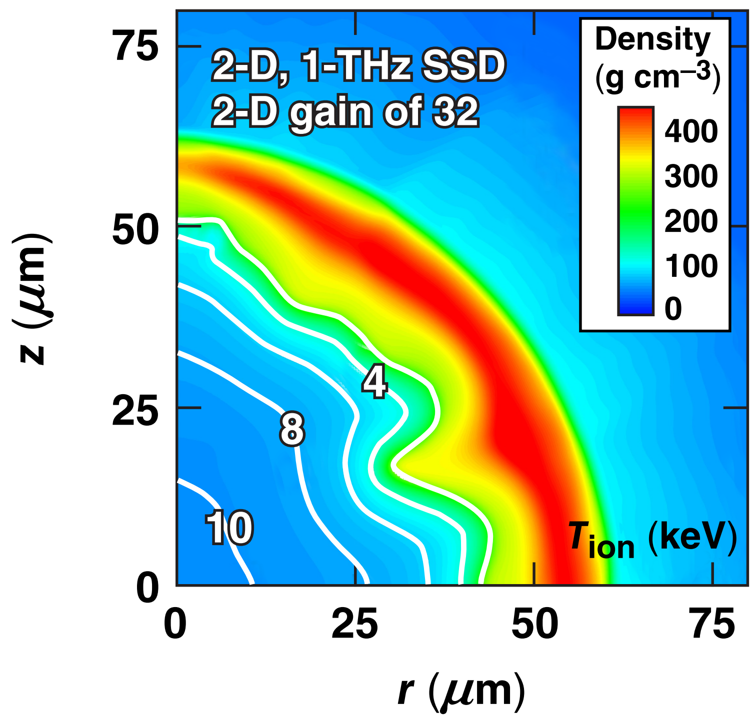
1-MJ, Wetted-Foam Target-Design Performance for the National Ignition Facility

Including imprint, power balance, surface, and ice roughness



T. J. B. Collins
University of Rochester
Laboratory for Laser Energetics

48th Annual Meeting of the American Physical Society Division of Plasma Physics
Philadelphia, PA
30 October–3 November 2006

Summary

A 1-MJ wetted-foam target will ignite on the NIF with baseline direct-drive laser smoothing

- A deuterium–tritium (DT)-saturated polymer foam, or “wetted-foam,” ablator provides better performance than the baseline direct-drive, all-DT design.
- Low implosion velocity is used to minimize the effects of laser imprint.
- A nonuniformity budget analysis shows that single-beam nonuniformity has the greatest effect on target performance.
- Simulations, including power imbalance, outer-surface and ice-surface roughness, and imprint show that with 2-D, 1-THz SSD smoothing this target ignites and produces a gain of 32.

Collaborators

R. Betti

T. R. Boehly

V. N. Goncharov

D. R. Harding

J. P. Knauer

J. A. Marozas

R. L. McCrory

P. W. McKenty

P. B. Radha

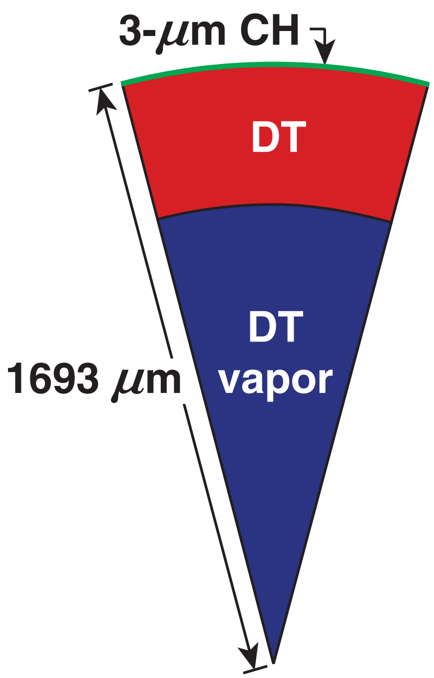
S. Skupsky

J. Zuegel

Outline

- Wetted foams and the 1-MJ design
- Sources of implosion nonuniformity
- Nonuniformity budget
- Integrated simulations
- Experimental plans

At 1.5 MJ, the all-DT design is projected to give a 1-D gain of 45



All-DT

$\langle\alpha\rangle = 4.2$

$\alpha = P/P_{Fermi}$

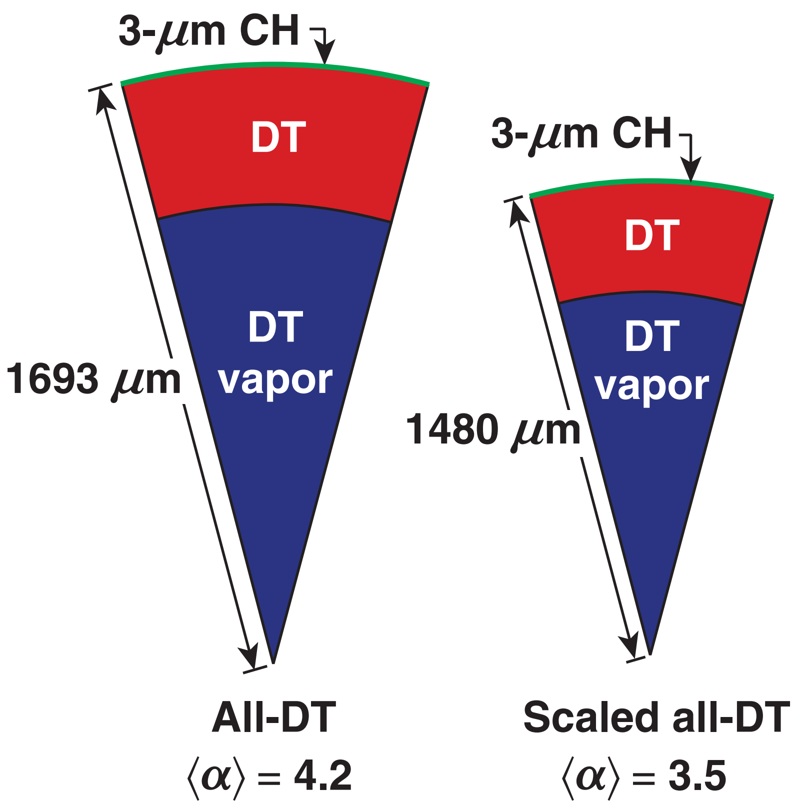
- Stability is gauged by the ratio of the rms bubble amplitude to the shell thickness $A/\Delta R$ determined with a 1-D post-processor.*

	All-DT
Energy (MJ)	1.5
Target radius (μm)	1695
Absorption (%)	65
$A/\Delta R$ (%)	30
1-D gain	45

TC7447

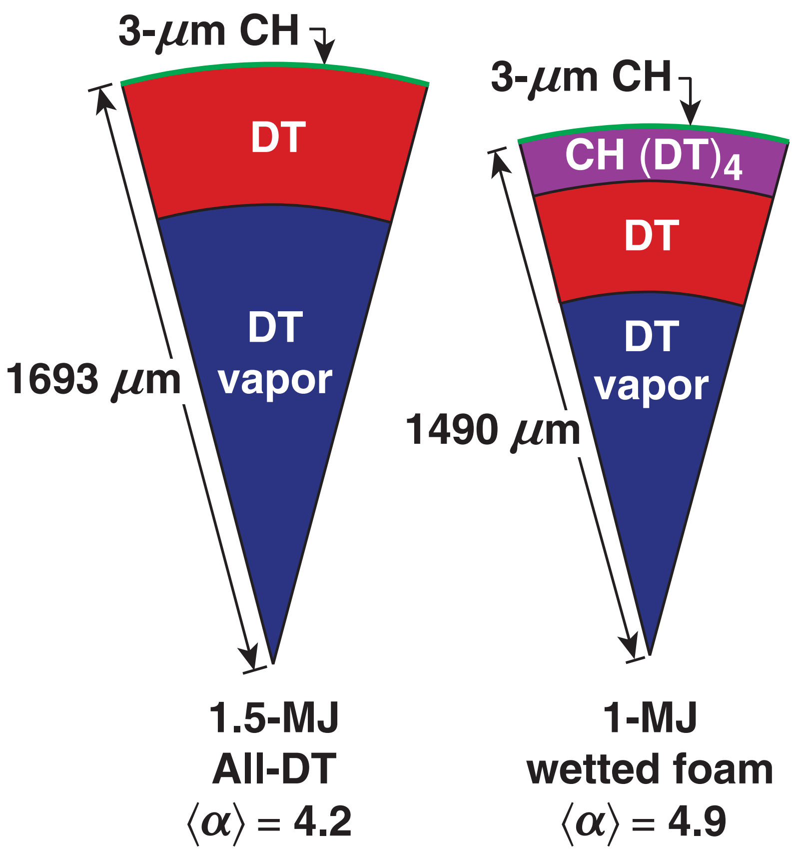
P. W. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).
*V. N. Goncharov *et al.*, Phys. Plasmas 10, 1906 (2003).

The 1.5-MJ all-DT design has been scaled to 1 MJ, resulting in lower gain and stability



	All-DT	Scaled All-DT
Energy (MJ)	1.5	1.0
Target radius (μm)	1695	1480
Absorption (%)	**65**	**59**
$A/\Delta R$ (%)	30	33
1-D gain	45	40

Wetted foam provides higher laser absorption, allowing a thicker shell and greater stability than the all-DT baseline target at 1 MJ



- The foam density balances higher absorption with increased radiative preheat.
- The foam-layer thickness is chosen so the foam is entirely ablated.

	All-DT	Scaled All-DT	Wetted-foam
Energy (MJ)	1.5	1.0	1.0
Target radius (μm)	1695	1480	1490
Absorption (%)	65	59	86
$A/\Delta R$ (%)	30	33	11
1-D gain	45	40	49

The 1-D, 1-MJ wetted-foam target gain is 49.

TC7449

The shell stability can be increased by lowering the implosion velocity and raising the in-flight shell thickness

- The most-dangerous Rayleigh–Taylor modes feed through to the inner surface and have wavelengths comparable to the shell thickness, with wave numbers $k \sim \Delta R^{-1}$.

- The linear growth of these modes depends on the in-flight aspect ratio, IFAR:

  $$\text{Number of } e \text{ foldings} = \gamma t \sim \sqrt{kgt^2} \sim \sqrt{\frac{R_0}{\Delta R}} \equiv \sqrt{\text{IFAR}}$$

- The in-flight aspect ratio depends mainly on the implosion velocity and average adiabat:*

$$\text{IFAR} \sim \frac{V^2}{\langle \alpha \rangle^{3/5}},$$

where $\alpha = P/P_{\text{Fermi}}$ is the adiabat.

TC7450

*J. Lindl, Inertial Confinement Fusion (1997).

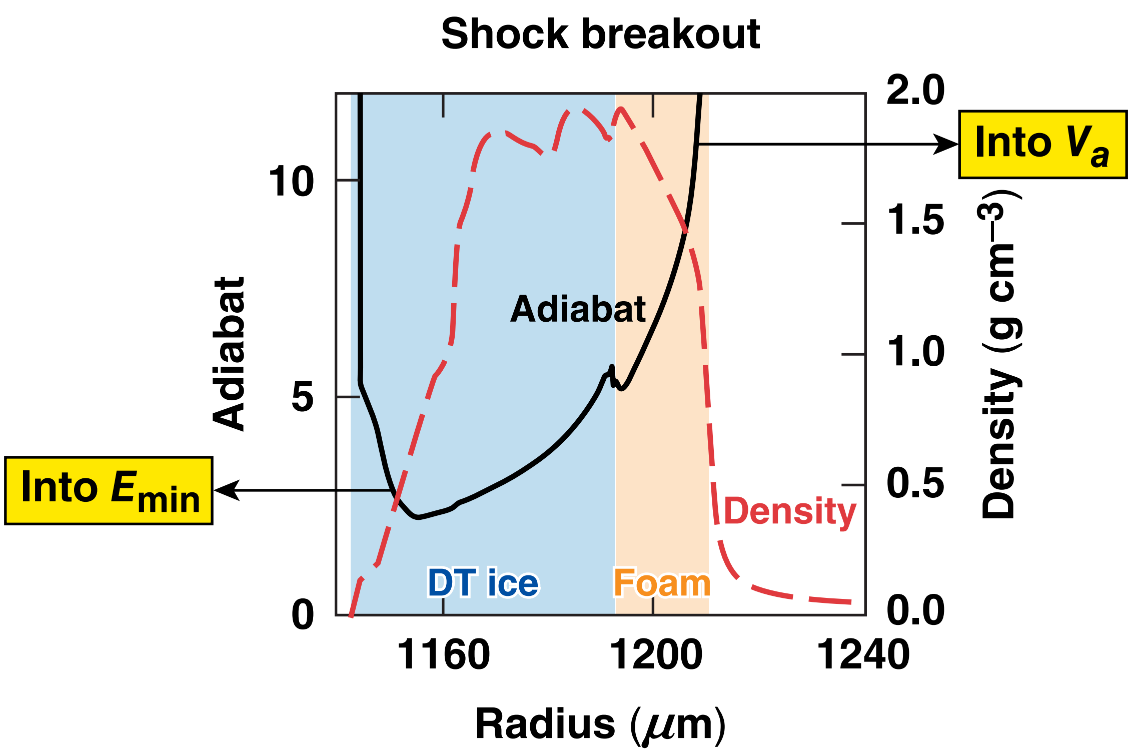
The foam design has a thicker shell and lower implosion velocity than the scaled all-DT design

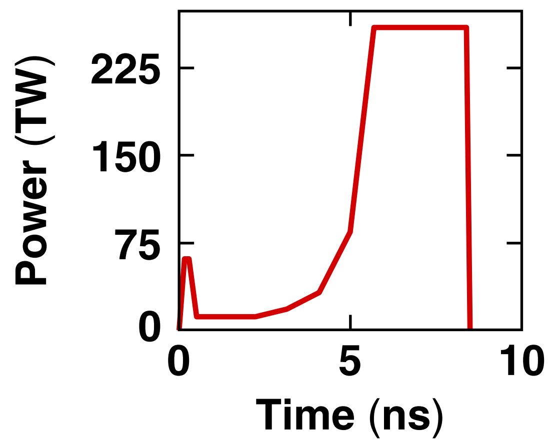
	V (μm/ns)	ΔR (μm)	IFAR	$A/\Delta R$ (%)	Areal density ρR(g cm^{-2})	Margin (%)
1-MJ All-DT	430	285	69	33	1.1	45
Wetted foam	372	323	28	11	1.4	30

- This improvement comes at the expense of margin, but with improved areal density.
- Margin = $\dfrac{\text{inward moving kinetic energy at ignition}}{\text{peak inward kinetic energy}}$
- The wetted-foam design tolerates realistic ice roughness in 2-D simulations, indicating sufficient margin.

Shell stability and compressibility depend on the adiabat

- Minimum energy required for ignition:[*,**] $E_{min} \sim \alpha^{1.88}$
- Rayleigh–Taylor instability growth rate: $\gamma = \alpha_{RT}\,(kg)^{1/2} - \beta_{RT}\,kV_a,\ V_a \sim \alpha^{3/5}$



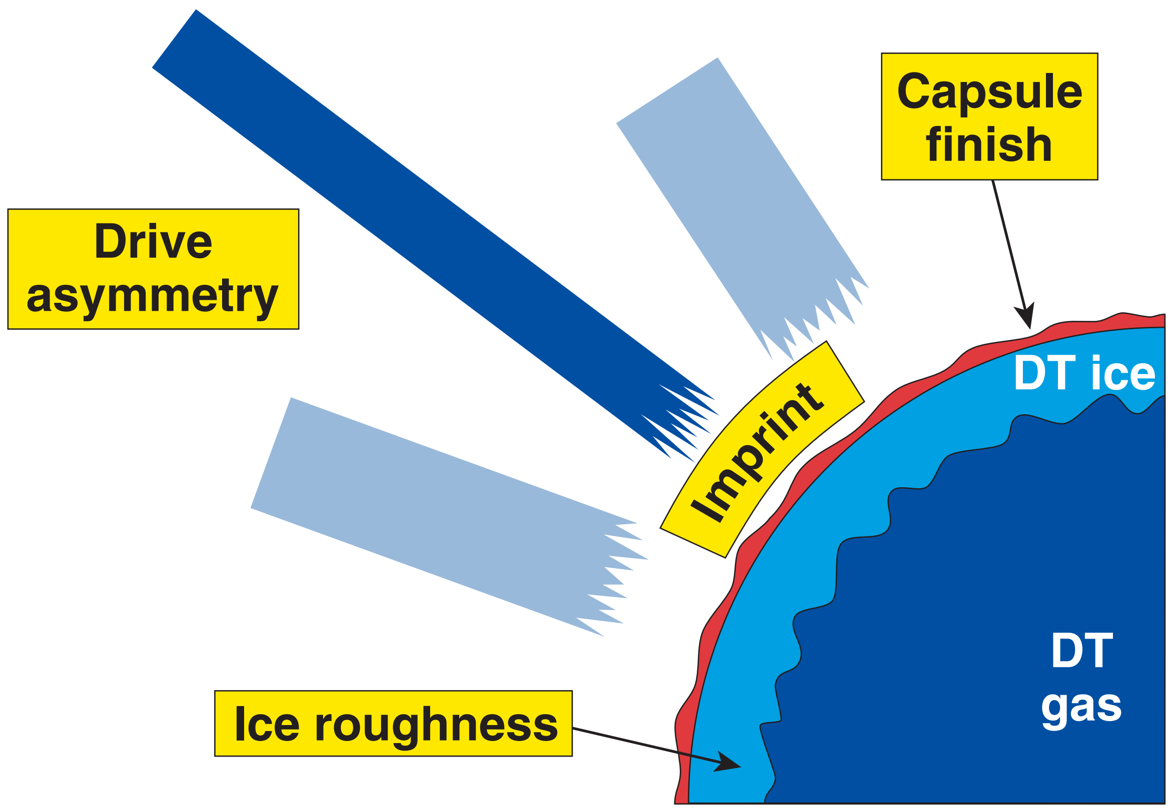


Adiabat shaping is achieved using a decaying-shock picket†

* M. Herrmann *et al*., Phys. Plasmas 8, 2296 (2001).
** R. Betti *et al*., Phys. Plasmas 9, 2277 (2000).
† M. Tabak, ICF Program Annual Report, LLNL (1989).

TC7452

A direct-drive capsule must tolerate several sources of nonuniformity to ignite and burn



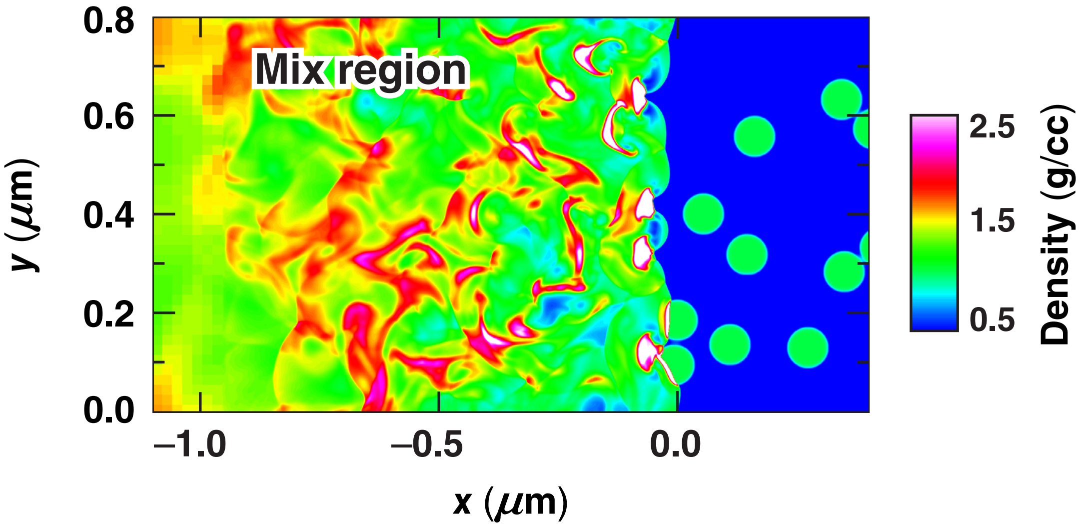
- Wetted-foam microstructure is a potential source of shock nonuniformity.

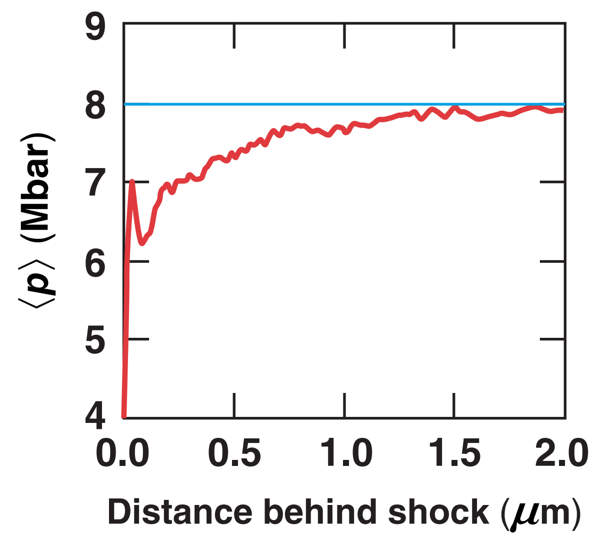
Nonuniformities: Microstructure

Foam microstructure is predicted to have minimal effect on target performance

UR LLE

- High-resolution adaptive-mesh-refinement hydro simulations of the wetted-foam microstructure were used to investigate shock propagation.*
- After initial undercompression,** the flow variables asymptote to the Rankine–Hugoniot values within a few percent.





- The fluctuation decay scale length is $\lesssim 2\ \mu$m.

This allows simulation of wetted-foam layers as a homogeneous mixture.

* T. J. B. Collins *et al.*, Phys. Plasmas, 12, 062705 (2005).
** G. Hazak *et al.*, Phys. Plasmas, 5, 4357 (1998).

TC7453

Power imbalance has little effect on target performance

UR LLE

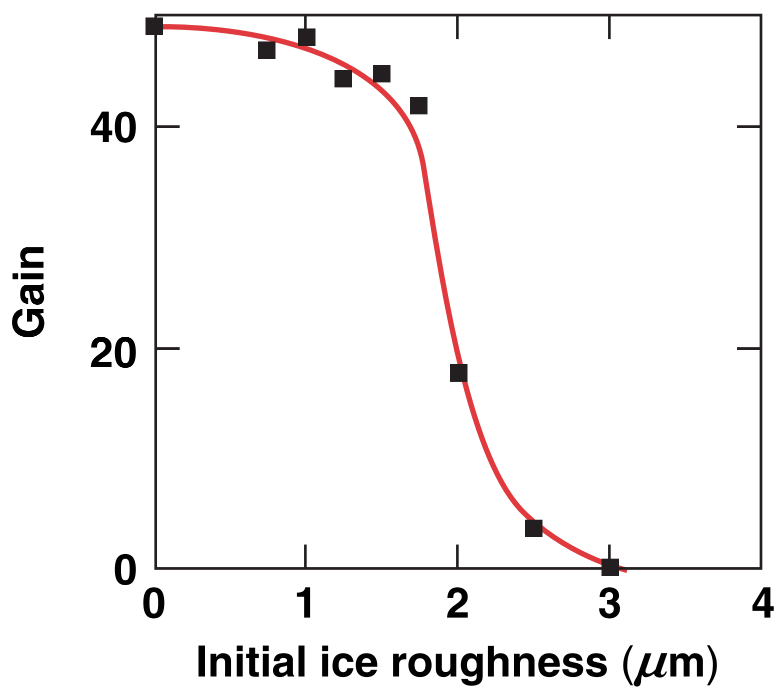
- The NIF beam-to-beam imbalance perturbation is 8% rms.
- Beam mistiming of the picket has been shown to have little effect on target performance.*
- The time-dependent illumination spectra taken from a series of power-imbalance histories** were simulated using modes $\ell = 2$ to 12.
- The average gain reduction due to these effects was ~6%.

* R. Epstein *et al.*, BAPS 50, 8114 (2005).
** O. S. Jones *et al.*, in *NIF Laser System Performance Ratings* (SPIE, Bellingham, WA, 1998), Vol. 3492, pp. 49–54.

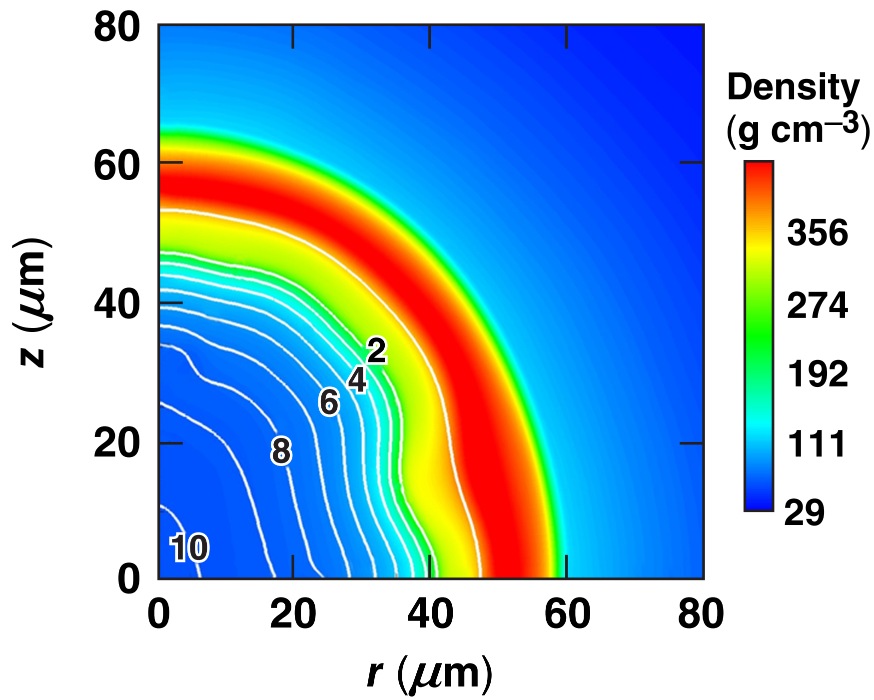
TC7454

The wetted-foam design can tolerate a 1.75-μm-rms initial ice roughness with little reduction in gain

- The ice-roughness spectrum is given by $A_\ell = A_0\,\ell^{-2}$, primarily in $\ell < 50$.



1.75-μm-rms ice roughness
(No other nonuniformities)



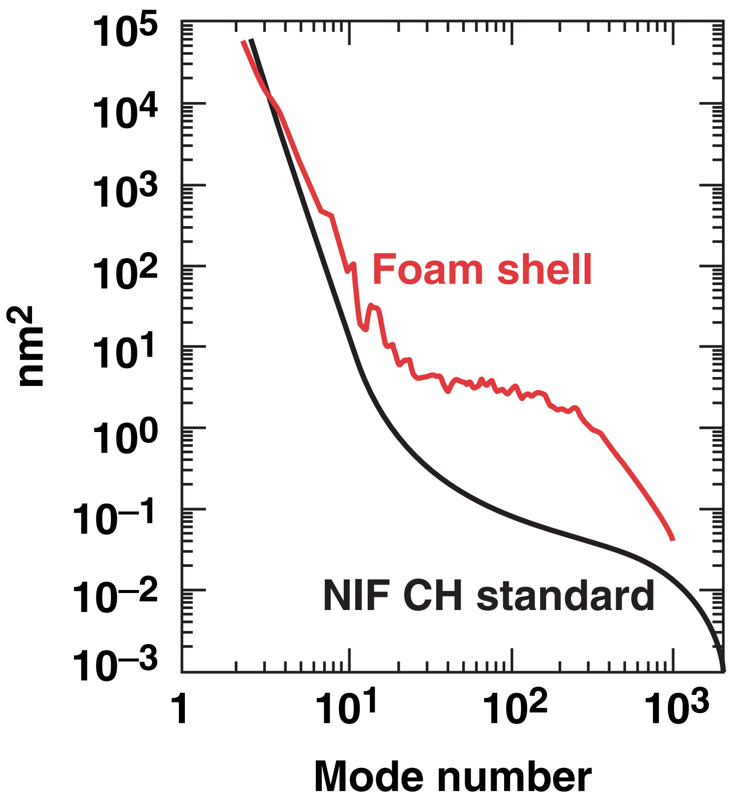
β-layered cryogenic all-DT target fabrication at LLE has achieved 1-μm ice roughness.*

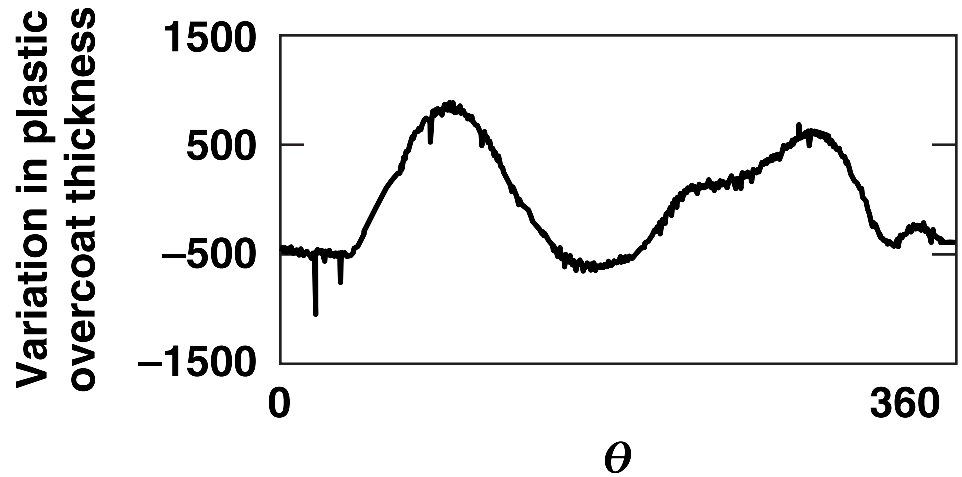
* Craig Sangster, QT1.00001.

Nonuniformities: Surface Roughness

Foam shells have been fabricated at General Atomics with outer-surface rms roughness as low as ~500 nm

- This spectrum also shows an ℓ^{-2} dependence.





Surface spectrum from the atomic-force microscope *Spheremapper* at General Atomics*

A 2-D simulation modeling this spectrum as ribbon modes showed negligible reduction in performance.

TC7456

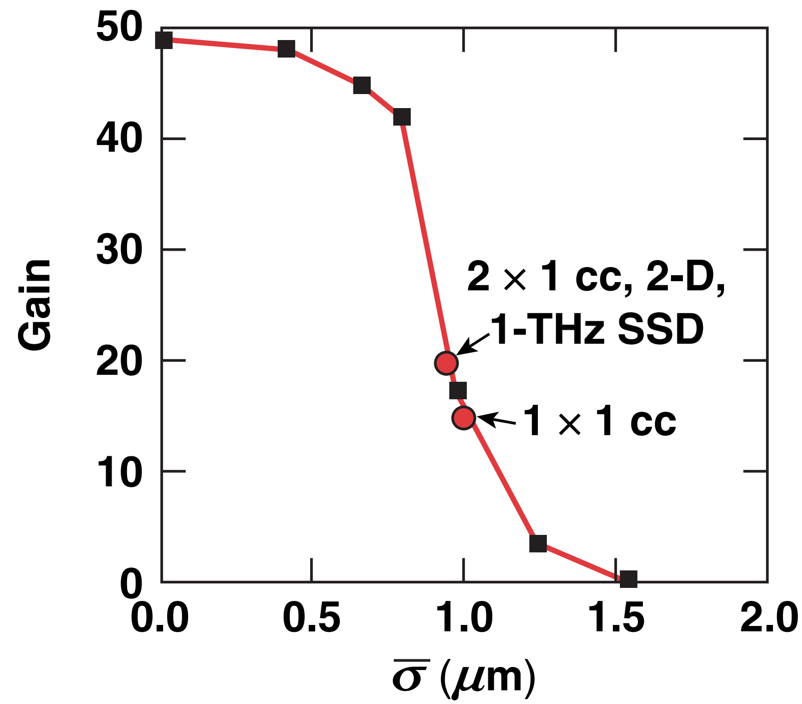
*Jared Hund, Abbas Nikroo, private communication (2006).

A weighted average $\overline{\sigma}$ of the ice nonuniformity at the end of acceleration is used to predict target performance

UR LLE

- Given the same initial amplitude, ice modes with $\ell > 10$ are more effective at reducing the hot-spot size and quenching burn.*
- A weighted average of the spectrum has been shown to map to target gain:**

$$\overline{\sigma}^2 = 0.06\,\sigma^2_{\ell < 10} + \sigma^2_{\ell > 9}$$



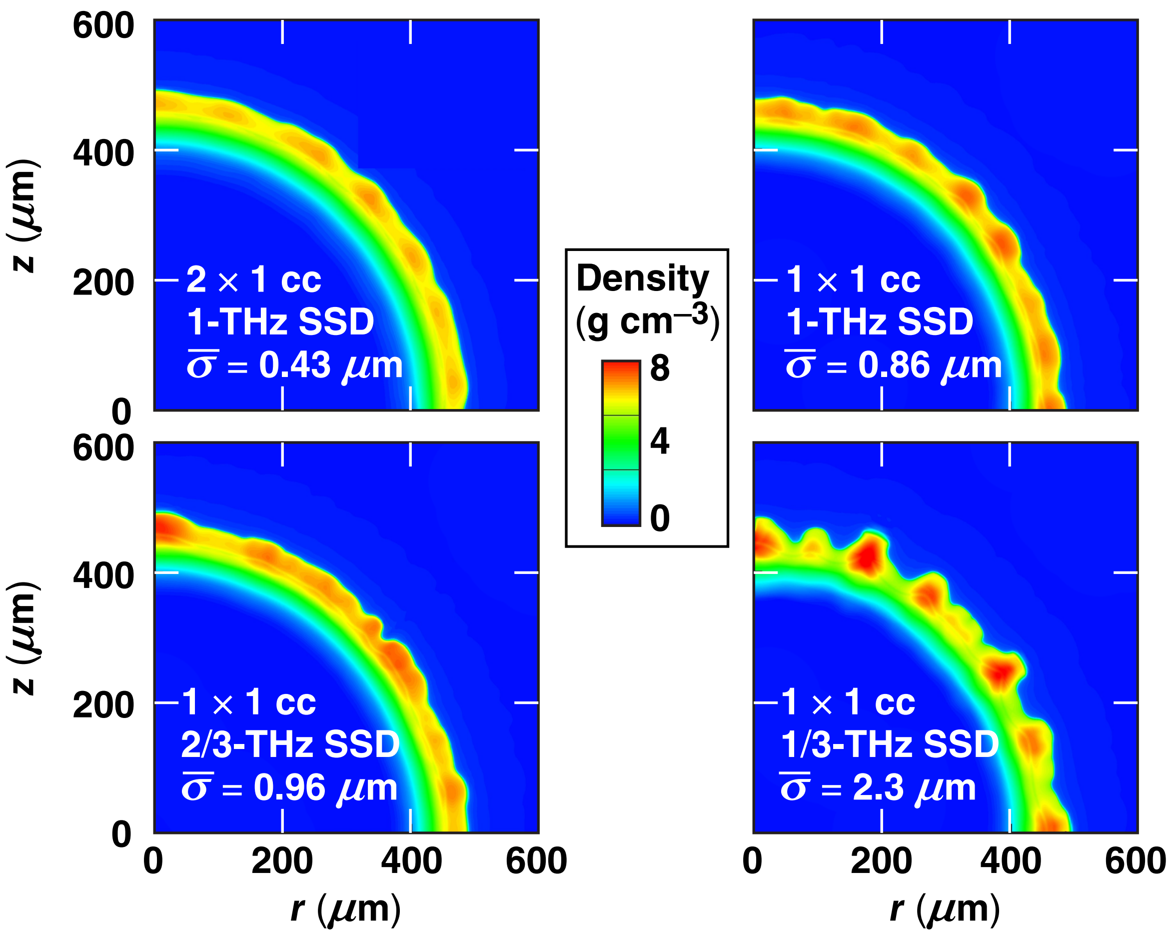
The target performance is estimated using the sum in quadrature of $\overline{\sigma}$ contributions from each source of nonuniformity.

*R. Kishony and D. Shvarts, Phys. Plasmas, 8, 4925 (2001).
** P. W. McKenty *et al.*, Phys. Plasmas, 8, 2315 (2001).

TC7457

The parameter $\overline{\sigma}$ increases rapidly as SSD smoothing is decreased

- Multimode simulations incorporating imprint modes $\ell = 2$ to 100 were simulated in 2-D with different levels of SSD.
- Modes $\ell > 100$ do not feed through effectively, contributing negligibly to the ice roughness at the end of the acceleration phase.



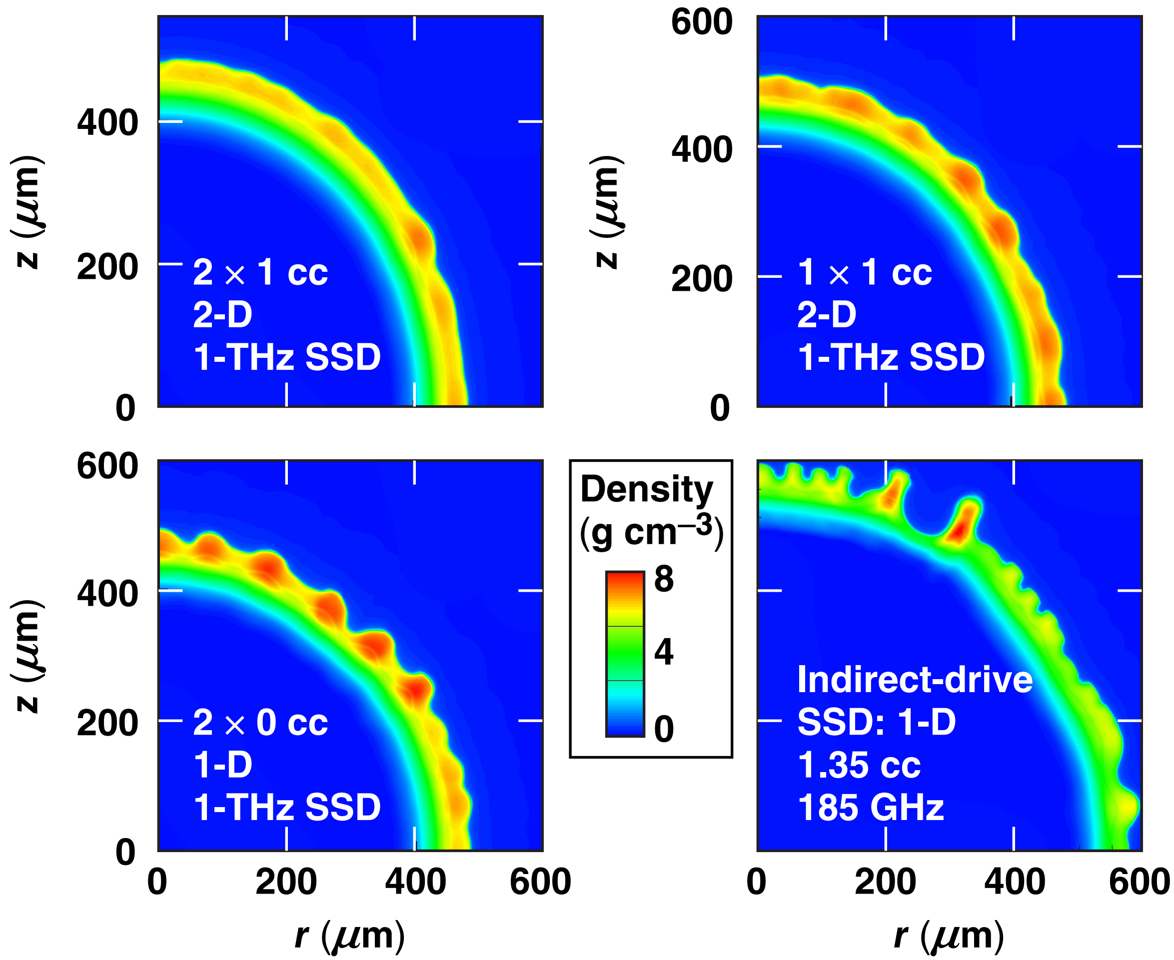
$\overline{\sigma}$ values for imprint alone are shown

2-D SSD appears to be required for target ignition

UR LLE

Sources of nonuniformity included 1-μm ice roughness, power imbalance, surface roughness, and imprint

		$\bar{\sigma}$ (μm)	Gain
2-D SSD	2 × 1 cc	0.94	21
	1 × 1 cc	1.00	16
1-D SSD	2 × 0 cc	2.0	0
	I.D. SSD	7.3	0

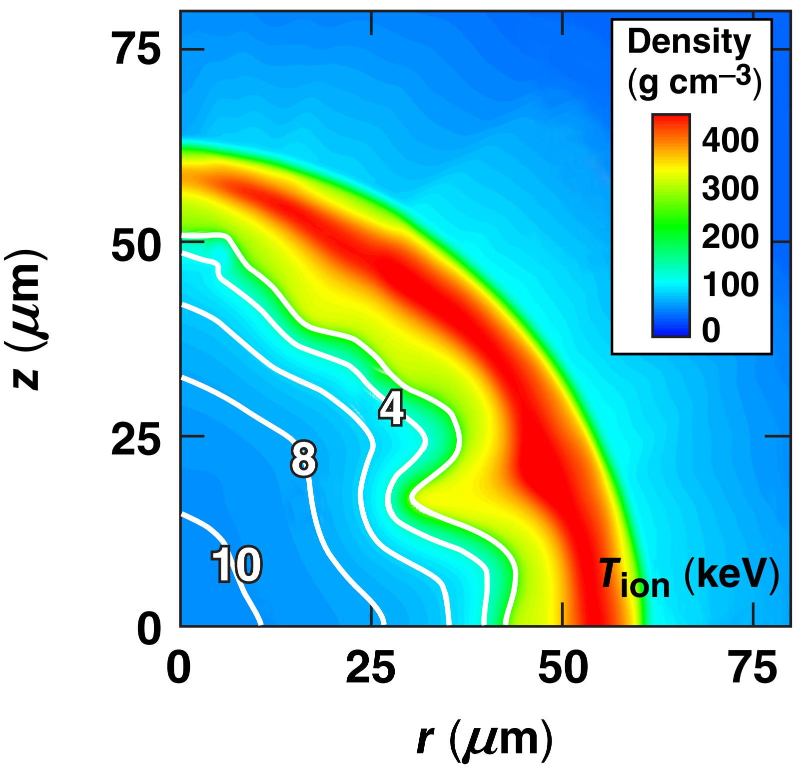


TC7459

A completed 2-D simulation with 2-D, 1-THz SSD produced a gain of 32

UR LLE

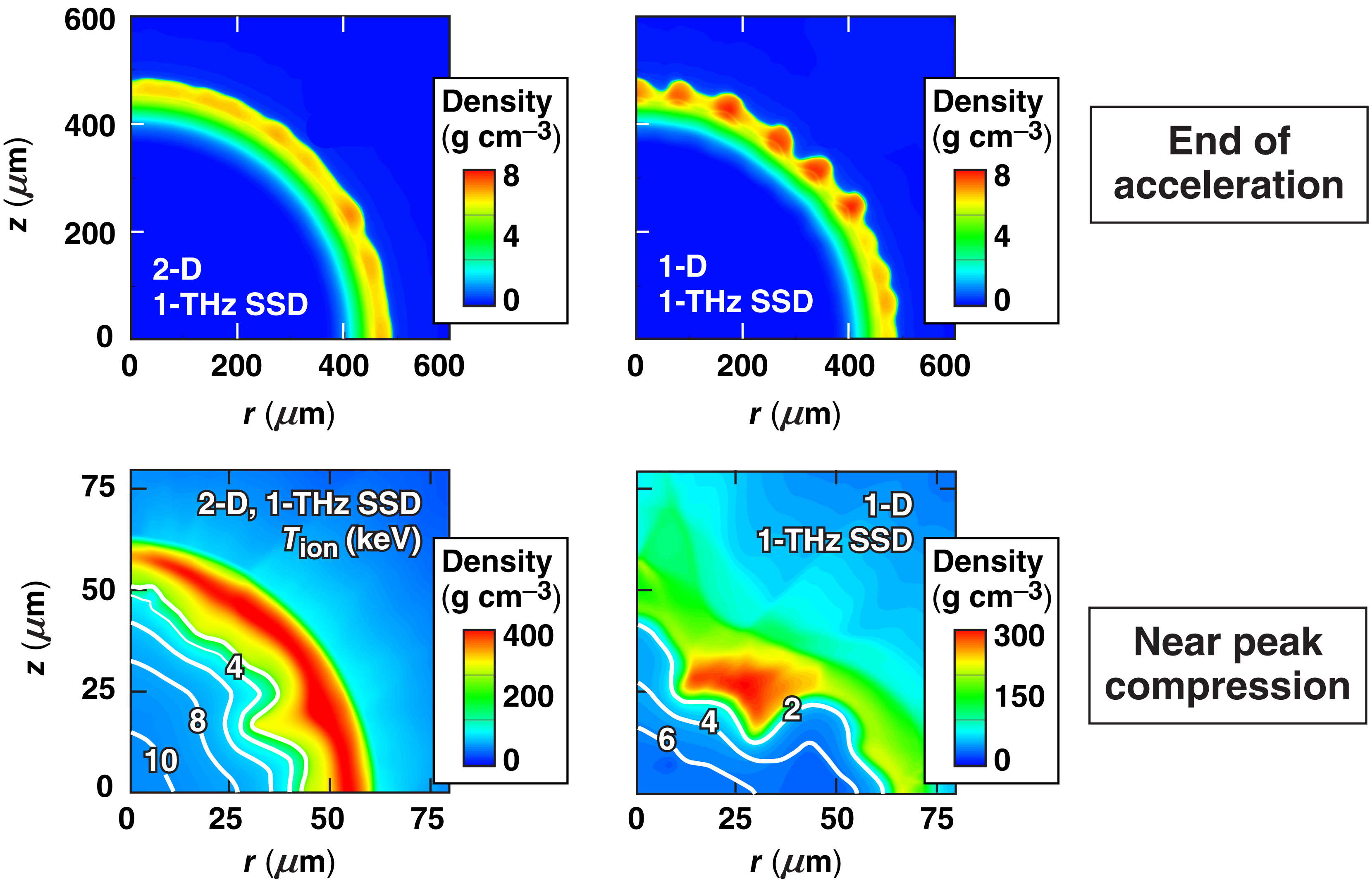
- Integrated simulations include imprint, power imbalance, foam-surface nonuniformity (370-nm rms), and 0.75-μm initial ice roughness.



Near peak compression

- $R_{hot\ spot}$ = 40 μm, neutron-averaged fuel areal density = 1.31 g cm^{-2}.

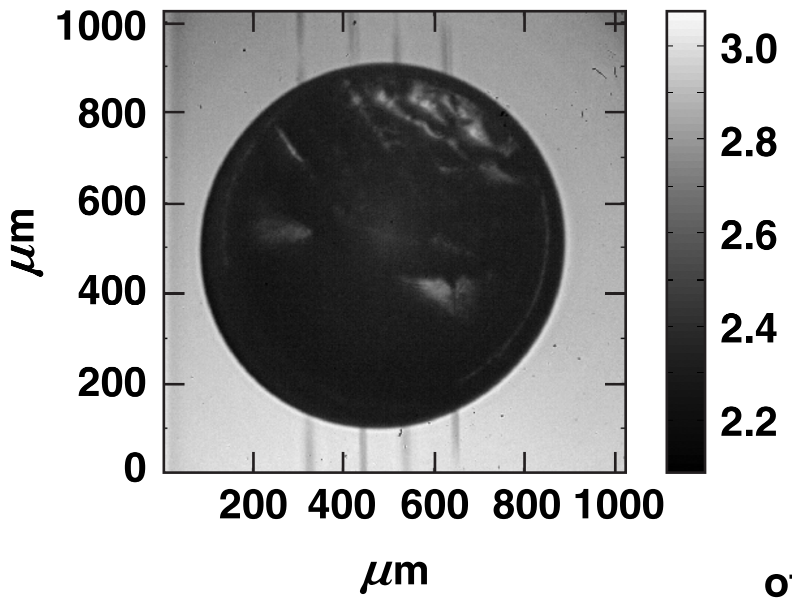
2-D SSD smoothing appears to be needed for ignition for the 1-MJ wetted-foam design



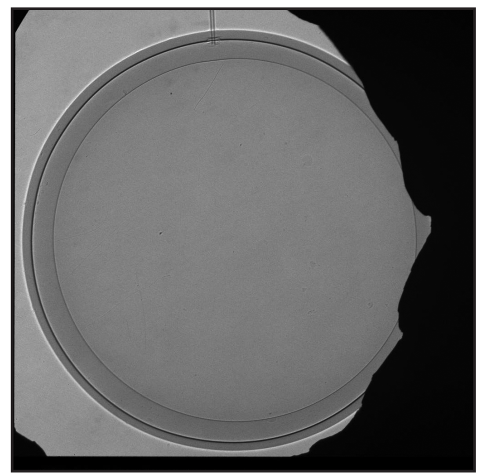
TC7645

Foam targets are produced by General Atomics and filled and diagnosed at LLE

- Ice roughness in cryogenic wetted-foam targets is currently diagnosed with limited sensitivity using optical shadowgraphy.
- With optical illumination it is difficult to distinguish the various interfaces and layers.
- X-ray phase-contrast imaging is being implemented at LLE, promising greater sensitivity.



Inner surface visible using optical Illumination

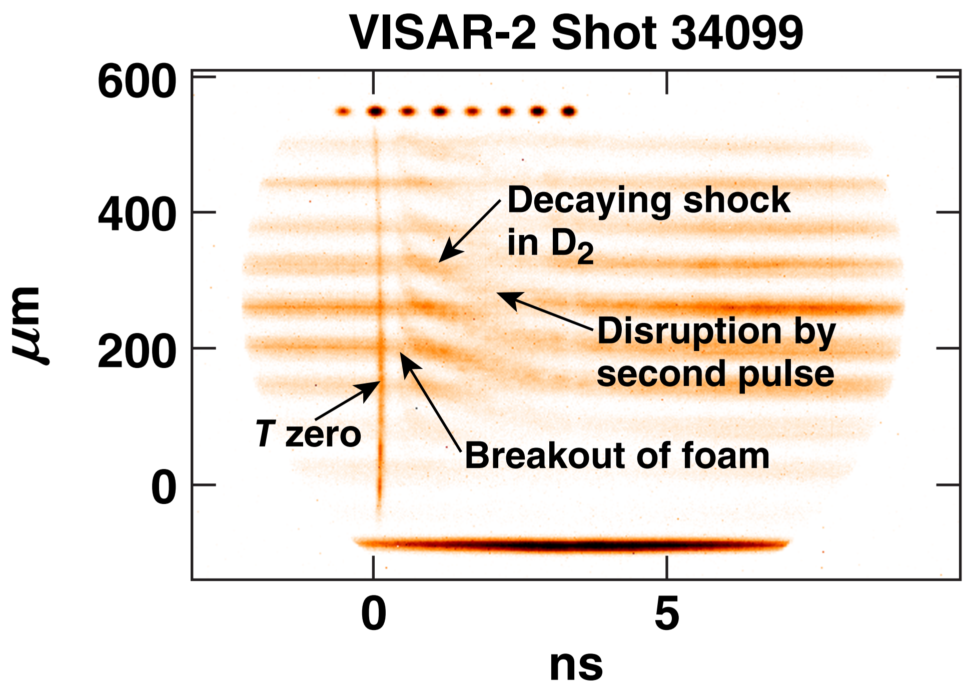


Phase-contrast image of a cryogenic DT-filled foam target*

*Bernard Kozioziemski, private communication (2006).

Both planar and spherical wetted-foam experiments are being planned at LLE

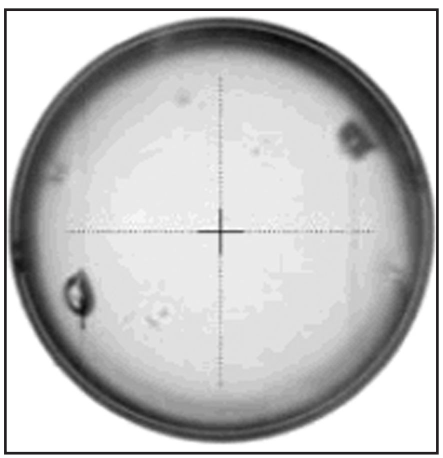
- VISAR has been used to diagnose shock speeds in planar experiments with foams wetted with liquid D_2, driven by two 100-ps pulses.



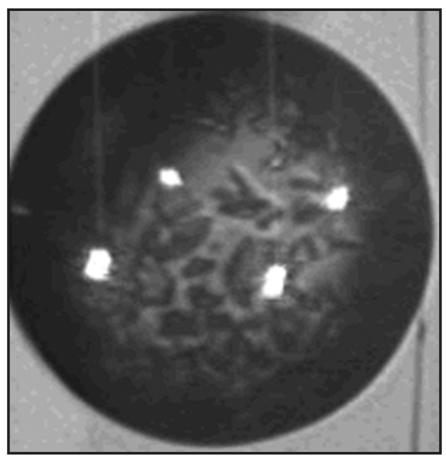
- Planar cryogenic experiments will address shock timing and coupling efficiency.
- Progress with β-layering of cryogenic DT targets at LLE gives confidence in high-quality wetted-foam layering.

A D_2-wetted-foam test implosion produced the highest cryogenic D_2 yield to date

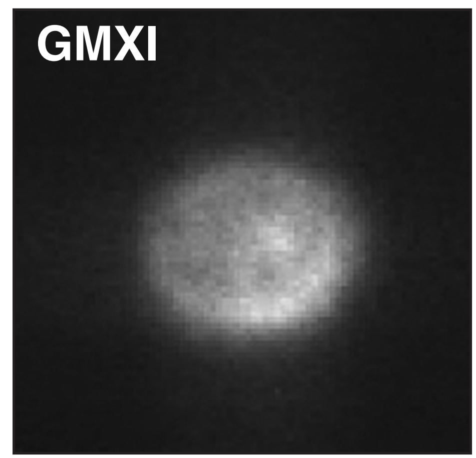
- **A high-adiabat pulse was used.**
- **The yield was $Y_{1n} = 1.7 \times 10^{11}$, 16% *greater* than the 1-D yield.**
- **The target was not well characterized, contributing to computational uncertainty.**
- **There remains much scope for experimental exploration.**



Unfilled foam capsule



Filled cryogenic capsule



X-ray image of the imploded core

TC7460

Summary/Conclusions

A 1-MJ wetted-foam target will ignite on the NIF with baseline direct-drive laser smoothing

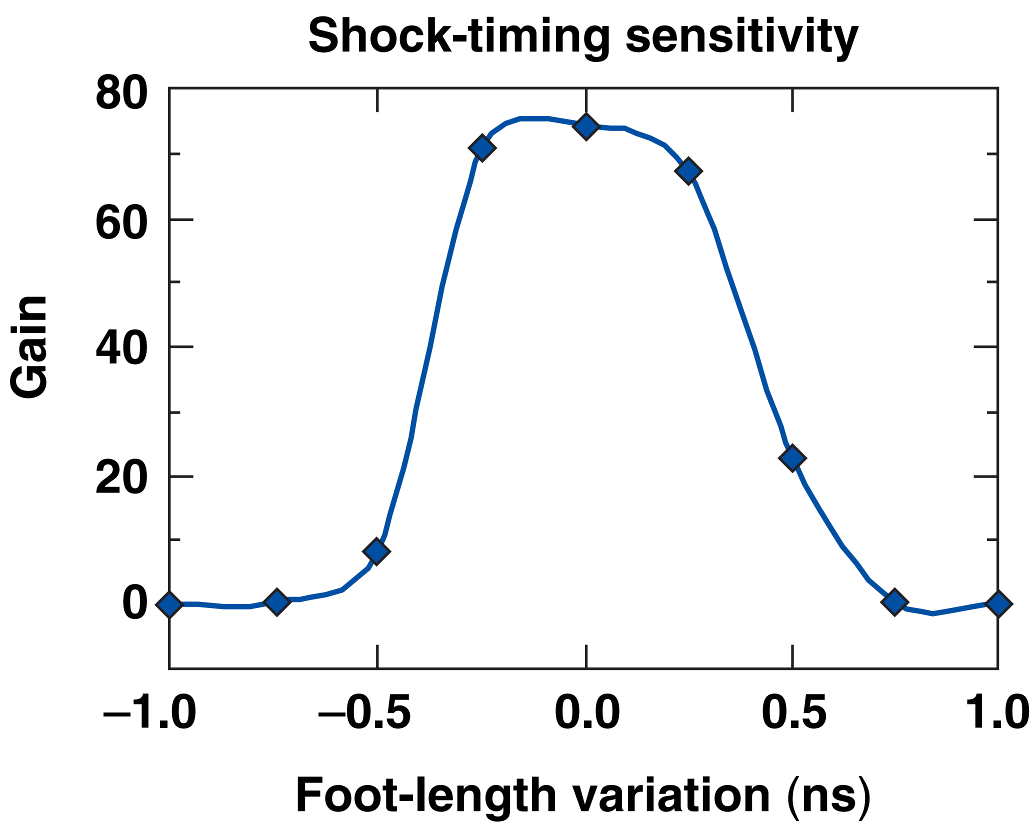
UR LLE

- A wetted-foam ablator provides greater laser coupling and better performance than the baseline direct-drive all-DT design.
- Low implosion velocity is used to minimize the effects of laser imprint.
- A nonuniformity budget analysis shows that the single-beam nonuniformity has the greatest effect on target performance.
- Simulations, including power imbalance, outer-surface and ice-surface roughness, and imprint show with 2-D, 1-THz SSD smoothing this target ignites and produces a gain of 32.
- Future plans include both planar and converging experiments with wetted foams on OMEGA.

This design is robust due to shock mistiming

UR LLE

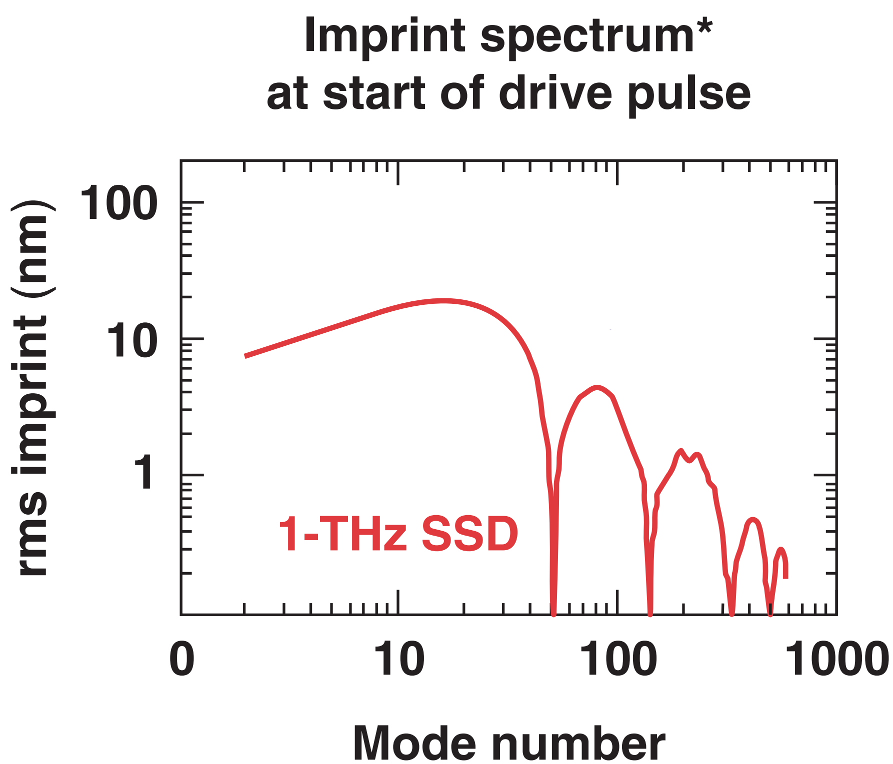
- Sensitivity to shock mistiming is determined in 1-D by varying the foot-pulse duration.
- This design can tolerate ±200 ps in shock-timing variation.

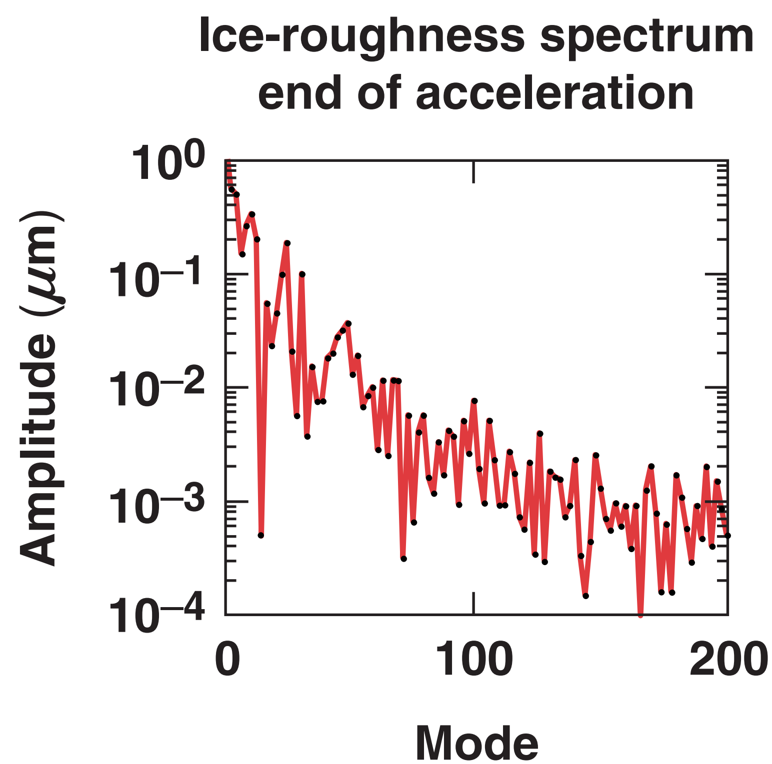


TC7464

Modes $\ell > 100$ contribute negligibly to the ice roughness at the end of acceleration

- Modes feed through to the inner surface, attenuated by $\exp(-k\Delta R)$.
- The resulting ice spectrum at the end of acceleration is dominated by modes $\ell < 100$, with over 99% of the rms due to these modes.





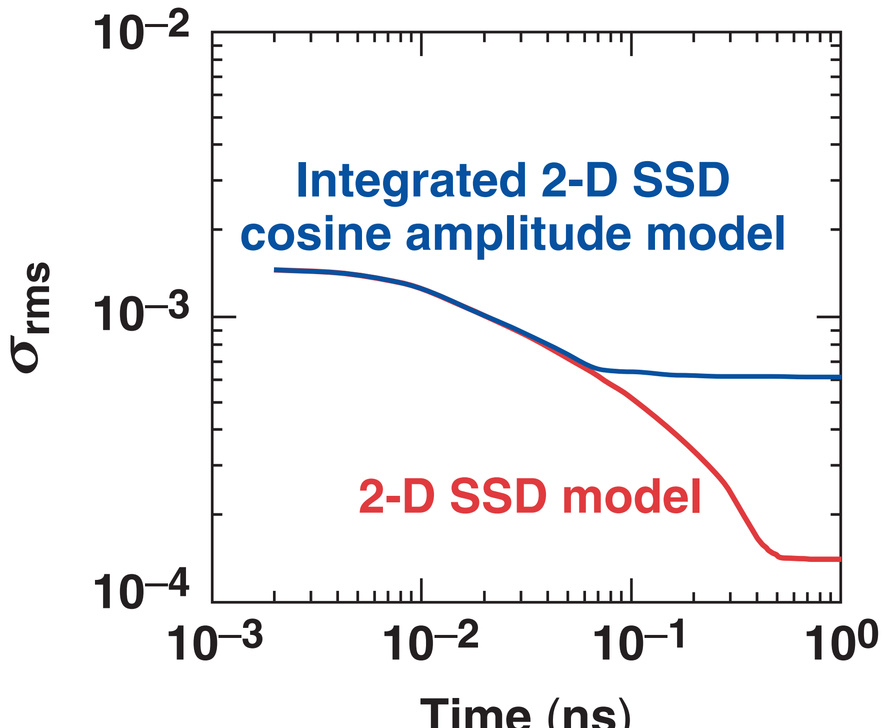
TC7465

*V. Goncharov *et al.*, Phys. Plasmas 7, 2962 (2000).

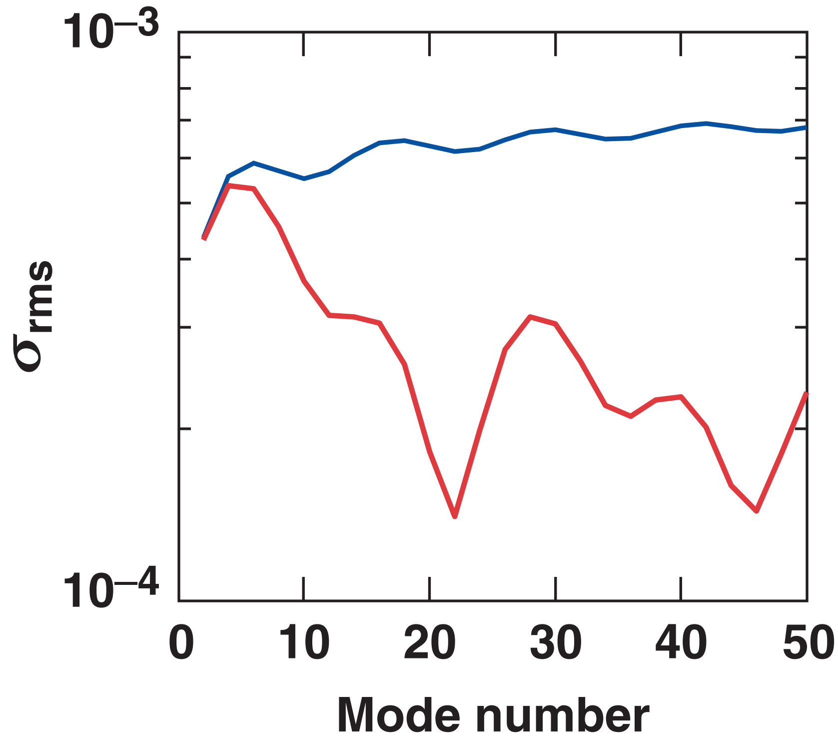
1-D SSD asymptotes much sooner than 2-D SSD

UR LLE

- SSD smoothes efficiently down to a mode number of $\ell_{min} = 2\pi R_0/(2F\Delta\theta) \sim 4$, where F is the focal length and $\Delta\theta^2 = \Delta\theta_1^2 + \Delta\theta_2^2$ is the effective far-field divergence.
- 1-D SSD smoothes at the same rate, but asymptotes much earlier than 2-D SSD.



Smoothing for $\ell = 22$



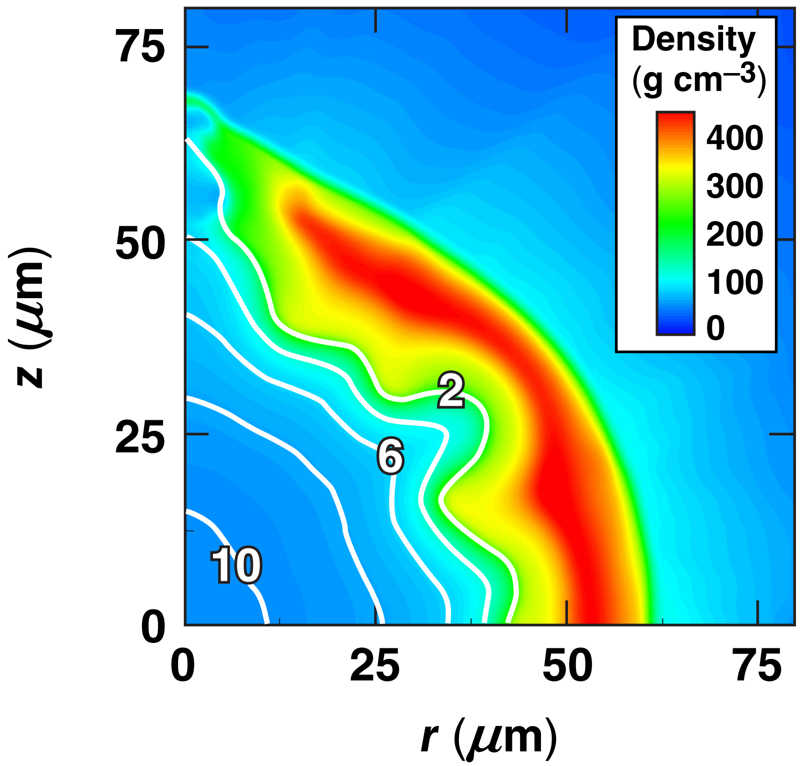
Smoothing for $\ell = 2$ to 50 at 1 ns

TC7646

A completed 2-D simulation with 2-D, 1-THz SSD, and an ice power-law index of 1 produced a gain of 27

UR LLE

- Integrated simulations include imprint, power imbalance, foam-surface nonuniformity (370-nm rms), and 1-μm initial ice roughness.
- An ice power-law index of $\beta = 1$ is used, determined experimentally from DT-ice layers at LLE.



Near peak compression

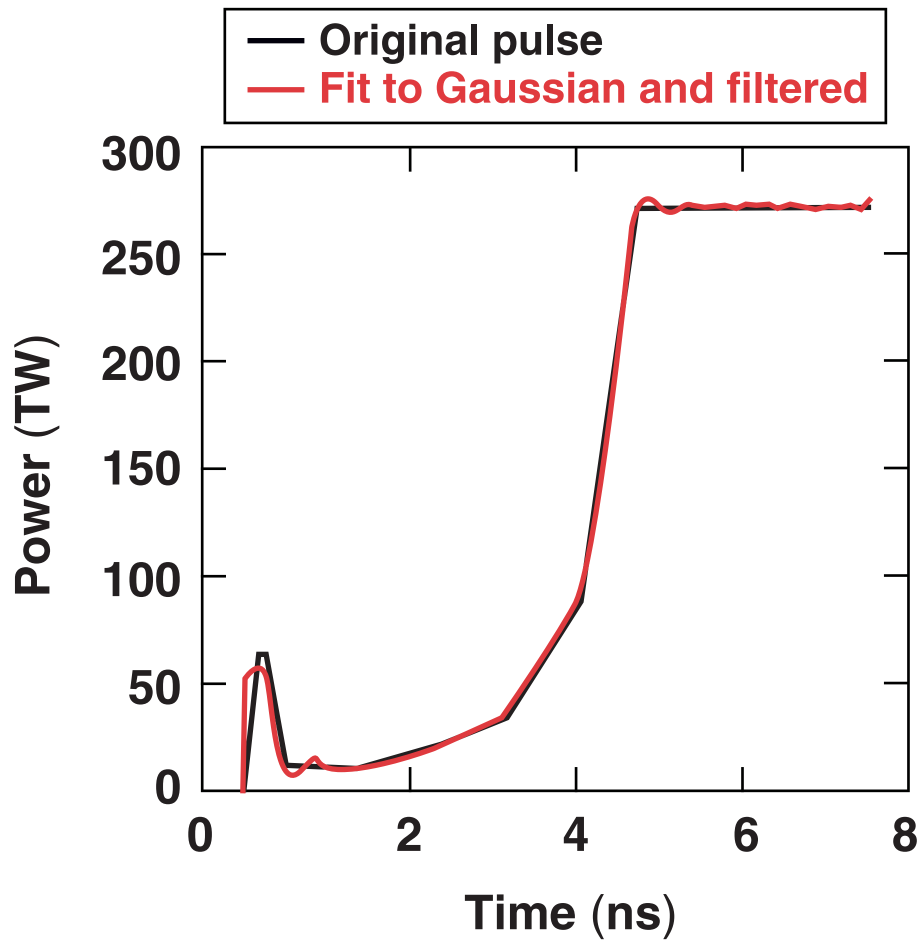
- $R_{hot\ spot}$ = ~35 μm, neutron-averaged fuel areal density = 1.32 g cm^{-2}.

TC7660

The pulse shape is within the limits of NIF pulse-shaping capabilities

UR LLE

- Pulses on the NIF are decomposed into a series of Gaussian impulses and filtered with a 1-GHz, low-pass filter.

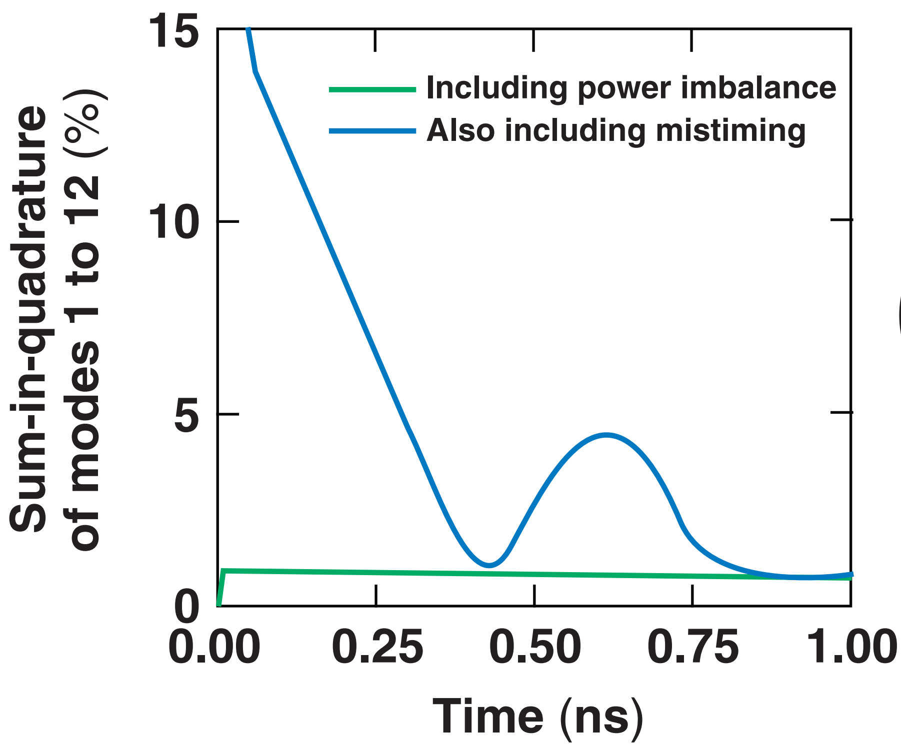


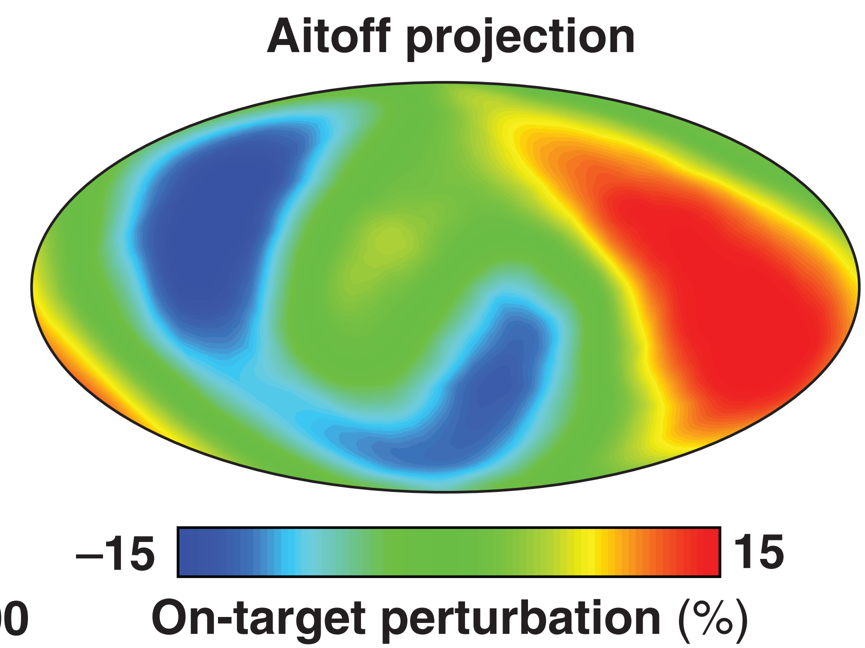
TC7466

Nonuniformities: Power Imbalance

Beam-to-beam imbalance imposes long-wavelength perturbations on the target

- Beam port locations contribute a perturbation of ~1% in ℓ = 6.
- Beam-to-beam imbalance is dominated by modes ℓ = 2 to 12, with an amplitude of ~1%.
- Beam mistiming contributes ~5 to 15% in modes ℓ = 1 to 3, primarily during the picket.





TC7158a