Two-Plasmon–Decay Scaling for Improved-Performance Cryogenic Implosion Strategies

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Summary

Hot-electron production at the Omega Laser Facility scales empirically with the two-plasmon–decay (TPD) common-wave gain and can guide experimental design.

- The TPD common-wave scaling indicates that cross-beam energy transfer (CBET) reduces the hot-electron production in current OMEGA cryogenic implosions by an order of magnitude.
- If CBET is mitigated to achieve ignition hydrodynamic equivalence then TPD mitigation will likely be required.
- The TPD scaling predicts that mitigation with mid-Z layers will reduce the hot-electron production in advanced OMEGA cryogenic implosions.
Collaborators

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Ice-layer preheat from hot electrons must be kept below 0.04% of the laser energy for ignition

• Theory suggests that TPD will vary as $I \cdot L_n / T_e$ at $n_e / 4$
  – $I =$ laser intensity
  – $L_n =$ density scale length
  – $T_e =$ electron temperature
• TPD transfers laser energy to Langmuir waves that produce hot electrons

Calculations suggest that the fraction of laser energy converted to hot electrons should be kept low*.

The common-wave gain provides a useful empirical scaling that unifies different experimental geometries.*

- Intensity was scanned during each study.
- During these intensity scans, $L_n/T_e$ differed between studies but was roughly constant within each scan.

The maximum TPD growth rate is driven by beams with a common angle to the electron plasma wave (EPW)

• Experiments suggest that TPD is driven by multiple beams*

• Linear theory shows that a resonant EPW is shared by multiple beams in the region bisecting the wave vectors of the beam**

• A hydrodynamic post-processing code finds the maximum gain from all possible beam groups at each point in the quarter-critical surface
  – ray tracing finds the intersection of the beams with the quarter-critical surface (positions and \( k \) vectors) and their intensities (including CBET)

\[
G_c \approx \frac{I_\Sigma (W/cm^2)L_n (\mu m)}{T_e (keV)} \times 10^{-16}
\]

CBET significantly lowers the single-beam peak intensity that reaches the quarter-critical surface.

Single-beam intensity at $n_c/4$ surface

No CBET

$I_{\text{max}} = 9.1 \times 10^{13} \text{ W/cm}^{-2}$

With CBET

$I_{\text{max}} = 6.4 \times 10^{13} \text{ W/cm}^{-2}$

30% reduction in peak intensity from CBET
CBET significantly lowers the common-wave gain and changes its distribution across the target surface.

**Maximum common-wave gain**

Without CBET:
\[ G_{\text{max}} = 3.8 \]

With CBET:
\[ G_{\text{max}} = 2.3 \]

If CBET is mitigated,* hot-electron production could increase.

*D. H. Froula et al., this conference.*
CBET mitigation strategies based on reduced beam size are being evaluated for implementation on OMEGA*

- CBET typically results in transfer of power from the center of the ingoing beam to the edge of the outgoing beam.
- Decreasing the beam profile diameter reduces the edge seed that takes power from the ingoing beams.

Power transferred in/out of beamlets is integrated along the path of each beamlet.

Net CBET along beamlets

\[ \sum_s dP_{\text{CBET}} \]

Net gain

Net loss

*D. H. Froula et al., this conference.
Experiments have shown that reducing the beam radius increases the hot-electron production.
A hydro-equivalent experiment on OMEGA will likely require TPD mitigation.

If CBET mitigation is needed to get a stable hydro-equivalent implosion, the TPD gain and hot-electron production will increase.

- Standard cryo: $G = 2.3$
- Full-aperture zooming: $G = 4.8$
- $0.8 \, R_t$: $G = 3.3$

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Multilayer targets are designed to reduce TPD by increasing the temperature at quarter critical.

**Reduced imprint**

**Increased rocket efficiency**

**Reduced laser–plasma instability (LPI)**

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Experimental tests of multilayer targets produced many fewer hot electrons than CH targets.

- The higher coronal temperatures in the mid-Z layer reduce the TPD-produced hot electrons.

\[ G_{\text{max}} = 2.9 \quad f_{\text{hot}} \approx 0.02\% \]

\[ G_{\text{max}} = 2.1 \quad f_{\text{hot}} \approx 0.2\% \]
Mid-Z multilayers are predicted to significantly reduce hot-electron production

Standard cryo design
SG4s, 26 kJ

Multilayer cryo design
SG4s, 25 kJ

$G_{max} = 2.3$
$f_{hot} \rightarrow 0.035\%$

$G_{max} = 1.6$
$f_{hot} \rightarrow 10^{-4}\%$
A new pulse shape with a high-intensity peak at the end of the pulse is being studied for cryo.

- Putting more of the drive pressure at the end of the pulse improves performance by delaying shell deceleration.

25 kJ, $P_{\text{max}} = 30$ TW
The proposed cryo pulse shape is predicted to keep the gain and electron production acceptably low.

New pulse shape cryo design
SG4s, 26 kJ

$G_{\text{max}} = 2.7$
$f_{\text{hot}} \rightarrow 0.13\%$

Multilayer with new pulse shape
SG4s, 27 kJ

$G_{\text{max}} = 1.8$
$f_{\text{hot}} \rightarrow 0.001\%$
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