Predicting Hot-Electron Generation in Inertial Confinement Fusion with Particle-in-Cell Simulations

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Summary

Hot-electron generation in direct drive can be predicted by PIC simulations

- A hot-electron scaling was obtained from PIC simulations as a function of laser-plasma conditions in the quarter-critical region
- Using this scaling and conditions from LILAC simulations, whole-pulse hot-electron generation can be predicted
- After accounting for realistic laser-smoothing techniques, speckle statistics, and inaccuracies in hydro-simulations, the predicted hot electrons for a collection of OMEGA warm target implosions agreed with the experimental data within experimental error bars, showing the promise of this approach

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PIC: particle-in-cell
Collaborators

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Laser-plasma instabilities in the OMEGA experiments were shown to be dominated by two-plasmon decay (TPD)*

A predictive hot-electron capability is required for direct inertial confinement fusion design.

Mode structure of TPD

\[ k_{1,EPW} \]

\[ k_{2,EPW} \]

\[ k_{0,\text{light}} \]

\[ \eta \equiv \frac{L_{\mu m} I_{14}}{233 T_{e, \text{keV}}} \]

Time-resolved \( \omega/2 \) spectra**

A predictive hot-electron capability is required for direct inertial confinement fusion design.


Previous efforts for hot-electron scaling focused on the dependency of $\eta$ *,**,†

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**Experimental $f_{\text{hot}}$**

$$I_q L_n \left( \frac{10^{14} \text{ W} \cdot \mu \text{m}}{\text{cm}^2 \cdot \text{keV}} \right)$$

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**Plasma conditions from LILAC ‡**

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$\eta$ changes in the whole pulse.
We used 2-D *OSIRIS* simulations* to study hot-electron scaling

59 simulations to scan laser-plasma conditions

\[ 100 < L_{\mu m} < 200 \]
\[ 1.5 < T_{e,\text{keV}} < 4.0 \]
\[ 1.5 < T_{i,\text{keV}} < 3.5 \]
\[ 4 \times 10^{14} < I_{\text{W/cm}^2} < 10^{15} \]

Each simulation represents one speckle in a realistic laser beam.

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Smoothing by spectral dispersion (SSD)\(^*\) induces intermittent speckles on a time scale of 3 ps

\[ L = 150 \ \mu m, \ I = 2.0 \times 10^{14} \ \text{W/cm}^2 \]
\[ T_e = 2.5 \ \text{keV}, \ T_i = 1.5 \ \text{keV} \]

The obtained scaling law depends on $\eta$ as well as $T_e$

\[ f_{\text{hot}} \sim \left\{ 1.9 - 0.64 L^{0.19} T_e^{-0.09} \left( \frac{T_i}{T_e} \right)^{0.08} \eta^{-0.16} - 2.0 L^{-0.25} T_e^{-0.18} \left( \frac{T_i}{T_e} \right)^{-0.23} \eta^{0.002} \right\} \]
Laser-smoothing effects need to be considered

Speckle intensity distribution* and hot-electron fraction

Far-field intensity distributions of beams from $R_{75}$ phase plate**

\[ P[\eta, \bar{\eta}, M] = \eta^M \exp[-M\eta/\bar{\eta}] \]

\[ L = 150 \mu m, \quad I = 2.0 \times 10^{14} \text{ W/cm}^2 \]

\[ T_0 = 2.5 \text{ keV}, \quad T_1 = 1.5 \text{ keV} \]

\[ I(r) = I_0 \exp\left[-\left(\frac{r}{287}\right)^{5.11}\right] \]

\[ \bar{f}_{\text{hot}} = \frac{\int_0^\infty \bar{f}_{\text{hot}} \cdot P d\eta}{\int_0^\infty P d\eta} \]

\[ F_{\text{hot}} = \frac{\int_0^\infty \bar{f}_{\text{hot}} \cdot 2\pi r dr}{\int_0^\infty 2\pi r dr} \]


Hot-electron energy and the measured charge can be predicted with $T_{\text{hot}}$

\[
\frac{dE_{\text{hot}}}{dt} = 4\pi R(t)^2 I_0(t) F_{\text{hot}}(t),
\]

\[
E_{\text{hot}} = \frac{Q}{(-1.12 + 0.66T_{\text{hot}} + 0.00097T_{\text{hot}}^2)}, *
\]

\[
T_{\text{hot}} \sim \left[ 0.097 + 9.3 \left( \frac{L_n}{150} \right)^{-0.80} \left( \frac{T_e}{2} \right)^{0.12} \left( \frac{T_i}{T_e} \right)^{0.071} \eta^{0.67} \right] \left[ 43 \left( \frac{L_n}{150} \right)^{-0.12} \left( \frac{T_e}{2} \right)^{0.28} \left( \frac{T_i}{T_e} \right)^{-0.020} \eta^{-0.0087} \right]\] \text{keV.}
\]

LILAC intensity was modified by minimizing the relative error of the measured charge.

\[ I^* = I_0 \cdot \left( a_0 + \sum_{i=1}^{2} a_i \cdot L_{b,i} \cdot T_{e,i}^{c_i} \cdot T_{i}^{d_i} \cdot \eta_{e,i} \cdot r_{f,i} \right) \cdot \left[ 1.0 - \tanh \left( g_0 + \frac{dr}{dt}/h_0 \right) \right]/2.0 \]

\( I_0 \) is laser intensity from LILAC.
The same approach was used to optimize the prediction of hot-electron energy and the average hot-electron temperature was calculated via calibration.
Summary/Conclusions

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