Energy Coupling and Hot-Spot Pressure in Direct-Drive Layered DT Implosions on OMEGA

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Summary

A 50-Gbar hot-spot pressure and an increase in hydroefficiency have been demonstrated on OMEGA

• A hot-spot pressure of $P_{hs} = 56\pm7$ Gbar was inferred from x-ray and nuclear diagnostics in direct-drive layered DT implosions on OMEGA

• Cross-beam energy transfer* (CBET) was reduced by increasing the initial target diameter while keeping the laser beam size constant
  – as $R_{\text{beam}}/R_{\text{target}}$ was varied from 1.0 to 0.8, the hydroefficiency increased by $\sim40\%$ because of CBET reduction

• Low-mode distortion of the hot spot causes early truncation of the neutron rate and lower $P_{hs}$

A path to 100-Gbar hot-spot pressure on OMEGA and spherical-direct-drive (SDD) at the National Ignition Facility (NIF) is being developed.

Collaborators


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Outline

• 50-Gbar hot-spot pressure
• CBET reduction
• Effect of low-mode distortions on hot-spot pressure
• Path to 100 Gbar on OMEGA and direct drive on the NIF
• 50-Gbar hot-spot pressure
  • CBET reduction
  • Effect of low-mode distortions on hot-spot pressure
  • Path to 100 Gbar on OMEGA and direct drive on the NIF
The hot-spot pressure and convergence ratio required for ignition decreases with increasing energy coupled to the hot spot.

- Pressure threshold for ignition
  \[ P_{\text{th}} \sim \frac{1}{\sqrt{E_{\text{hs}}}} \]

- Generalized Lawson criterion
  \[ \chi = \frac{P_{\tau}}{P_{\tau_{\text{ign}}}} = (\rho R)^{0.61} \left( 0.24 \frac{Y^{16}}{M} \right)^{0.34} \]
  \[ \chi_{\text{OMEGA}} \rightarrow \chi_{\text{NIF}} \sim E^{0.37} \]

Direct-drive ignition: \( \text{CR}^\dagger > 22 \) and \( P_{\text{hs}} > 120 \) Gbar.
X-ray-drive ignition: \( \text{CR} = 30 \) to 40 and \( P_{\text{hs}} > 350 \) Gbar.

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\( ^\dagger \text{R. Betti et al., Phys. Rev. Lett. 114, 255003 (2015); A. R. Christopherson, CI3.00006, this conference (invited).} \)

\( ^\ddagger \text{R. Betti et al., Phys. Plasmas 17, 058102 (2010).} \)

\( ^\star \text{CR: convergence ratio} \)
Layered DT targets were imploded on OMEGA for the 50-Gbar campaign*

Target-design parameters

- $V_{\text{imp}} = 3.6 \text{ to } 3.8 \times 10^7 \text{ cm/s}$
- $\alpha = 2.5 \text{ to } 4.5$
- $\text{CR} = 20 \text{ to } 23$
- $\text{IFAR}^{**} = 15 \text{ to } 25$

$\alpha = \frac{P}{P_F}$

IFAR = shell radius/ shell thickness

Sources of low-mode drive nonuniformity

1. Laser beam power imbalance (15% to 20%)
2. Target offset (5 to 30 $\mu$m)
3. Laser beam mispointing (10-$\mu$m rms)

OMEGA layered DT implosions are hydrodynamically scaled from the NIF direct-drive–ignition design.

*V. N. Goncharov et al., UO4.00005, this conference.

**IFAR: in-flight aspect ratio
Improvements to the laser, target, and diagnostics were required to increase $P_{hs}$ on OMEGA

- **Laser**
  - SG5 phase plates (820 $\mu$m diameter, 95% energy encircled)
  - multipulse driver [more energy on target, apply smoothing by spectral dispersion (SSD) to pickets only]
- **Target—Isotope Separator System**
  - D:T is 50:50 at the inner ice layer and gas vapor with <0.1% H
- **Diagnostics**
  - high-temporal (30-ps) and spatial-resolution (6-$\mu$m) Kirkpatrick–Baez microscope (KBframed)
  - neutron temporal diagnostic with 40-ps temporal response (P11NTD)
A new set of phase plates designed to improve the on-target drive uniformity were developed for this campaign.

$$I \sim \exp\left[\left(-\frac{r}{r_0}\right)^n\right]$$

Log scale of far field from previous SG4 equivalent-target-plane (ETP) image

Log scale of far field from new SG5 equivalent-target-plane (ETP) image
The 16-channel, gated, Kirkpatrick–Baez microscope (KBframed) measures the evolution of the hot-spot size around stagnation.

OMEGA cryogenic DT target implosion, shot 76828

$\begin{align*}
\text{t} & = 2.717 \text{ ns} \\
\text{t} & = 2.729 \text{ ns} \\
\text{t} & = 2.766 \text{ ns} \\
\text{t} & = 2.774 \text{ ns} \\
\text{t} & = 2.786 \text{ ns} \\
\text{t} & = 2.792 \text{ ns} \\
\text{t} & = 2.811 \text{ ns} \\
\text{t} & = 2.825 \text{ ns} \\
\text{t} & = 2.838 \text{ ns} \\
\text{t} & = 2.855 \text{ ns}
\end{align*}$

100 × 100-μm regions

Relative x-ray intensity

KBframed has 30-ps temporal resolution and 6-μm spatial resolution, and records an image every 15 ps in the 4- to 8-keV photon-energy range.


*PSF: point spread function
The neutron rate is recorded with the neutron temporal diagnostic (NTD*).

P11NTD can measure a minimum burnwidth of 50 ps with a 10% accuracy and absolute bang time ±25 ps (signal-to-background is ~100).

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** IRF: instrument response function
A primary DT neutron yield up to $\sim 5 \times 10^{13}$ with a $\rho R$ of $\sim 200$ mg/cm$^2$ has been recorded.

Yield-over-clean (YOC) $\equiv$ measured $Y/1$-D $Y = 0.2$ to $0.6$

$\rho$ROC $\equiv$ measured $\rho R/1$-D $\rho R = 0.5$ to $1$

$T_i = 2.7$ to $3.8$ keV
A hot-spot pressure of $56\pm7$ Gbar was inferred from nuclear and x-ray diagnostics assuming isobaric hot spot*

$$N_{\text{max}} = n_T n_D T^2 \int_{V_{\text{hs}}} \frac{dV\langle\sigma v\rangle}{T^2}$$

$$N_{\text{max}} = 2Y \sqrt{\ln 2/\pi} / \Delta t_{\text{burn}}$$

(assuming a Gaussian neutron rate with FWHM** = $\Delta t_{\text{burn}}$)

$$P_{\text{hs}} \simeq \left[ 8Y \sqrt{\ln 2/\pi} \left( \Delta t_{\text{burn}} \int_{V_{\text{hs}}} \frac{dV\langle\sigma v\rangle}{T^2} \right) \right]^{1/2}$$

**FWHM: full width at half maximum

$T(r) = T_c \left[ 1 - \left( r / R_{\text{hs}} \right)^2 \left( 1 - 0.15^{3/2} \right) \right]^{2/3}$

$T_c$ is the maximum hot-spot temperature

$$\left< T_i \right>_n = \left( \int_{V_{\text{hs}}} \frac{dV\langle\sigma v\rangle}{T} \right) \left/ \int_{V_{\text{hs}}} \frac{dV\langle\sigma v\rangle}{T^2} \right.$$}

$R_{\text{hs}} = 1.06 R_{17}$

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**OMEGA cryogenic target shot 77066**

$R_{17} = 22.0\pm0.4 \mu m$ (KBframed + framed pinholes)

$Y = 4.0 \times 10^{13}$

$\Delta t_{\text{burn}} = 63\pm5$ ps (x rays), $67\pm5$ ps (neutrons), 66 ps (1-D)

$\langle T_i \rangle_n = 3.2\pm0.4$ keV

$P_{\text{hs, exp}} = 56\pm7$ Gbar

$P_{\text{hs, 1-D}} = 90$ Gbar

$\alpha = 3.3$

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**FWHM: full width at half maximum
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• Path to 100 Gbar on OMEGA and direct drive on the NIF
$R_b/R_t$ was varied from 1.0 to 0.8 by changing the target diameter to reduce CBET*

The target diameter is varied from 800 to 1000 $\mu$m, while keeping the laser beam size constant, to reduce CBET.

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CBET modeling is required in the 1-D simulation to match the measurements*

Outside diameter (OD) = 805 μm
\[ I = 1.1 \times 10^{15} \text{ W/cm}^2 \]
\[ f_{\text{abs, expt}} = 54 \pm 6\% \]
\[ f_{\text{abs, 1-D with CBET}} = 52\% \]
\[ f_{\text{abs, 1-D without CBET}} = 71\% \]

• Absorption reduced 27% by CBET

Outside diameter (OD) = 1017 μm
\[ I = 0.7 \times 10^{15} \text{ W/cm}^2 \]
\[ f_{\text{abs, expt}} = 75 \pm 2\% \]
\[ f_{\text{abs, 1-D with CBET}} = 77\% \]
\[ f_{\text{abs, 1-D without CBET}} = 92\% \]

• Absorption reduced 16% by CBET

The effect of CBET is reduced for the larger target.

CBET modeling is required in the 1-D simulation to match the measurements*.

The measured shell trajectory constrains the model during the acceleration phase.

CBET modeling is required in the 1-D simulation to match the measurements*

The measured neutron rate shows deviation from the 1-D prediction near stagnation.

More kinetic energy is coupled to the larger target because of a reduction in CBET

\[ V_{\text{imp, 1-D}} = 3.6 \times 10^7 \text{ cm/s for both designs} \]

**EKE shell (1-D)** = 1.3 kJ

1-D simulations agree with the measured shell trajectories; energy coupling to the imploding shell is taken from the 1-D simulation.
An ~40% increase in the hydrodynamic efficiency was inferred because of a reduction in CBET.
The observed increase in energy coupling with target diameter does not result in a higher hot-spot pressure.

The peak hot-spot pressure of $56 \pm 7$ Gbar inferred for the smaller targets corresponds to 50% to 65% of the 1-D prediction.
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Three-dimensional simulations predict early burn truncation because of low-mode ($\ell \leq 5$) hot-spot distortion growth.

Larger targets have a higher level of low-mode drive nonuniformity because of reduced beam overlap.

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**Perturbation sources**
- 15% rms laser power imbalance
- 20-\(\mu\)m target offset
- 10-\(\mu\)m rms laser beam mispointing

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*I. V. Igumenshchev et al., UO4.00015, this conference.*
The measured neutron rate shows burn truncation similar to the 3-D simulation. The measured rising slope deviates from the 1-D prediction around $10^{23}$ s$^{-1}$ and the peak measured neutron rate is 36% of the 1-D value.
The measured neutron rate shows the onset of burn truncation occurs earlier for the larger targets.

The measured rising slope deviates from the 1-D prediction around $10^{22}$ s$^{-1}$ and the peak measured neutron rate is 15% of the 1-D value.
The 1-D predictions are closer to the inferred $P_{hs}$ and $\rho R$ in implosions with $CR < 17$ and $\alpha > 3.5$ when burn truncation is included in the analysis.

Low-mode distortion of the hot-spot is the primary factor degrading target performance for the high-adiabat OMEGA DT cryo implosions.
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The National Direct-Drive Program has four elements

1. Hydro-equivalent implosions on OMEGA
   - demonstration and physics understanding of ignition-relevant hot-spot pressure (100 Gbar)
   - OMEGA experiments will also demonstrate laser-plasma interaction (LPI) control (CBET mitigation: laser-beam zooming, wavelength detuning, preheat mitigation) strategies

2. LPI, energy coupling, imprint mitigation at MJ-scale plasmas on the NIF
   - will involve both planar and implosion platforms

3. Strategy for conversion of the NIF to SDD
   - cost, schedule, phased approach
   - laser technology development

4. Robust target designs for a range of performances

The National Direct-Drive strategy involves multiple laboratories.
Summary/Conclusions

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