Direct Measurements of Hot-Electron Preheat in the Dense Fuel of Inertial Confinement Fusion Implosions

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Cryo 77064
CD
DT
DT gas
378.3 μm
8.0 μm
50.2 μm

All CD 77062
CD
DT gas
420 μm
17.6 μm

HXRD (pC/ns)
0
200
400
600
1.6
1.8
2.0
2.2
2.4
2.6
Time (ns)

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Preheat in cryogenic implosions is directly inferred by comparison of hard x rays between all-plastic and DT layered implosions

- Differences in hard x-ray signals between mass-equivalent all-CH and cryo implosions can be used to infer hot-electron energy deposition into the payload.
- Hot-electron deposition into the payload increases proportionally with the payload mass.
- Modeling of these experiments indicated an ~10-20% degradation in areal density as a result of hot-electron preheat for typical $\alpha = 4$ designs.
- A similar experimental campaign is underway on the NIF to assess the viability of direct drive on the NIF.
Collaborators


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Massachusetts Institute of Technology
Outline

• Hot-electron preheat and the preheat formula
• Hot-electron transport experiments and modeling on OMEGA
• Hot-electron transport experiments on the NIF
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Hot-electrons from laser–plasma interactions can preheat the DT fuel, thereby raising the adiabat and degrading the areal density

Lawson parameter $\chi = \left( \rho R_g / \text{cm}^2 \right)^{0.61} \left( \frac{0.12 \text{ Yield}_{16}}{M_{\text{stag,mg}}} \right)^{0.34}$

$\chi \sim \frac{E_k^{0.35} P_{\text{max}}^{0.14} v_{\text{imp}}^2}{\alpha^{0.84}}$

- $\alpha$ = shell adiabat
- $E_k$ = shell kinetic energy
- $v_{\text{imp}}$ = shell implosion velocity
- $P_{\text{max}}$ = ablation pressure
- $M_{\text{stag}}$ = stagnated DT mass

Previous studies* of hot-electron transport on OMEGA suggest that hot electrons intersect the target at a large divergence angle or are transported isotropically. Although the divergence of electrons was measured, the exact amount coupled into the dense fuel of cryo implosions is still unknown.

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TCS: type quartz crystal spectrometer
XRS: x-ray spectrometer
HXR: hard x ray
MC: moving cryostat

A single hard x-ray measurement in a cryo implosion cannot discriminate between hard x rays emitted from electrons slowing down in DT versus CD.
Hot-electron energy deposited in DT is inferred by comparing hard x-ray signals of all-CD and DT-layered targets

- The key parameter is “radiative power” \( \frac{E_{\text{rad}}}{E_{\text{dep}}} \), which represents the radiated energy by the hot electrons per unit of energy lost via Coulomb collisions.

\[
\frac{E_{\text{rad}}}{E_{\text{dep}}} = 5.9 \times 10^{-4}
\]

\[
\frac{E_{\text{rad}}}{E_{\text{dep}}} = 1.1 \times 10^{-4}
\]
The radiative power $E_{\text{rad}}/E_{\text{dep}}$ depends on background plasma atomic number $Z$ and hot-electron temperature

- $E_{\text{rad}}/E_{\text{dep}}$ is proportional to $\langle Z^2 \rangle/\langle Z \rangle$
- $E_{\text{rad}}/E_{\text{dep}}$ depends on the hot-electron temperature that is measured by the multichannel hard x-ray detector (40 keV and up, assuming a Maxwellian distribution of hot electrons)

$$
\frac{E_{\text{rad}}}{E_{\text{dep}}} = \frac{\int_0^\infty f(E_0) \int_0^{E_0} \frac{dE_{\text{rad}}}{dE_{\text{collision}}} dE\, dE_0}{\int_0^\infty f(E_0) E_0 dE_0}
$$
The DT preheat energy is directly proportional to the difference in hard x-ray signals between the cryo and all-CD implosion.

\[ E_{\text{hot,DT}} = \frac{\text{HXR}_{\text{all CD}} - \text{HXR}_{\text{cryo}}}{\left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{CD}} - \left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{DT}}} \]

- Key assumption: the hot-electron source is the same for both the cryo and the all-CD experiments.
One-dimensional LILAC simulations indicate that mass-equivalent all-CD and cryo targets have the same coronal plasma conditions, and therefore the same hot-electron source.

\[
\eta = \frac{I_{14} \text{W/cm}^2 \cdot L_{\mu m}}{233 \cdot T_{\text{keV}}}
\]

- The TPD threshold* \( \eta \)

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* A. Simon et al., Phys. Fluids 26, 3107 (1983);
The 1-D code *LILAC* uses a straight-line model where electrons lose energy according to a slowing-down formula*.

- The radiation emitted by hot electrons is calculated from NIST tables.
- The hot-electron source is Maxwellian with the measured temperature.
- Electrons are born at the quarter-critical surface and are initialized with a user-specified divergence angle.

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LILAC simulations show that the preheat formula correctly predicts the energy deposited into the payload regardless of the payload material, divergence angle, and electron transport model.

\[
\frac{\text{HXR}_{\text{all CD}} - \text{HXR}_{\text{multilayered target}}}{\left( \frac{E_{\text{rad}}}{E_{\text{dep}}} \right)_{\text{CD}} - \left( \frac{E_{\text{rad}}}{E_{\text{dep}}} \right)_{\text{payload}}}
\]

DT layer replaced with copper-doped CH

Exact \( E_{\text{hot, payload}} \) from LILAC (J)
The ratio of DT preheat energy to hard x-ray difference is a function of the hot-electron temperature.

Hot electron energy deposited into DT (J)

$$\text{HXRD}_{\text{All CH, pC}} - \text{HXRD}_{\text{cryo, pC}}$$

![Diagram showing the ratio of DT preheat energy to hard x-ray difference as a function of hot-electron temperature. The typical range in cryo experiments is highlighted.](image-url)
Although the preheat formula predicts electron energy into the total DT, the $\rho R$ degradation depends on electron energy into the unablated DT

- The difference in hard x-ray signal predicts electron energy into the total DT
- A fraction of DT mass is ablated during an OMEGA implosion
Although the preheat formula predicts hot-electron energy into the total DT, the $\rho R$ degradation depends on hot-electron energy into the unablated DT.

Outline

- Hot-electron preheat and the preheat formula
- Hot-electron transport experiments and modeling on OMEGA
- Hot-electron transport experiments on the NIF
An experimental platform that utilized Cu-doped payloads of varying thicknesses was developed to measure where the hot electrons deposit their energy.
ω/2 images indicate that the TPD activity in the corona is identical between the all-CH and CH (Cu) payload implosions.

These data support the assumption that the hot-electron source between the all-CH and multilayered implosions is the same.
The energy deposition into the Cu-doped payload increases proportionately with the payload mass.
A simple model based on uniform deposition per unit mass was developed to describe the multilayered experiments.

\[ K \equiv \frac{1}{E_{\text{hot,tot}}} \frac{dE_{\text{dep}}}{dM} = \text{const} \]

\[ E_{\text{hot,CH(Cu)}} = K E_{\text{tot}} M_{\text{payload}} \]

\[ E_{\text{hot,tot}} = \frac{\text{HXRD}_{\text{All CH}}}{E_{\text{rad}}/E_{\text{dep}}}_{\text{CH}} \]

\[ HXRD_{\text{CH(Cu)}} = E_{\text{hot,CH(Cu)}} \left[ \frac{E_{\text{rad}}}{E_{\text{dep}}}_{\text{CH(Cu)}} \right] + \left[ E_{\text{hot,tot}} - E_{\text{hot,CH(Cu)}} \right] \left[ \frac{E_{\text{rad}}}{E_{\text{dep}}}_{\text{CH}} \right] \]

- \( M_{\text{payload}} = \) payload mass
- \( E_{\text{hot,CH(Cu)}} = \) energy deposited into CH (Cu)
- \( E_{\text{hot,tot}} = \) total hot-electron energy
- \( \frac{dE_{\text{dep}}}{dM} = \) electron energy deposited per unit mass
The good agreement between the model and data confirms the hypothesis that hot-electron deposition is approximately uniform with respect to mass.
The same model applied to DT layered targets of typical $\alpha \approx 4$ implosions* leads to areal-density degradation of about 15% to 20% with respect to the calculated 1-D

$$E_{\text{hot,DT}} = \frac{\text{HXR}_{\text{all CD}} - \text{HXR}_{\text{cryo}}}{(\frac{E_{\text{rad}}}{E_{\text{dep}}})_{\text{CD}} - (\frac{E_{\text{rad}}}{E_{\text{dep}}})_{\text{DT}}}$$

$$E_{\text{hot, unabl.}} = E_{\text{hot,DT}} \left( \frac{M_{\text{unabl.}}}{M_{\text{DT}}} \right)$$

<table>
<thead>
<tr>
<th>Shot number</th>
<th>$E_{\text{hot,DT}}$</th>
<th>$E_{\text{hot, unabl.}}$</th>
<th>$\rho R_{\text{experiment}}$</th>
<th>$\rho R_{\text{LILAC, no hots}}$</th>
<th>$\rho R_{\text{LILAC, hots}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>77064</td>
<td>14 ± 3 J</td>
<td>5 ± 1 J</td>
<td>195 ± 17 mg/cm²</td>
<td>230 mg/cm²</td>
<td>198 ± 5 mg/cm²</td>
</tr>
<tr>
<td>85784</td>
<td>22 ± 4 J</td>
<td>8 ± 2 J</td>
<td>160 ± 14 mg/cm²</td>
<td>210 mg/cm²</td>
<td>170 ± 9 mg/cm²</td>
</tr>
</tbody>
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As implosions scale from OMEGA to the NIF, the scale length is also expected to increase, resulting in more expected LPI for the same coronal conditions.

<table>
<thead>
<tr>
<th></th>
<th>NIF</th>
<th>OMEGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale length at quarter-critical $L_{\mu m}$</td>
<td>$\sim 400 \mu m$</td>
<td>$\sim 150 \mu m$</td>
</tr>
<tr>
<td>Electron temperature at quarter-critical $T_{e,\text{keV}}$</td>
<td>$\sim 3.2 \text{ keV}$</td>
<td>$\sim 2.5 \text{ keV}$</td>
</tr>
<tr>
<td>Intensity at quarter-critical $I_{14}$</td>
<td>$\sim 4 \times 10^{14}$ W/cm²</td>
<td>$\sim 3.5 \times 10^{14}$ W/cm²</td>
</tr>
<tr>
<td>$\eta_{\text{TPD}}$</td>
<td>$\sim 2 \text{ to } 5$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>$\eta_{\text{SRS}}$</td>
<td>$\sim 5 \text{ to } 10$</td>
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$$\eta_{\text{TPD}} = \frac{I_{14}L_{\mu m}/233}{T_{e,\text{keV}}} \quad \eta_{\text{SRS}} = \frac{I_{14}L_{\mu m}^{4/3}}{2377}$$

LPI: laser–plasma interaction
SRS: stimulated Raman scattering
The OMEGA preheat platform is being developed on the NIF to measure the coupling of hot electrons into the target.

Different buried depths of the Ge-doped layer are examined to diagnose the hot-electron deposition profile in the imploding shell.

* A. A. Solodov et al., NO5.00011, this conference.
Experiments on the NIF indicate that approximately one quarter of the total hot-electron energy is coupled into the unablated shell*.

More detailed hydro-scaled experiments are still needed to quantify the scaling of preheat with laser energy.

* A. A. Solodov et al., N05.00011, this conference.
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- A similar experimental campaign is underway on the NIF to assess the viability of direct drive on the NIF
On OMEGA, TPD is the dominant hot-electron source, while NIF experiments show significant amounts of SRS.

\[ \text{Absolute SRS at } \omega/2 \]  
\[ (\lambda = 700 \mu m = 2\lambda_0) \]

SRS emission \((700 \mu m > \lambda > \lambda_0)\)
Hot-electrons from laser–plasma interactions can preheat the DT fuel, thereby raising the adiabat and degrading the areal density

- The TPD instability is thought to be the prevalent source of hot electrons in direct-drive ICF

- TPD occurs in the corona where the density is near quarter-critical density ($0.2n_c < n_e < 0.25n_c$)
Electron transport is described with a two-parameter *ad hoc* model to fit the data where the electron divergence angle and coronal stopping power are varied.
The best fit to the experimental data occurs at a full divergence angle of 40°.
The hot-electron model almost captures the measured hard x-ray signal in the cryo experiment and predicts that $9\pm 5$ out of $44\pm 10$ J of preheat energy is coupled into the unablated DT.

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