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

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48th Annual Anomalous Absorption Conference
Bar Harbor, ME
8–13 July 2018

$f_{\text{hot}}$ versus laser intensity at $n_c/4$

Shot N160420-003
optical spectrometer (SRS)

Laser intensity ($\times 10^{15}$ W/cm²)

Time (ns)

$\lambda$ (nm)

$\log_{10}$

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

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

- Hot-electron generation of the order of $f_{\text{hot}} \sim 0\%$ to 3\% and $T_{\text{hot}} \sim 50$ keV have been observed.
  - $I_{n_c}/4 \sim 5 \times 10^{14}$ W/cm$^2$ may be acceptable for preheat.

- 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.

- Upcoming spherical experiments will diagnose hot-electron coupling (preheat) to an implosion.
Collaborators


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Outline

• Motivation for direct-drive LPI experiments on the NIF and planar platform development
• Hot-electron results and LPI mechanisms: Predominantly SRS
• Future work: Hot-electron coupling
• Motivation for direct-drive LPI experiments on the NIF and planar platform development

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• Future work: Hot-electron coupling
The National Direct Drive Program is underway at OMEGA and the NIF to demonstrate the ignition physics of direct drive.

**Motivation**

OMEGA 100-Gbar Campaign: Demonstrate hot-spot pressure of 100 Gbar in hydro-scaled implosions.

NIF Megajoule Direct-Drive (MJDD) Campaign: Demonstrate laser–plasma coupling physics at the ignition scale.

The MJDD campaign is predominantly focused on understanding and mitigating: laser imprint, cross-beam energy transfer (CBET), and LPI/hot-electron preheat.
Motivation

Hot-electron preheat is a potential concern for direct-drive ignition designs

Limit of \(~0.15\%\) laser energy into fuel preheat; wide angular divergence*

Laser intensity attenuated by \(~2\times\) at \(n_c/4\)

LPI hot electrons, some enter the DT fuel (wide angular divergence, according to OMEGA experiments*)

Limit of \(~0.7\%\) laser energy into hot electrons generated.

Motivation

Direct-drive ignition designs predict long density scale lengths and high electron temperatures at which LPI may generate hot electrons.

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.

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

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

- $n_c/4$
- $I \sim 8 \times 10^{14}$ W/cm²
- $L_n \sim 550$ μm
- $T_e \sim 4$ keV

**NIF ignition scale**

- $L_n$ (μm): 500 to 600, 400 to 700
- $T_e$ (keV): 3.5 to 5, 3 to 5
- $I_L$ (W/cm²): $(6 \text{ to } 8) \times 10^{14}$, $(4 \text{ to } 15) \times 10^{14}$

* A. A. Solodov et al., this conference.
Based on simulated plasma conditions, and considering overlapped laser intensities, these experiments are well above LPI thresholds.

- Absolute instability thresholds for a single beam at normal incidence

  TPD *
  \[ I_{14,\text{thr,TPD}} = 230T_e \text{keV}/L_n \mu m \]
  \[ \eta_{\text{TPD}} = I_{\text{overlapped}}/I_{14,\text{thr,TPD}} \sim 3 \text{ to } 8 \]

  SRS **
  \[ I_{14,\text{thr,SRS}} = 2377/(L_n \mu m)^{4/3} \]
  \[ \eta_{\text{SRS}} = I_{\text{overlapped}}/I_{14,\text{thr,SRS}} \sim 10 \text{ to } 25 \]

- These experiments overlapped up to 64 beams (16 NIF quads)

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*A. Simón et al. Phys. Fluids 26, 3107 (1983).*

Two initial planar experiments were performed on the NIF to constrain plasma conditions.

Cross-beam energy transfer does not have a strong influence on conditions at $n_e/4$. 

**Shot N150520**: 23° and 30° beams (32 beams total)
- CH
- Mo layer
- Mn/Co microdot (for $T_e$)

**Shot N150521**: 45° and 50° beams (60 beams total)

2-D DRACO simulation: N150521 at 4 ns

- $n_e$ (cm$^{-3}$)
- $r$ ($\mu$m)
- $T_e$ (keV)

<table>
<thead>
<tr>
<th>$n_e$ (cm$^{-3}$)</th>
<th>$r$ ($\mu$m)</th>
<th>$T_e$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{22}$</td>
<td>1000</td>
<td>3</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>250</td>
<td>1</td>
</tr>
<tr>
<td>$10^0$</td>
<td>125</td>
<td>0</td>
</tr>
</tbody>
</table>

Power (TW)

Shot N150520: 23° and 30° beams (32 beams total)
- Total laser power

Shot N150521: 45° and 50° beams (60 beams total)
- Total laser power

Mo layer
- Mn/Co microdot (for $T_e$)
Microdot spectroscopy was used to infer electron temperatures around 3 keV, in reasonable agreement with DRACO modeling.

Time-resolved x-ray spectrum on shot N150520

<table>
<thead>
<tr>
<th>Photon energy (keV)</th>
<th>Time (ns)</th>
<th>Log_{10} (counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>0</td>
<td>2.0</td>
</tr>
<tr>
<td>6.5</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>7.0</td>
<td>4</td>
<td>3.0</td>
</tr>
<tr>
<td>7.5</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>8.0</td>
<td>8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Measured and modeled spectra at 2.5 ns on shot N150521

Spectral flux ($J/\text{keV/sr/ns}$) vs. Photon energy (keV)

$T_e$ inferred from spectral fitting versus DRACO-simulated $T_e$
In subsequent experiments at higher laser intensity, the wavelength of $\omega/2$ emission was used to infer $T_e \sim 4.5$ keV at $n_c/4$.

These results validate hydro modeling of the plasma conditions and demonstrate that ignition-relevant coronal temperatures are achieved.

$T_e \sim 4.5$ keV agrees with DRACO

$\Delta \lambda_{nm} = 3.09 \times T_{e,keV} - \delta \lambda_{Doppler} - \delta \lambda_{Dewandre}$

Outline

• Motivation for direct-drive LPI experiments on the NIF and planar platform development
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• Future work: Hot-electron coupling
Hard x-ray measurements have been used to infer $f_{\text{hot}}$ and $T_{\text{hot}}$ as functions of laser intensity in planar experiments.
$f_{\text{hot}}$ up to 3% and $T_{\text{hot}}$ of 40 to 60 keV are measured in CH and Si targets for $n_c/4$ intensities up to $1.3 \times 10^{15}$ W/cm$^2$; $5 \times 10^{14}$ W/cm$^2$ may be acceptable for preheat.

$f_{\text{hot}}$ is close to levels thought to be tolerable in direct-drive ignition designs; need to understand (1) LPI mechanisms (for mitigation), (2) coupling of hot electron to implosion (preheat).

* M. Rosenberg et al. Phys. Rev. Lett. 120, 055001 (2018); A. A. Solodov et al., this conference.
Scattered-light measurements to identify the hot-electron source were optimized by orienting the target normal to the optical diagnostics.

View along target normal is optimal for $\omega/2$ since most emission occurs within $\sim 10^\circ$ of normal\textsuperscript{*}.

If TPD is dominant, expect to see an $\omega/2$ doublet feature, as has been observed previously on OMEGA.\textsuperscript{*}

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, ~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.

SRS observations correlate with hard x-ray measurements

Shot N171012-002

Time-resolved SRS and hard x-ray signal

- Laser pulse total
- B315 SRS streak
- B365 SRS streak
- Q33B streak Ch2
- FFLEX Ch9

Hot-electron fraction versus SRS signal at 30°

Normalized signal

- Laser pulse total

Time (ns)

0
2
4
6
8
10
12

Normalized signal

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Hot-electron fraction versus SRS signal at 30°

- CH outers—after 4.5 ns
- CH inners—after 4.5 ns
- Si inners—after 4.5 ns

SRS signal/laser energy (arbitrary units)

0.00
0.02
0.04
0.06

Hot-electron fraction (%)

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
The dominance of SRS at the NIF scale may be partially explained by evaluating the absolute thresholds of SRS versus TPD

\[ \frac{I_{\text{thr,TPD}}}{I_{\text{thr,SRS}}} \]

Increasingly prone to SRS (relative to TPD)


Ramp-pulse experiments show thresholds and growth of both unsaturated “convective” SRS and saturated absolute SRS
Sidescatter is observed as one of several SRS mechanisms

Shot N160421-001

Optical streaked spectrometers

Observation at 50° can only be sidescatter.

Optical spectrometers

This observation is explained by tangential SRS sidescatter, * which allows for SRS observation at large angles and wavelength independent of drive-beam angle.

\[ n_e \text{ resonant for } \lambda_{\text{SRS}} \]

\[ k_{\text{SRS}} = k_0 + \nabla n_e \]

\[ \theta_{\text{out}} \]

Tangential sidescatter exit angle does not depend on the incidence angle.

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Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off.
Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off.

**Graph:**
- X-axis: Time (ns)
- Y-axis: Power (TW)
- Marked points: 45°, 50° (63 beams) and 23°, 30° (32 beams)

**Diagram:**
- CH: Q36B off and Q13B off
- Wavelength (nm): 550, 650, 750
- Time (ns): 0, 2, 4, 6, 8, 10

**Note:** Strong single-quad “self-sidescatter” for outer beams.
Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off.
Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off.
In addition, recent experiments diagnosed $3\omega/2$ emission, which revealed evidence of TPD activity.

The $3\omega/2$ doublet is suggestive of some TPD activity, although this is consistent with a SRS-dominated regime.
In addition, recent experiments diagnosed $3\omega/2$ emission, which revealed evidence of TPD.

Caveat: observed scattered $3\omega/2$ light is sensitive to hydrodynamics.
The next planar experiments will measure $3\omega/2$ along target normal to determine the prevalence of absolute and convective SRS/TPD instabilities. The $3\omega/2$ measurement along target normal will provide access to plasma waves at all densities at all times.

Knowledge of where the dominant LPI is occurring is critical for mitigation (if needed).
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Reminder: The tolerable fraction of hot electrons generated ($f_{\text{hot}}$) depends on how the electrons couple to an implosion.

A spherical-geometry platform was developed on OMEGA to diagnose coupling of hot electrons to an imploding shell.

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

This platform is being adapted to the NIF in order to determine hot-electron coupling in a different LPI regime at longer scale lengths.

Experiments in September 2018 and March 2019

NIF target designs

- CH (4% Ge)
- D₂ gas

- CH
- D₂ gas

NIF target designs:

- CH (4% Ge)
- D₂ gas 45 μm
- D₂ gas 58.6 μm
- CH 1160 μm (all)
- CH 1056.4 μm
- CH 120 μm
- CH 1040 μm

Predicted NIF hard x-ray data

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

HXR above 50 keV (arbitrary units)

Time (ns)

- Ge-doped target, 40-μm outer CH ablator
- Ge-doped target, 60-μm outer CH ablator
- CH target

Hot-electron energy coupled to an implosion constrains usable laser intensities in direct-drive ignition designs.
Summary/Conclusions

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

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

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- 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.

- Upcoming spherical experiments will diagnose hot-electron coupling (preheat) to an implosion.

Overall: encouraging results (so far) for direct drive in a new LPI regime.
APPENDIX
Knowledge of SRS mechanisms—absolute SRS ($\omega/2$) and sidescattered SRS—allows for extrapolation to the total SRS generated

Distribution of the observed sidescattered SRS is based on ray-tracing of 2-D simulated plasma conditions

Approximately 5% of laser energy converted to SRS is consistent with the observed hot-electron fraction.

Various single-beam and potential multiple-beam effects have been identified in experiments with beams selectively turned off.

Some near-backscatter from outers refracted into the inner-beam location.

Neighboring quads have some (multibeam?) effect on inner-beam SRS.
Various single-beam and potential multibeam effects have been identified in experiments with beams selectively turned off.
Ramp-pulse experiments show thresholds and growth of both non-saturated “convective” SRS and saturated absolute SRS.
**N180104 Experiments**

**LPSE simulations (TPD only) qualitatively reproduce the $3\omega/2$ doublet spectrum from N180104-001 at early times**

R. Follett simulations 2017-09-19

*Caveat: preliminary LPSE simulations with SRS and TPD may also be consistent with this—SRS seeding TPD, or both instabilities occurring simultaneously.*
Si targets produce reduced SRS reflectivity in comparison to CH, a similar trend to the hot-electron results.

2-D DRACO-simulated plasma conditions at $n_c/4$ during 23°, 30° beam drive

<table>
<thead>
<tr>
<th></th>
<th>CH ablator (N160421-001)</th>
<th>Si ablator (N160719-001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_n$ (nm)</td>
<td>690</td>
<td>560</td>
</tr>
<tr>
<td>$T_e$ (keV)</td>
<td>4.4</td>
<td>5.2</td>
</tr>
<tr>
<td>$I_L$ (W/cm²)</td>
<td>$1.1 \times 10^{15}$</td>
<td>$0.92 \times 10^{15}$</td>
</tr>
</tbody>
</table>