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

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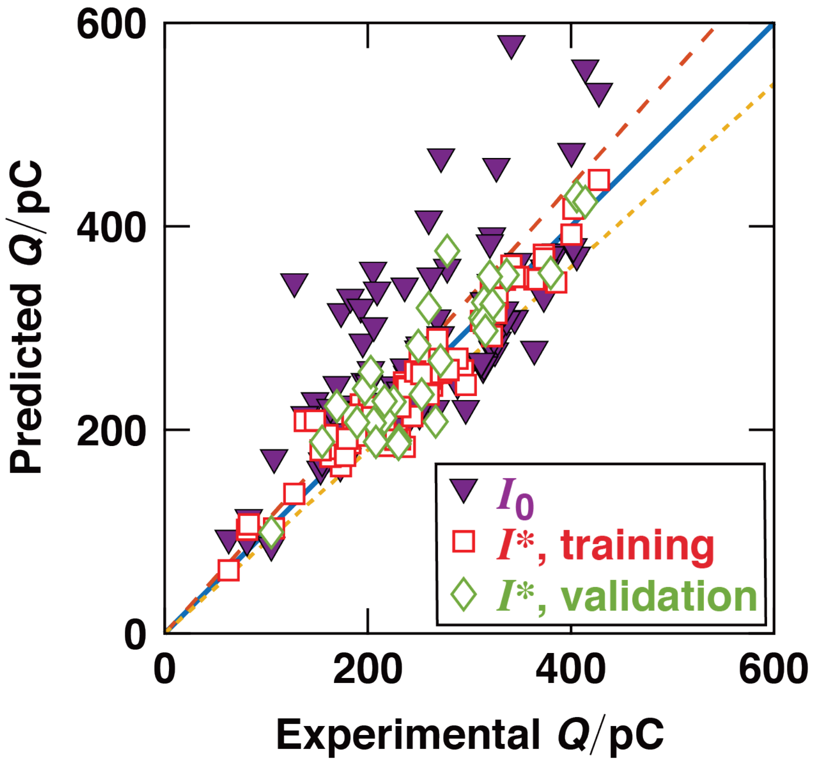
Predicted charge of hot electrons



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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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We thank the UCLA-IST OSIRIS Consortium for the use of *OSIRIS*.

PIC: particle-in-cell

Collaborators

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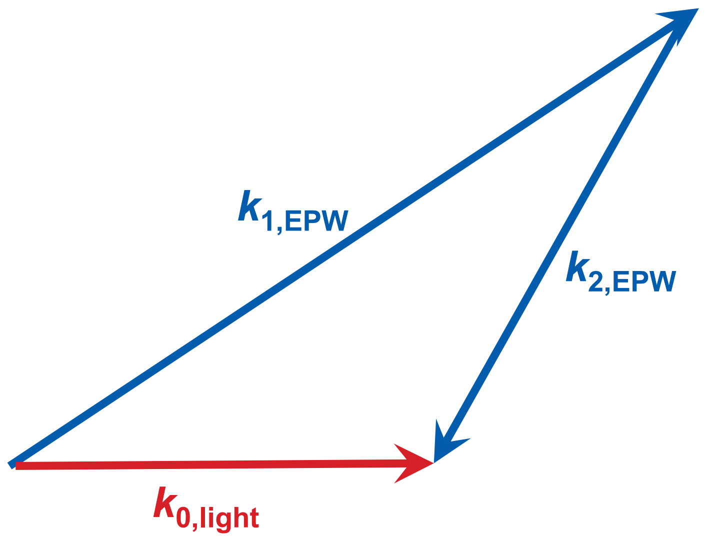
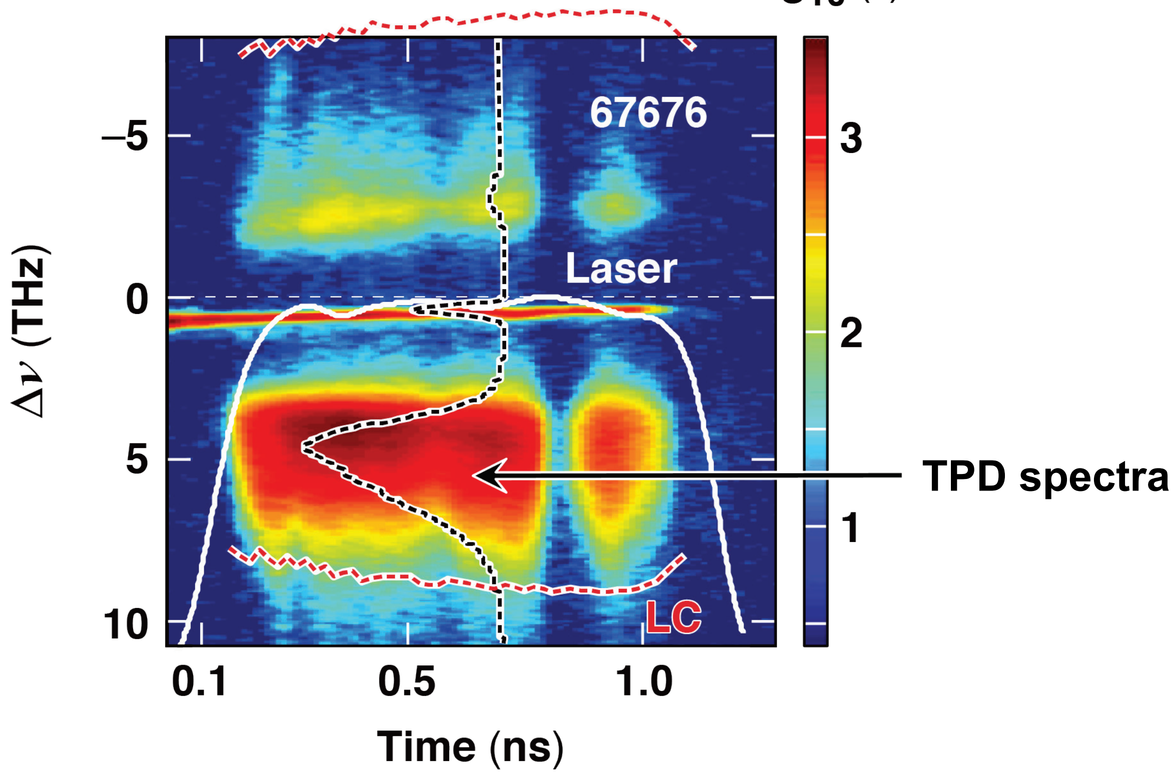
Laser-plasma instabilities in the OMEGA experiments were shown to be dominated by two-plasmon decay (TPD)*

Mode structure of TPD



$$\eta \equiv \frac{L_{\mu m} I_{14}}{233 T_{e,\mathrm{keV}}} \quad *$$

Time-resolved $\omega/2$ spectra**

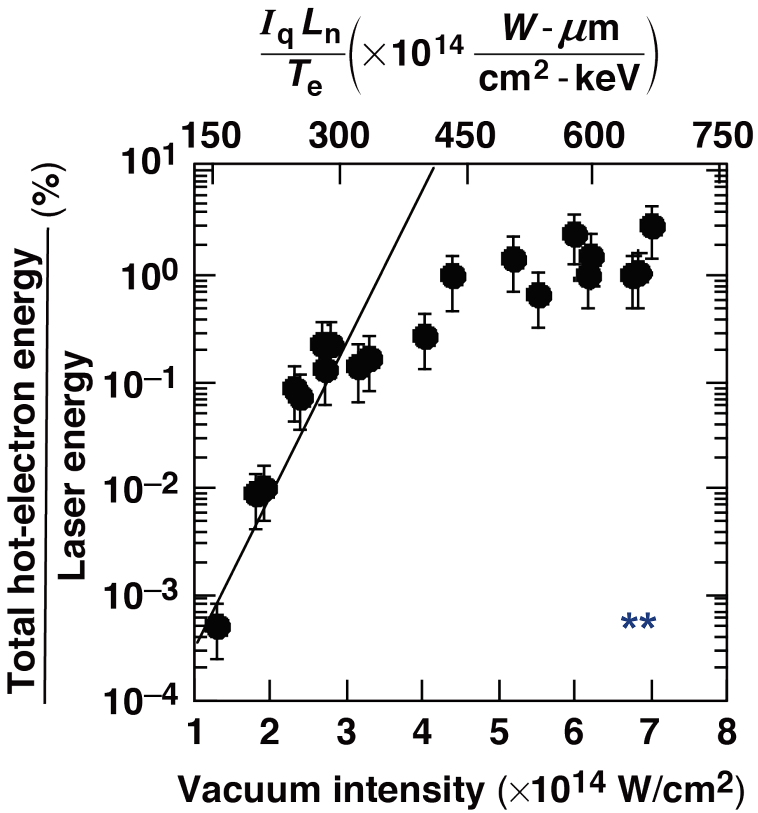


A predictive hot-electron capability is required for direct inertial confinement fusion design.

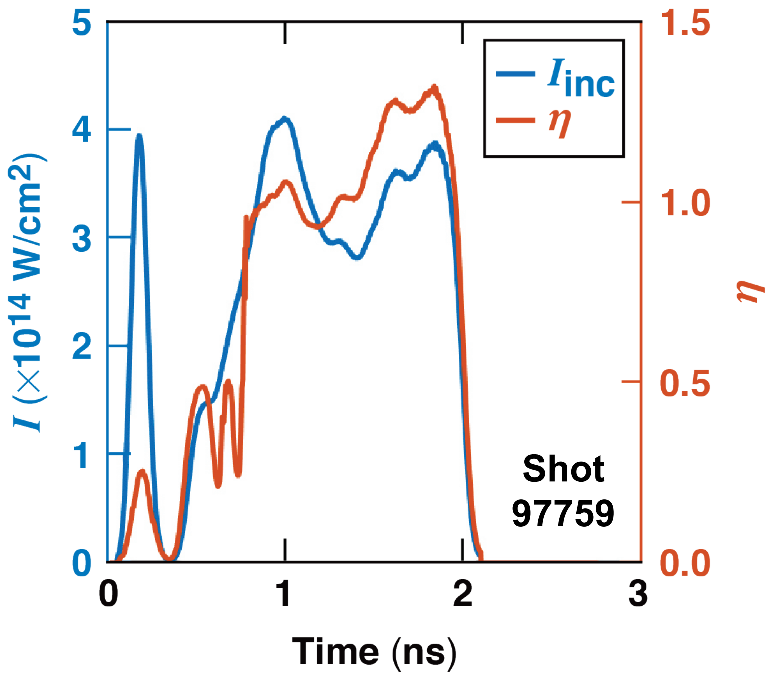
* A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).
** W. Seka *et al.*, Phys. Rev. Lett. 112, 145001 (2014).

Previous efforts for hot-electron scaling focused on the dependency of η *,**,†

Experimental f_{hot}



Plasma conditions from *LILAC* ‡



η changes in the whole pulse.

* C. Stoeckl *et al.*, Phys. Rev. Lett. 90, 235002 (2003).
** D. H. Froula *et al.*, Phys. Rev. Lett. 108, 165003 (2012).
† D. Turnbull *et al.*, Phys. Plasmas 27, 102710 (2020).
‡ J. Delettrez *et al.*, Phys. Rev. A 36, 3926 (1987).

We used 2-D *OSIRIS* simulations* to study hot-electron scaling

59 simulations to scan
laser-plasma conditions

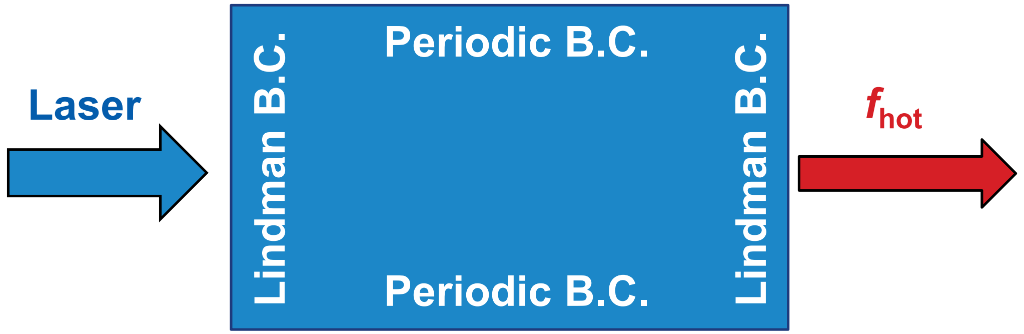
$100 < L_{\mu m} < 200$

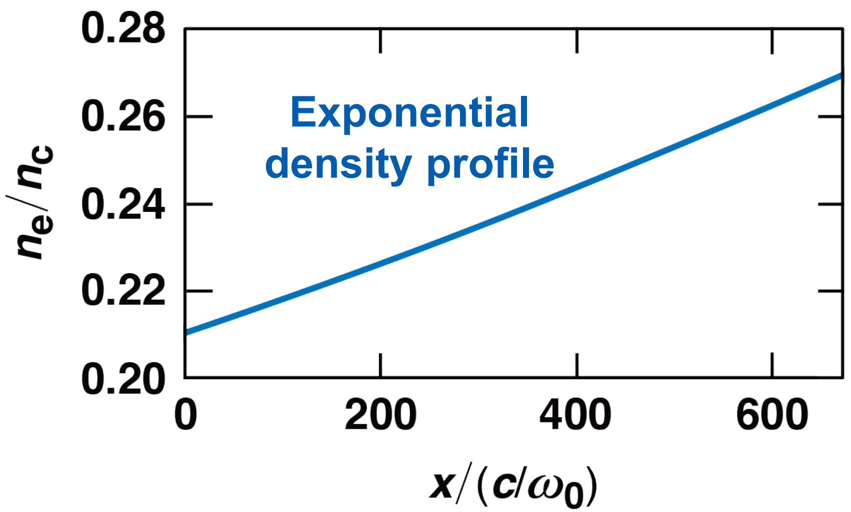
$1.5 < T_{e,keV} < 4.0$

$1.5 < T_{i,keV} < 3.5$

$4 \times 10^{14} < I_{W/cm^2} < 10^{15}$

Each simulation represents one speckle in a realistic laser beam.





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*R. A. Fonseca *et al.*, in Computational Science – ICCS 2002, edited by P. M. A. Sloot *et al.*, Lecture Notes in Computer Science, Vol. 2331 (Springer, Berlin, 2002), p. 342.
B.C.: boundary condition

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

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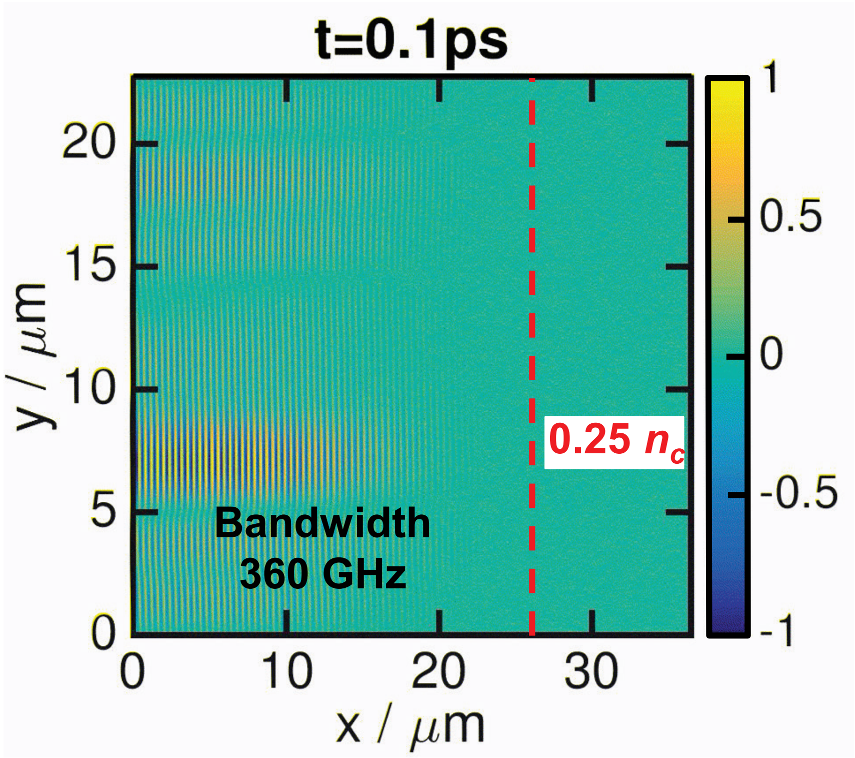
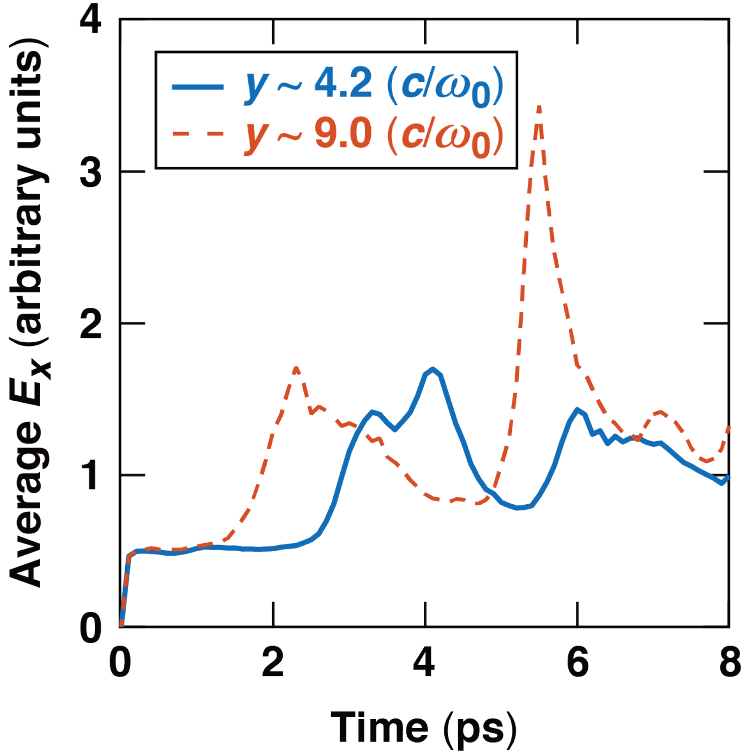
Laser E_y with SSD



Average E_x energy



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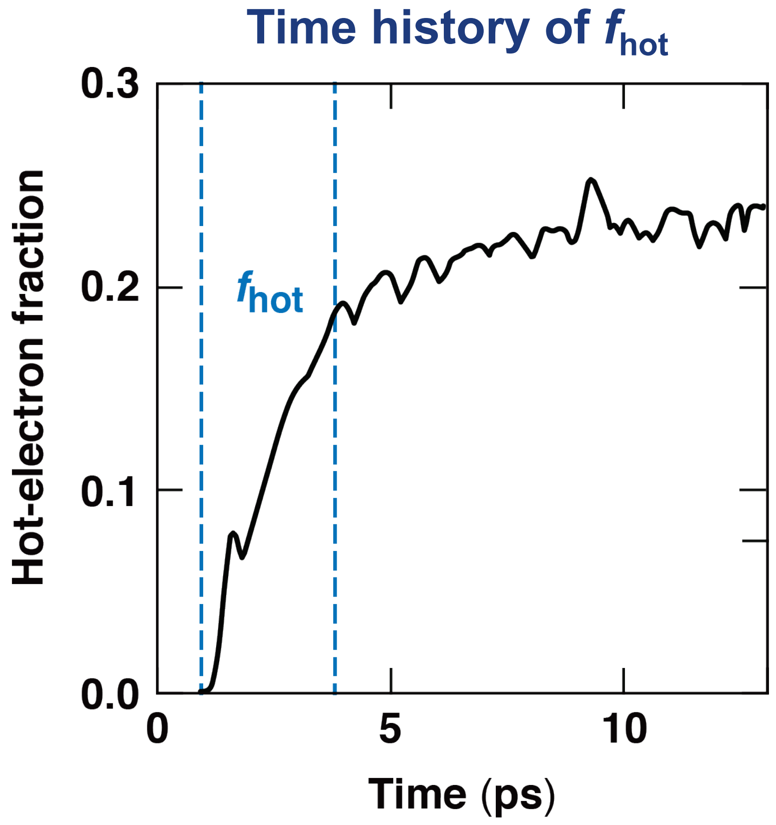
L = 150 μm, I = 2.0 $\times$ 10^{14} W/cm^2
T_e = 2.5 keV, T_i = 1.5 keV

*S. Skupsky *et al.*, J. Appl. Phys. 66, 3456 (1989).

The obtained scaling law depends on η as well as T_e



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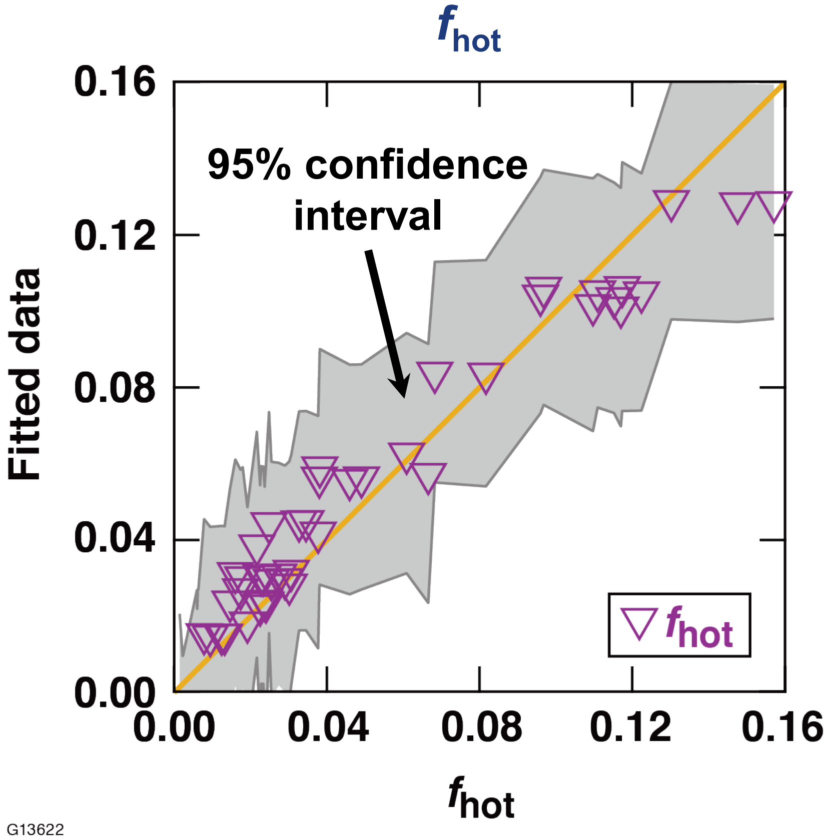

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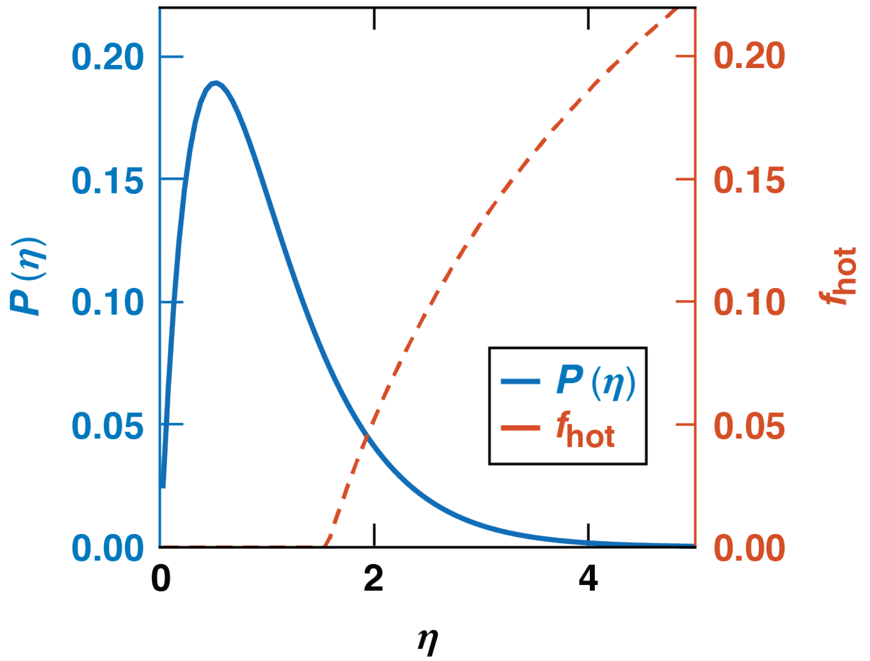
$$f_{hot} \sim \left\{ 1.9 - 0.64 L^{0.19} T_e^{-0.09} \left(\frac{T_i}{T_e}\right)^{0.08} \eta^{-0.16} - 2.0 L^{-0.25} T_e^{-0.18} \left(\frac{T_i}{T_e}\right)^{-0.23} \eta^{0.002} \right\}$$

Laser-smoothing effects need to be considered

Speckle intensity distribution* and hot-electron fraction



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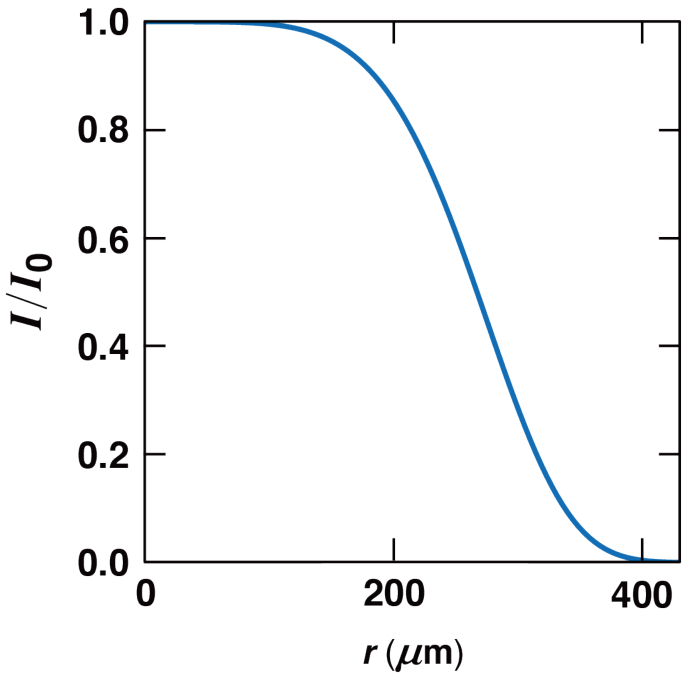
$P[\eta,\bar{\eta},M] = \eta^M \exp[-M\eta/\bar{\eta}]$

$L = 150\ \mu m$, $I = 2.0 \times 10^{14}\ W/cm^2$

$T_e = 2.5$ keV, $T_i = 1.5$ keV

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



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

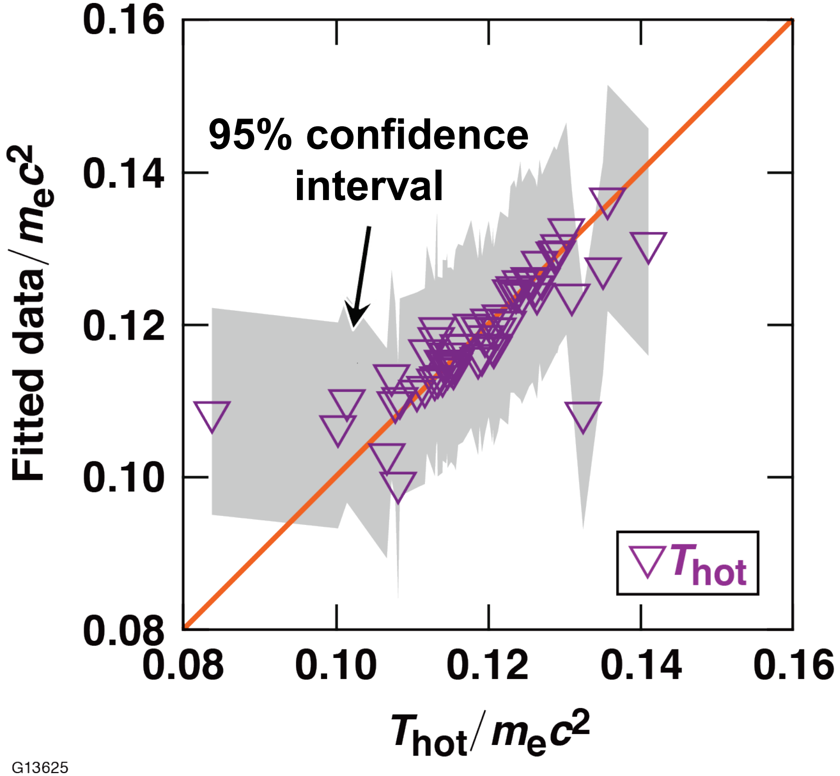
$$\bar{f}_{hot} = \frac{\int_0^\infty f_{hot} * P d\eta}{\int_0^\infty P d\eta}$$

$$F_{hot} = \frac{\int_0^\infty \bar{f}_{hot} * 2\pi r I dr}{\int_0^\infty 2\pi r I dr}$$

* *Laser Speckle and Related Phenomena*, 1, Topics in Applied Physics, Vol. 9, edited by J. C. Dainty (Springer Berlin, Heidelberg, 1975).
** VisRad User's Guide, Phase Plate Parameters, Accessed 19 May 2022, http://prism-cs.com/Manuals/VisRad/power_sources/phase_plate_params.html.

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

Hot-electron temperature scaling



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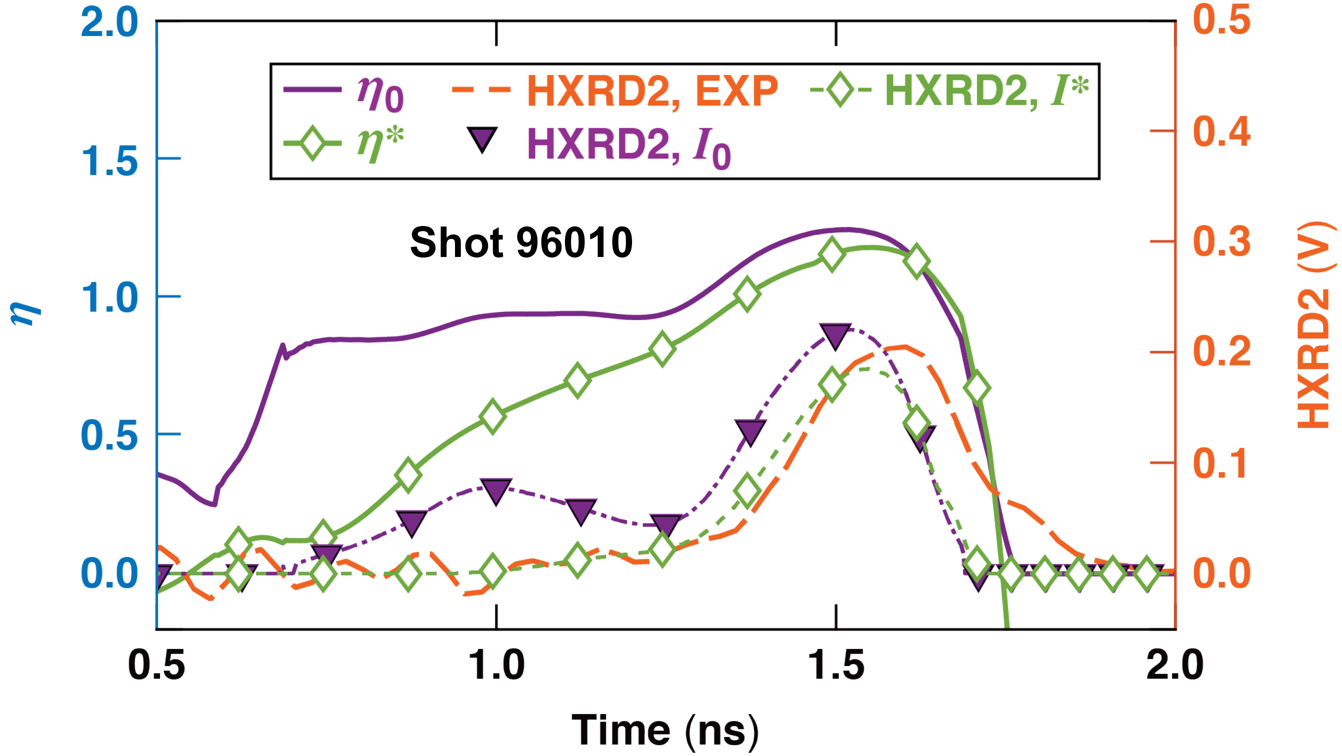
$$dE_{\text{hot}}/dt = 4\pi R(t)^2 I_0(t) F_{\text{hot}}(t),$$

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

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

* D. Turnbull *et al.*, Phys. Plasmas 27, 102710 (2020);
A. Christopherson, Ph.D thesis, University of Rochester, 2020.

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



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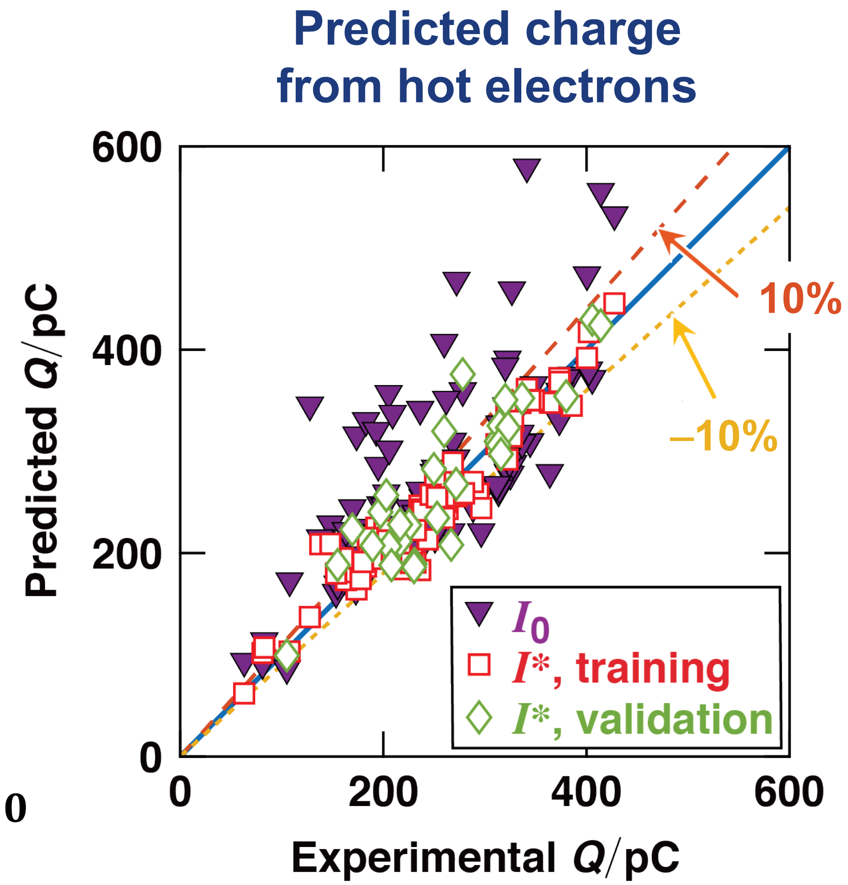

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$$I* = I_0 \cdot \left(a_0 + \sum_{i=1}^{2} a_i \cdot L^{b_i} \cdot T_e^{c_i} \cdot T_i^{d_i} \cdot \eta^{e_i} \cdot r^{f_i} \right) \cdot \left[1.0 - \tanh\left(g_0 + \frac{\mathrm{d}r}{\mathrm{d}t} / h_0 \right) \right] / 2.0$$

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

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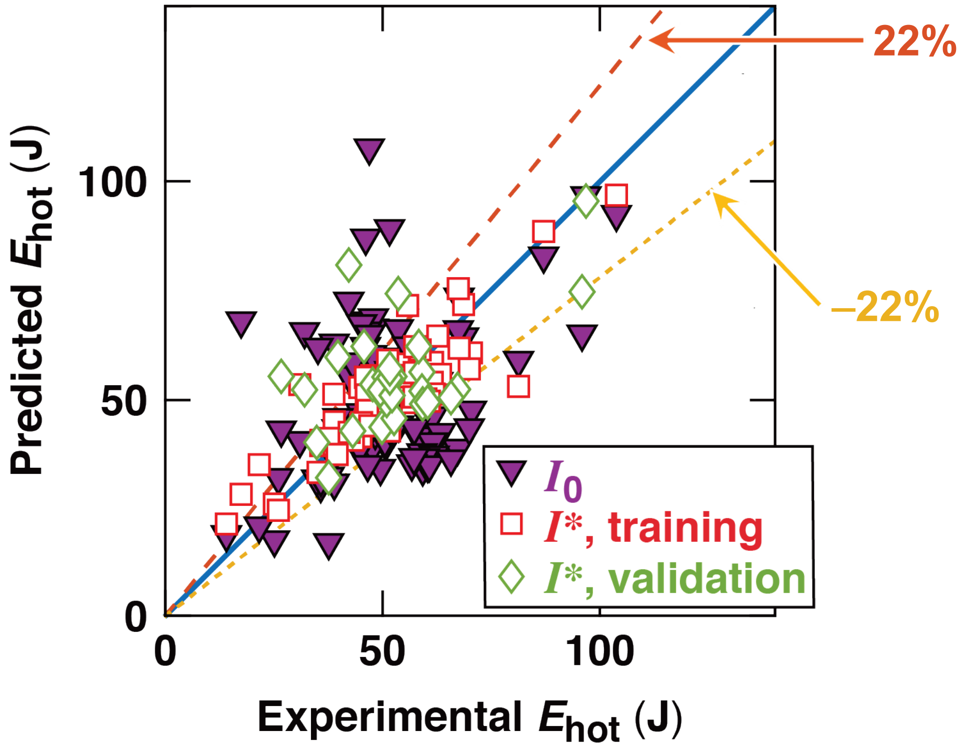
Predicted hot-electron energy



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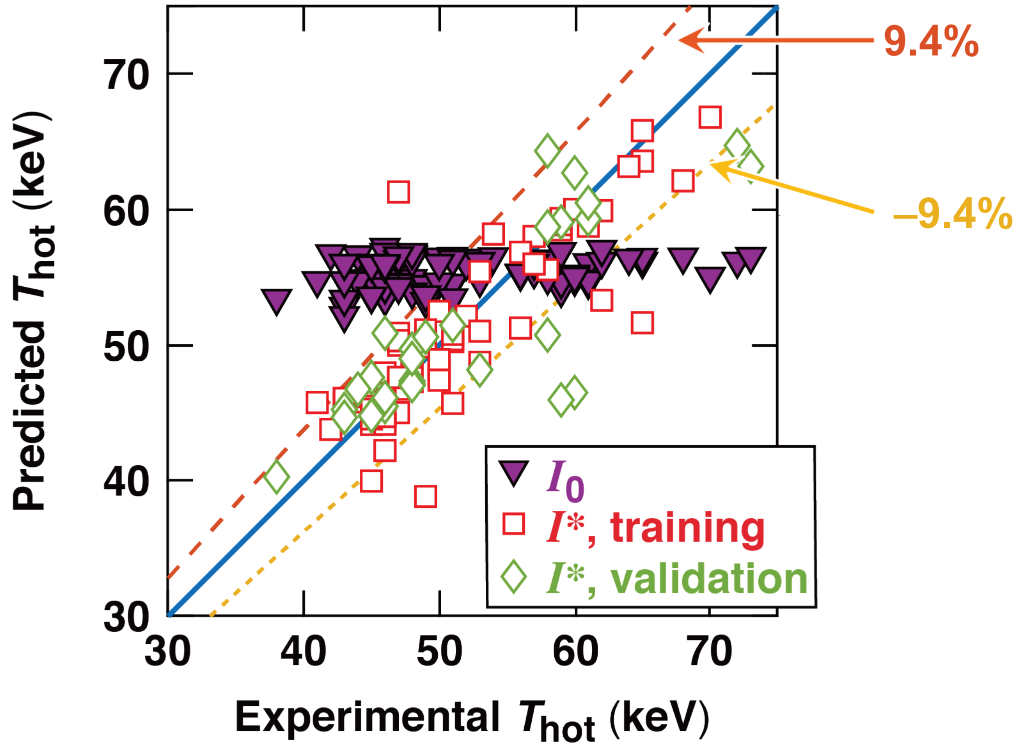
Predicted hot-electron temperature



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