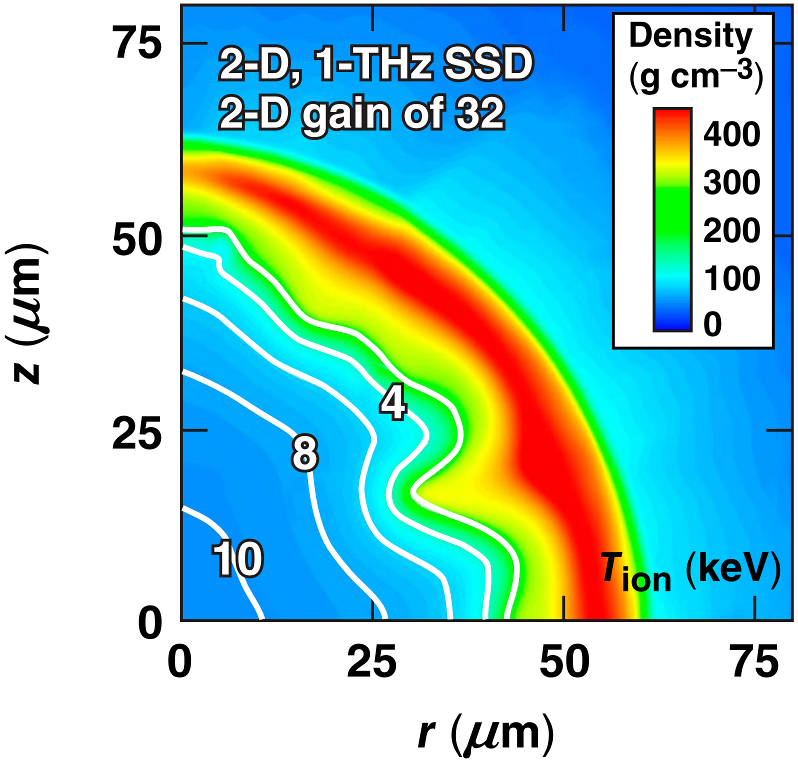
1-MJ, Wetted-Foam Target-Design Performance for the National Ignition Facility

Including imprint, power balance, surface, and ice roughness



Tim Collins

Research Review
16 February 2007

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.
- This design has been re-optimized using a downhill simplex method, achieving a 2-D gain of 60 with 2-D SSD and the same sources of nonuniformity
- A 1.5-MJ wetted-foam design achieves a gain of over 30 with 2-D SSD and fails with 1-D SSD.

Collaborators

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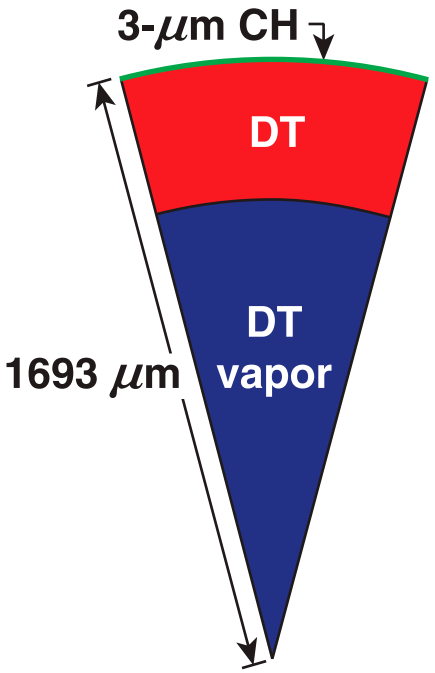
Outline

- Wetted foams and the 1-MJ design
- Sources of implosion nonuniformity
- Nonuniformity budget
- Integrated 1-MJ wetted-foam simulations
- Automatic target optimization
- 1.5-MJ wetted-foam design
- Experimental plans

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



All-DT

$\langle\alpha\rangle = 4.2$

$\alpha = P/P_{\mathrm{Fermi}}$

- 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

P. W. McKenty *et al*., Phys. Plasmas 8, 2315 (2001).

*V. N. Goncharov *et al*., Phys. Plasmas 10, 1906 (2003).

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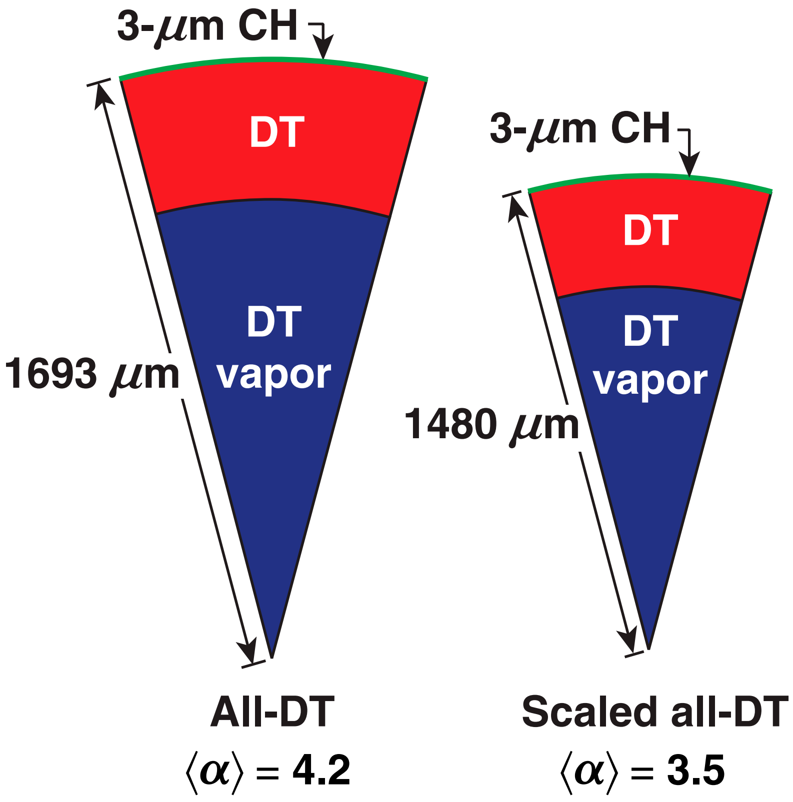
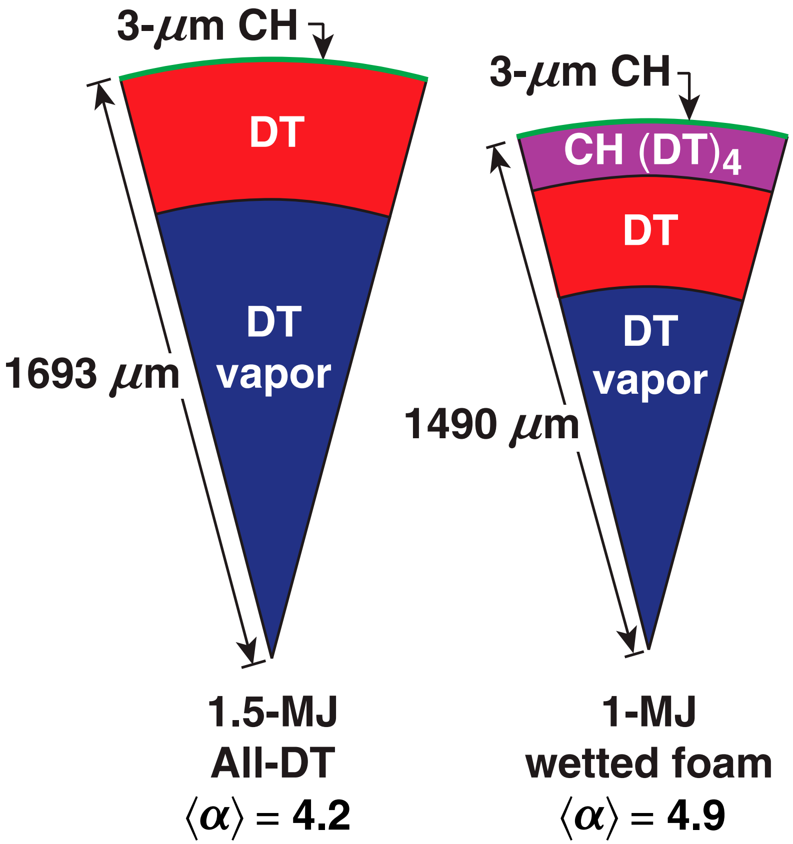
The 1.5-MJ all-DT design has been scaled to 1 MJ, resulting in lower gain and stability



	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 design

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.

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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.

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*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

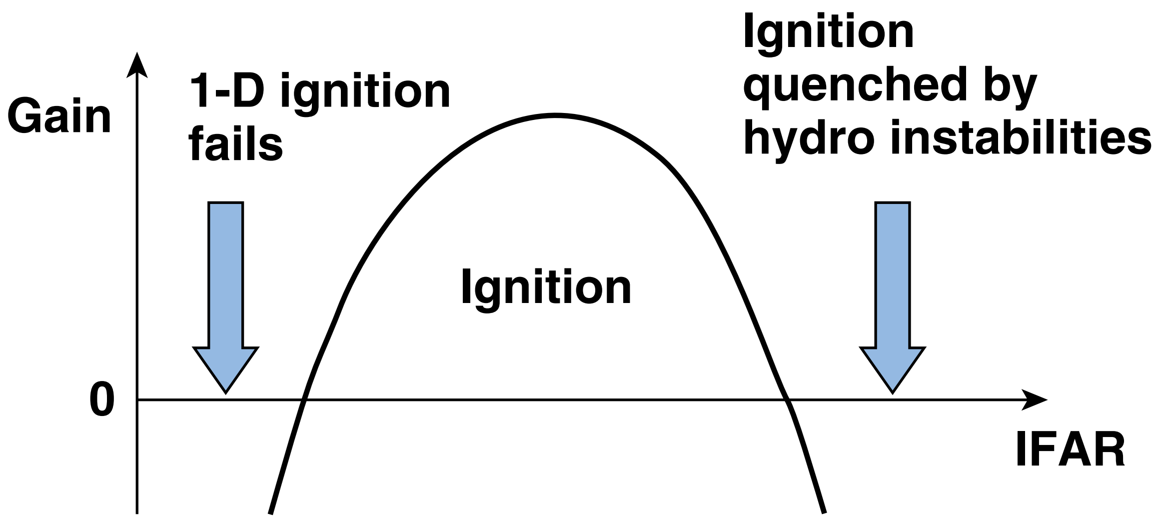
- This improvement comes at the expense of margin, but with improved areal density.

- 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.

Conventional ICF must operate within an IFAR window

- If the IFAR is too high, ignition is quenched by hydrodynamic instabilities.
- If the IFAR is too low, the resulting low implosion velocity results in too low a hot-spot temperature:
- The minimum energy for ignition scales as $E \sim (\mathrm{IFAR})^{-3*}$



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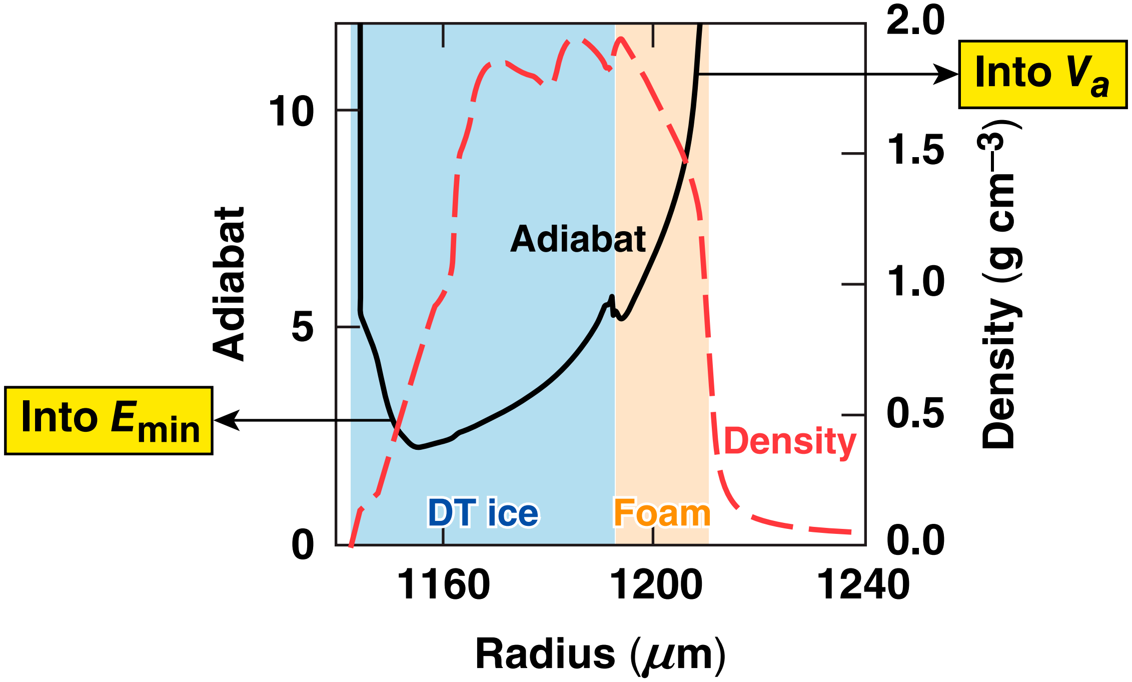
*R. Betti, *et al*., Plas. Phys. and Cont. Fusion, 48 (2006).

Shell stability and compressibility depend on the adiabat

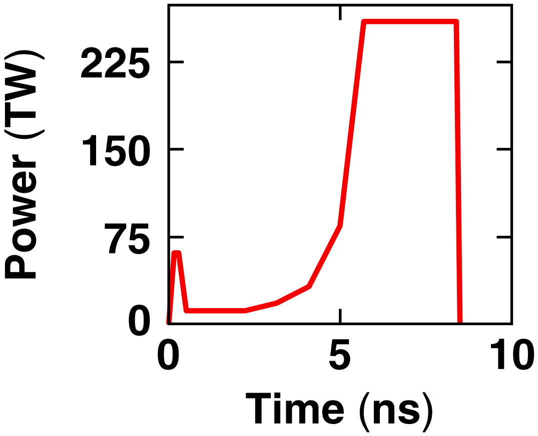
- Minimum energy required for ignition:[*,**] $E_{\mathrm{min}} \sim \alpha^{1.88}$
- Rayleigh–Taylor instability growth rate: $\gamma = \alpha_{\mathrm{RT}}\,(kg)^{1/2} - \beta_{\mathrm{RT}}\,kV_{\mathrm{a}},\ V_{\mathrm{a}} \sim \alpha^{3/5}$

Shock breakout



Into V_a

Into E_{min}



Adiabat shaping is achieved using a decaying-shock picket[†]

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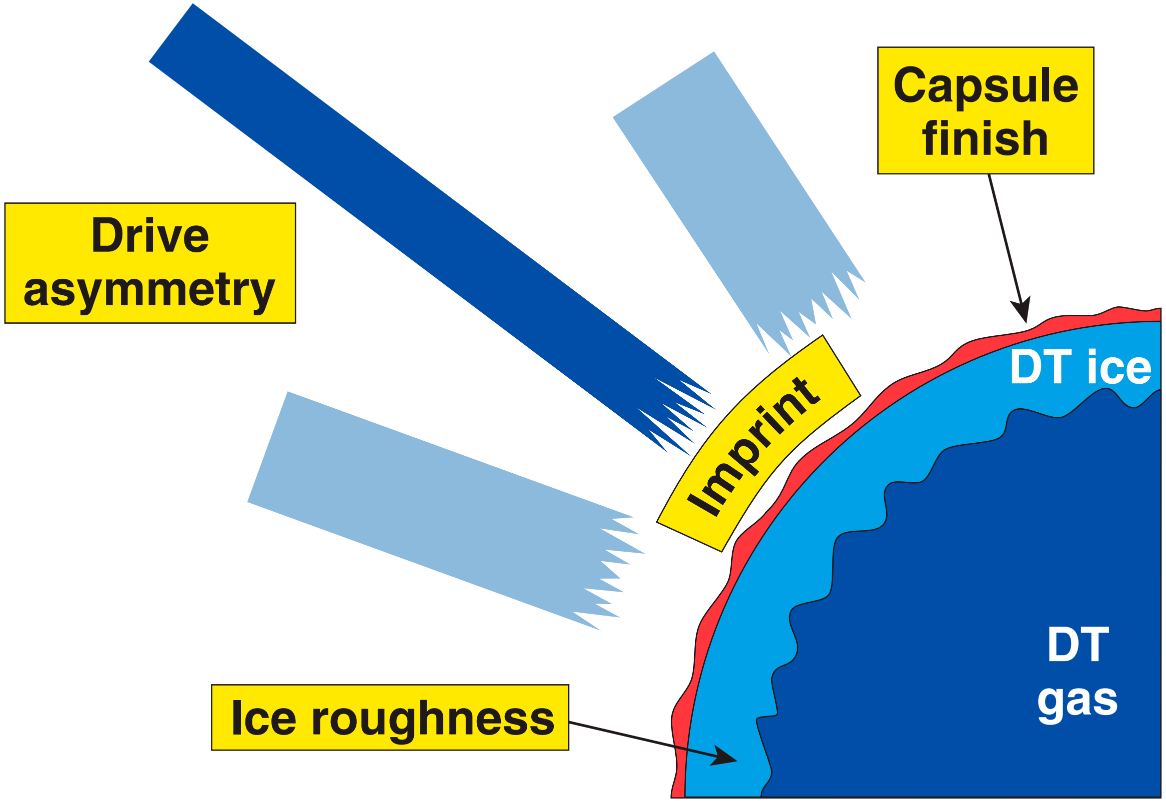
[*] M. Herrmann *et al.*, Phys. Plasmas 8, 2296 (2001).

[**] R. Betti *et al.*, Phys. Plasmas 9, 2277 (2000).

Implosion Nonuniformities

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

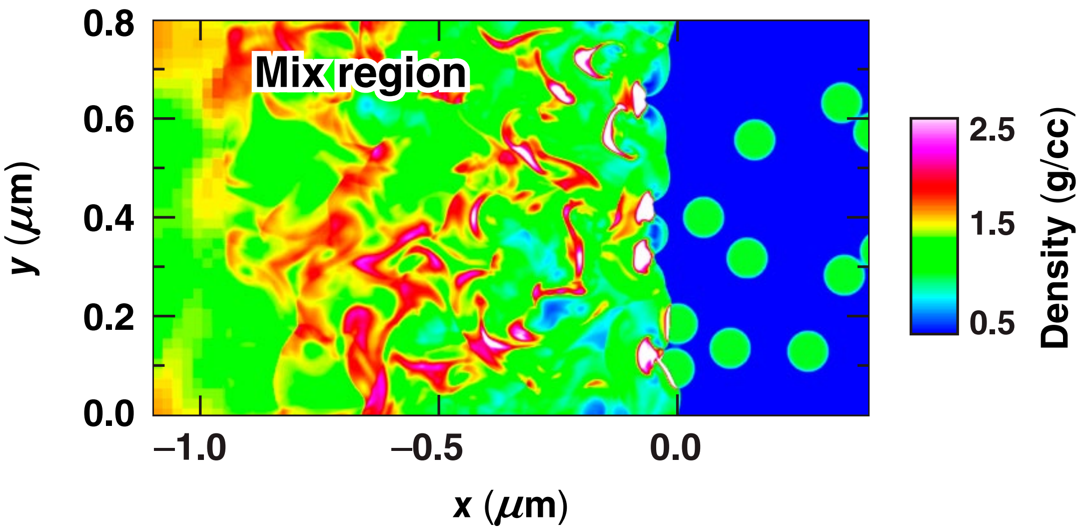


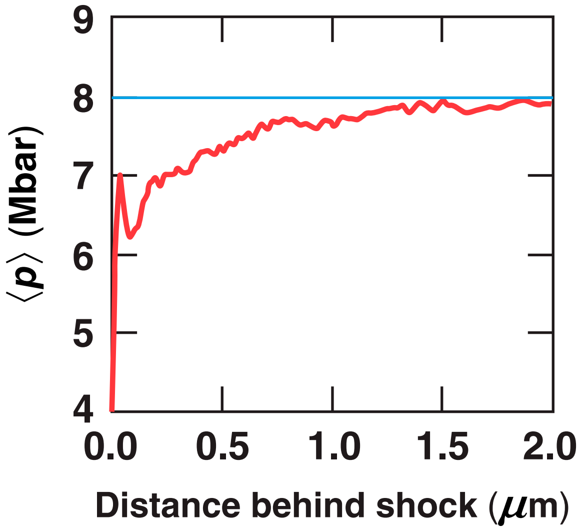
- Wetted-foam microstructure is a potential source of shock nonuniformity.

Nonuniformities: Microstructure

Foam microstructure is predicted to have minimal effect on target performance

- 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.

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* T. J. B. Collins *et al*., Phys. Plasmas, 12, 062705 (2005).

** G. Hazak *et al*., Phys. Plasmas, 5, 4357 (1998).

Power imbalance has little effect on target performance

- **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%.**

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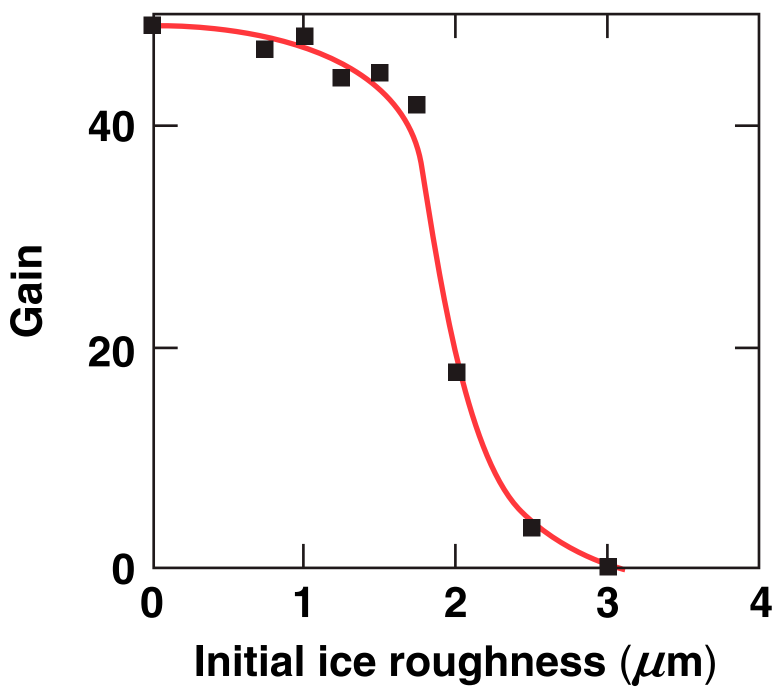
* R. Epstein *et al*., BAPS 50, 8114 (2005).

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

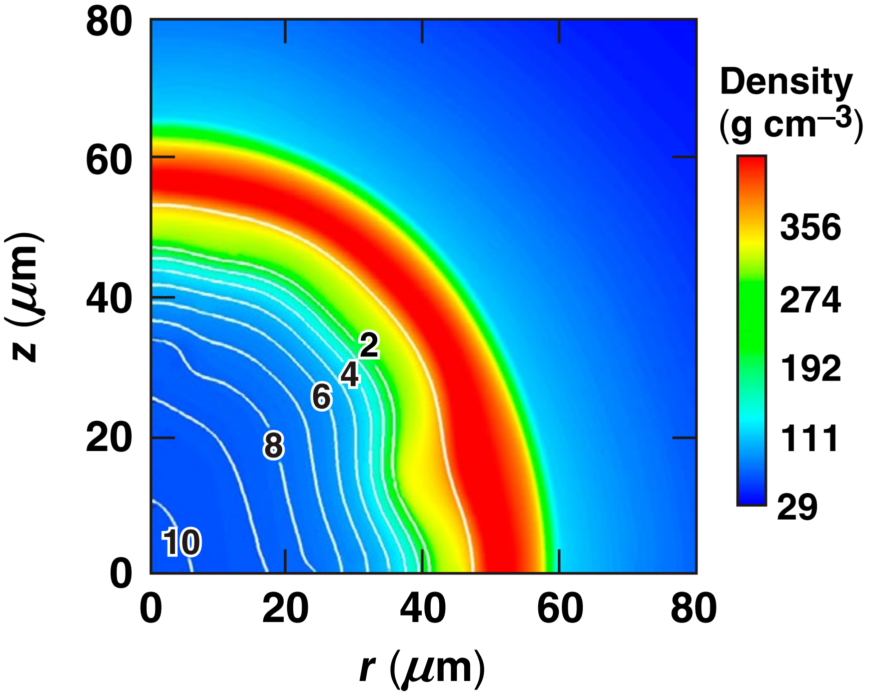
Nonuniformities: Ice Roughness

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.*

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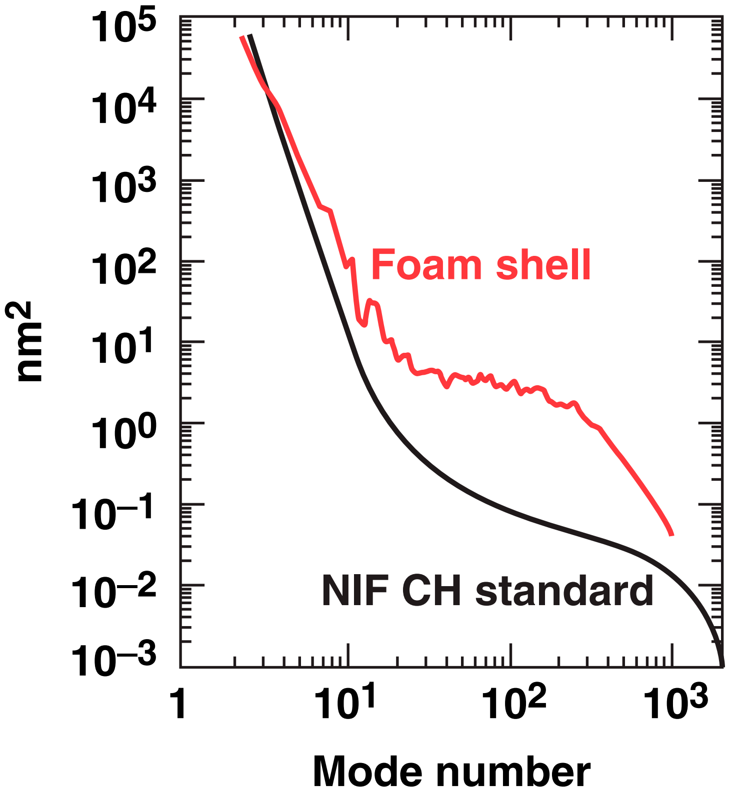
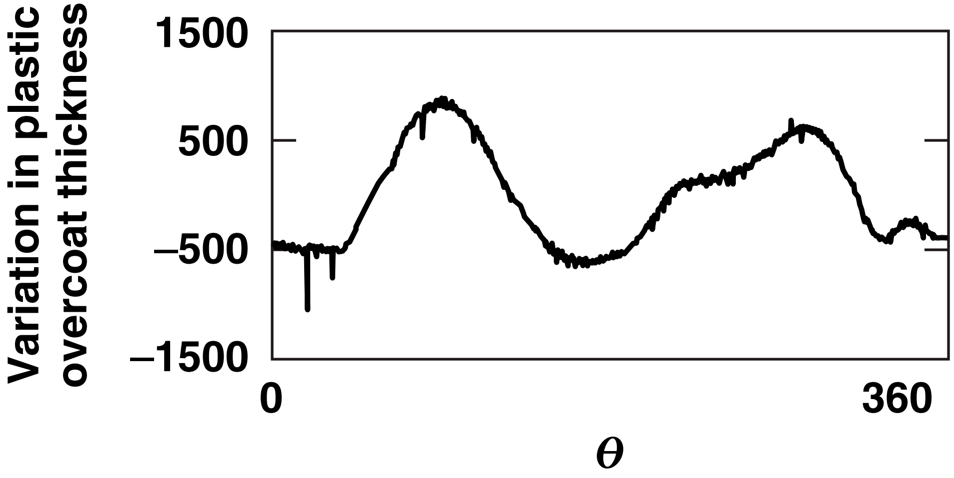
* Craig Sangster, QT1.00001.

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.

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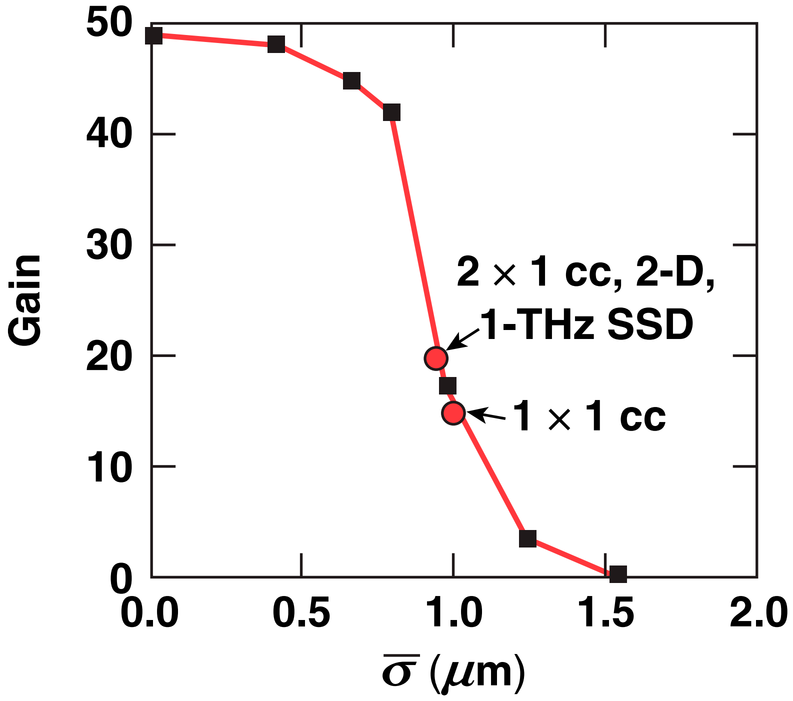
*Jared Hund, Abbas Nikroo, private communication (2006).

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

- 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.



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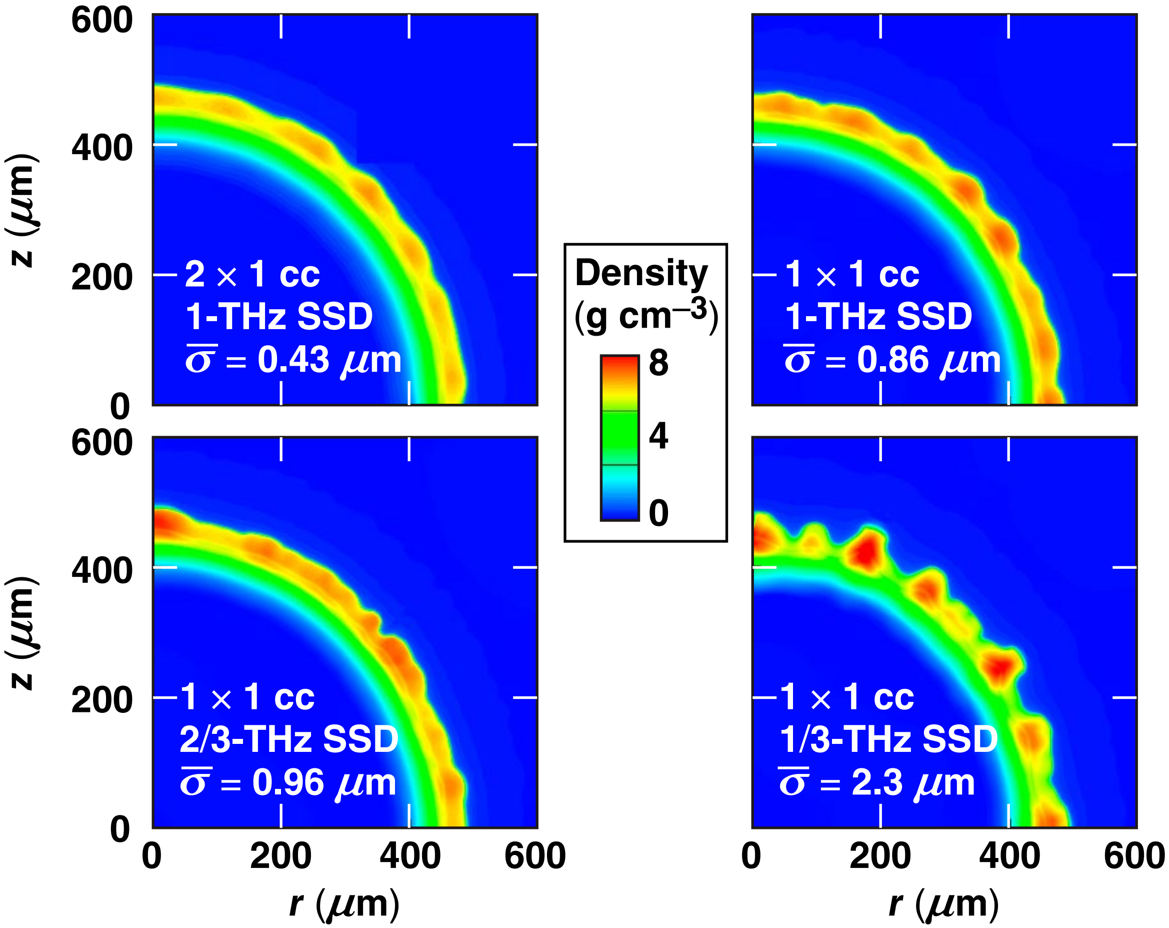
*R. Kishony and D. Shvarts, Phys. Plasmas, 8, 4925 (2001).

** P. W. McKenty *et al*., Phys. Plasmas, 8, 2315 (2001).

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.

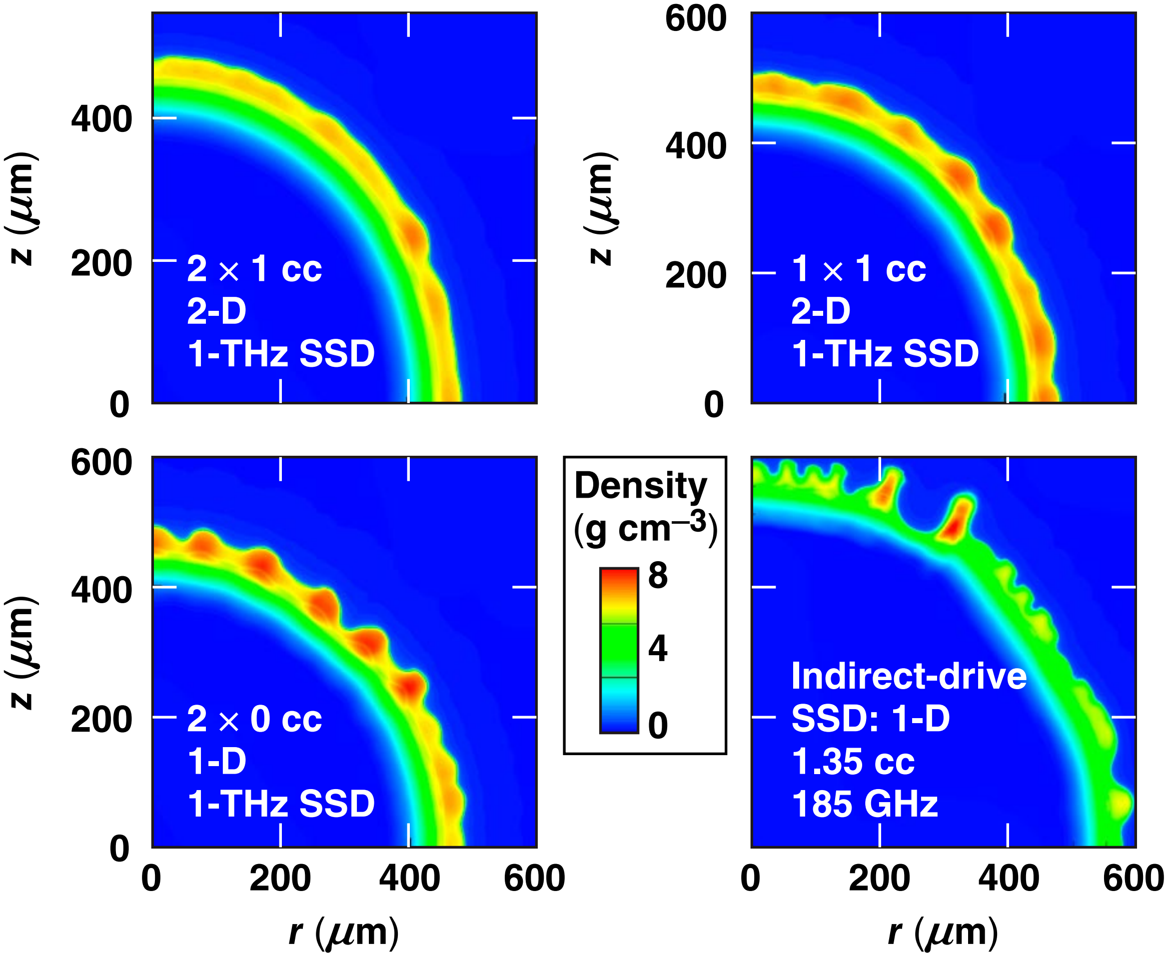


$\overline{\sigma}$ values for imprint alone are shown

2-D SSD appears to be required for target ignition

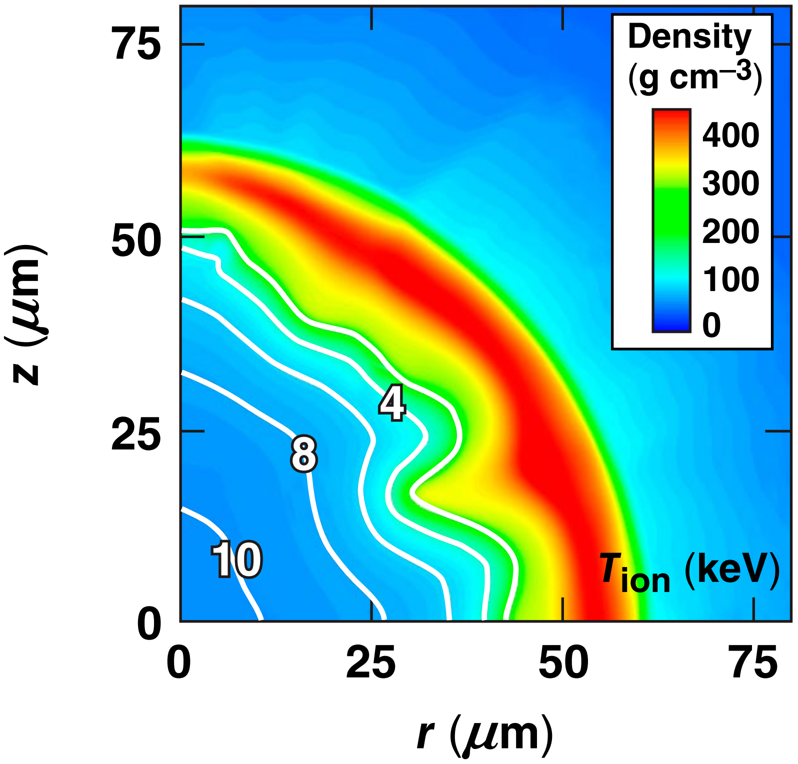
Sources of nonuniformity included 1-μm ice roughness, power imbalance, surface roughness, and imprint

		$\overline{\sigma}$ (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



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

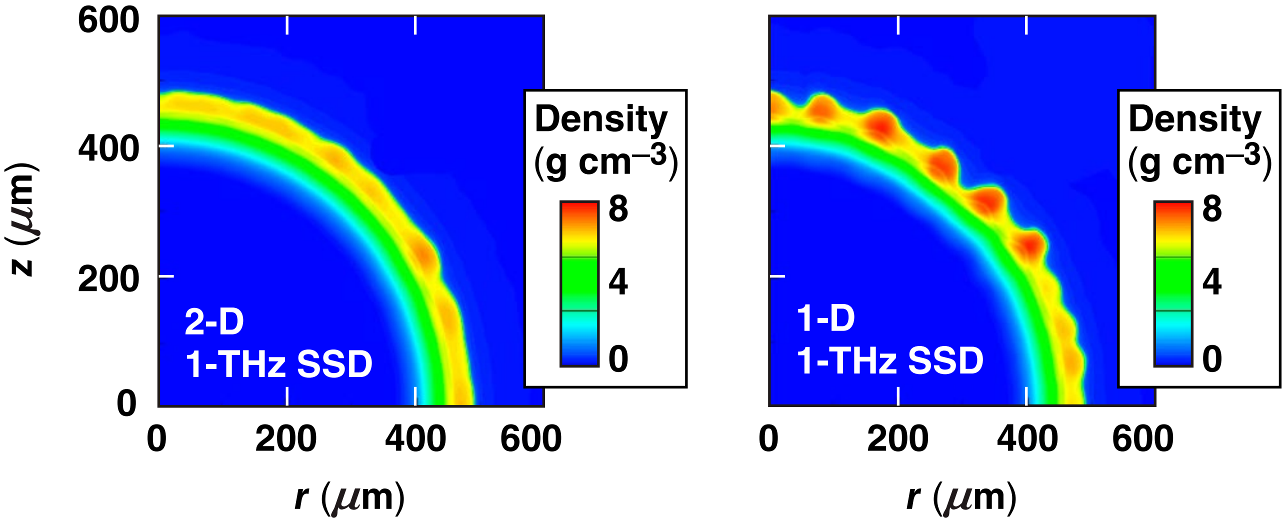
- Integrated simulations include imprint, power imbalance, foam-surface nonuniformity (370-nm rms), and 0.75-μm initial ice roughness.



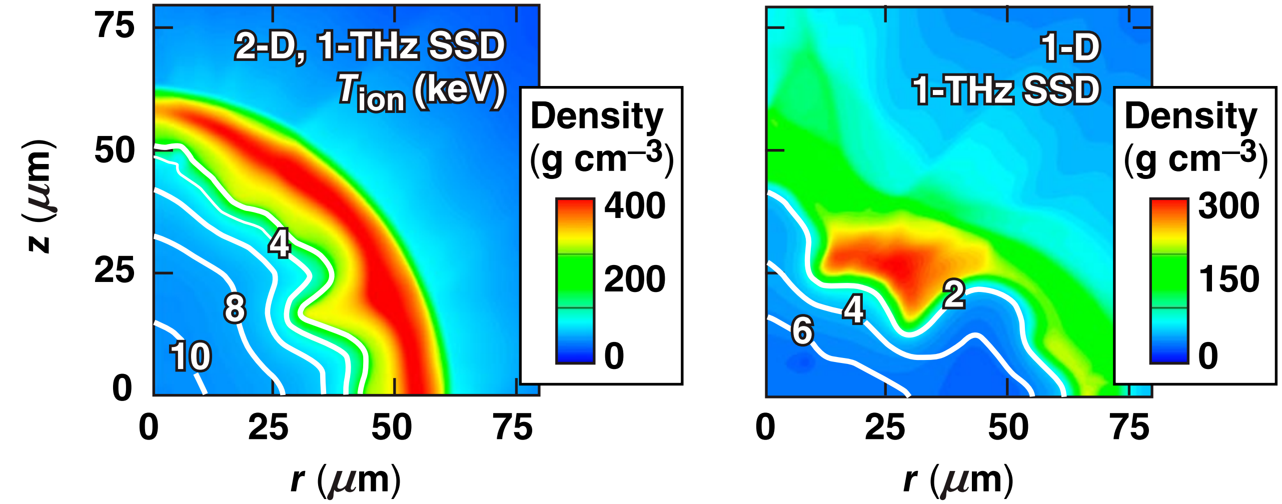
Near peak compression

- $R_{\text{hot spot}}$ = 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



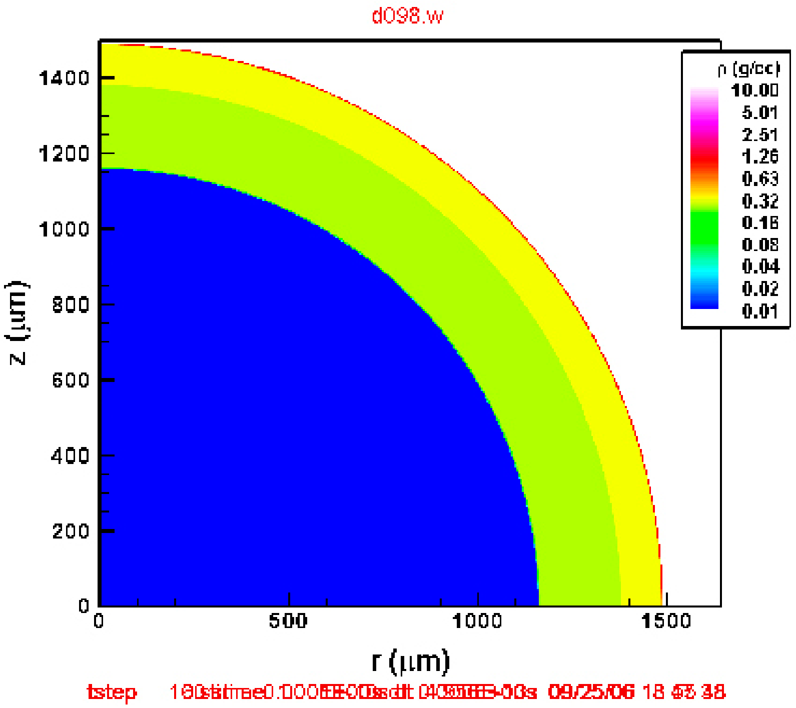
End of acceleration



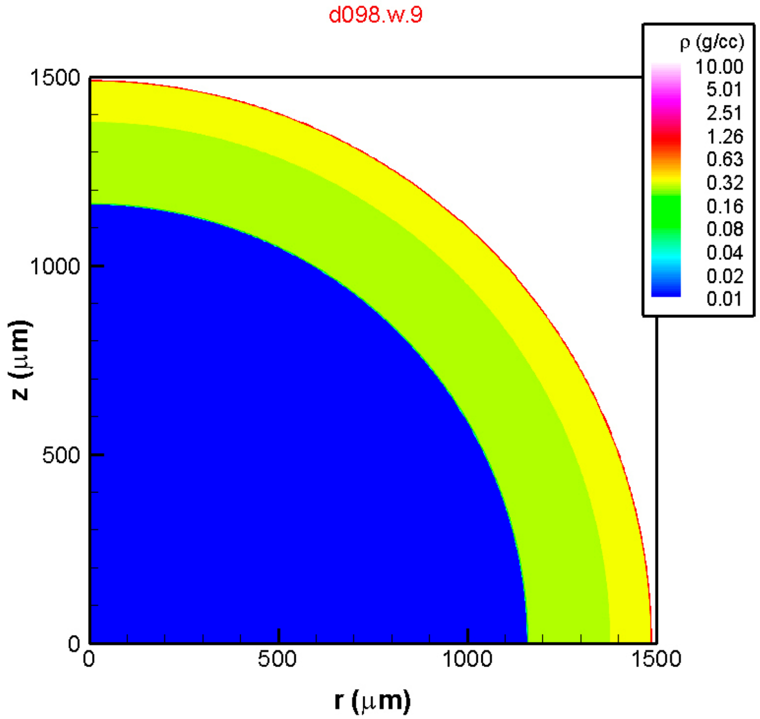
Near peak compression

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

Acceleration phase



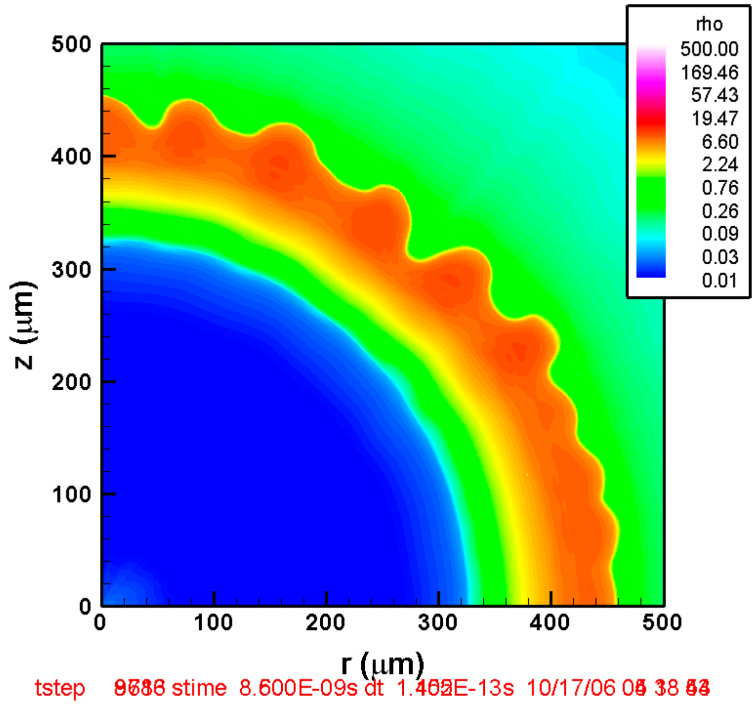
1-D 1-THz SSD



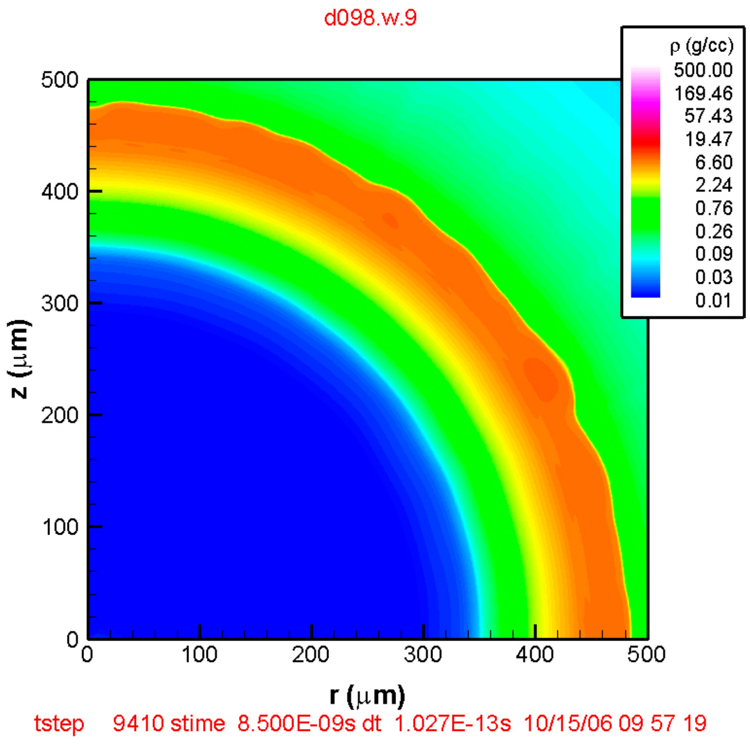
2-D 1-THz SSD

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

Deceleration phase



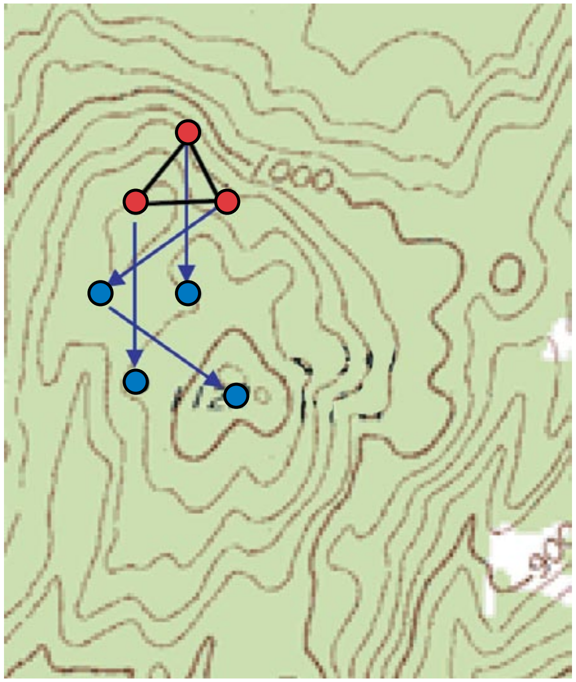
1-D 1-THz SSD



2-D 1-THz SSD

The 1-MJ wetted-foam design has been optimized in 1-D with a simplex method

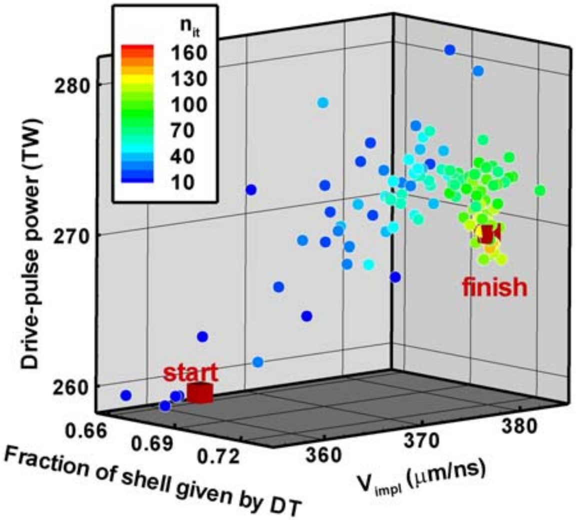
- A *simplex* is a polyhedron in *n* dimensions with *n* + 1 vertices.
- The lowest point is reflected across the plane connecting the others.
- The points in the pulse shape (power, time) and target dimensions may be optimized.
- This design was optimized to maximize gain, requiring $\rho R \gtrsim 1.4$ g cm^{-2} and $v_{imp} \lesssim 380$ μm/s.

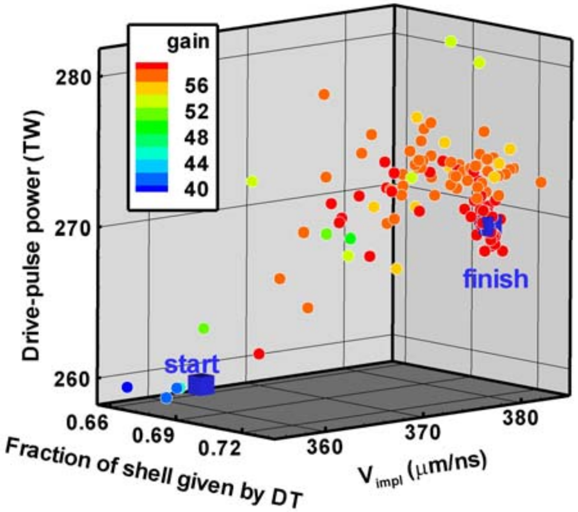


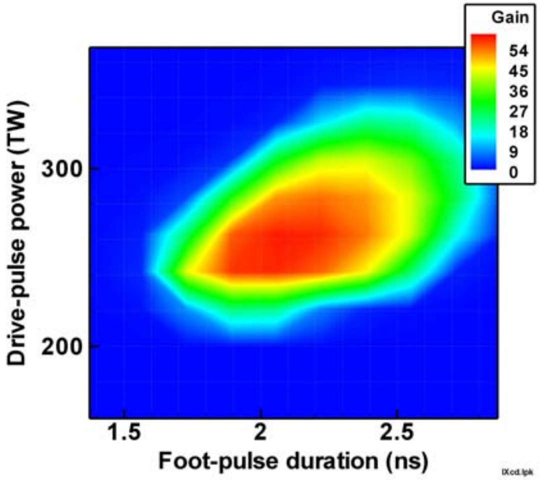
This method allows tuning of more variables than would be feasible by hand (in this case, seven).

The re-optimized design has higher gain and implosion velocity, and comparable IFAR

- **Picket power, foot length, foot power, drive-pulse power, layer thicknesses and target radius were varied.**
- **The result is robust to pulse-shape variations.**



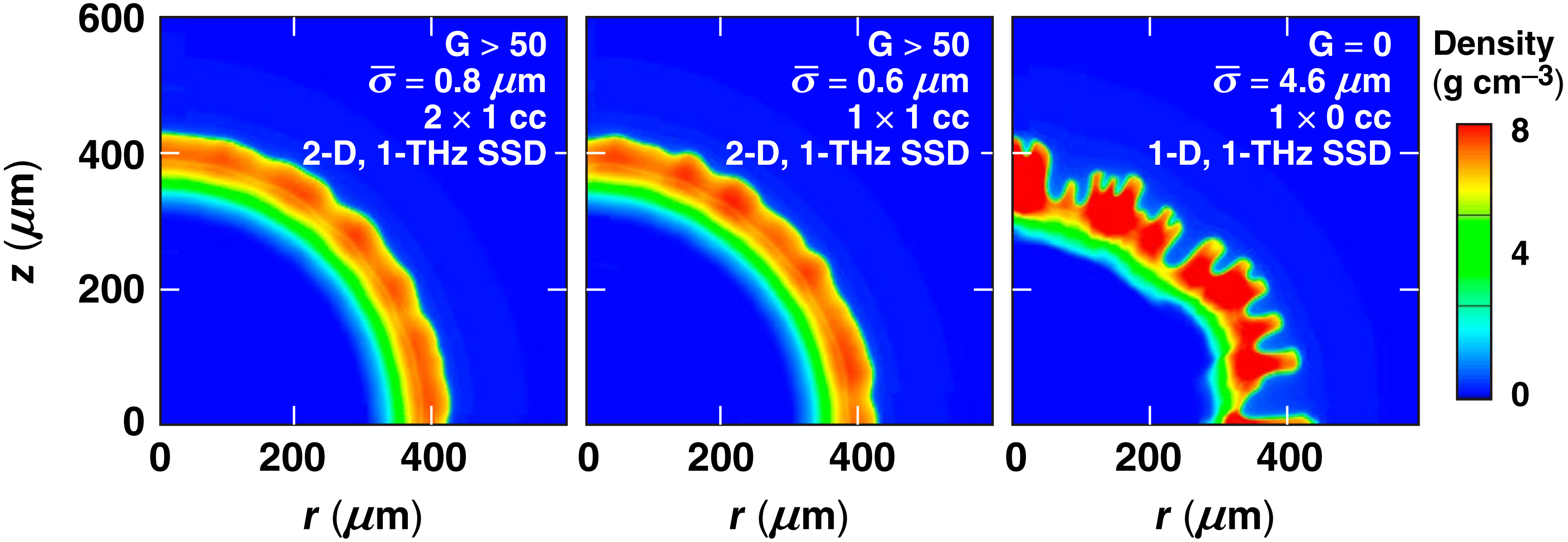




	V (μm/ns)	Gain	IFAR	$A/\Delta R$ (%)	ρR (g cm^{-2})	Margin (%)
Before	**372**	**45**	**28**	**11**	**1.4**	**30**
After	**380**	**60**	**30**	**6**	**1.4**	**40**

The re-optimized design has comparable nonuniformity at the end of the acceleration phase

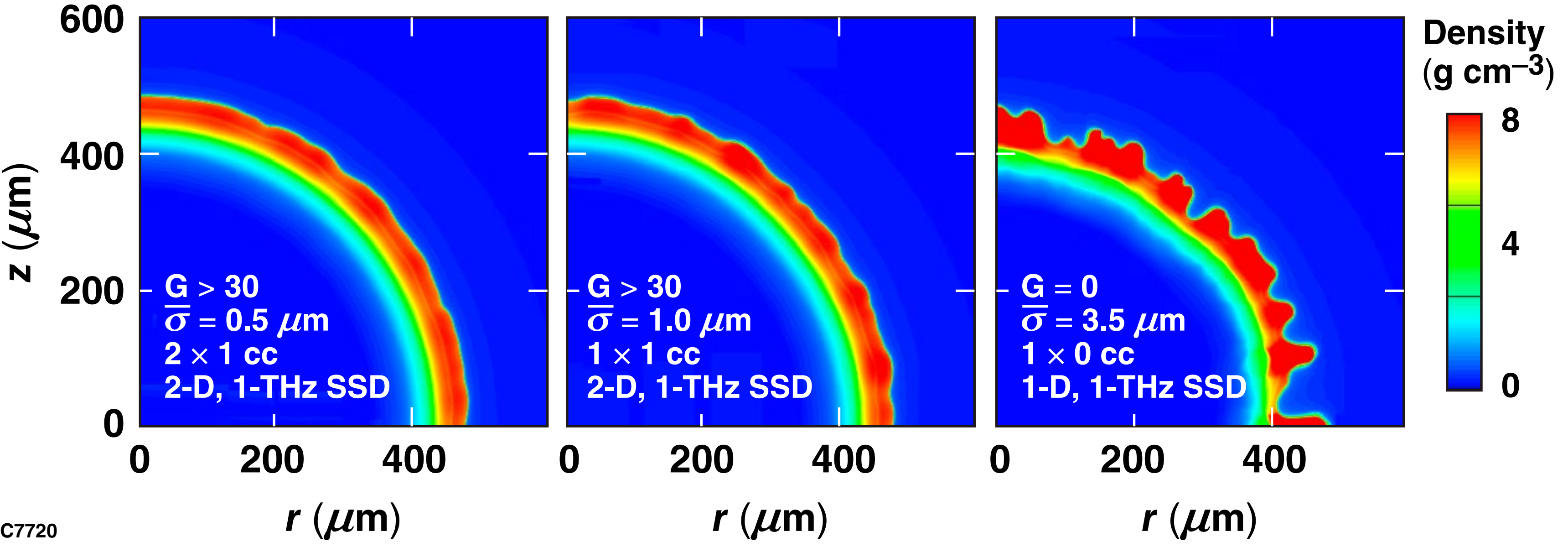
- **Power imbalance, imprint, surface and ice roughness are included.**



A 1.5-MJ wetted-foam target ignites with 2-D SSD but not with 1-D SSD

- A low-IFAR, wetted-foam design, based on the 1.5-MJ all-DT point design, was simulated with power imbalance, surface and ice roughness and imprint.

	V (μm/ns)	Gain	IFAR	$A/\Delta R$ (%)	ρR (g/cm^2)	Margin (%)
All-DT pt. design	450	45	60	30	1.2	40
1.5-MJ foam	409	44	33	5	1.4	40



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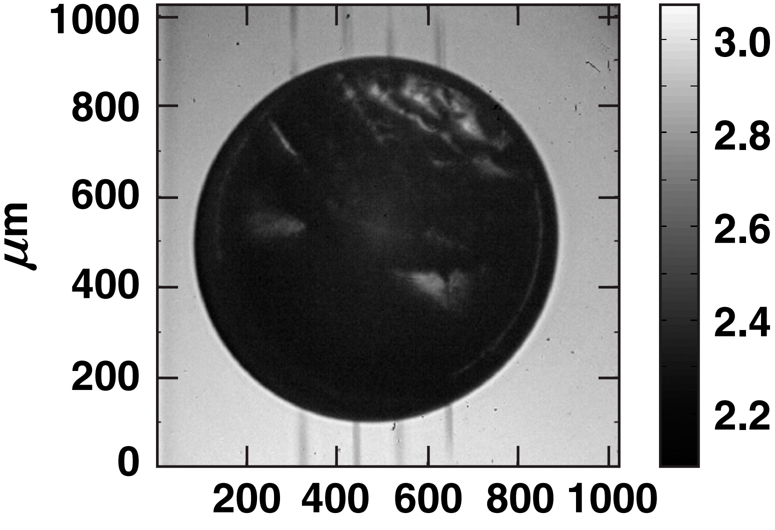
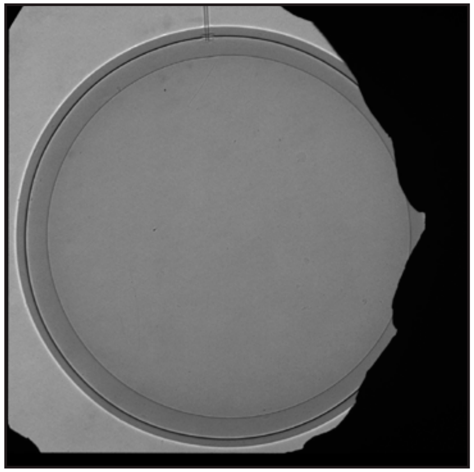
Foam targets are produced by General Atomics and filled and diagnosed at LLE

- 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*

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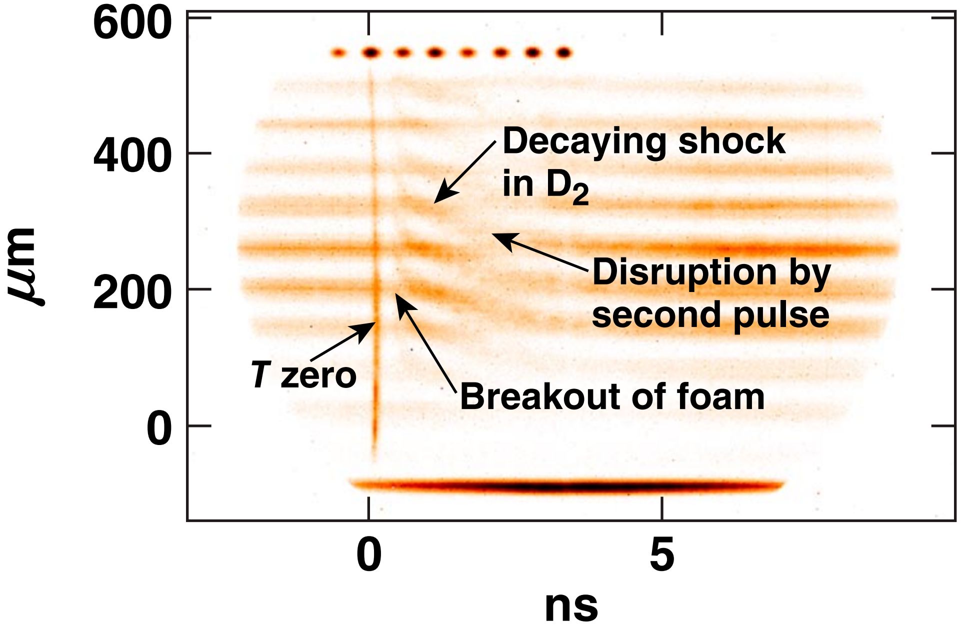
*Bernard Kozioziemski, private communication (2006).

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.

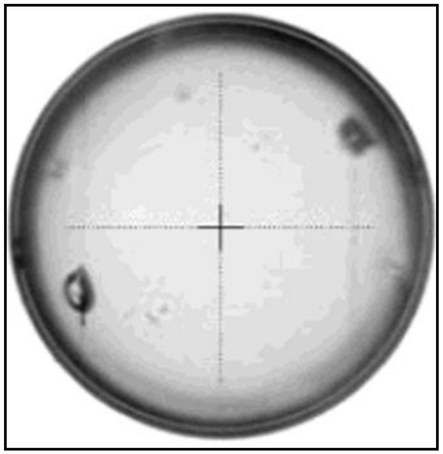
VISAR-2 Shot 34099



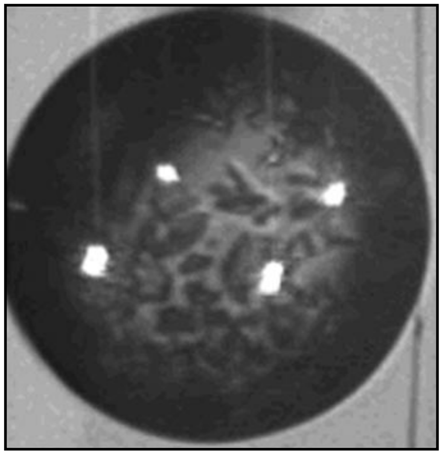
- Planar cryogenic experiments will address shock timing and coupling efficiency.
- Progress with β-layering of cryogenic DT targets at LLE gives confidence in high-quality wetted-foam layering.

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

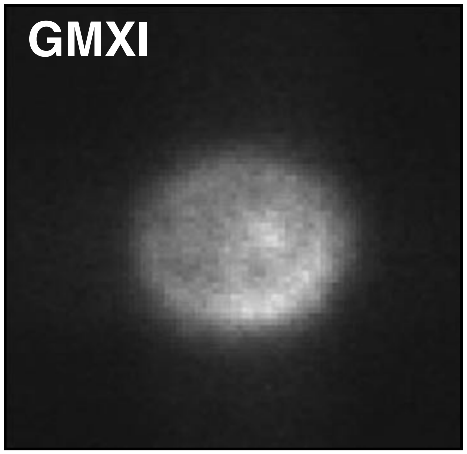
- A high-adiabat pulse was used.
- The yield was $Y_{1n} = 1.7 \times 10^{11}$, 16% *greater* than the 1-D yield.
- The target was not well characterized, contributing to computational uncertainty.
- There remains much scope for experimental exploration.



Unfilled foam capsule



Filled cryogenic capsule



X-ray image of the imploded core

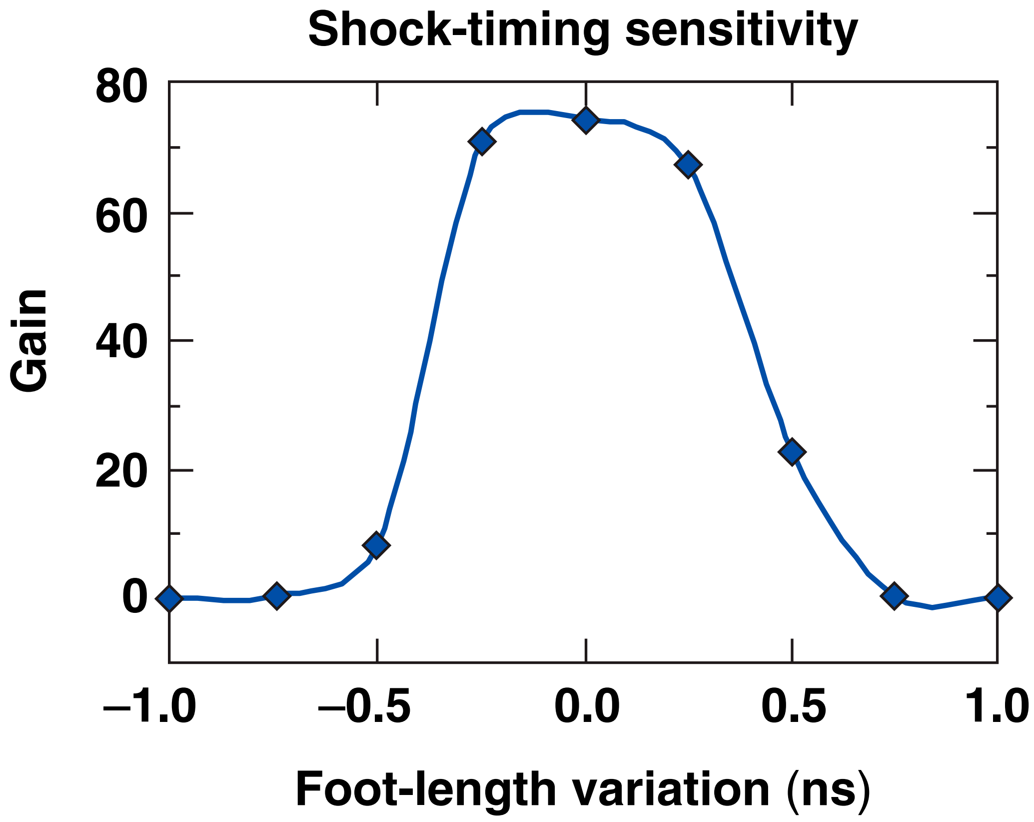
Summary/Conclusions

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

- 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.
- This design has been re-optimized using a downhill simplex method, achieving a 2-D gain of 60 with 2-D SSD and the same sources of nonuniformity
- A 1.5-MJ wetted-foam design achieves a gain of over 30 with 2-D SSD and fails with 1-D SSD.
- Future plans include both planar and converging experiments with wetted foams on OMEGA.

This design is robust due to shock mistiming

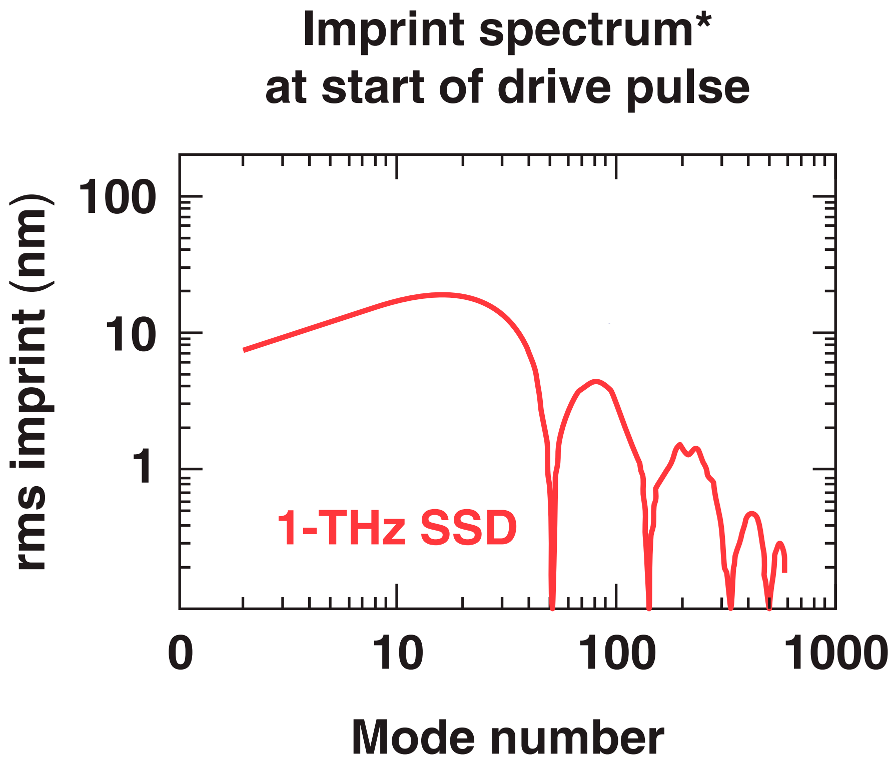
- Sensitivity to shock mistiming is determined in 1-D by varying the foot-pulse duration.
- This design can tolerate ±200 ps in shock-timing variation.

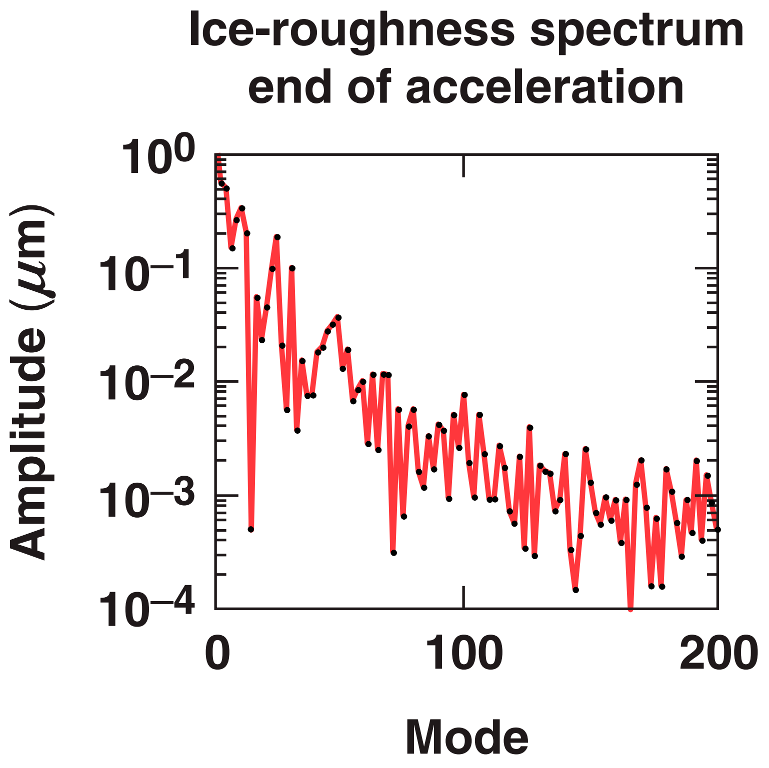


Modes $\ell > 100$ contribute negligibly to the ice roughness at the end of acceleration

UR LLE

- 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.





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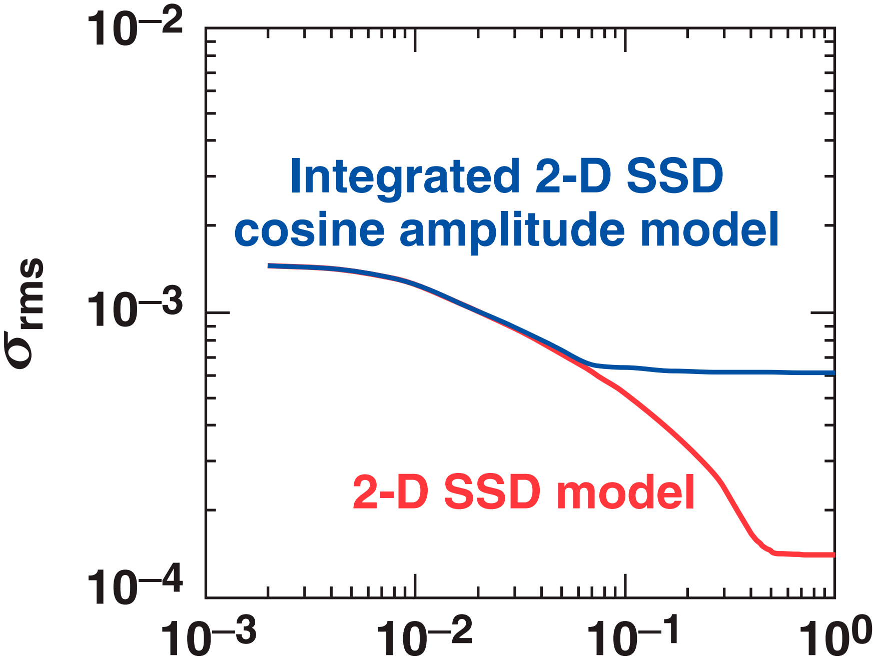
*V. Goncharov *et al*., Phys. Plasmas 7, 2962 (2000).

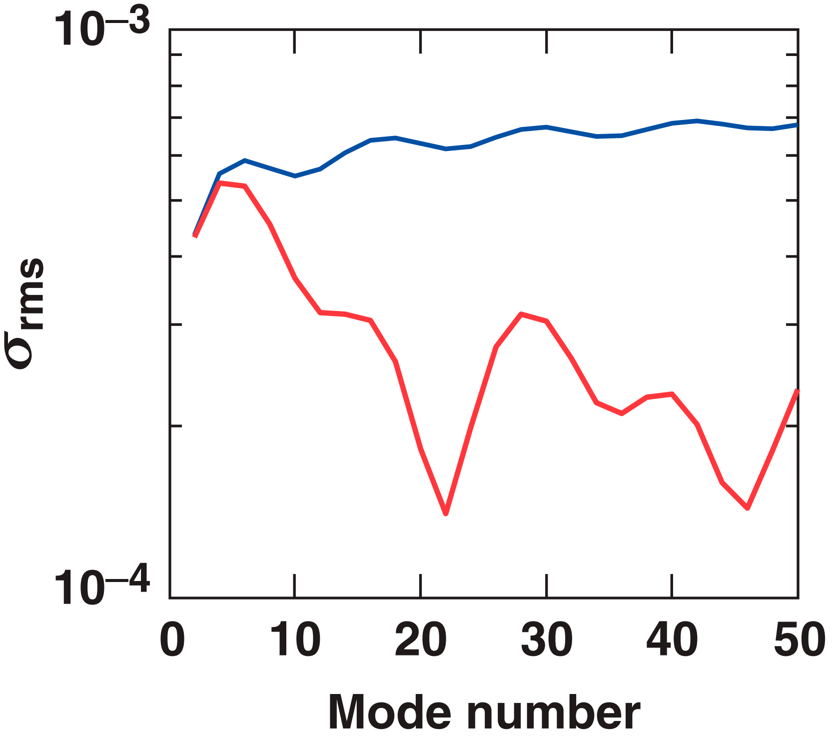
1-D SSD asymptotes much sooner than 2-D SSD

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 $\ell = 22$

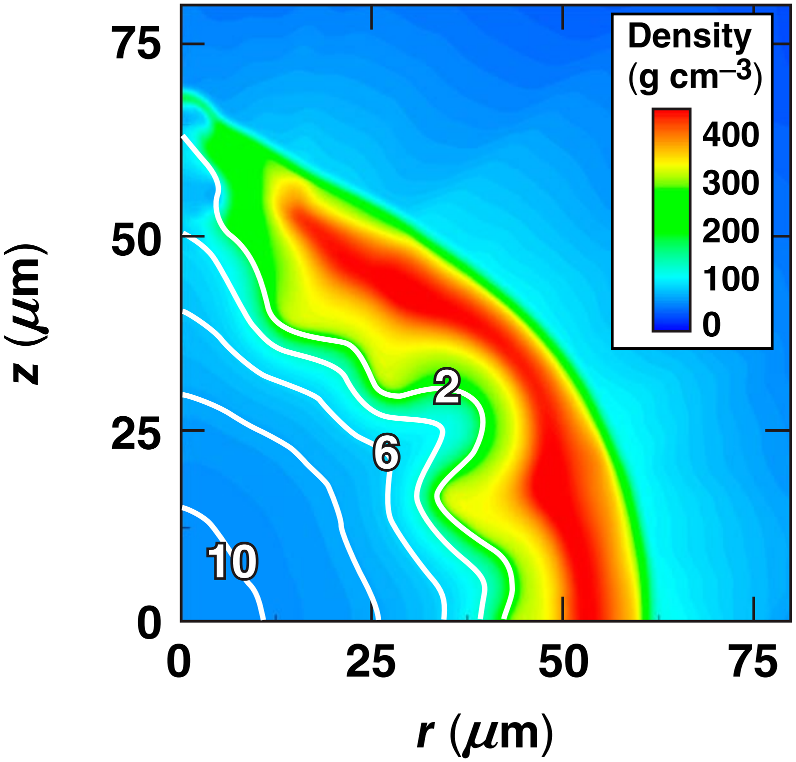


Smoothing for $\ell = 2$ to 50 at 1 ns

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

- 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.

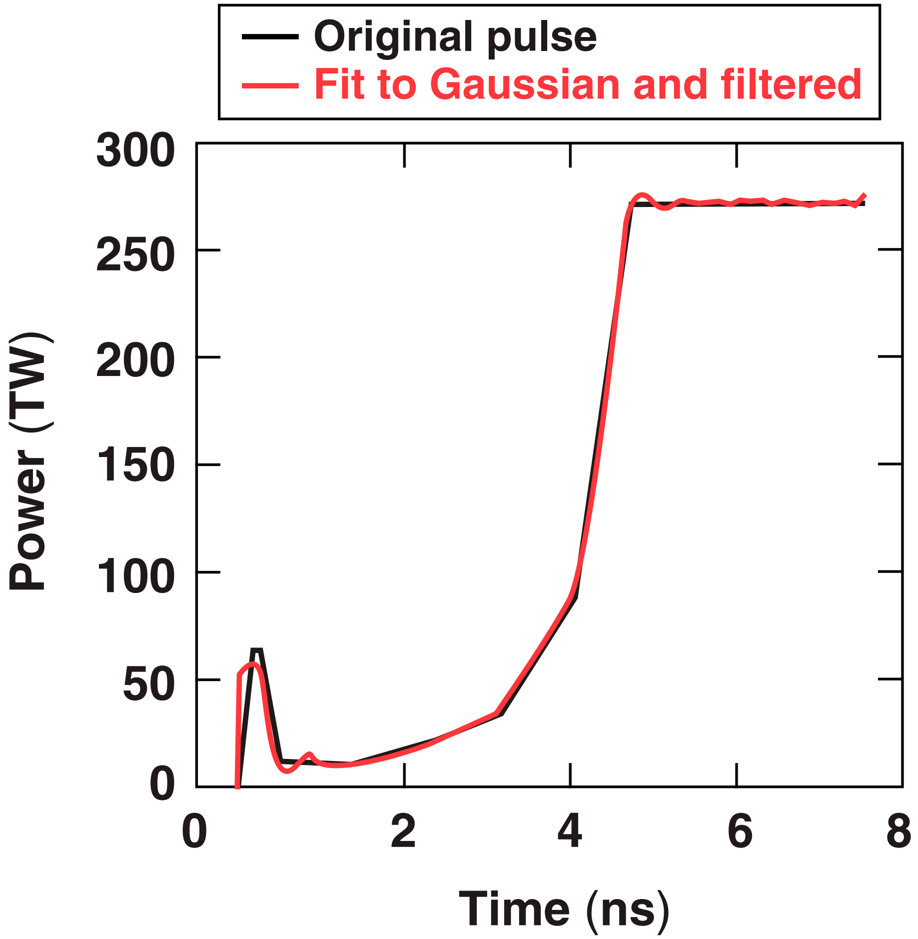


Near peak compression

- $R_{\text{hot spot}} = \sim 35\ \mu$m, neutron-averaged fuel areal density = 1.32 g cm^{-2}.

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

- **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 $\ell = 6$.
- Beam-to-beam imbalance is dominated by modes $\ell = 2$ to 12, with an amplitude of ~1%.
- Beam mistiming contributes ~5 to 15% in modes $\ell = 1$ to 3, primarily during the picket.