SSD bandwidth is necessary for shell integrity during the entire implosion



TC5587

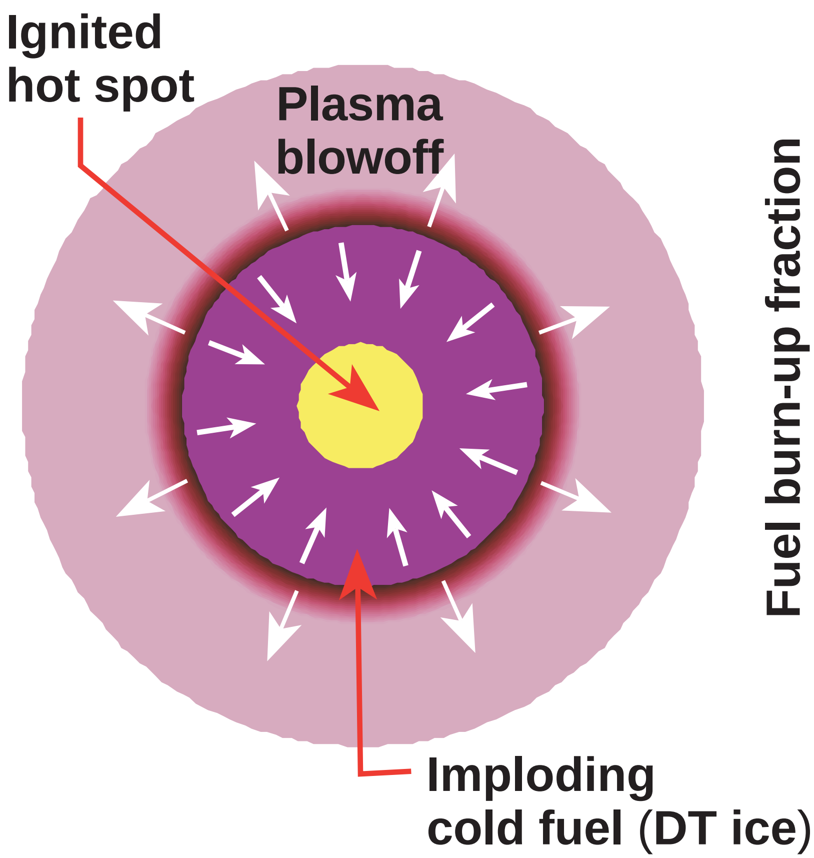
Scaling gain with $\bar{\sigma}$, taken from *ORCHID* calculations, indicates that NIF must deploy at least 1-THz bandwidth

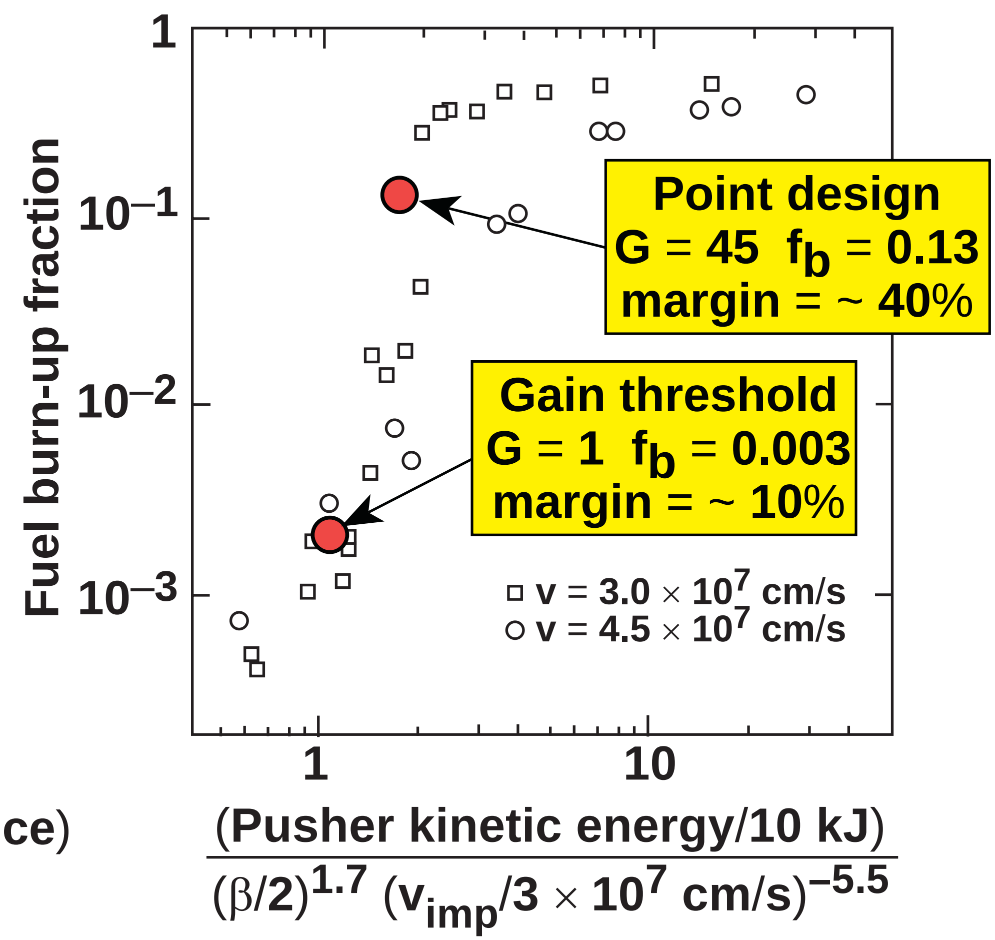


TC5588

Failure Analysis

To achieve high gain for NIF capsules ignition must occur while the cold fuel still retains a significant fraction (margin) of its peak kinetic energy

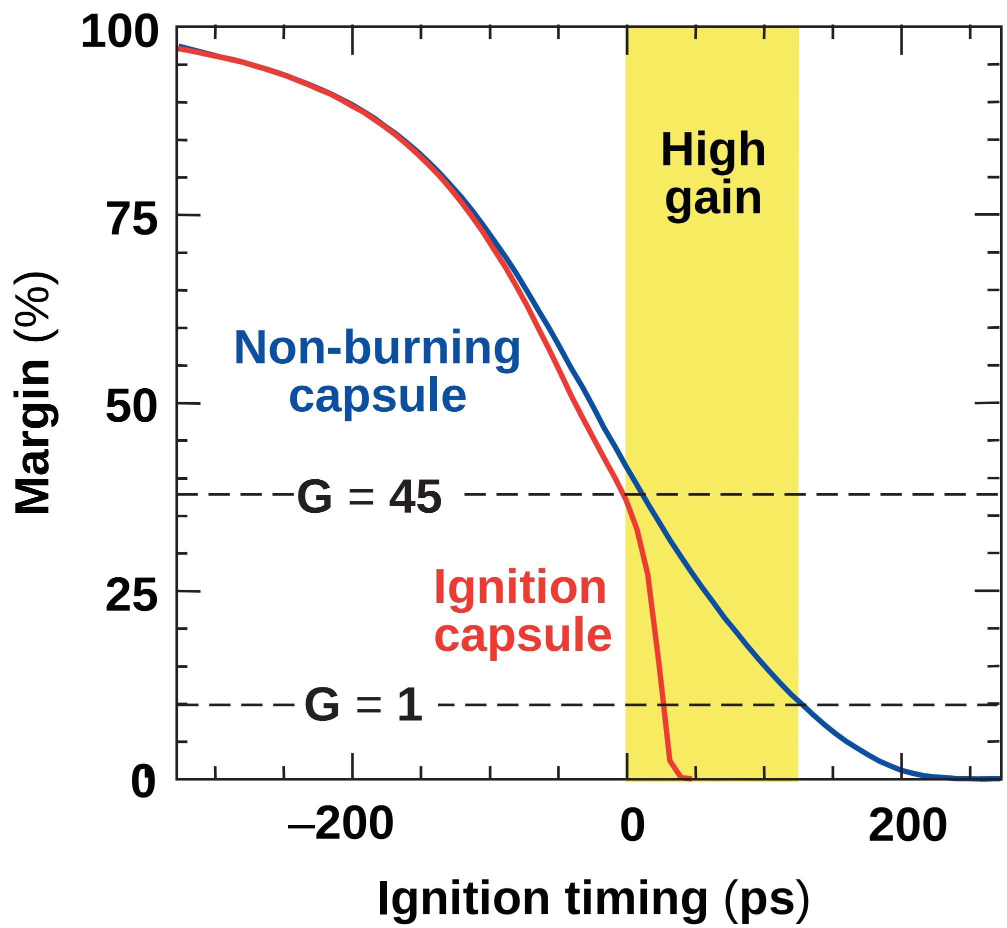




Graph taken from Levedahl and Lindl, Nucl. Fusion 37 (2), 170 (1997).

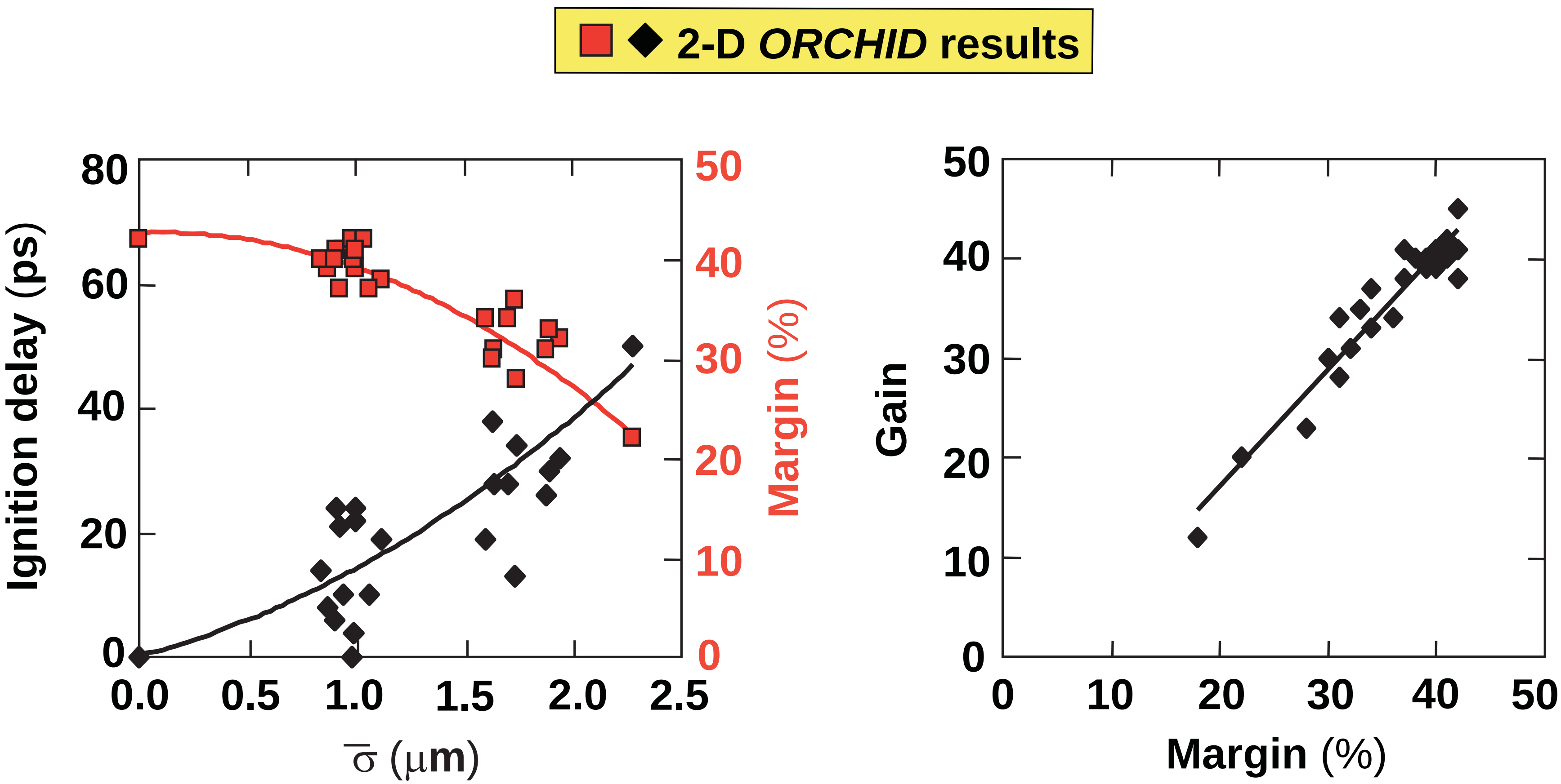
TC5545

Shell stagnation determines the margin trajectory that defines the window for high gain



TC5580

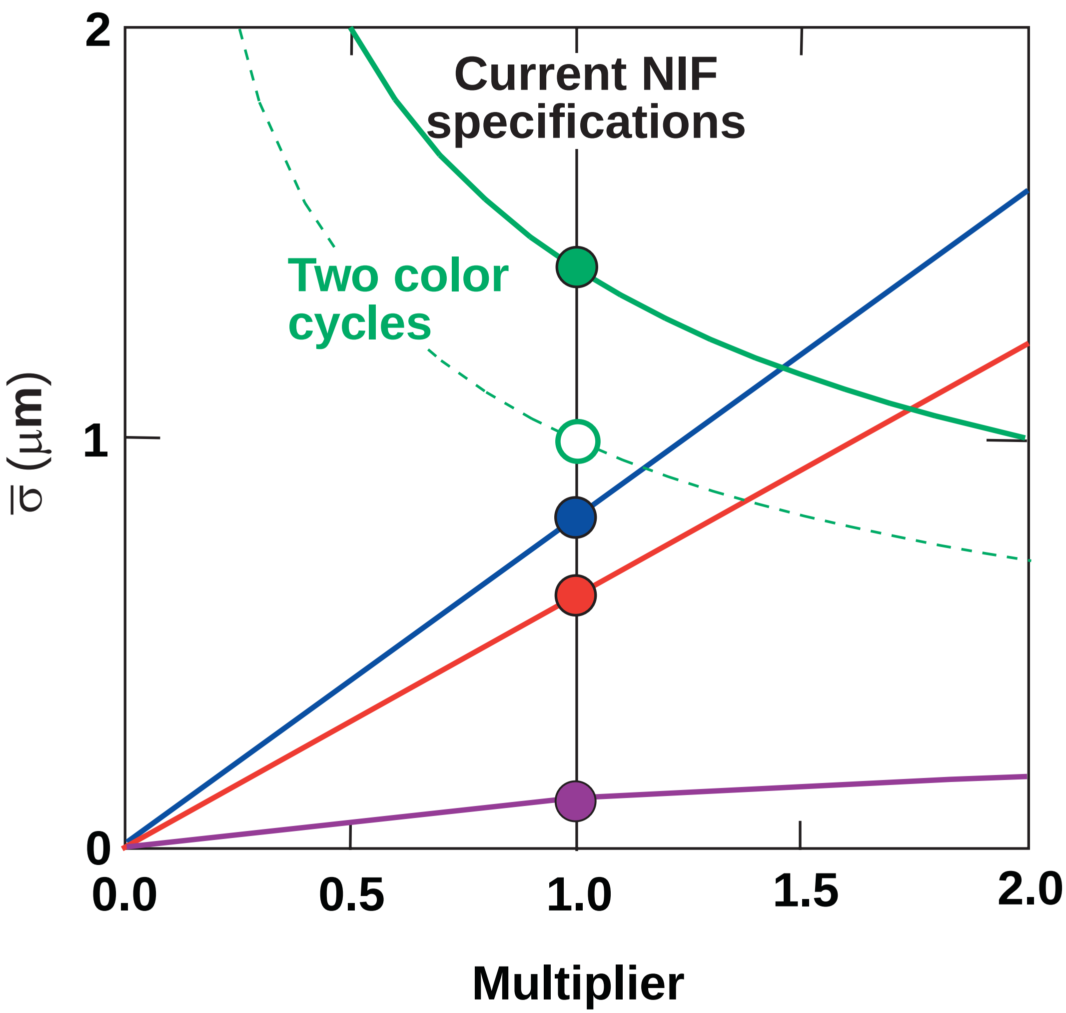
ORCHID simulations indicate that as ice/vapor interface perturbations increase, ignition is delayed and gain is reduced

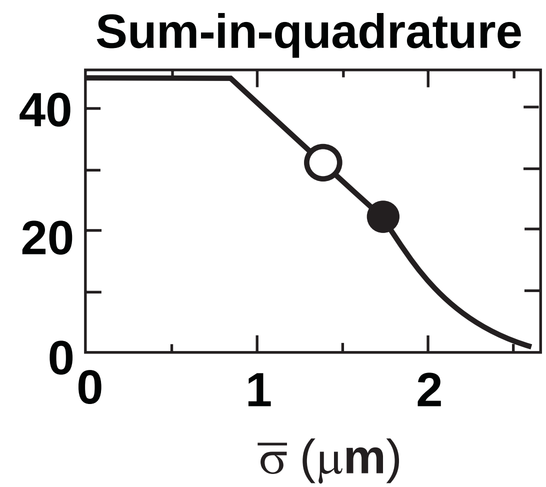


TC5544

Nonuniformity budget

Scaling gain with $\overline{\sigma}$ allows forming a global nonuniformity budget for the direct-drive point design





- Applied SSD bandwidth (× 1 THz)
- On-target power imbalance (× 2% rms)
- Inner-surface roughness (× 1-μm rms)
- Outer-surface roughness (× 80 nm)

TC5577

Summary/Conclusion

Scaling target gain with $\overline{\sigma}$ provides the basis for developing a global nonuniformity budget for the NIF direct-drive point design

- **Results from the nonuniformity budget, accounting for all four sources of nonuniformities, indicate that direct-drive targets can achieve gains in excess of 30 using current NIF specifications <u>and</u> the deployment of SSD with two color cycles.**
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