Hot-Electron Preheat and Mitigation in Polar-Direct-Drive Experiments at the National Ignition Facility

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Mid-Z Si layers and dopants provide a promising hot-electron preheat mitigation strategy for direct-drive–ignition designs

- Surrogate plastic implosion experiments were performed at the National Ignition Facility (NIF) to quantify preheat levels and directly measure the spatial hot-electron energy deposition profile inside the imploding shell.

- Hot-electron coupling from 0.2% to 0.6% of the laser energy to the unablated shell is found for the incident laser intensity from $(0.75 \text{ to } 1.25) \times 10^{15} \text{ W/cm}^2$, with half of the preheat coupled to the inner 80% of the unablated shell.

- Si layers buried in the ablator mitigate the growth of laser–plasma instabilities (LPI’s), suppressing preheat at the intensity of $7.5 \times 10^{14} \text{ W/cm}^2$ and reducing by a factor of ~2 at higher intensities; hot-electron preheat is reduced by 30% using Si dopant at $10^{15} \text{ W/cm}^2$.

- Shell convergence is found to significantly reduce hot-electron preheat late during the implosion.
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Hot-electron preheat in NIF polar-direct-drive (PDD) implosions was studied by comparing hard x-ray (HXR) emission between plastic and multilayered implosions.

Different thicknesses of the Ge-doped layer were examined to diagnose the hot-electron deposition profile in the imploding shell.

Time-resolved scattered-light spectra indicate that LPI is dominated by SRS and is similar between the all-CH and Ge-doped payload implosions.

Similar LPI → similar hot-electron energy source
Hot-electron preheat was inferred from comparison of the measured HXR spectra to simulations using the hydrocode *LILAC* and the Monte Carlo code Geant4.

- Hot-electron temperature, total energy, divergence angle, and refluxing fraction were varied to reproduce the measured HXR spectra.
- The hot-electron divergence half-angle is found to exceed 45°, the angular size of the cold shell from the $n_c/4$ surface.

**Time-integrated HXR spectra**

- Incident intensity = $10^{15}$ W/cm²
- $T_{hot} \approx 55$ keV

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The hot-electron energy deposition profile was inferred from Geant4 Monte Carlo simulations.

Incident intensity = $10^{15}$ W/cm²

- Red circles: energy deposition in the Ge-doped layer in multilayered targets

About half of the preheat (~0.2% of $E_{\text{laser}}$) is deposited in the inner 80% of the unablated shell.
Si layers strategically placed in the ablator were found to mitigate LPI and hot-electron preheat

- SRS is mitigated in Si by
  - shortening the density scale length at $n_c/4$ from $-420 \mu m$ to $-340 \mu m$ according to hydro simulations
  - increasing the electron–ion collisionality $\nu_{ei} \propto Z_{eff} = \langle Z^2 \rangle / \langle Z \rangle$, which enhances absorption of the incident and scattered light and damps electron plasma waves

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Hot-electron preheat is reduced by $\sim 2\times$ with a Si layer at an incident intensity of $10^{15}$ W/cm$^2$.

Incident intensity = $10^{15}$ W/cm$^2$

About half of the preheat is deposited in the inner 80% of the unablated shell.
Si-doped plastic ablators have advantageous hydrodynamic properties* and are promising to mitigate hot-electron preheat

Benefits of Si-doped plastic ablators:

- increase laser inverse bremsstrahlung absorption
- reduce cross-beam energy transfer
- reduce imprint
- better hydrodynamic stability than a Si layer


~30% preheat reduction using Si dopant, compared to plastic ablators

\[^{1}\text{V. N. Goncharov et al., Phys. Plasmas 21, 056315 (2014) and references therein.}\]
Hot-electron preheat scaling with the incident laser intensity has been obtained with and without mitigation using Si layer or dopant.

About half of the preheat is deposited in the inner 80% of the unablated shell:

- 0.1% to 0.15% of $E_L$ at $I \sim (1$ to $1.25) \times 10^{15}$ W/cm$^2$ with a Si layer
- 0.14% of $E_L$ at $I = 10^{15}$ W/cm$^2$ with Si dopant

$\sim 0.15\%$ of the laser energy is an acceptable preheat fraction for high-gain ignition designs.*

Si layers and dopants provide a promising preheat mitigation strategy for ignition designs at an on-target intensity of about $10^{15}$ W/cm$^2$.

Recent experiments studied the effect of shell convergence during the implosion on preheat

Shell convergence ratio:

\[ \frac{R_{\text{shell}}(t = 0)}{R_{\text{shell}}(t = 6 \text{ ns})} \sim 1.8 \]

\[ \frac{R_{\text{shell}}(t = 0)}{R_{\text{shell}}(t = 7.5 \text{ ns})} \sim 3.7 \]
Hot-electron preheat decreases as the shell converges

Energy deposition in the Ge-doped layer decreases as the solid angle of the dense shell from the $n_c/4$ surface: by a factor of $\sim 4$ during the last 1.3 ns of the 3.5-ns flattop pulse.

Inferred hot-electron energy deposition: total and in the Ge-doped layer for two flattop durations

- Energy deposition in the Ge-doped layer decreases as the solid angle of the dense shell from the $n_c/4$ surface: by a factor of $\sim 4$ during the last 1.3 ns of the 3.5-ns flattop pulse.

Shell convergence can decrease preheat in high-gain ignition cryo designs,* in which convergence of 1.5 to 4 at peak hot-electron production is expected.

NIF experiments in September 2022 will measure preheat in ~30% larger ignition-scale implosions.
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