Progress in Direct-Drive Inertial Confinement Fusion Research

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OMEGA DT equivalent of the NIF point design
NIF 0.5 MJ
OMEGA D2, 16 kJ 2007

Hydro equivalent curve $V_i = \text{const.}, \alpha = \text{const.}$

Ignition and Gain
NIF point design 1.5 MJ
1-D marginal ignition

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These are exciting times for inertial confinement fusion

- Experiments on Nova (previously) and OMEGA are developing the target-physics understanding.

- Recent OMEGA experiments have demonstrated ignition-relevant areal densities.

- New concepts will extend ignition possibilities.

- This talk will review direct-drive ICF progress.*

- After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the National Ignition Facility (NIF).

*More ICF, see Lindl (SR1.00001).
Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition conditions.

"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm².
A “Lawson’s criterion” in terms of burn-averaged $\rho R$ and $T_i$ shows the requirements for ignition

- Simple scaling relations for ignition condition from Zhou et al.* and Herrmann et al.**
  \[
  \langle \rho R \rangle_n > 1.3 \left( \frac{4}{\langle T_i \rangle_n (\text{keV})} \right)^{2.4} \text{g/cm}^2
  \]

- Fitting the results of 1-D simulations with Gain = 1 yields an ignition condition that depends on the burn-averaged $\rho R$ and ion temperature without alpha deposition.

- For sub-ignited implosions $T_i(\text{no–}\alpha) \equiv T_i$

Both $T_i$ and $\rho R$ can be measured experimentally.

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The fundamental physics of direct- and indirect-drive ICF implosions is the same.

Key physics issues are common to both:
- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities
- Compressibility

Direct-drive cryogenic implosions provide essential information for ICF physics.
The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain.

Under construction and beginning experiments at LLNL.

Omega experiments are integral to an ignition demonstration on the NIF.
The NIF is on track for completion in FY09

120 main laser beams operationally qualified October 31, 2007

World’s highest energy laser – 2.5 MJ, 1ω

NIF status: 94% complete 4642 LRU’s installed
The OMEGA laser is designed to achieve high irradiation uniformity with flexible pulse-shaping capability.

- 60 beams
- ~30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

Fully instrumented
Successfully operated for 10 years
1500 target shots/year
Laser-beam smoothing is critical to ICF ignition

Phase Plates

Measured far field of an OMEGA indirect-drive phase plate

Measured
\( I_{50} = 1 \times 10^{15} \text{W/cm}^2 \)
\( I_{95} = 3.8 \times 10^{15} \text{W/cm}^2 \)

0.1 mm

Polarization Smoothing

Wedge of KDP

\( \theta_d \)
\( \Delta \theta_d \)

Phase plate

Lens

“o”

“e”

Target plane

Smoothing by Spectral Dispersion

Oscillator

Grating

EO phase modulator

Amplifiers

Grating

Angular dispersion

Focusing optics

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Y. Lin, T. J. Kessler, and G. N. Lawrence,
Ignition requires smooth cryogenic DT targets

- Thick (>50 \(\mu\)m) DT ice layers are required for ignition.
- \(\beta\)-layered 50:50 DT cryogenic targets have measured ice-roughness nonuniformities <1-\(\mu\)m rms, meeting ignition specifications.

Multiple views are essential for full characterization.

D. R. Harding (YO5.00001).
About 80% of the DT capsules created to date have produced layers with sub-1-\(\mu\)m rms roughness.

- High-mode (\(\ell > 20\)) roughness is minimal for “single-crystal” layers.
- Low-mode roughness (\(\ell < 6\)) is due to asymmetries in the triple-point isotherm.
- Mid-mode roughness (6 < \(\ell < 20\)) is likely related to outer-surface features (glue for silks).
- The best layers are achieved at the triple point.

DT layer quality meets ignition requirements.

LLE has learned how to reliably field cryogenic capsules

• Deuterium implosion experiments began in 2001
  – three-day fill, cool, and layer cycle
  – provide up to eight cryogenic targets per week
  – imploded 139 D₂ targets

• Tritium implosion experiments began in 2006
  – targets are filled by permeation (no fill tube); requires 6000 Ci T₂
  – safe operation: facility emissions <3 Ci/yr
  – imploded 35 cryogenic DT targets (D:T, 45:55)

Improvements in the ice-layer quality and target position have proceeded in parallel with implosion experiments.
The fuel areal density and hot-spot ion temperature determine ignition performance

- Areal density ($\rho R$)
  - shock timing and strength
  - preheat
  - compressibility
  - hydrodynamic instabilities

- Ion temperature ($T_i$)
  - implosion velocity
  - hydrodynamic instabilities
  - absorption/drive coupling

Our strategy is to first increase $\rho R$ and then $T_i$
The laser power is tailored to drive the target on a low fuel adiabat, including adiabat shaping*

- High outer $\alpha$ reduces the RTI growth rates through higher ablation velocity
  \[ \gamma_{\text{RTI}} = 0.9 \sqrt{kg - 3kV_a^\dagger} \quad k = 2\pi/\lambda \quad V_a \sim \alpha_{\text{out}}^{0.6} \]
- High $\langle \alpha \rangle$ increases the shell thickness and reduces feedthrough, $\Delta \sim \langle \alpha \rangle^{0.6}$
- Low inner $\alpha$ reduces the shell kinetic energy required for ignition, $E_{\text{ign}} \sim \alpha_{\text{in}}^{1.8\ddagger}$

ICF ignition targets have $\alpha_{\text{in}} \sim 1$ to 3, $\alpha_{\text{out}} \sim 3$ to 6, and $\alpha_{\text{avg}} \sim 2$ to 3.

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‡W. K. Levedahl and J. D. Lindl, Nucl. Fusion 37, 165 (1997).
Shock Timing

The shock and isentropic compression must be precisely timed to reach the areal density required for ignition.

- Accurate shock and compression wave timing sets the proper $\alpha_{in}$, $\rho R \sim \alpha_{in}^{-0.6}$

![Diagram showing shock and compression wave timing](diagram.png)

$\frac{\Delta t_{shock}}{t_{shock}} < 5\%$, $t_{shock} \sim E_p^{-1/2} \Rightarrow \frac{\Delta E_p}{E_p} < 10\%$

($E_p$ is the picket energy)

V. N. Goncharov (Gl1.00001).
A nonlocal model is required to correctly predict electron thermal transport.

- Flux limiter: \( q = \min \left\{ \frac{-k\nabla T}{f n_e m_e v_{th}^3} \right\} \)  
  \( f \): flux limiter

- Previously, \( f = \text{const.} \sim 0.06 \) was used based on heuristic and experimental observations.

\[ f_{\text{eff}} = \frac{q_{\text{nl}}}{n_e m_e v_{th}^3} \]

- A more accurate model based on the solution of the Fokker–Planck equation predicts a time-dependent flux limiter.
Accurate modeling of electron thermal transport is crucial for shock timing and setting the shell adiabat.

Nonlocal model explains early-time absorption

*W. Seka (Gl1.00003).
The fuel areal density and hot-spot ion temperature determine the compression performance of ICF targets.

- Precise pulse shaping, including a picket, sets the target on the appropriate adiabat.
- Current experiments have demonstrated ignition-relevant areal densities:
  - shock timing and strength
  - preheat
  - compressibility
  - hydrodynamic instabilities
- Future experiments will increase the ion temperature:
  - implosion velocity
  - hydrodynamic instabilities
  - absorption/drive coupling

Understanding cryogenic dynamics is a key to successful ICF ignition.
Implosions demonstrate compression of cryogenic fuel to ignition-relevant areal densities

- Cryogenic targets are energy scaled from NIF ignition designs
- Target designs are being refined based upon these experiments

A systematic experimental scan of fuel adiabat and drive intensities has been conducted

\[ \rho R \begin{cases} 2 < \alpha < 10; \alpha = \text{fuel pressure/Fermi-degenerate pressure} \\ I_L = 0.25 \text{ to } 1.5 \times 10^{15} \text{ W/cm}^2 \\ V_{\text{imp}} = 2.5 \text{ to } 4.0 \times 10^7 \text{ cm/s} \\ T_i \end{cases} \]

In-flight aspect ratio: 30 to 50
Number of perturbation e-folds \( \sim 5 \) to 7
Areal Density

Downshifted secondary proton spectra measure* the compressed fuel areal density

\[ (\rho R)_{\text{max}} > 0.3 \text{ g/cm}^2 \]
\[ (\rho R)_n = 0.2 \text{ g/cm}^2 \]

A severe degradation of \( \rho R \), up to 40% of 1-D predictions, was observed in high-intensity mid- and low-adiabat cryogenic implosions on OMEGA.

- Thick targets minimize hydro-instabilities: in-flight aspect ratio \( \sim 30 \)

\[
\langle \rho R \rangle (\text{mg/cm}^2) (\text{exp})
\]

- Laser intensity \( I \sim 10^{15} \text{ W/cm}^2 \)
- \( E_L \sim 23 \text{ kJ} \)

\[
\langle \rho R \rangle (1\text{-D})
\]

\[
\alpha \sim 25 \quad \alpha \sim 7 \quad \alpha \sim 4 \text{ to } 6 \quad \alpha \sim 2
\]

\[
\text{Modeled with } f = 0.06
\]
The nonlocal thermal-transport model improves the agreement between 1-D simulation and experimental areal densities.

Areal Density

The measured areal densities remain somewhat lower than 1-D simulations with nonlocal heat conduction.
There are two plausible explanations for the reduction of the experimental areal density relative to the 1-D simulations:

- preheat by hot electrons generated by the two-plasmon-decay instability (discussed next)
- measured nuclear burn histories can be different from 1-D simulations due to hydrodynamic instabilities*

  - protons may sample lower areal densities
  - a similar effect has been seen in warm plastic-target implosions
  - statistics need to be improved to measure this in cryogenic implosions

Hot-electron preheat generated by laser–plasma interactions can significantly degrade the final areal density.

- Low-\(\alpha\) designs \(T_0 \sim 20\) eV
- 20\% \(\rho R\) reduction for \(\Delta T_{\text{shell}} \sim 6\) eV
- For OMEGA experiments, \(E_{\text{preheat}} \sim 10\) to 20 J (~0.1\% of laser energy)

\[
p \sim \alpha \rho^{5/3}
\]

\[
\rho R \sim \alpha^{-0.6} \Rightarrow \rho R = \frac{\rho R_0}{\left[\left(T_0 + \Delta T_{\text{shell}}\right)/T_0\right]}
\]
3/2\omega light and hard x rays\(^*\) indicate the presence of the two-plasmon-decay instability.

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\[ \omega_0 \]

Electron density

\[ n_{c/4} \]

At \( n_{c/4} \)

Wave breaking

\( > 50 \text{ keV e}^- \)

\[ \omega_{pe} = \omega_0/2 \]

3/2\omega_0

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\[ 3/2\omega \text{ emission for shot 46520} \]

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\[ \text{Laser power (arbitrary units)} \]

\[ \text{Normalized 3/2\omega emission} \]

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\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \]

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\[ ^* \text{C. Stoeckl et al., Rev. Sci. Instrum. 72, 1197 (2001).} \]
Preheating by hot electrons from the two-plasmon-decay instability is a candidate for additional cryo $\rho R$ degradation

- $I_{th,2\omega_p} \approx 2 \times 10^{14} \frac{T(\text{keV})}{L_n(100 \ \mu\text{m})}$ W/cm$^2$
- Measured $T_{\text{hot}} > 50$ keV – electron range is greater than the D$_2$ thickness

The two-plasmon-decay threshold is exceeded when the laser burns into the D$_2$ fuel

- Above-threshold parameter* for 2 $\omega_p$ instability $\eta = \frac{I_{14}L_{\mu m}}{230T_{keV}}$
- Instability develops when $\eta > 1$

V. N. Goncharov (Gl1.00001).

An improved agreement between simulated and measured $\rho R$ is observed for low intensity implosions*

*V. A. Smalyuk et al., Anomalous Absorption (2007); and to be published in Phys. Rev. Lett.
D. Shvarts et al., Anomalous Absorption and IFSA (2007).

All simulations use nonlocal thermal-transport model
Hard x rays due to energetic electrons from the two-plasmon-decay instability increases rapidly with laser intensity

- Hard x-ray signals produced by bremsstrahlung radiation from fast electrons may indicate preheating*

*V. A. Smalyuk et al., to be published in Phys. Rev. Lett.
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Preheat

Hard x rays due to energetic electrons from the two-plasmon-decay instability increases rapidly with laser intensity.

- Hard x-ray signals produced by bremsstrahlung radiation from fast electrons may indicate preheating.

![Graph showing the relationship between hard x-ray signals and on-target laser intensity.](image)

Hard x rays from energetic electrons are reduced by increasing the CD thickness.

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*V. A. Smalyuk et al., to be published in Phys. Rev. Lett.*
Ignition-relevant areal densities (~200 mg/cm²) are achieved by accurate shock timing and mitigating fast-electron preheat. These are, by far, the highest areal densities measured in ignition-relevant laboratory implosions—very important for direct- and indirect-drive ignition.

- Target design tuned to be insensitive to the thermal transport model and has low hard x-ray signal.

10-μm CD cryogenic implosion

Secondary D³He proton spectrum

\[ \langle \rho R \rangle_n = 202 \pm 7 \text{ mg/cm}^2 \]

Detector cutoff

X-ray pinhole camera

D₂ fuel density reaches ~100 g/cc (500× liquid density)

These are, by far, the highest areal densities measured in ignition-relevant laboratory implosions—very important for direct- and indirect-drive ignition.

T. C. Sangster et al., (JO3.00001) and to be published in Phys. Rev. Lett.
Areal Density

Predictive capability for the shock timing is validated by adjusting picket timing.

\[ \rho R_{\text{exp}} = 202 \text{ mg/cm}^2 \]
\[ \rho R_{1-D} = 224 \text{ mg/cm}^2 \]
\[ \rho R_{\text{exp}} = 182 \text{ mg/cm}^2 \]
\[ \rho R_{1-D} = 192 \text{ mg/cm}^2 \]
Good agreement between simulated and measured $\rho R$ is observed for implosions with low hard x-ray signals.

All simulations use nonlocal thermal-transport model.
Areal Density

2-D DRACO simulations of cryogenic high-$\rho R$ shots confirm experimentally observed areal densities

- Target offset from target chamber center by 20 $\mu$m
- Observed yield is one third of 2-D prediction
Path to $T_i$

Direct-drive research is on a path to ignition on the NIF

- Ignition-relevant areal densities have been achieved
- The next step is to increase $T_i$

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Total $\langle \rho R \rangle_n$ (g/cm$^2$)

$\langle T_i \rangle_n$ (keV) (no alpha deposition)

OMEGA D$_2$, 16 kJ 2007

OMEGA DT equivalent of the NIF point design

NIF point design 1.5 MJ

1-D marginal ignition

Ignition and Gain

Hydro equivalent curve $V_i = \text{const.}, \quad \alpha = \text{const.}$

$\langle 4 \times 10^7 \text{ cm/s} \rangle (2.5)$
Future experiments will increase the ion temperature while mitigating preheat and hydro-instabilities

- $T_i$ increases with implosion velocity, $T_i \sim V_{\text{imp}}^{1.3}$
- Increase the implosion velocity to $4 \times 10^7$ cm/s
  - thinner ice layer (60-μm D$_2$)
  - higher intensity
  - re-time shock waves with the nonlocal model
- Doped ablators (Si and Ge) can minimize energetic electron preheat and Rayleigh–Taylor growth rate
  - 3-μm Si (5 at. %)–CH
  - 7-μm CD
  - 60-μm D$_2$/DT
Initial experiments with high-Z doped plastic shells show reduced hard x-ray production

- High-Z dopants reduce hot-electron generation

- High-Z dopants reduce Rayleigh–Taylor growth rates*

*P. B. Radha (JO3.00002).
J. P. Knauer (PO6.00010).
Direct drive can achieve ignition conditions while NIF is in the x-ray-drive configuration.

Pointing for x-ray drive

Repointing for polar drive*

The polar-drive point design achieves a yield of 17 MJ with all current levels of NIF nonuniformities included in the calculation.
Advanced Concepts

New ignition concepts separate compression (ρR) and heating (T_i)—two-step ignition

- In the current hot-spot ignition, the driver provides both compression (ρR) and heating (T_i).
- Both fast ignition and shock ignition use a second drive to provide heating (T_i).

Fast Ignition

- Compression + HEPW laser
  - generated hot e−’s

Shock Ignition

- Compression + shock pulse

- Measured cryogenic target areal densities are relevant to these schemes.

Two-step ignition offers lower driver energies with the possibility of higher gain.
Fast and shock ignition can trigger ignition in massive (slow) targets leading to high gains.
Launching a spherically convergent shock wave at the end of the laser pulse can trigger ignition at lower driver energies.

- Low-velocity implosions can be shock-ignited to yield moderately high gains (~50 to 70) at relatively low UV driver energies (~400 to 500 kJ).

- 2-D simulations indicate that shock ignition survives the detrimental effects of laser imprinting for UV driver energies in the 500-kJ range.

- Implosion experiments on thick CH shells filled with 4- to 25-atm D₂ show that pulse shapes with shock spikes give higher neutron yields and higher areal densities than standard pulse shapes.

![Graph showing laser power and time]

- A ~350-kJ shock-ignition design gives a 1-D gain of 60

Shock-ignition pulse shapes lead to higher compression and more favorable ignition conditions.

Marginal shock ignition (with $\lambda_L = 0.35 \, \mu m$) requires 350 kJ. Hydro-equivalent conventional ignition requires 1.3 MJ.
Initial shock-ignition research on OMEGA is encouraging.

Warm target

\[
\begin{align*}
E_L &= 17 \text{ to } 18 \text{ kJ} \\
\alpha &= 1.3
\end{align*}
\]

Pulse shape with and without shock spike

The neutron yield increases considerably when a shock is launched at the end of the pulse.
Plastic-shell implosions with a shock-ignition pulse shape show larger yield and higher compressibility.

- YOC is the measured yield divided by the 1-D predicted yield.
- Hot-spot convergence ratio: ratio of the original target radius to the compressed hot-spot radius.
High-energy petawatt lasers will extend ignition capabilities

- Backlighting of target implosions
- Fast ignition (reviewed by M. Key APS/DPP 06)

**OMEGA EP (2008)**

- 60-beam OMEGA

2 HEPW beamlines
2.6 $k_{JIR}$ each in 10 ps

**NIF ARC (2009)**

- Short-pulse seed laser system
- Preamplification and injection into the main chain
- 2 x 1.2 kJ one beamline
- 1 x 3.3 kJ one beam
- 13.2 kJ uni-phase quad

Redirection and compression of the beam near the Target Chamber

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*D. D. Meyerhofer (TO6.00001).
†M. Key, ECLIM (2006).
These are exciting times for inertial confinement fusion

- Experiments on Nova (previously) and OMEGA are developing the target-physics understanding.
- Recent OMEGA experiments have demonstrated ignition-relevant areal densities.
- New concepts will extend ignition possibilities.
- This talk reviewed direct-drive ICF progress.*
- After 35 years, the ICF community is ready to exploit advances in physics understanding and drivers, leading to ignition experiments on the National Ignition Facility (NIF).

The achievement of ICF ignition will change the fusion landscape.

*More ICF, see Lindl (SR1.00001).