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

Including imprint, power balance, surface, and ice roughness

Tim Collins

Research Review
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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.

Summary
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

- 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.*

<table>
<thead>
<tr>
<th></th>
<th>All-DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MJ)</td>
<td>1.5</td>
</tr>
<tr>
<td>Target radius ($\mu$m)</td>
<td>1695</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>65</td>
</tr>
<tr>
<td>$A/\Delta R$ (%)</td>
<td>30</td>
</tr>
<tr>
<td>1-D gain</td>
<td>45</td>
</tr>
</tbody>
</table>

$\langle \alpha \rangle = 4.2$

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

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

<table>
<thead>
<tr>
<th></th>
<th>All-DT</th>
<th>Scaled All-DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MJ)</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Target radius (μm)</td>
<td>1695</td>
<td>1480</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>65</td>
<td>59</td>
</tr>
<tr>
<td>$A/ΔR$ (%)</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>1-D gain</td>
<td>45</td>
<td>40</td>
</tr>
</tbody>
</table>
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.

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

The 1-D, 1-MJ wetted-foam target gain is 49.
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:
  \[
  \text{Number of e foldings} = \gamma t \sim \sqrt{kgt^2} \sim \sqrt{\frac{R_0}{\Delta R}} \equiv \text{IFAR}
  \]

- 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.

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

<table>
<thead>
<tr>
<th></th>
<th>( V (\mu m/\text{ns}) )</th>
<th>( \Delta R (\mu m) )</th>
<th>IFAR</th>
<th>( A/\Delta R ) (%)</th>
<th>Areal density ( \rho R ) (g cm(^{-2} ))</th>
<th>Margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-MJ All-DT</td>
<td>430</td>
<td>285</td>
<td>69</td>
<td>33</td>
<td>1.1</td>
<td>45</td>
</tr>
<tr>
<td>Wetted foam</td>
<td>372</td>
<td>323</td>
<td>28</td>
<td>11</td>
<td>1.4</td>
<td>30</td>
</tr>
</tbody>
</table>

- This improvement comes at the expense of margin, but with improved areal density.
- Margin = inward moving kinetic energy at ignition 
  \[ \frac{\text{peak inward kinetic energy}}{V} \]
- 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 $E \sim (\text{IFAR})^{-3^{*}}$

Shell stability and compressibility depend on the adiabat

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

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

- Wetted-foam microstructure is a potential source of shock nonuniformity.
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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Nonuniformities: Power Imbalance

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 $\sim 6\%$.

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

* Craig Sangster, QT1.00001.
Nonuniformities: Surface Roughness

Foam shells have been fabricated at General Atomics with outer-surface rms roughness as low as \( \sim 500 \) nm.

- This spectrum also shows an \( \ell^{-2} \) dependence.

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

A weighted average $\bar{\sigma}$ 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:**

$$\bar{\sigma}^2 = 0.06 \sigma_{\ell < 10}^2 + \sigma_{\ell > 9}^2$$

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

Nonuniformities: Imprint

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

<table>
<thead>
<tr>
<th></th>
<th>$\bar{\sigma}$ (μm)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2-D SSD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 × 1 cc</td>
<td>0.94</td>
<td>21</td>
</tr>
<tr>
<td>1 × 1 cc</td>
<td>1.00</td>
<td>16</td>
</tr>
<tr>
<td><strong>1-D SSD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 × 0 cc</td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td>I.D. SSD</td>
<td>7.3</td>
<td>0</td>
</tr>
</tbody>
</table>

![Graphs showing density and z-axis data for different SSD conditions]
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.

- $R_{\text{hot spot}} = 40 \mu m$, 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.
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**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
Re-optimized 1-MJ design

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 $\rho R \geq 1.4 \text{ g cm}^{-2}$ and $v_{\text{imp}} \leq 380 \mu \text{m/s}$.

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.

<table>
<thead>
<tr>
<th></th>
<th>V (μm/ns)</th>
<th>Gain</th>
<th>IFAR</th>
<th>Λ/ΔR (%)</th>
<th>ρR (g cm⁻²)</th>
<th>Margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>372</td>
<td>45</td>
<td>28</td>
<td>11</td>
<td>1.4</td>
<td>30</td>
</tr>
<tr>
<td>After</td>
<td>380</td>
<td>60</td>
<td>30</td>
<td>6</td>
<td>1.4</td>
<td>40</td>
</tr>
</tbody>
</table>
The re-optimized design has comparable nonuniformity at the end of the acceleration phase.

- Power imbalance, imprint, surface and ice roughness are included.
1.5-MJ Wetted-Foam Design

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.

<table>
<thead>
<tr>
<th></th>
<th>V (μm/ns)</th>
<th>Gain</th>
<th>IFAR</th>
<th>A/ΔR (%)</th>
<th>ρR (g/cm²)</th>
<th>Margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-DT pt. design</td>
<td>450</td>
<td>45</td>
<td>60</td>
<td>30</td>
<td>1.2</td>
<td>40</td>
</tr>
<tr>
<td>1.5-MJ foam</td>
<td>409</td>
<td>44</td>
<td>33</td>
<td>5</td>
<td>1.4</td>
<td>40</td>
</tr>
</tbody>
</table>

![Graph showing density distribution](image)
Future Experiments

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.

\[
\text{Phase-contrast image of a cryogenic DT-filled foam target*}
\]

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 $\beta$-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 $\pm 200$ ps in shock-timing variation.
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.

*V. Goncharov et al., Phys. Plasmas 7, 2962 (2000).*
1-D SSD asymptotes much sooner than 2-D SSD

- SSD smooths efficiently down to a mode number of
  \[ \ell_{\text{min}} = \frac{2\pi R_0}{(2F\Delta\theta)} \sim 4, \]
  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.
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.

$R_{\text{hot spot}} = \sim 35 \mu m$, neutron-averaged fuel areal density $= 1.32 \text{ g cm}^{-2}$. 
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.
Beam-to-beam imbalance imposes long-wavelength perturbations on the target

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