Modeling Crossed-Beam Energy Transfer in Implosion Experiments on OMEGA

Simulated laser absorption

\[ dE/dV \text{ (relative units)} \]

Without SBS

With SBS

\[ n_c/4 \]

\[ n_c \]

\[ R (\mu m) \]

Laser

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Inclusion of crossed-beam energy transfer in simulations of OMEGA implosions significantly improves agreement with absorption and timing data

- A self-consistent algorithm* for crossed-beam energy transfer has been developed and implemented in the radiative-hydrodynamic code LILAC

- Simulations show significant beam-to-beam energy transfer that reduces the laser absorption and requires a modification of the thermal transport model

- Efficient light scattering occurs in the regions with $n_e \sim 0.1$ to $0.5 \ n_c$ and involves mainly light from the central part of the laser beam**

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*See D. H. Edgell (JO5.00014).
**See A. Shvydky (UO5.00009).
Collaborators

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Beam-to-beam energy transfer in direct-drive implosions occurs near the transonic \((M = 1)\) region

- The transfer takes place through the stimulated Brillouin scattering (SBS) process.
- Incoming light (Ray 1) typically loses energy.
- Outgoing light (Ray 2) typically gains energy.
- The reflected light bypasses the highest absorbed region near the turning point that can significantly reduce the overall energy absorption and target drive.
The model of energy transfer between two crossing laser beams involves a steady resonantly induced ion-acoustic wave.

\[
\begin{align*}
\vec{k}_1 &= \vec{k}_2 + \vec{k}_a \\
\omega_1 &= \omega_2 + \omega_a
\end{align*}
\]

\(I^{(1)}\) – probe-beam intensity  
\(I^{(2)}\) – pump-beam intensity

Beam intensity change due to SBS:

\[
I^{(1)} = I_0^{(1)} \exp \left( \eta \int L^{-1} d\ell \right); \quad \eta = 0 - 1
\]

\[
L^{-1} = 3 \times 10^2 \frac{n/n_c}{(1-n/n_c)} \frac{\lambda_{\mu m}I_{14}^{(2)}}{f(Z)T_{keV}} \frac{P(\chi)}{\tilde{\nu}_a} \text{ cm}^{-1}
\]

\[
P(\chi) = \frac{\tilde{\nu}_a^2 \chi}{\tilde{\nu}_a^2 \chi^2 + (1-\chi^2)^2}; \quad \chi = -\frac{\omega_a}{k_a c_a} + \frac{\vec{k}_a \cdot \vec{u}}{k_a c_a}
\]

Damping coefficient: \(\tilde{\nu}_a = \frac{\nu_a}{k_a c_a} \approx 0.2\) (CH plasma)

Scattered-light simulations include the integral effect of all crossed beams and consider the 3-D distribution of ray trajectories

- Plasma flow is assumed to be spherically symmetric (1-D)
- An infinite number of laser beams (instead of OMEGA’s 60 beams) are assumed to be uniformly distributed over the sphere
- Each beam is characterized by a super-Gaussian profile with the index $n = 4$ (OMEGA SG4 phase plates)
- Energy conservation is enforced by normalizing the total energy gain of outgoing rays with respect to the total energy loss of incoming rays
Simulations show that less energy is absorbed near the critical surface due to SBS effects.

Absorption and transferred energy rates at $t = 0.5$ ns

- Plastic-shell target
- 1-ns square pulse
- $I \approx 10^{15}$ W/cm$^2$

Reflected light bypasses the highest absorption region eliminating the absorption peak.
Results of implosion simulations with SBS effects have demonstrated a good agreement with bang-time and laser absorption measurements.

A sample of 1-ns square pulse, warm plastic-shell implosions

- Bang-time difference (ps)
- Absorption fraction difference

Energy (kJ) vs. Energy (kJ)

○ Standard flux limiter ($f = 0.06$) without SBS ($\eta = 0$)
Results of implosion simulations with SBS effects have demonstrated a good agreement with bang-time and laser absorption measurements.

A sample of 1-ns square pulse, warm plastic-shell implosions

![Graph showing bang-time difference and absorption fraction difference vs. energy.]

- Bang-time difference (ps)
- Absorption fraction difference

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>Bang-time difference</th>
<th>Absorption fraction difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>16.2</td>
<td>22.6</td>
</tr>
<tr>
<td>22.9</td>
<td>23.1</td>
<td>23.3</td>
</tr>
<tr>
<td>23.4</td>
<td>24.1</td>
<td>24.1</td>
</tr>
<tr>
<td>23.5</td>
<td>23.0</td>
<td>23.0</td>
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</tr>
<tr>
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<tr>
<td>23.8</td>
<td>24.1</td>
<td>24.1</td>
</tr>
<tr>
<td>24.1</td>
<td>27.0</td>
<td>29.0</td>
</tr>
</tbody>
</table>

- ○ Standard flux limiter ($f = 0.06$) without SBS ($\eta = 0$)
- ● Nonlocal model* without SBS ($\eta = 0$)

Results of implosion simulations with SBS effects have demonstrated a good agreement with bang-time and laser absorption measurements.

A sample of 1-ns square pulse, warm plastic-shell implosions

- **Standard flux limiter** ($f = 0.06$) without SBS ($\eta = 0$)
- **Nonlocal model** without SBS ($\eta = 0$)
- **Nonlocal model** with SBS ($\eta = 0.5$)

SBS effects enhance the late-time reflection of laser light in agreement with experimental data.
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Reflection-light measurement and simulation for OMEGA shot 53309 (warm plastic-shell target)

\[ I \sim 7 \times 10^{14} \text{ W/cm}^2 \]
Time-resolved experimental spectra of scattered light are better explained by models with SBS effects.

1-ns square pulse, warm plastic-shell implosion (OMEGA shot 50601)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Time (ns)</th>
<th>Experiment</th>
<th>log₁₀(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>351.2</td>
<td>0.0</td>
<td>Shot 50601</td>
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<tr>
<td>351.0</td>
<td>0.4</td>
<td></td>
<td>2</td>
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<td>350.8</td>
<td>0.8</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>350.6</td>
<td>1.2</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Simulations

- Standard LILAC
  - Underestimated initial blue-shift
  - Incorrect overall shape

- Nonlocal with SBS
  - Correct initial blue-shift*
  - Correct later-time red-shift due to SBS

Summary/Conclusions

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