Hot-Electron Preheat in Hydrodynamically Scaled Direct-Drive Implosions at the National Ignition Facility and OMEGA

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Summary

Hot electron preheat in hydro-scaled PDD implosions on NIF and OMEGA is ~0.2% of laser energy at ignition-relevant intensities

- Hydrodynamic scaling underpins the extrapolation of direct-drive implosion performance from OMEGA to NIF, but not all aspects of physics scale (e.g. hot electron preheat)

- Hydro-scaled NIF and OMEGA implosions at $10^{15}$ W/cm$^2$ (720 kJ and 18 kJ, respectively) both produce ~0.2% of laser energy deposited as hot electron preheat in the inner ~80% of unablated shell, though NIF experiments generate more hot electrons overall

- Extrapolation of these results to MJ-scale cryogenic PDD implosions indicates preheat around 0.1-0.2% of laser energy and that $10^{15}$ W/cm$^2$ intensity is in the acceptable range
Collaborators


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Hydrodynamic scaling is used to extrapolate performance of direct-drive cryogenic implosions from OMEGA to NIF energies

Motivation

Hydrodynamic scaling relations for how parameters vary with laser energy
- All intrinsic properties (temperature, density, pressure, velocity) = fixed
  - \( M \propto E \)
  - \( R \propto E^{1/3} \)
  - \( t \propto E^{1/3} \)
  - \( P \propto E^{2/3} \)

ICF observables
- Yield \( \propto E^{4/3} (R^4) \)

Certain aspects of physics that affect performance, e.g. hot electron preheat, do not scale hydrodynamically and their scaling needs to be studied.
To study preheat scaling, hydrodynamically equivalent polar direct drive (PDD) implosions were designed for NIF and OMEGA, spanning 40x in laser energy.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NIF</th>
<th>OMEGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_L$ (kJ)</td>
<td>720</td>
<td>18</td>
</tr>
<tr>
<td>$P_L$ (TW)</td>
<td>172</td>
<td>15</td>
</tr>
<tr>
<td>$&lt;I_L&gt;$ (W/cm$^2$)*</td>
<td>$1.0 \times 10^{15}$</td>
<td>$1.0 \times 10^{15}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>6.9 ns</td>
<td>2.0 ns</td>
</tr>
<tr>
<td>Capsule OD (μm)</td>
<td>2360</td>
<td>690</td>
</tr>
<tr>
<td>Shell thickness</td>
<td>120 μm</td>
<td>35 μm</td>
</tr>
</tbody>
</table>

*Average on-target laser intensity
Hot electron preheat deposited into the inner layer of the shell is diagnosed using implosions with or without a Ge-doped layer.

For an identical laser drive and identical hot electron source, the difference in hard x-rays $\propto$ hot electron energy deposited in Ge-doped layer.

LILAC simulations for $T_{\text{hot}} = 55$ keV, hot-electron divergence full angle of $2\pi$, Ge-doped target at 3.9%
Hard x-ray (HXR) emission on NIF shows the expected variation with Ge-doped layer thickness, with identical LPI

Identical LPI/hot e⁻ source

Different HXR emission due to <Z>

See also A. A. Solodov et al. U004.00005 (this session)
Hot electron preheat in NIF implosions is inferred to be \(~0.2\%\) of laser energy over the inner \(~80\%\) of unablated shell.

See also A. A. Solodov et al. UO04.00005 (this session)
NIF and OMEGA experiments show 0.2% of hot electron energy deposited to the inner shell layer, despite more hot e\textsuperscript{−} generation on NIF.

Hypothesis: higher ablated-plasma $p_L$ and SRS hot electrons on NIF generated at larger radius than TPD on OMEGA.

Results show that hot electron preheat does not invalidate hydrodynamic scaling between OMEGA and NIF warm implosions.

See also A. A. Solodov et al. UO04.00005 (this session)
These results contribute to extrapolation of preheat in ignition-scale cryogenic direct drive implosions of around 0.15% of laser energy

<table>
<thead>
<tr>
<th>Multiplier</th>
<th>Preheat (% of laser)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheat into inner 80% of unablated shell in warm subscale NIF implosion</td>
<td>~0.2%</td>
</tr>
<tr>
<td>Increase scale length to full scale</td>
<td>~1.5-2</td>
</tr>
<tr>
<td>Increase convergence ratio at end of pulse</td>
<td>~0.4-0.8</td>
</tr>
<tr>
<td>DT shell and some DT in ablator</td>
<td>~1-1.8</td>
</tr>
<tr>
<td>Improve beam smoothing</td>
<td>~0.8</td>
</tr>
<tr>
<td>Si layer*</td>
<td>~0.5</td>
</tr>
<tr>
<td>Total</td>
<td>~0.5-1 ~0.1-0.2%</td>
</tr>
</tbody>
</table>

~0.15% is acceptable preheat fraction for ignition designs**
→ Intensities around $10^{15}$ W/cm² produce acceptable preheat for ignition designs

Note: current preheat results are near-“worst case scenario” given poor beam smoothing on NIF

* See A. A. Solodov et al. UO04.00005 (this session)
Upcoming experiments will explore scaling of preheat within NIF scale, between 2.3 mm (720 kJ) and 3.0 mm (1.5 MJ) capsule diameter (laser energy).

Data will help set intensity limits for direct-drive ignition designs.
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Future experiments will directly diagnose preheat at 1.5 MJ scale to constrain the extrapolation