Cross-Beam Energy Transfer Mitigation in Cryogenic Implosions on OMEGA

3-D ASTER simulation mass-density map

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Summary

Increased hydrodynamic efficiency by mitigating cross-beam energy transfer (CBET) has been demonstrated in cryogenic implosions on OMEGA

• Target illumination with a focal spot size smaller than the target size ($R_b/R_t < 1$) was used to mitigate CBET; the target size varied from $R_t = 400\ \mu m$ to $500\ \mu m$ to reduce $R_b/R_t$

• Current cryogenic implosions on OMEGA have reached $P_{hs} = 56\pm7$ Gbar ($P_{hs}^{ign} > 120$ Gbar); implosions with convergence ratio (CR) < 17 and $\alpha > 3.5$ proceed close to 1-D prediction ($CR_{ign} > 22$)

• Improving target performance with $R_b/R_t < 1$ on OMEGA will require reducing long-wavelength nonuniformity seeded by power imbalance and target offset
Collaborators


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The hot-spot pressure in an ignition design must exceed a threshold value

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

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

Current high-foot indirect drive
- Required: \( P_{hs} = 350 \text{ to } 400 \text{ Gbar} \)
- Achieved: \( P_{hs} = 230 \text{ Gbar} \)

\( \chi_{\text{no}} \alpha \sim 0.7 \)

Energy-scaled current OMEGA (\( E_{hs} = 0.44 \text{ kJ} \))
- Required: 140 Gbar
- Achieved: 56±7 Gbar

\( \chi_{\text{no}} \alpha \) (energy scaled) \( \sim 0.7 \)

Mitigated CBET

Direct-drive designs are in a less-challenging hydrodynamic regime with CR \( \leq 22 \) and \( P_{hs} > 120 \text{ Gbar} \); indirect-drive–ignition targets require CR = 30 to 40 and \( P_{hs} > 350 \text{ Gbar} \).

The cryogenic implosion campaign on OMEGA was designed to demonstrate enhanced laser coupling by mitigating CBET.
Implosions with $R_b/R_t < 1$ reach a larger hydrodynamic efficiency

Simulations
- $R_b = 380 \, \mu m \quad R_b/R_t = 0.77$: experimental condition
- $R_b = 500 \, \mu m \quad R_b/R_t = 1.00$: test run
Current cryogenic implosions on OMEGA have reached $P_{\text{hs}} = 56 \pm 7$ Gbar

Typical error bar

$(\pm 300 \text{ eV} \ T_i, \pm 6 \text{ to } 10 \text{ ps} \ \Delta t_{\text{burn}}, \pm 0.2 \text{ to } 1 \text{ } \mu\text{m} \ R_{17})$

Yield $= \int_{\Delta t_{\text{burn}}}dt \int_{V_{\text{hs}}} n_D \ n_T \ (\langle \sigma v \rangle) \ dV$

Yield $\sim n_D \ n_T \ T_i^2 \ (\int_{V_{\text{hs}}} \frac{\langle \sigma v \rangle}{T^2} \ dV) \ \Delta t_{\text{burn}}$

Measured yield $\ P_{\text{hs}}^2$

Depends on measured $T_i$ and $V_{\text{hs}}$

Measured burnwidth

- Target yield and hot-shot pressure degrade (relative to 1-D predictions) with an increase in target diameter and a reduction in $R_b/R_t^*$

* S. P. Regan et al., Cl3.00005, this conference (invited)
Long-wavelength modes \((1 < \ell < 5)\) cause a reduction in peak pressure and burn truncation.

On-target nonuniformities caused by beam geometry, power imbalance, beam mispointing.

Illumination nonuniformity
3-D solid-sphere projection

\textbf{ASTER* 3-D simulation of a CR = 20 cryogenic implosion \(R_b/R_t = 0.75\) (10-\(\mu\)m offset, 15% power imbalance, 10-\(\mu\)m rms mispointing)}

\begin{itemize}
\item Peak neutron production in 3-D
\item Time of peak neutron production in 1-D; bubble burst causes drop in \(P_{hs}\) and burn truncation
\end{itemize}

The nonuniformity spectrum shifts to more-damaging shorter wavelengths for smaller \(R_b/R_t\) (larger \(R_t\)).

I. V. igumenshchev et al., UO4.00015, this conference.
Three-dimensional simulations predict an early burn truncation because of long-wavelength, hot-spot distortion growth.
Measurements show earlier peak burn and burn truncation

Pressure evolves on an \(~100\)-ps time scale; a tens of picoseconds shift in the temporal sampling region makes a significant difference in the inferred pressure.
When the measured burn rate is included in the analysis, inferred $P_{hs}$ and $\rho R$ agree with 1-D predictions in implosions with CR < 17 and $\alpha > 3.5$.

Because of a reduced beam overlap, long-wavelength nonuniformity increases with a reduction in $R_b/R_t$, truncating burn earlier and reducing the observed $P_{hs}$. Reducing beam power imbalance and target offset are required to improve the target performance with $R_b/R_t < 1$. 
Increased hydrodynamic efficiency by mitigating cross-beam energy transfer (CBET) has been demonstrated in cryogenic implosions on OMEGA

- Target illumination with a focal spot size smaller than the target size \(\left(\frac{R_b}{R_t} < 1\right)\) was used to mitigate CBET; the target size varied from \(R_t = 400\ \mu\text{m}\) to \(500\ \mu\text{m}\) to reduce \(\frac{R_b}{R_t}\).

- Current cryogenic implosions on OMEGA have reached \(P_{hs} = 56\pm7\ \text{Gbar}\) \(\left(P_{hs}^{\text{ign}} > 120\ \text{Gbar}\right)\); implosions with convergence ratio \(\left(\text{CR} < 17\right)\) and \(\alpha > 3.5\) proceed close to 1-D prediction \(\left(\text{CR}^{\text{ign}} > 22\right)\).

- Improving target performance with \(\frac{R_b}{R_t} < 1\) on OMEGA will require reducing long-wavelength nonuniformity seeded by power imbalance and target offset.