Crossed-Beam Energy Transfer for Direct-Drive Implosions

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Simulations with CBET
Simulations without CBET
Measurements

Scattered-light fraction

$R_{\text{beam}} / R_{\text{target}}$

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Summary

Crossed-beam energy transfer (CBET) can reduce the performance of direct-drive ICF implosions

- CBET is observed in time-resolved reflected-light spectra as a suppression of red-shifted light during the main laser drive
- CBET extracts energy from the center-beam incoming light and transfers it to outgoing light, reducing the laser absorption and hydrodynamic efficiency
- CBET can be reduced
  - using beams smaller than the target diameter
  - using laser beams with two or more colors

Mitigation strategies are being tested on OMEGA.
Collaborators


Laboratory for Laser Energetics
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L. Divol and P. Michel
Lawrence Livermore National Laboratory
Outline

- Introduction
- Modeling CBET
- CBET in symmetric OMEGA implosions
- Mitigation of CBET: experiments and simulations
- Conclusions
Scaled-down implosion experiments on OMEGA are used to validate direct-drive NIF implosion designs.

Symmetric NIF ignition design*
(1-D gain = 50)

OMEGA targets

\[ E = 1.5 \text{ MJ} \]

\[ E = 20 \text{ kJ} \]

\[ E = 16 \text{ kJ} \]

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Experiments on OMEGA have been modeled using hydrodynamic codes *LILAC* and **DRACO**

- Radiation transport package
  - multi-group diffusion
- Equation-of-state package
  - *SESAME*
  - QEOS
- Laser absorption package
  - inverse bremsstrahlung
- Thermal transport package
  - flux-limited transport
  - nonlocal transport**

Measured bang time is late by ~200 ps, indicating reduced laser coupling.
Simulations overpredict the red-shifted scattered light

Time-resolved scattered-light spectra from a spherical implosion
Simulations overpredict the red-shifted scattered light

Time-resolved scattered-light spectra from a spherical implosion

- Blocking the central portion of the beam in the simulations reproduces the observed spectrum
CBET can be responsible for the discrepancy between experiments and simulations

- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light*
- The transferred light bypasses the highest absorption region near the critical surface*

CBET reduces laser absorption and hydrodynamic efficiency.**

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The CBET numerical algorithm considers pairwise interactions of light rays

\[
\frac{dI_i}{d\ell} = -\sum_j I_i \times L_{ij}^{-1}
\]

\[
L_{ij}^{-1} = I_j \times \frac{e^2 \lambda_L}{m^2 c^3} \frac{k_a^2}{\omega_{pe}^2} \frac{n_e/n_{cr}}{\sqrt{1 - n_e/n_{cr}}} Im \left[ \frac{X_e (1 + X_i)}{1 + X_e + X_i} \right]
\]

\[
\omega_a = \omega_{\text{probe}} - \omega_{\text{pump}} \\
\bar{k}_a = \bar{k}_{\text{probe}} - \bar{k}_{\text{pump}} \left\{ \text{Three-wave matching condition} \right\}
\]

- The CBET model*† is implemented in LILAC absorption package assuming spherical symmetry**

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An ion-acoustic wave saturation model is required to match the scattered-light power for intensities \( I \gtrsim 4 \times 10^{14} \text{ W/cm}^2 \)

- The amplitude of ion-acoustic waves is limited by clamping electron-density fluctuations

\[
\frac{dI_i}{d\ell} = \sum_j F(\omega_a, \tilde{k}_a, n_e, T_e, \ldots) \left( \frac{\delta n}{n_e} \right)_{ij} \times \sqrt{I_i I_j}
\]

\[
\left( \frac{\delta n}{n_e} \right)_{ij} = G(\omega_a, \tilde{k}_a, n_e, T_e, \ldots) \times \sqrt{I_i I_j}
\]

\[
\left( \frac{\delta n}{n_e} \right)_{ij} = \min \left\{ \left( \frac{\delta n}{n_e} \right)_{\text{clamp}}, \left( \frac{\delta n}{n_e} \right)_{ij} \right\}
\]

- The value of the clamping parameter \((\delta n/n_e)_{\text{clamp}}\) is determined by fitting the simulation results with the scattered-light measurements
  - for CH ablators: \((\delta n/n_e)_{\text{clamp}} \approx 0.1\%\)

*P. Michel et al., Phys. Rev. Lett. 102, 025004 (2009).*
Outline

- Introduction
- Modeling CBET
- **CBET in symmetric OMEGA implosions**
- Mitigation of CBET: experiments and simulations
- Conclusions
Simulations including CBET agree well with scattered-light spectral measurements

Time-resolved scattered-light spectra from a spherical implosion

CBET extracts the energy from the center-beam incoming rays and transfers it to outgoing rays.
CBET reduces the absorption by \(~10\%\), but the implosion hydrodynamic efficiency is reduced by \(~20\%\).
Laser coupling at intensities up to $I \sim 6 \times 10^{14} \text{ W/cm}^2$ is accurately predicted by the CBET model.
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The accuracy of the CBET model was demonstrated using OMEGA implosions with different pulse shapes and targets.
High-intensity implosions ($I \sim 10^{15}$ W/cm$^2$) show disagreements with the CBET model.

The missing scattered light may be caused by
  - two-plasmon-decay instability*
  - enhanced absorption in laser hot spots**

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* W. Seka, U06.00005
** A. V. Maximov, UO6.00007
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CBET can be mitigated in symmetric direct-drive implosions by reducing the energy in beam edges.
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Simulations suggested an optimum neutron yield can be achieved on OMEGA by reducing the laser beam to $R_{\text{beam}}/R_{\text{target}} \sim 0.8$.

* $R_{\text{beam}}$ defined at 95% energy
Experiments* on OMEGA are investigating the optimum laser-beam diameter by balancing CBET with nonuniformities in low-adiabat implosions.

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**Fixed targets**

Small phase plates

Beam profiles for different defocusing

<table>
<thead>
<tr>
<th>$R_{\text{beam}}/R_{\text{target}}$</th>
<th>Normalized intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>0.7</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>0.5</td>
<td>$10^{-1}$</td>
</tr>
</tbody>
</table>

**Fixed beams**

Standard SG4 phase plates

<table>
<thead>
<tr>
<th>$R_{\text{beam}}/R_{\text{target}}$</th>
<th>Beam profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>860 μm</td>
</tr>
<tr>
<td>0.87</td>
<td>950 μm</td>
</tr>
<tr>
<td>0.83</td>
<td>1000 μm</td>
</tr>
</tbody>
</table>

$I \approx 4.5 \times 10^{14} \text{ W/cm}^2$

**Not optimal single-beam uniformity**

**Optimal single-beam uniformity**

*D. Froula, UO6.00009*
Experiments with small beams recover the red-shifted part of the spectrum.
The scattered light decreases rapidly with reduced beam size.

Less CBET

Simulations with CBET

Simulations without CBET

Measurements

Scattered-light fraction vs. $R_{\text{beam}}/R_{\text{target}}$
The increased absorption results in earlier bang time.

Bang time shifts ~20% earlier, indicating increasing hydro efficiency.
Higher implosion velocities are achieved with smaller beams.

Predicted effects of small beams are consistent with scattered-light, bang-time, and shell trajectory measurements.
Smaller beams introduce more nonuniformities caused by the laser-beam geometry

X-ray framing-camera images at the same target radius

- For beam radii < 70% to ~80% of the target radius, significant nonuniformities develop
- Neutron yields in these experiments are affected by single-beam nonuniformities
Experiments* on OMEGA are investigating the optimum laser-beam diameter by balancing CBET with nonuniformities in low-adiabat implosions.

**Fixed beams**

Standard SG4 phase plates

- $R_{\text{beam}}/R_{\text{target}} = 0.97$
- $R_{\text{beam}}/R_{\text{target}} = 0.87$
- $R_{\text{beam}}/R_{\text{target}} = 0.83$

*D. Froula, UO6.00009
Neutron yield sensitivity was addressed in experiments with varying target size.

Experiments demonstrate beneficial effects of reducing beam sizes.
CBET can be mitigated by using multiple-color laser beams

Separation of the wavelengths by $\Delta \lambda > \lambda_L(c_a/c) \sim 5 \text{ Å}$ (for a 351-nm laser) reduces the CBET by a factor of 2.
Future work

- Implementation of the CBET model in 2-D* to simulate polar-drive designs
- Using truncated phase plates to mitigate CBET
- Optimization of phase plates for polar drive when including CBET

*J. A. Marozas, PO8.00003
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