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

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

42nd Annual Meeting of the American Physical Society
Division of Plasma Physics
Québec City, Canada
23–27 October 2000

\[
\frac{\sigma^2}{\bar{\sigma}^2} = 0.06 \sigma_{1-9}^2 + \sigma_{>10}^2
\]
Analysis of a Direct-Drive Ignition Capsule Designed for the NIF

P. W. McKenty

Laboratory for Laser Energetics, U. of Rochester

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 design1,2 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.

Collaborators

V. N. Goncharov
R. P. J. Town
S. Skupsky
R. Betti
R. L. McCrory
J. A. Delettrez
D. L. Harding
M. Wittman
R. L. Keck
Summary

Scaling target gain with $\sigma$ 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
The “all-DT” direct-drive target is a thick DT-ice layer enclosed by a thin CH shell.
Numerical modeling

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

\[ \sigma^2 = 0.06 \sigma^2_{1-9} + \sigma^2_{>10} \]
Sources of implosion nonuniformities

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

- **Target fabrication issues**
  - Outside capsule finish
  - Inner DT ice roughness

- **Laser irradiation issues**
  - Laser imprinting
  - Drive symmetry
Heuristically, there are four sources of perturbations a direct-drive capsule must tolerate to ignite and burn.

\[
\left( \frac{\sigma_{rms_{drive symmetry}}}{\text{Max allowed value}_{drive symmetry}} \right)^2 + \left( \frac{\sigma_{rms_{laser imprinting}}}{\text{Max allowed value}_{laser imprinting}} \right)^2 + \left( \frac{\sigma_{rms_{DT ice}}}{\text{Max allowed value}_{DT ice}} \right)^2 + \left( \frac{\sigma_{rms_{outside capsule finish}}}{\text{Max allowed value}_{outside capsule finish}} \right)^2 < 1
\]
Power balance

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

- **Inside DT-ice surface**
- **Feedout of perturbation to the ablation surface**
- **Ablation surface growth and feed-through to the inner surface during the acceleration phase**
- **Growth of the hot spot–main fuel layer interface during the deceleration phase**
*ORCHID* simulations indicate that target gain depends strongly on the development of the low-order modes.

---

**Ice/vapor interface spectra**

- **Initial spectrum**
- **Final spectrum**

- **Gain** = 1.75

---

**Tables**

<table>
<thead>
<tr>
<th>Perturbation amplitude (µm)</th>
<th>Ice/vapor interface spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>Final spectrum</td>
</tr>
<tr>
<td>1.00</td>
<td>Initial spectrum</td>
</tr>
<tr>
<td>0.10</td>
<td>( \sigma_c = 95% \ \sigma_{tot} )</td>
</tr>
</tbody>
</table>

**Graphs**

- **Z (µm)**
- **R (µm)**

---

**Gain** = 1.75

---

TC5211
Scaling target gain with $\tilde{\sigma}$ correctly balances the individual contributions of the low and high order modes during the implosion.

$$a = a_0 / l^\beta, \quad \beta = 0(\triangle), 0.75(\square), \text{and} \ 1.50(\Diamond)$$

![Graph showing gain versus $\sigma$ for different values of $\beta$.](image-url)
Outer surface roughness

The smoothness and concentricity of thin-wall polyimide targets (1.5 to 2.0 \(\mu\)m) 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-frequency roughness.
Twice the NIF standard specification (~165 nm) for outer surface roughness does not result in any significant disruption of the ice/vapor interface.
SSD reduces time-averaged laser nonuniformity

- DPP spectrum
- Beam Overlay
- PS

\[ \langle \sigma_{\text{rms}} \rangle \sim \sqrt{\frac{t_c}{\langle t \rangle}} \langle \sigma_{\text{rms}}^0 \rangle \]

\[ t_c^* = \left[ \frac{\Delta \nu \sin(k\delta/2)}{\Delta \nu} \right]^{-1} \]

\[ \Delta \nu: \text{bandwidth} \]
\[ \delta: \text{speckle size} \]

*S. Skupsky, Phys. Plasmas 6, 2157 (1999).*
Application of SSD bandwidth is necessary for shell integrity during the entire implosion.
Scaling gain with $\bar{\sigma}$, taken from *ORCHID* calculations, indicates that NIF must deploy at least 1-THz bandwidth.

![Graph showing scaling gain with SSD bandwidth](image)

- **Projected 2-D ORCHID results**
- **NIF Direct-drive specification**
- **2 color cycles**

Gain vs. SSD bandwidth (THz, 1 color cycle)
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).
Shell stagnation determines the margin trajectory that defines the window for high gain.
*ORCHID* simulations indicate that as ice/vapor interface perturbations increase, ignition is delayed and gain is reduced.
Scaling gain with $\bar{\sigma}$ allows forming a global nonuniformity budget for the direct-drive point design.
Summary/Conclusion

Scaling target gain with $\bar{\sigma}$ 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.