Laser–Plasma Interaction Experiments at Direct-Drive Ignition-Relevant Scale Lengths at the National Ignition Facility

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optical spectrometer (SRS)

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Planar and spherical experiments at the National Ignition Facility (NIF) have investigated laser–plasma interaction (LPI) hot-electron production and coupling at direct-drive ignition-relevant coronal conditions

Summary

- Planar experiments achieve scale lengths of $L_n \sim 400$ to $700 \ \mu m$, electron temperatures of $T_e \sim 3$ to $5 \ \text{keV}$, and laser intensities of $0.5$ to $1.5 \times 10^{15} \ \text{W/cm}^2$

- Hot-electron generation of the order of $f_{\text{hot}} \sim 0\%$ to $3\%$ and $T_{\text{hot}} \sim 50 \ \text{keV}$ has been observed

- Stimulated Raman scattering (SRS) is inferred to be the dominant LPI mechanism, although recent measurements ($3\omega/2$) have uncovered evidence of two-plasmon decay (TPD) as well

- Recent spherical experiments have diagnosed hot-electron coupling (preheat) to an implosion and estimate a wide angular divergence
Collaborators


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Direct-drive ignition designs predict long density scale lengths and high electron temperatures at which LPI may generate hot-electron preheat. Experiments must be performed at these conditions to understand LPI at the NIF ignition scale.

- Electron density \((\text{cm}^{-3})\)
- Electron temperature (keV)

1-D simulated plasma conditions for an igniting direct-drive design:

- Quarter-critical density: \(n_c/4\)
- Quarter-critical surface: \(I \sim 8 \times 10^{14} \text{ W/cm}^2\)
- Electron temperature: \(T_e \sim 4 \text{ keV}\)
- Laser intensity: \(I_n \sim 550 \mu\text{m}\)

Experiments must be performed at these conditions to understand LPI at the NIF ignition scale.
Planar experiments on the NIF were designed to achieve plasma conditions comparable to direct-drive ignition designs.

**Motivation**

Experiments must be performed at these conditions to understand LPI at the NIF ignition scale.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NIF ignition scale</th>
<th>NIF planar experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_n$ ($\mu$m)</td>
<td>500 to 600</td>
<td>400 to 700</td>
</tr>
<tr>
<td>$T_e$ (keV)</td>
<td>3.5 to 5</td>
<td>3 to 5</td>
</tr>
<tr>
<td>$I_L$ (W/cm$^2$)</td>
<td>(6 to 8) $\times 10^{14}$</td>
<td>(4 to 15) $\times 10^{14}$</td>
</tr>
</tbody>
</table>

A. A. Solodov et al., J06.00010, this conference.

Electron density ($\text{cm}^{-3}$)

Electron temperature (keV)

Radius (mm)

$I \sim 8 \times 10^{14} \text{ W/cm}^2$

$L_n \sim 550 \mu\text{m}$

$T_e \sim 4 \text{ keV}$

Quarter-critical density

Quarter-critical surface

$I \sim 8 \times 10^{14} \text{ W/cm}^2$

$L_n \sim 550 \mu\text{m}$

$T_e \sim 4 \text{ keV}$
Hot-electron generation of $f_{\text{hot}}$ up to 3% and $T_{\text{hot}}$ of 40 to 60 keV has been inferred in planar CH and Si targets at intensities around $10^{15}$ W/cm$^2$.

Intensity around $5 \times 10^{14}$ W/cm$^2$ may be acceptable for preheat, but we need to understand:

1. LPI mechanisms (for mitigation), and
2. how hot electrons diverge or couple to an implosion.

Optical data demonstrate different LPI physics on the NIF than on OMEGA—SRS dominates the scattered-light spectrum (both at and below $n_c/4$).

On the NIF, $\sim 5\%$ of laser energy is converted to SRS, consistent with the observed hot-electron fraction and suggestive of SRS being the dominant hot-electron source, although this does not rule out the presence of TPD.

$\text{NIF: } L_n = 525 \, \mu m$
$T_e = 4.5 \text{ keV}$

$\text{OMEGA: }^* L_n = 150 \, \mu m$
$T_e = 2.8 \text{ keV}$

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In addition to optical measurements, recent NIF experiments diagnosed $3\omega/2$ emission, which revealed evidence of TPD.

The $3\omega/2$ doublet is suggestive of some TPD activity, although this is consistent with a SRS-dominated regime.
A spherical-geometry platform has been implemented on the NIF to diagnose the coupling of hot electrons to an imploding shell.

Target designs*

Predicted NIF hard x-ray (HXR) data

LILAC simulations for $T_{\text{hot}} = 55$ keV, hot-electron divergence full angle of $2\pi$, Ge-doped target at 3.9%.

Difference in hard x-ray signals between mass-equivalent CH and multilayered implosions → hot-electron energy deposited in the inner shell layer.

Experiments demonstrate an identical SRS/hot-electron source and an $\sim 2\times$ enhancement of HXR signal in the doped targets.

Hard x-ray enhancement is consistent with a wide angular divergence and a small fraction of hot-electron energy coupled to the inner shell layer.

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Summary/Conclusions

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These results indicate a viable ignition-design space for direct drive.
Appendix
SRS observations correlate with hard x-ray measurements

Shot N171012-002

Time-resolved SRS and hard x-ray signal

Hot-electron fraction versus SRS signal at 30°

FFLEX: filter-fluorescer x-ray diagnostic
The dominance of SRS at the NIF scale may be partially explained by evaluating the absolute thresholds of SRS versus TPD.

The tolerable fraction of hot electrons generated (\(f_{\text{hot}}\)) depends on how the electrons couple to an implosion.

\[ f_{\text{hot}} \approx 0.7\% \]

\[ f_{\text{hot}} \approx 0.2\% \]