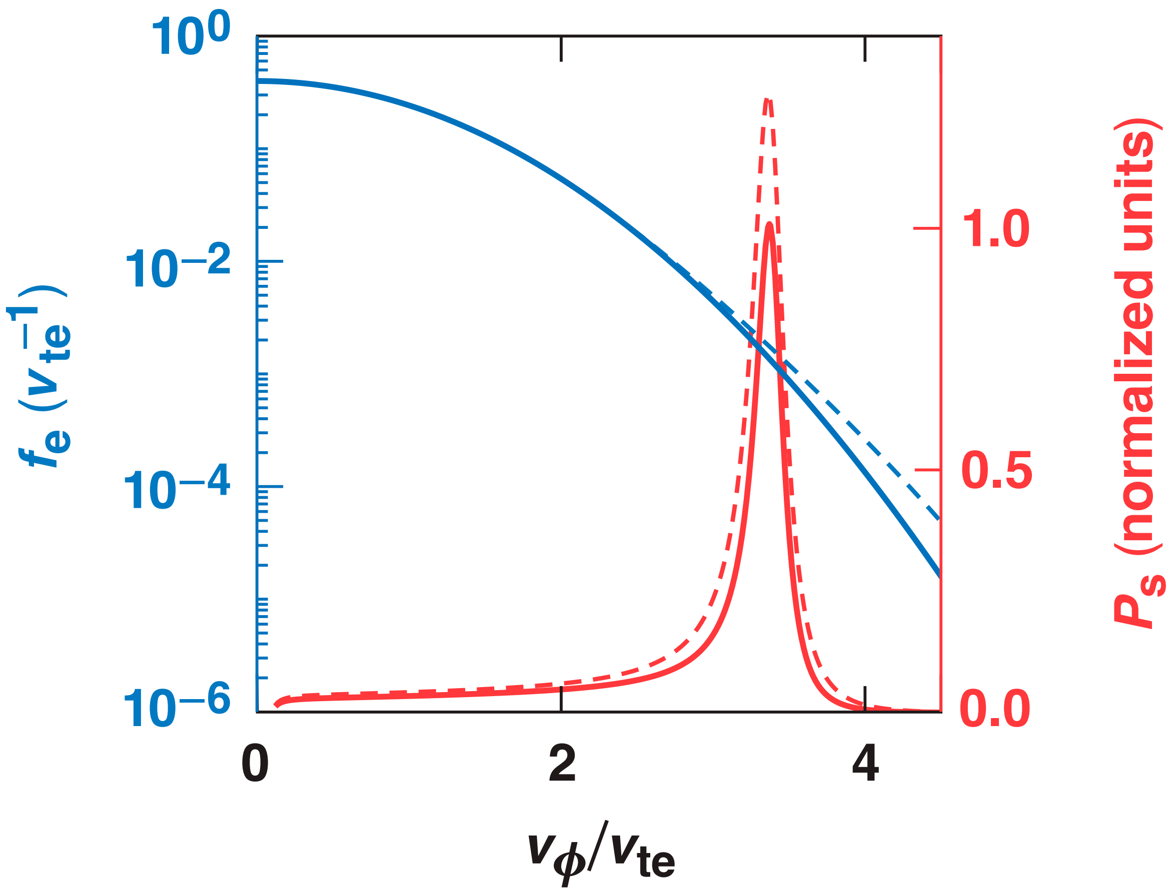
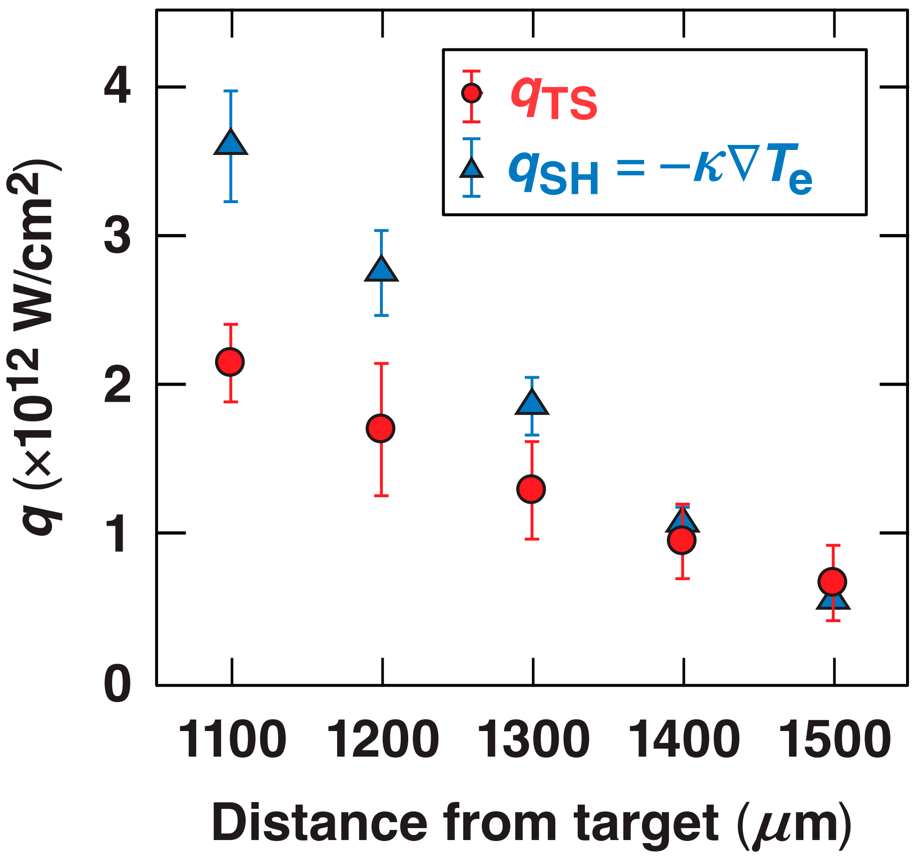
Direct Measurements of Nonlocal Heat Flux by Thomson Scattering





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60th Annual Meeting of the
American Physical Society
Division of Plasma Physics
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Summary

Nonlocal heat flux was measured using Thomson scattering from electron plasma waves

- **Classical theory is in good agreement with the measurement at the lowest-gradient location**
- **The measurements show a reduction in heat flux from classical Spitzer–Härm theory in regions of large temperature gradients ($\lambda_{ei}/|L_T| > 0.01$)**
- **The differences are consistent with nonlocal effects**
- **Simulations using the Schurtz–Nicolaï–Busquet (SNB) model calculate heat flux slightly reduced from classical values in the nonlocal region and overestimate the heat flux in low-gradient locations**

E27782

R. J. Henchen *et al.*, Phys. Rev. Lett. 121, 125001 (2018).

Collaborators

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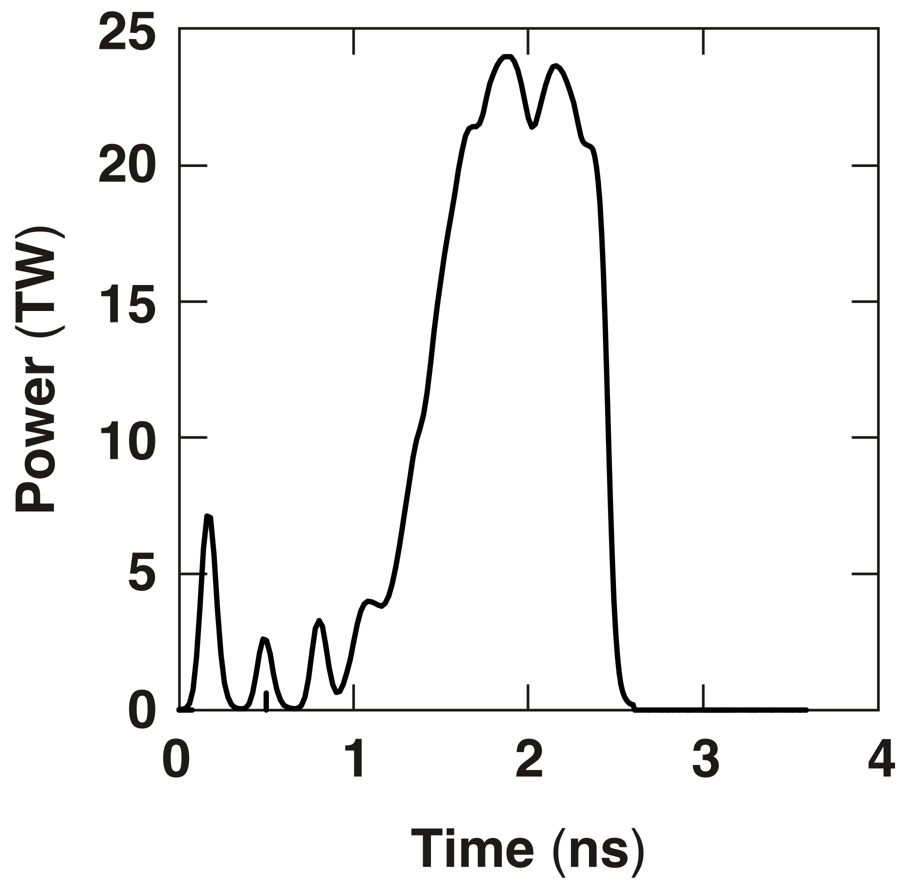
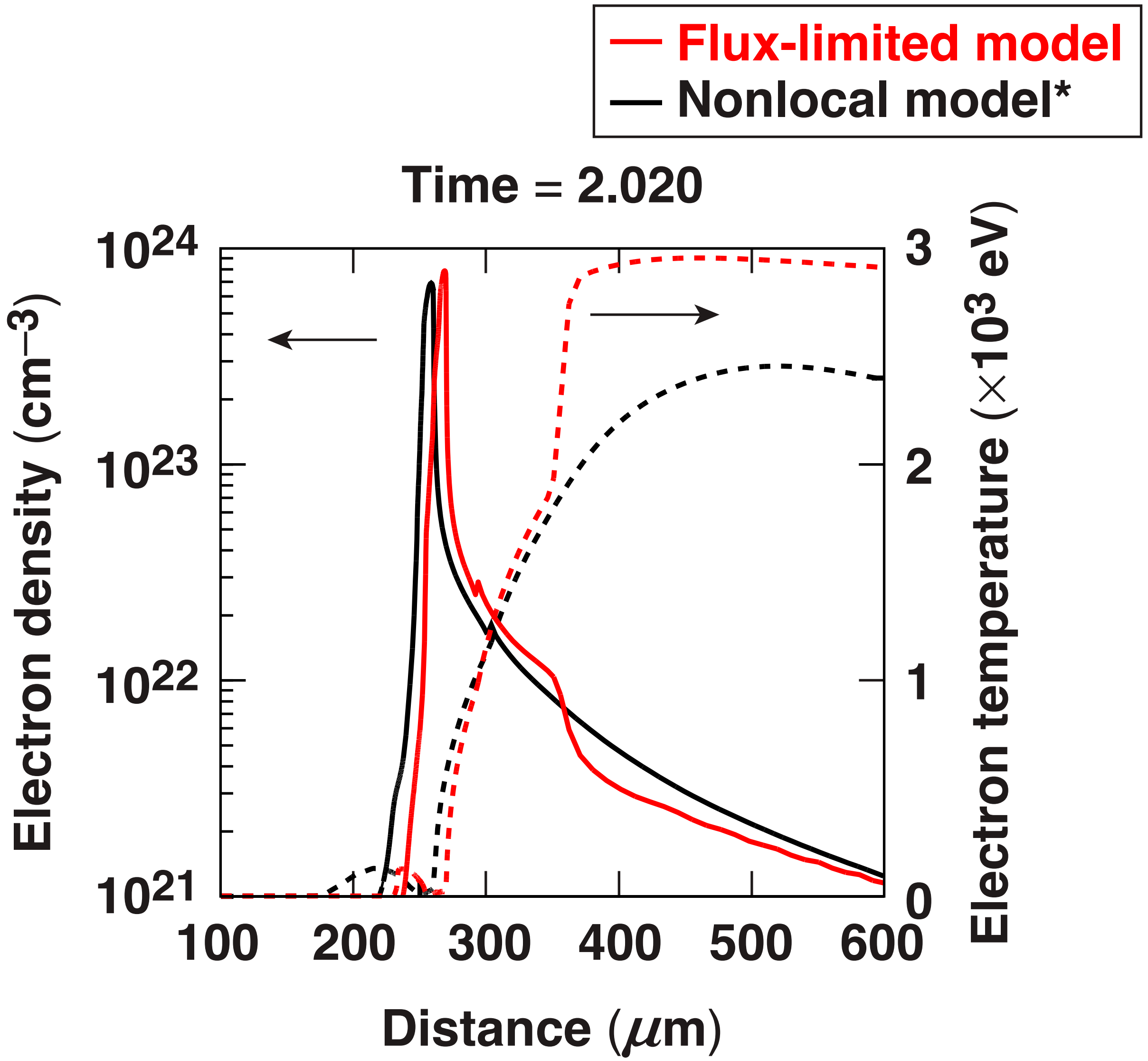
Motivation

An accurate description of thermal transport in plasmas has large implications in direct-drive inertial confinement fusion





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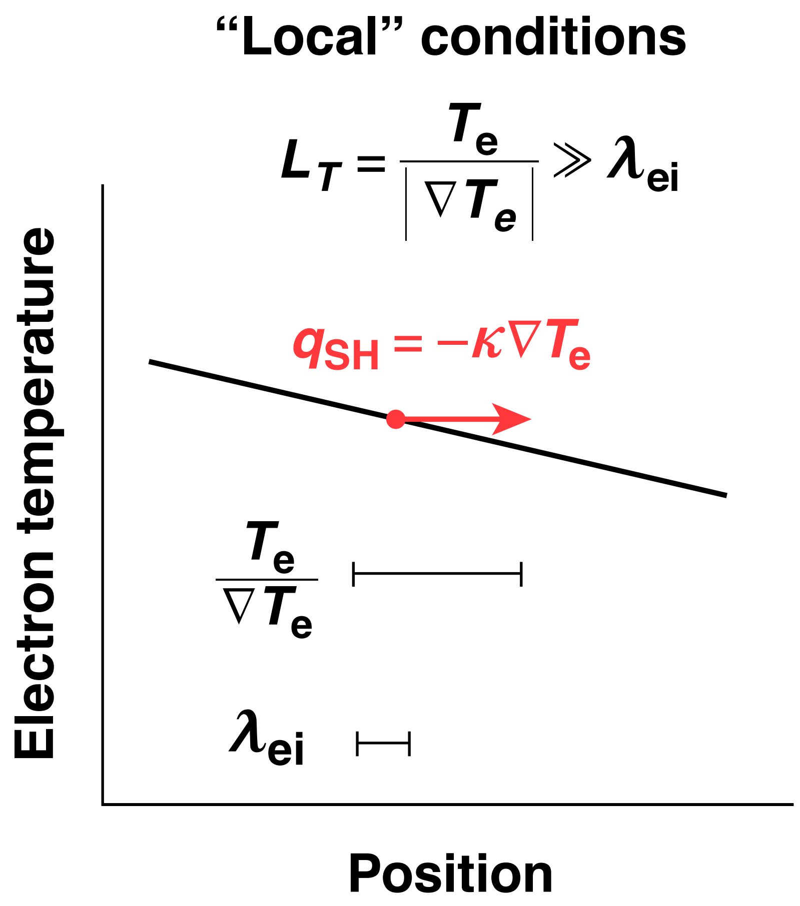
*V. N. Goncharov *et al.*, Phys. Plasmas 13, 012702 (2006).

Classical thermal transport (i.e., Spitzer–Härm) requires the collisional distance of electrons to be small compared to the temperature scale length



Classical theory only requires information (including ∇T_e) at a particular location to determine heat flux.

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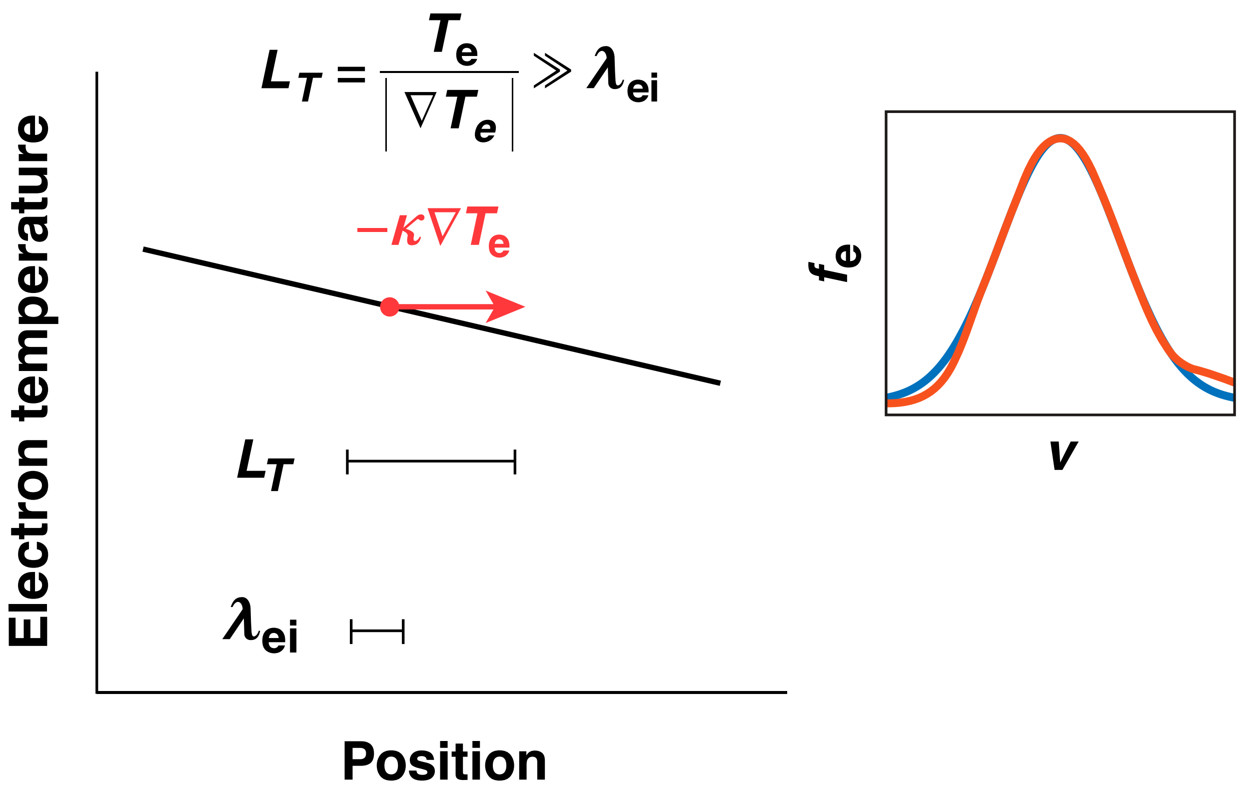
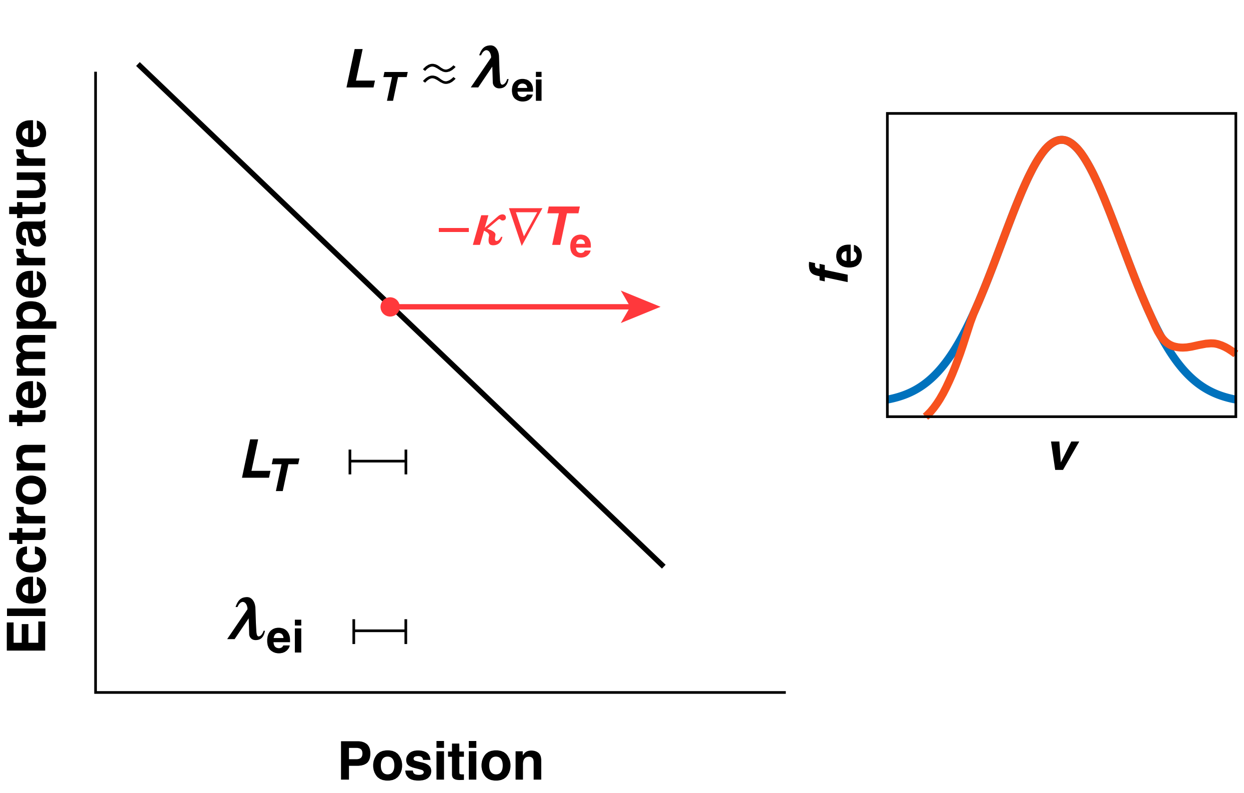
The classical model breaks down in regions with large temperature gradients



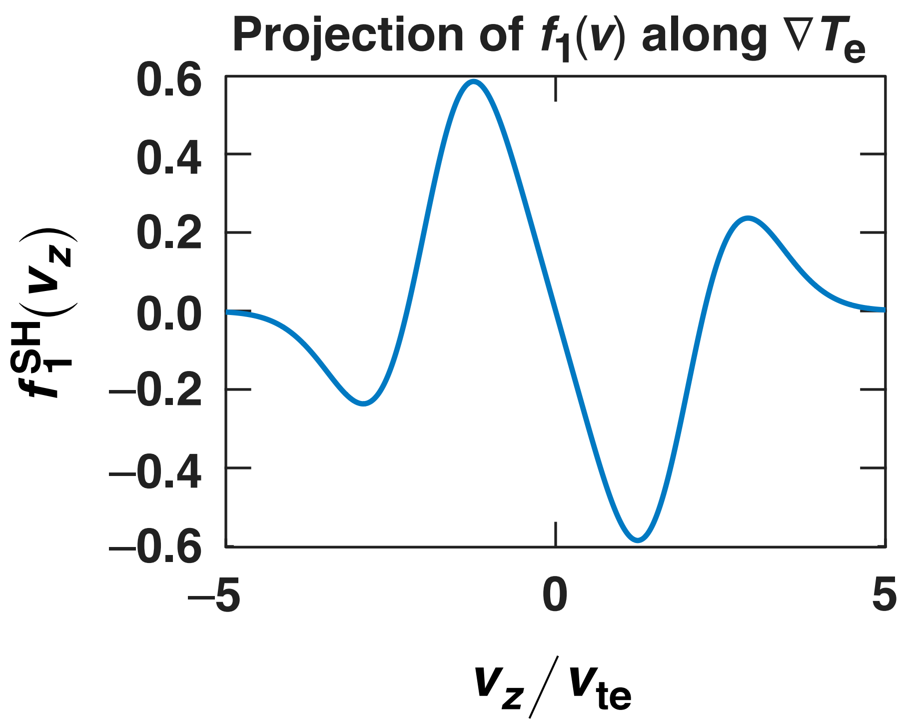


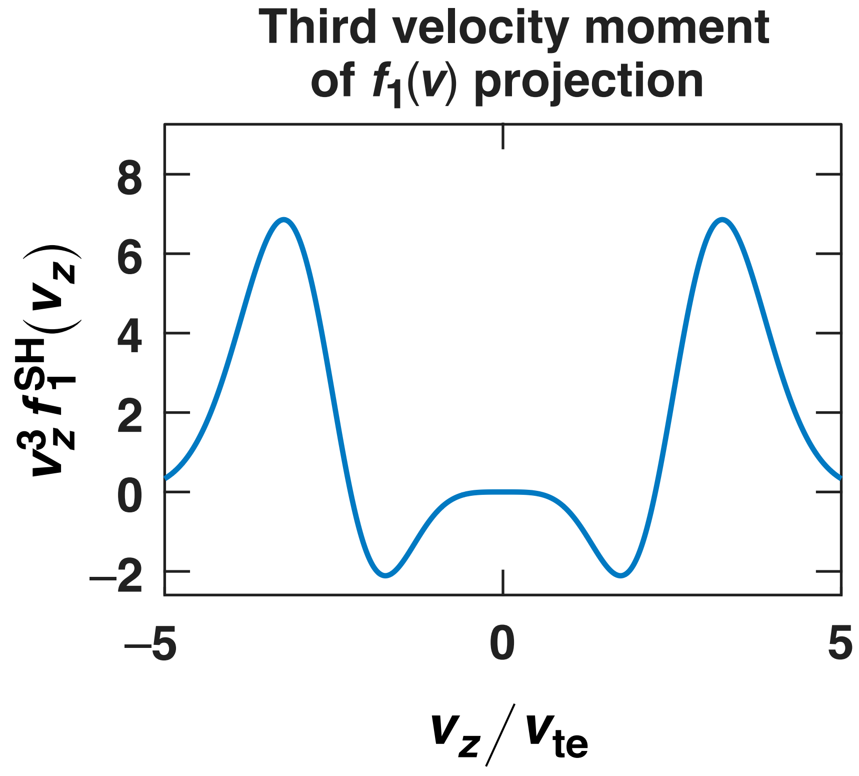
The validity of the classical theory can be expressed in terms of the collision parameter λ_{ei}/L_T.

E27784

The Spitzer–Härm (classical theory) model accounts for heat flux by introducing a correction term to the electron distribution function

$$f_e^{SH}(v) = f_0^M(v) + \frac{\lambda_{ei}}{L_T} f_1(v)$$





$$\int_{-\infty}^{\infty} f_1^{SH}(v_z)\,dv_z = 0$$

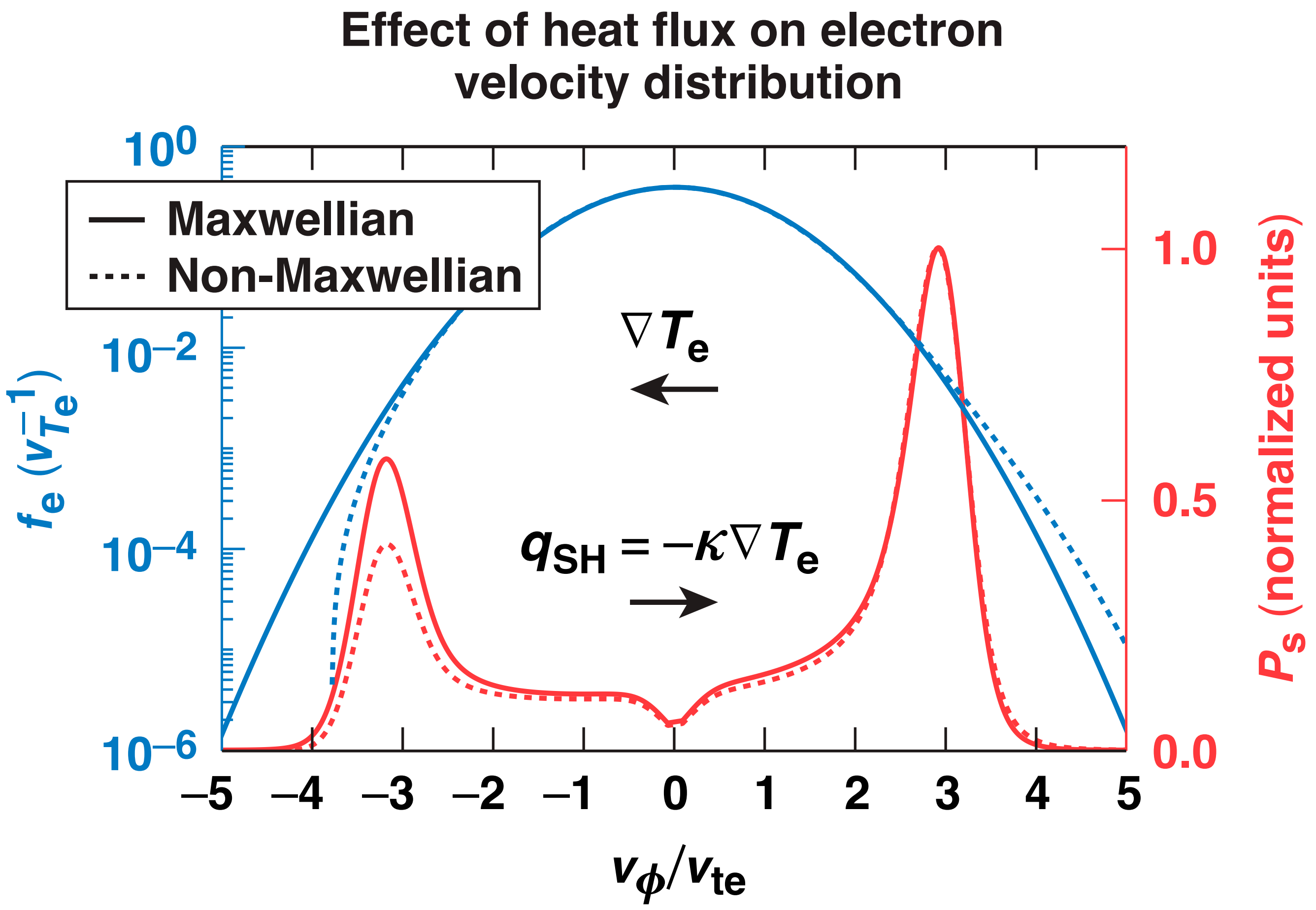
Conserves number of particles

$$q \propto \frac{\lambda_{ei}}{L_T} \int_{-\infty}^{\infty} v^3 f_1^{SH}(v_z)\,dv_z = -\kappa \nabla T_e > 0$$

Nonzero heat flux

E27786

The collective Thomson-scattering spectrum is sensitive to the electron distribution function



$$P_s \propto \frac{f_e(\omega/k)}{\left|1+\chi_e\right|^2}$$

$$\chi_e \propto \int_{-\infty}^{\infty} \frac{k \cdot \partial f_e/\partial v \big|_{v=\omega/k}}{\omega - k \cdot v} dv$$

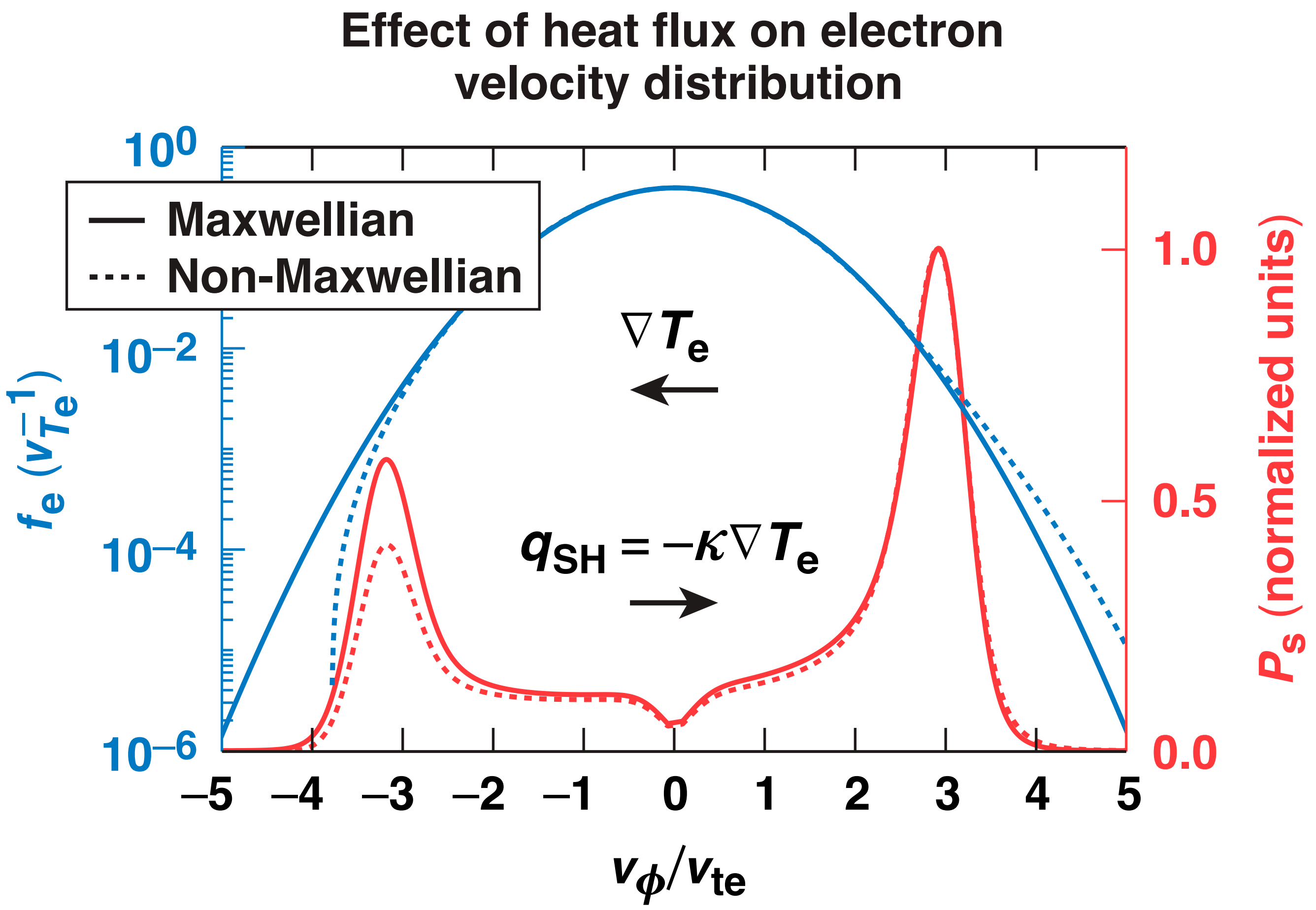
$$f_e^{SH}(v) = f_0^M(v) + \frac{\lambda_{ei}}{L_T} f_1(v)$$

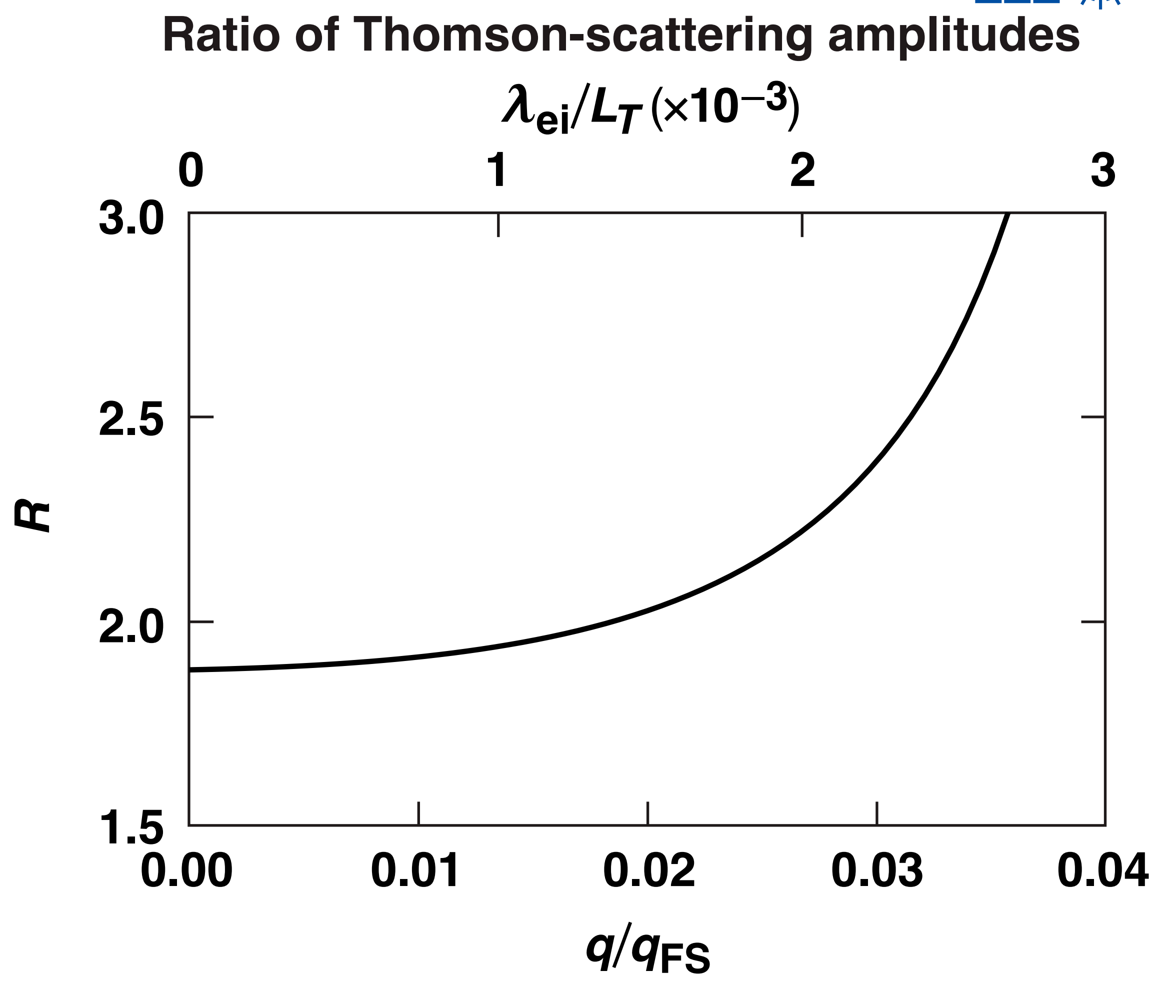
$$v_\phi = \omega/k$$
$$q_{fs} = n_e T_e v_{te}$$

A Milder *et al.*, BO7.00015, this conference.

E27955

The collective Thomson-scattering spectrum is sensitive to the electron distribution function





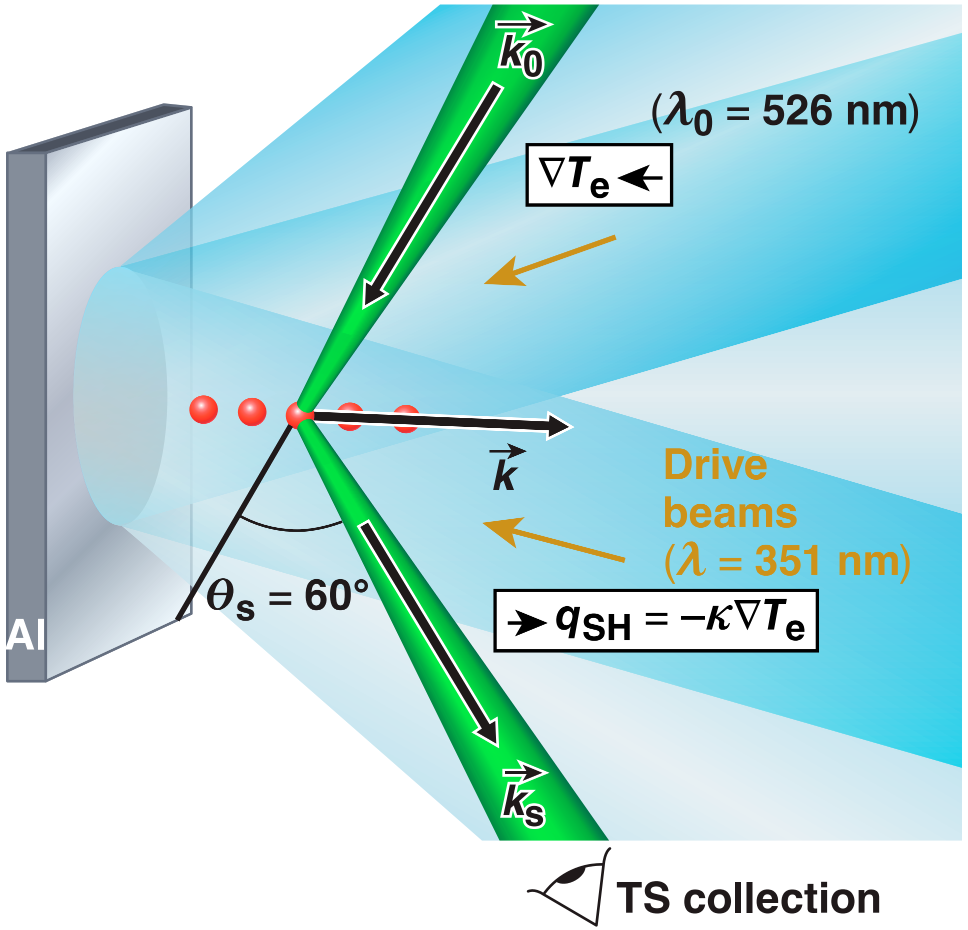
The amplitudes of the electron plasma wave features provide a measure of heat flux.

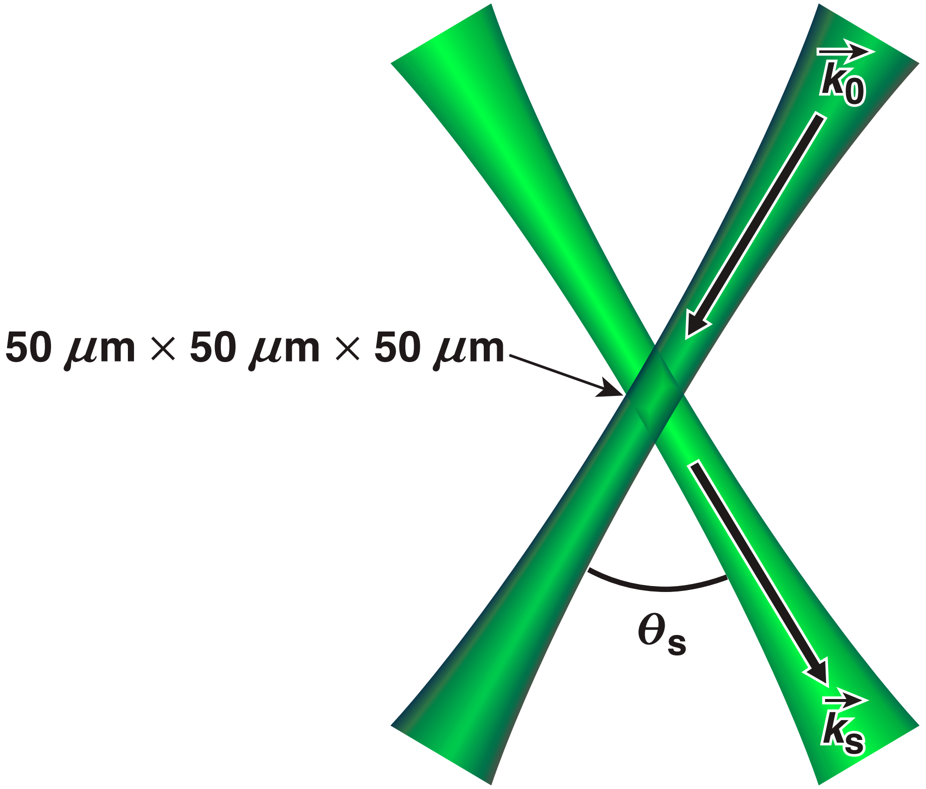
$v_\phi = \omega / k$

$q_{fs} = n_e T_e v_{te}$

E27788

Thomson scattering (TS) makes local measurements of plasma parameters (e.g., heat flux, electron temperature, and density)





$$\frac{v_{\phi}^{EPW}}{v_{te}} \sim \sqrt{\frac{n_e}{T_e\left[1-\cos\theta_s\right]}}\,\lambda_0$$

Experiments were set up to measure electron plasma waves parallel and antiparallel to the temperature gradient.

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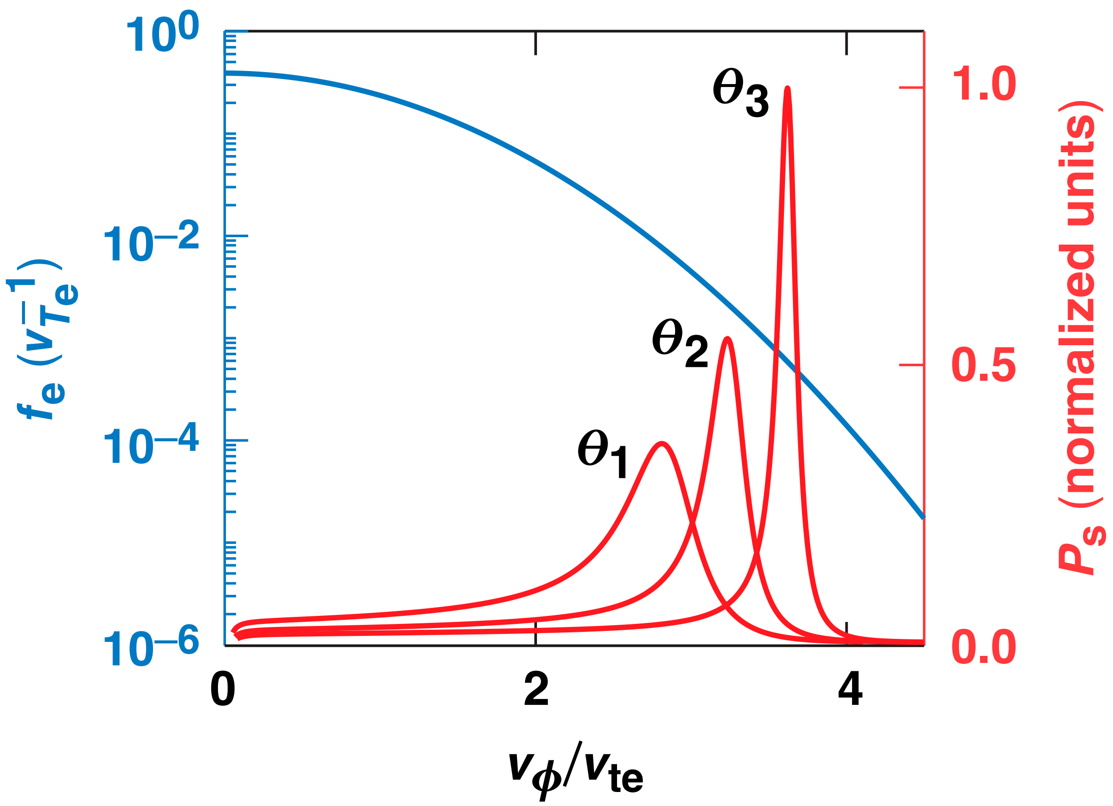

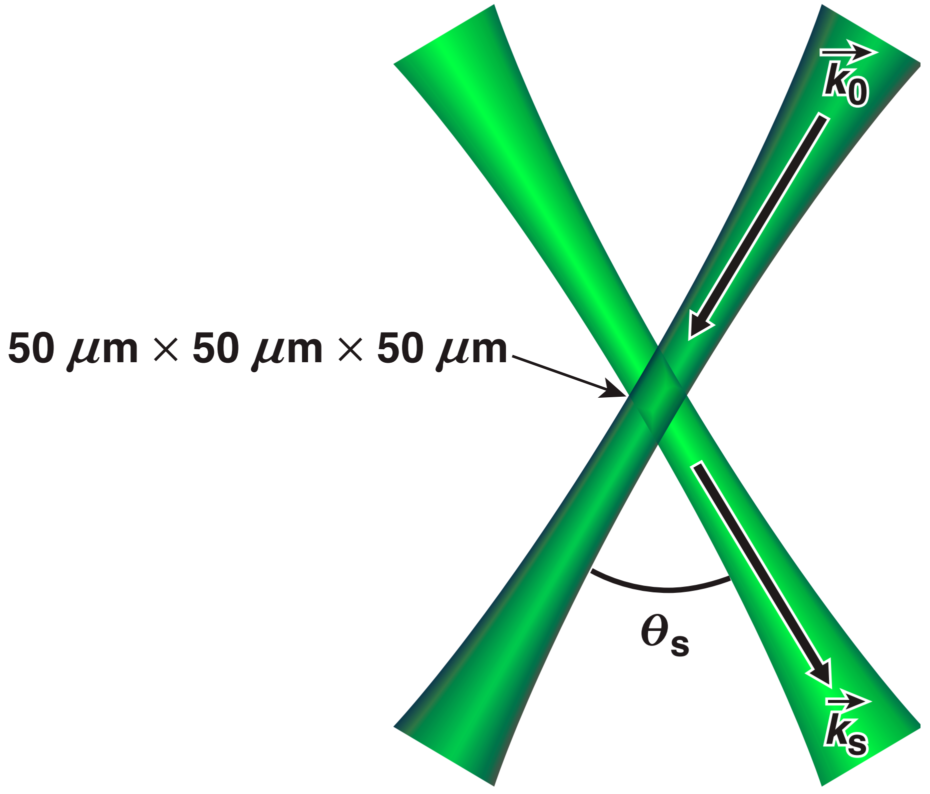

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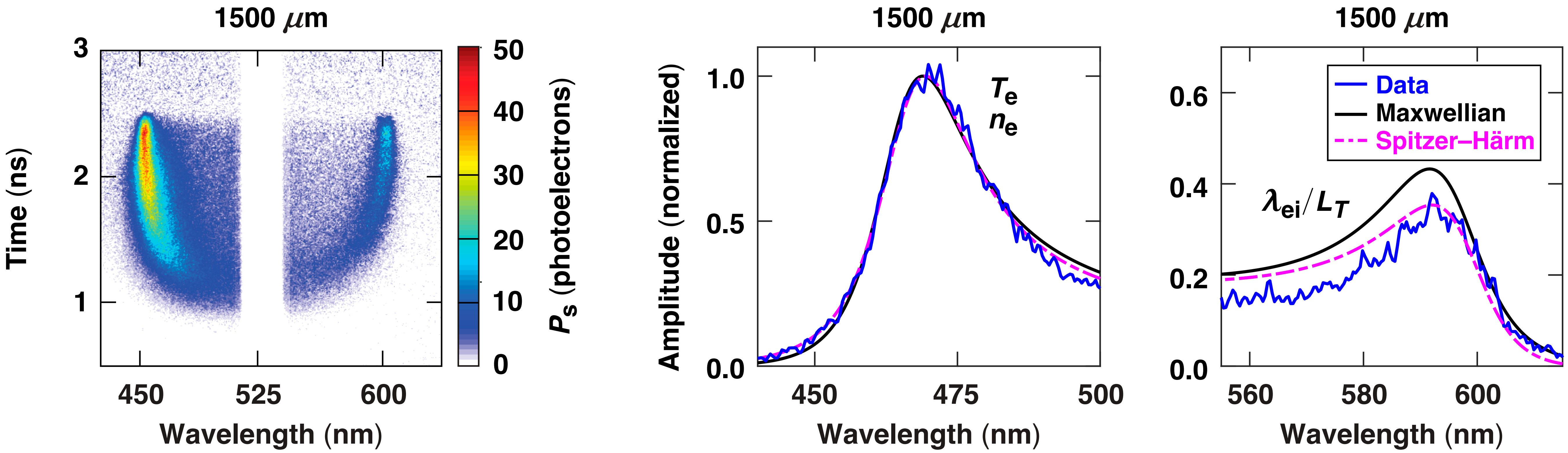
E27956

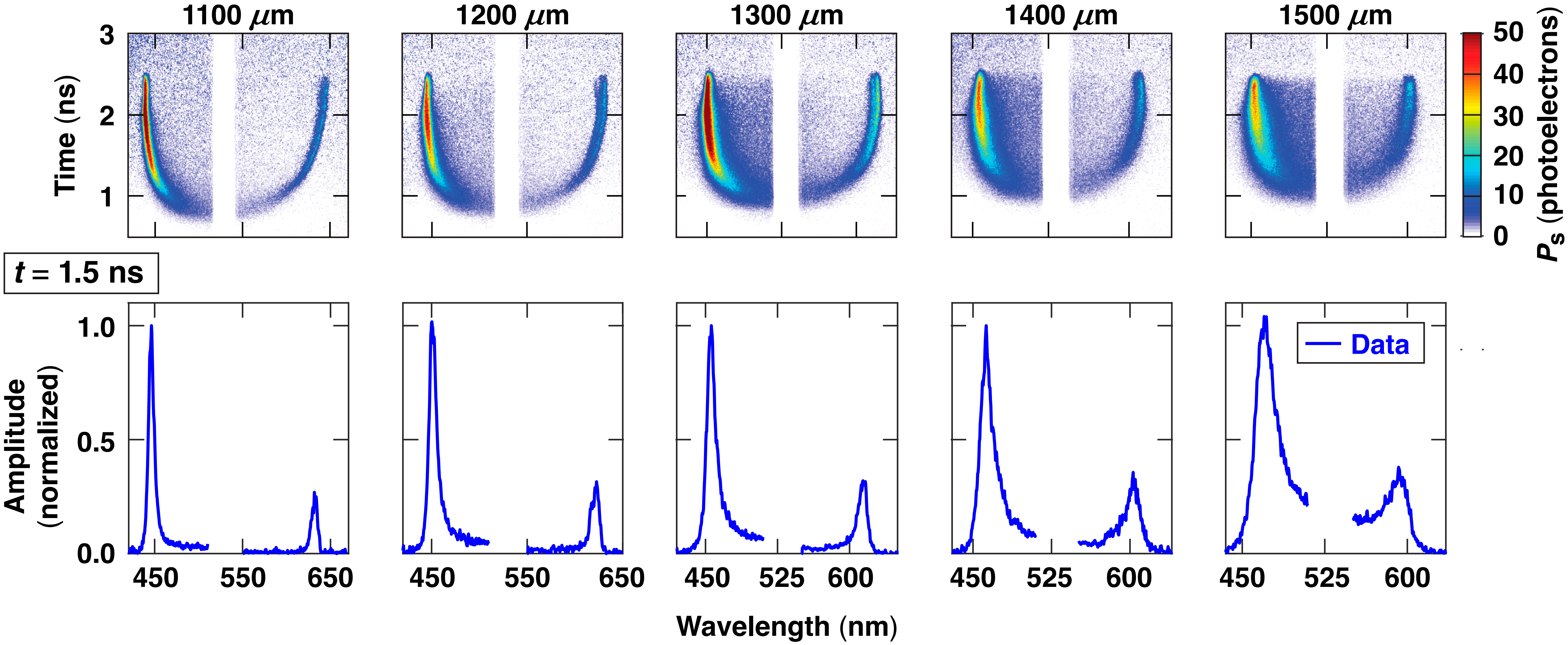
The Thomson-scattering spectrum provides an accurate measure of the electron temperature, density, and heat flux



Classical theory is in good agreement with the measured spectrum ($\lambda_{ei}/L_T = 6 \times 10^{-3}$).

E27818

Measurements at five locations in the corona provided high-quality Thomson-scattering data



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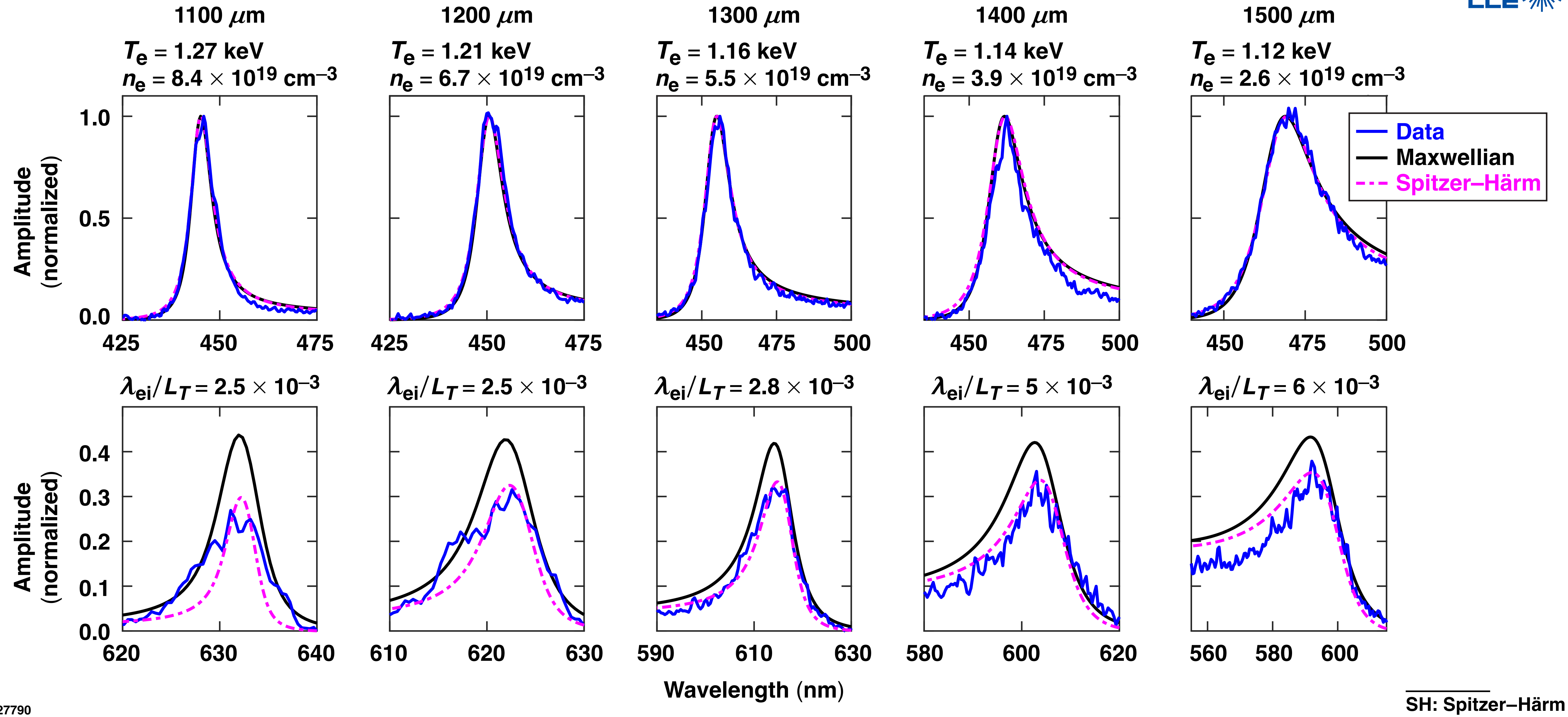
Using classical (SH) theory, the Thomson-scattering spectra were used to determine the electron temperature, density, and heat flux (λ_{ei}/L_T) at all five locations



E27790

SH: Spitzer–Härm

Measurements of electron temperature, density, and λ_{ei}/L_T were obtained using classical theory (SH)

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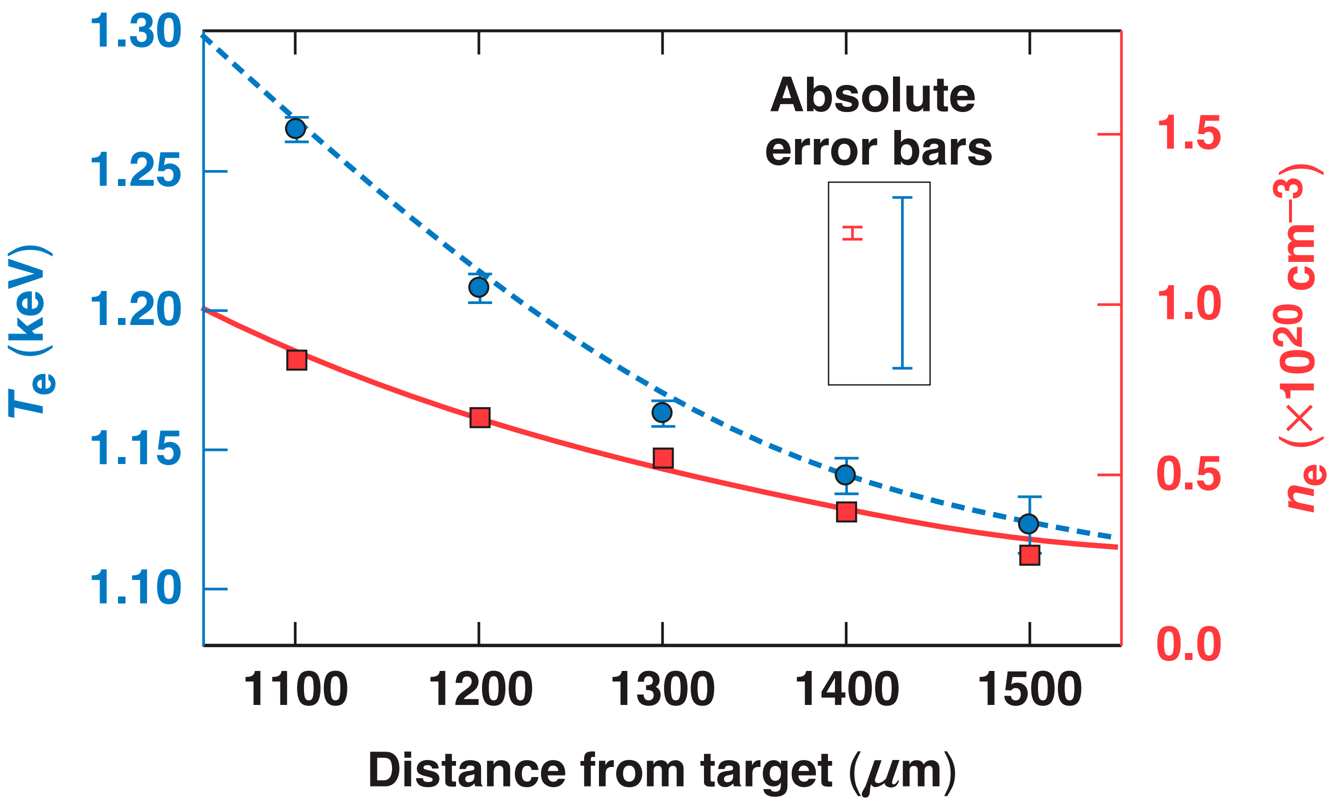
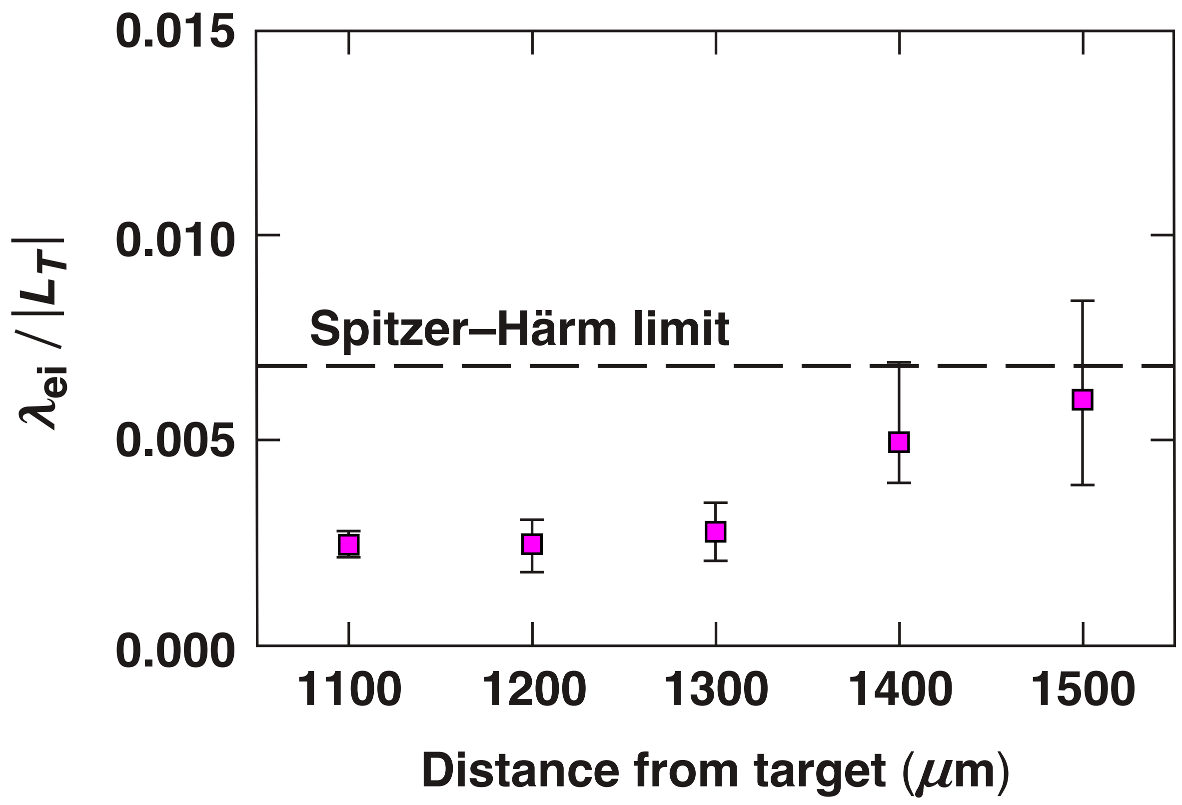
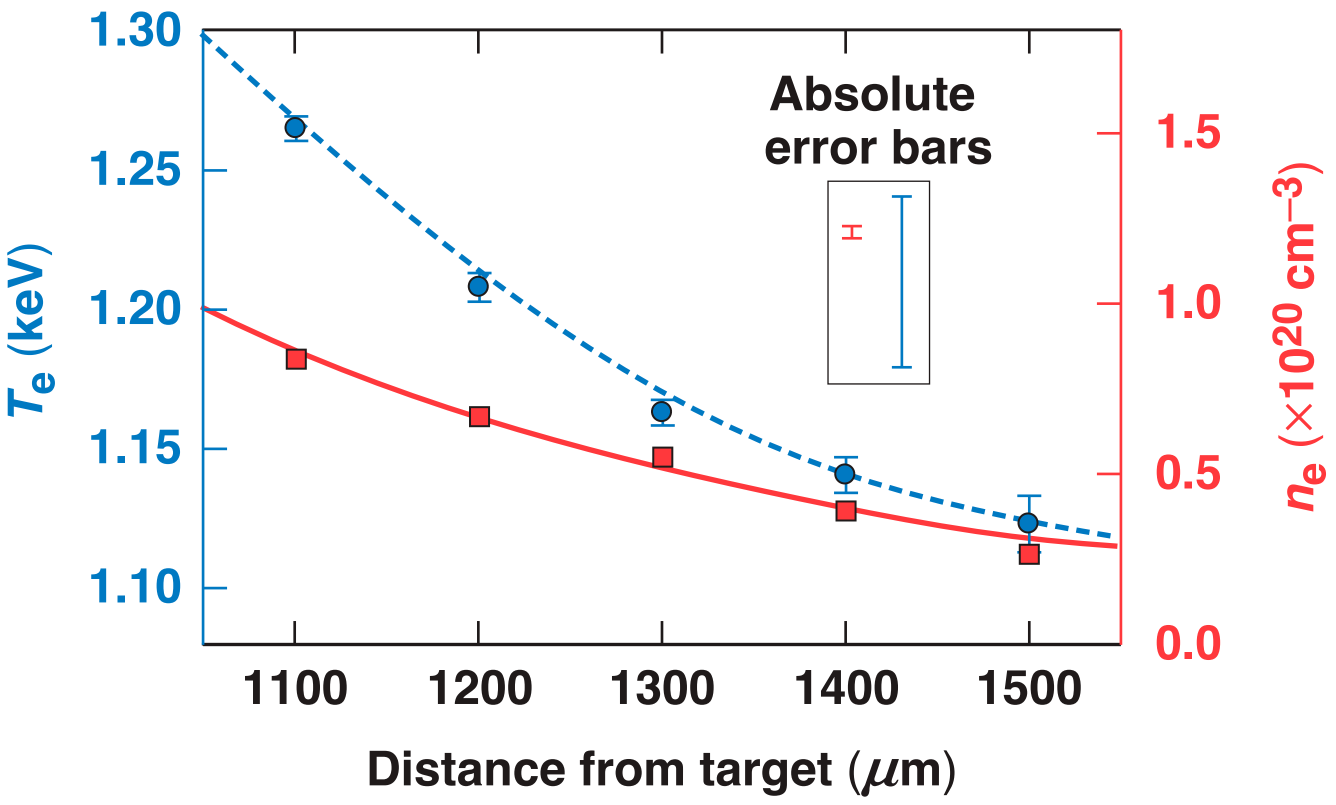
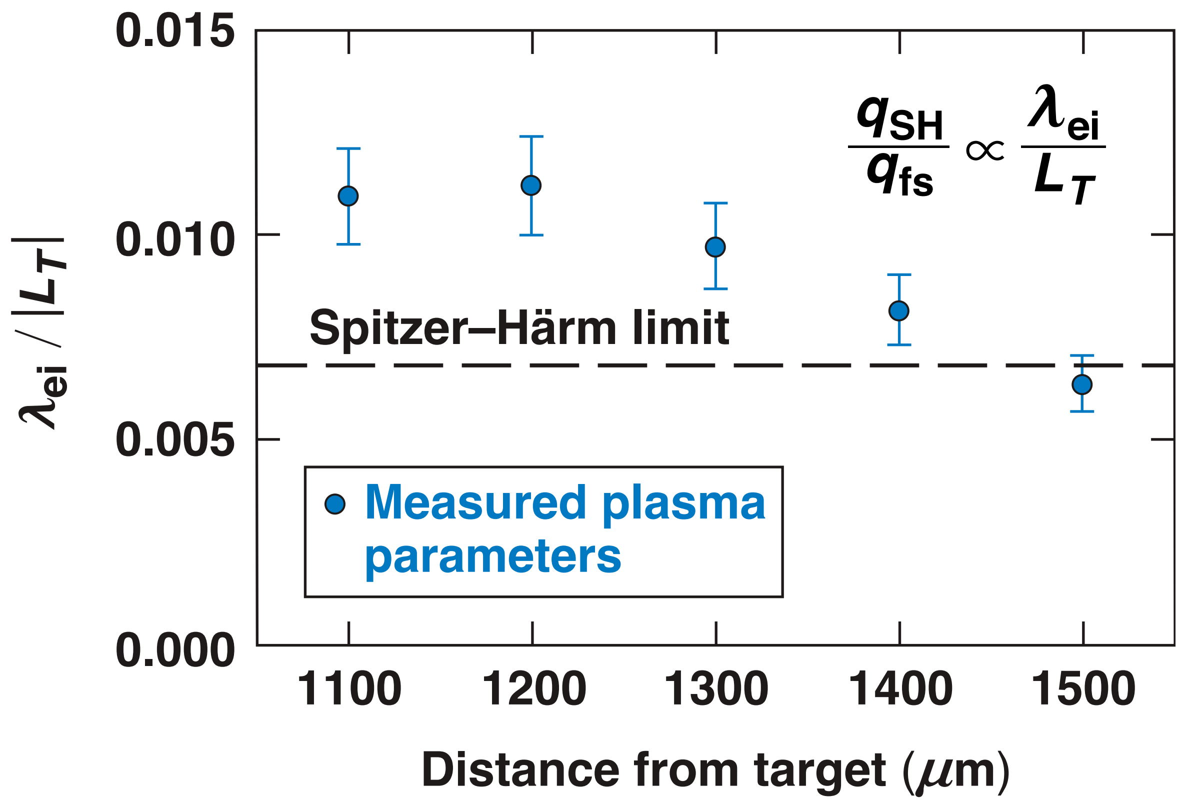




E27791

Temperature and density profiles were used to infer the classical thermal flux

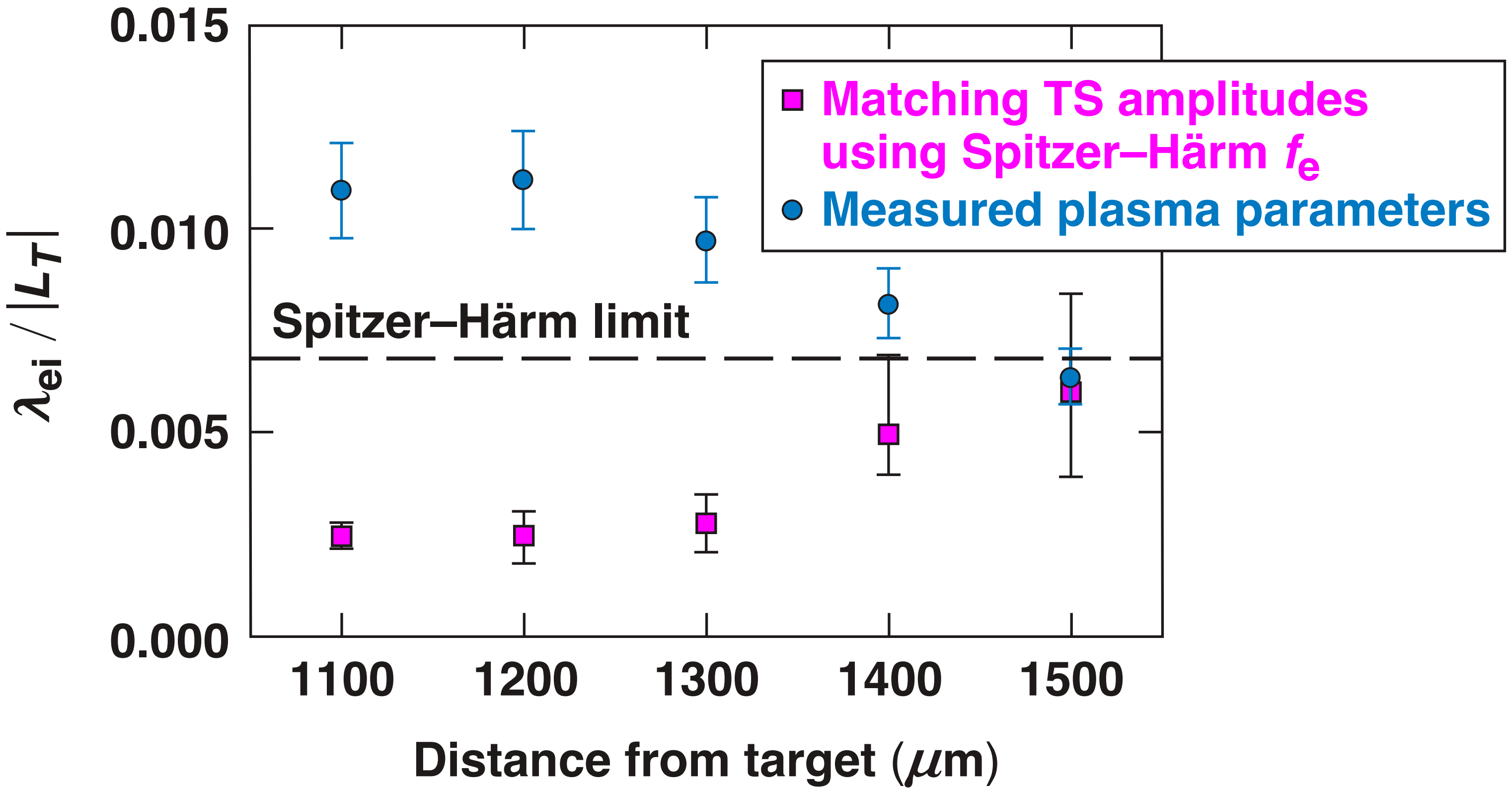




Heat flux inferred by temperature and density profiles violate classical theory ($\lambda_{ei}/|L_T| > 7 \times 10^{-3}$).

E27735a

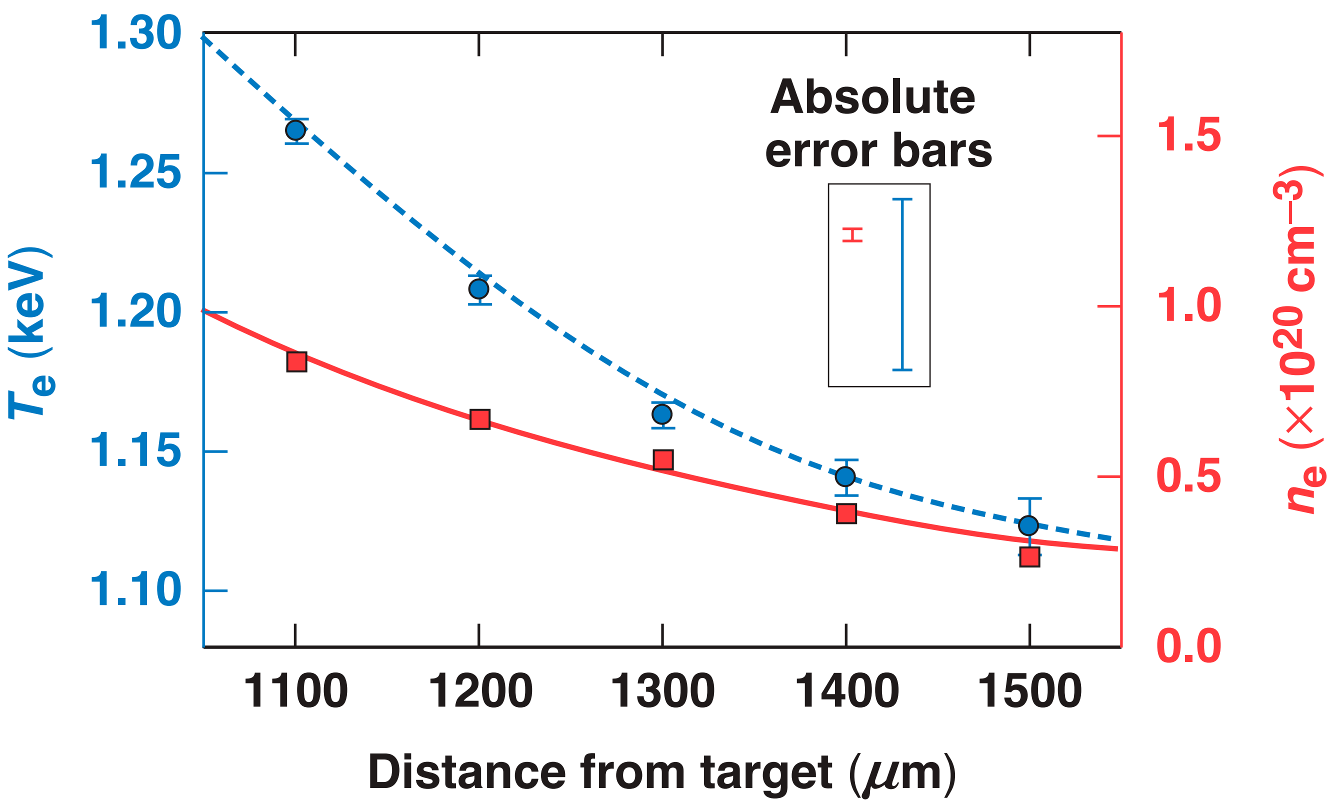
When $\lambda_{ei}/|L_T| > 7 \times 10^{-3}$, there are noticeable discrepancies between the flux inferred from the measured plasma conditions ($q_{SH} = -\kappa\nabla T_e$) and the measured Thomson-scattering spectra



Nonlocal electron distribution functions that maintain the measured plasma profiles are required when $\lambda_{ei}/|L_T| > 7 \times 10^{-3}$.

E27792

Fokker–Planck calculations,* which include the relevant nonlocal thermal transport physics, were used to determine electron distribution functions consistent with the measured plasma conditions



$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} = \left(\frac{\delta f}{\delta t}\right)_c$$

$$f(t, x, v) = \sum f_n(t, x, v) P_n(\theta)$$

Fokker–Planck calculations extended the electron distribution function to higher-order terms; nine terms were required to accurately resolve the electron distribution functions at high velocities.

E27793

*M. Sherlock, J. P. Brodrick, and C. P. Ridgers, Phys. Plasmas 24, 082706 (2017).

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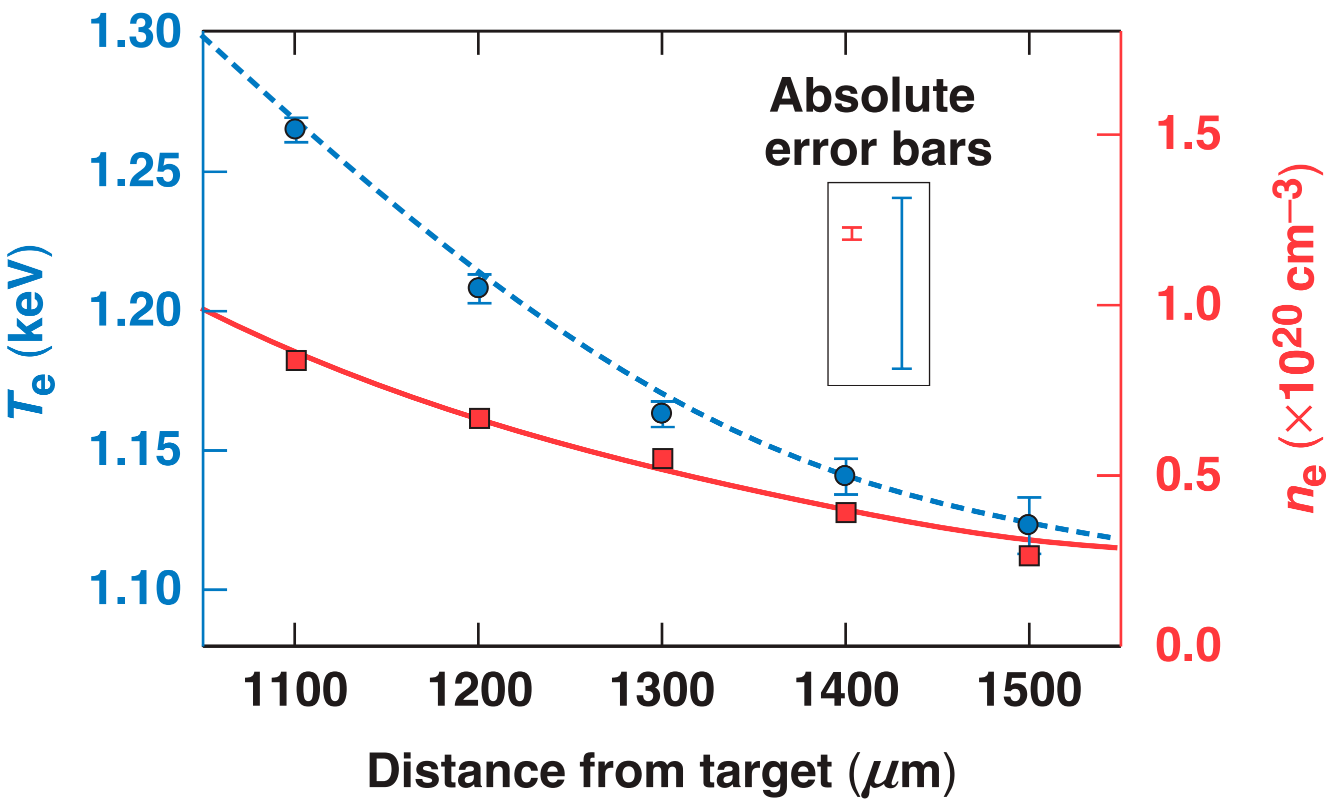
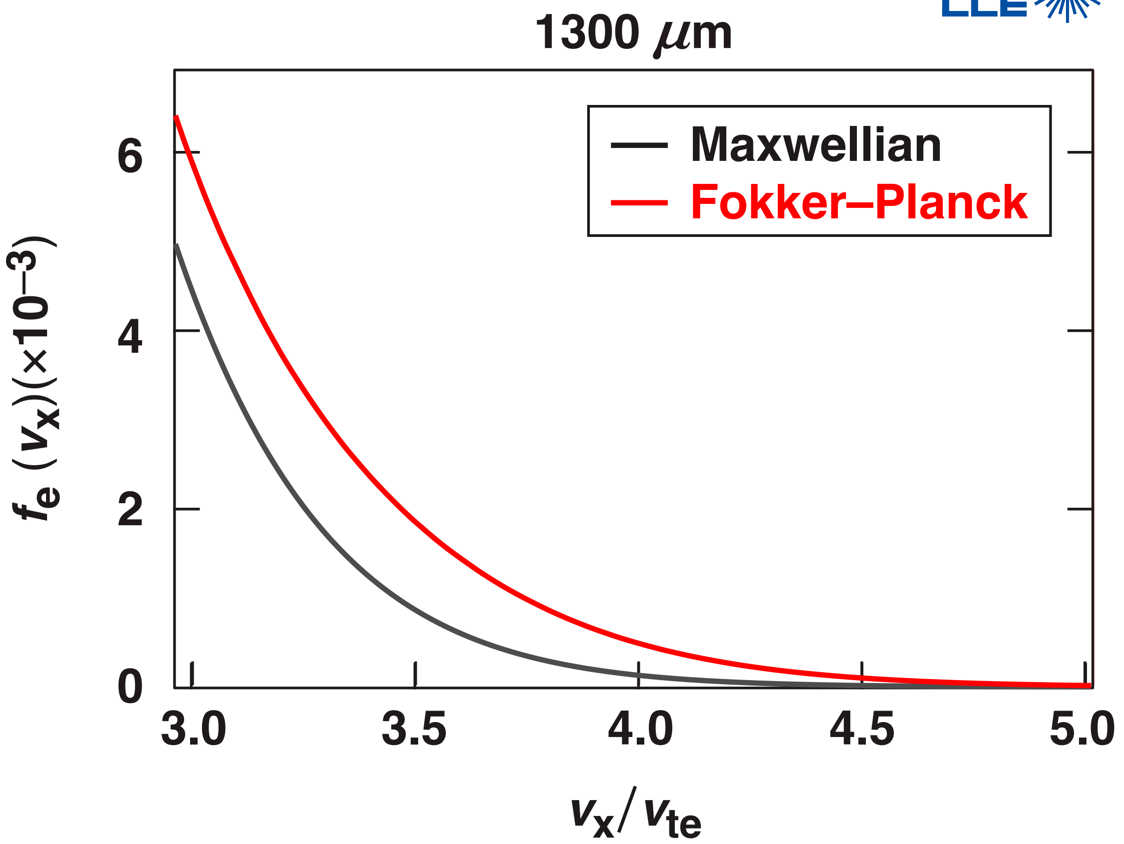


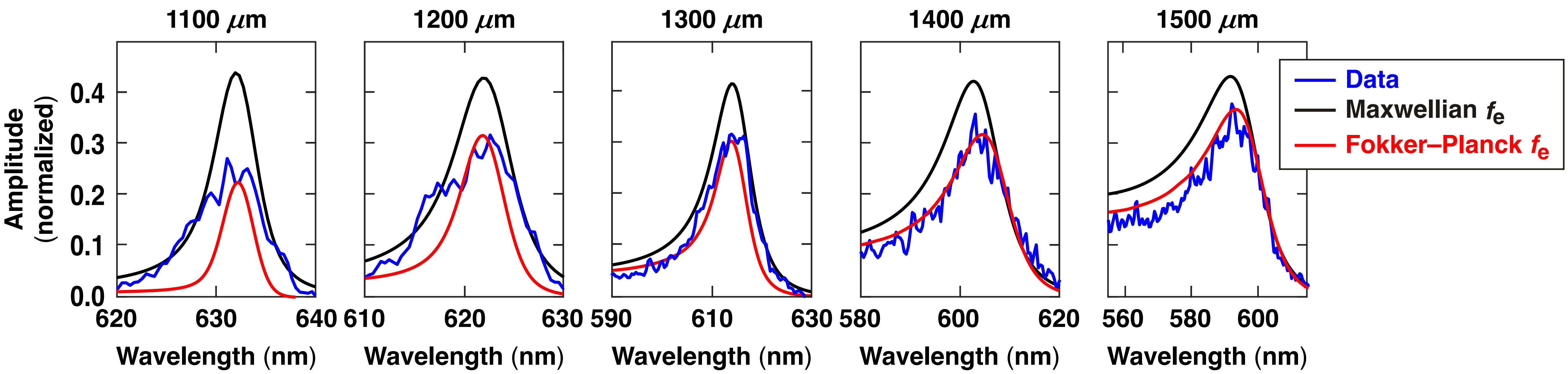


Electron distribution functions were determined at each measurement location.

E27736a

*M. Sherlock, J. P. Brodrick, and C. P. Ridgers, Phys. Plasmas 24, 082706 (2017).

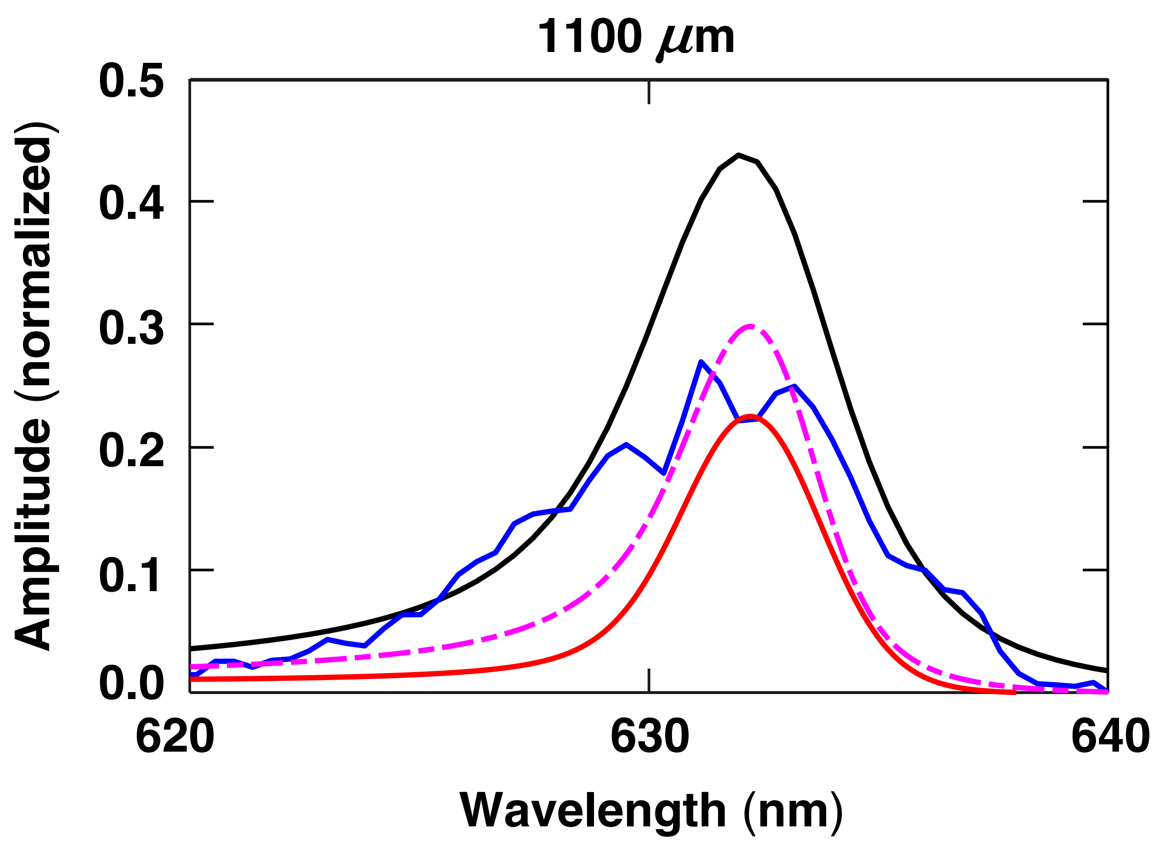
Fokker–Planck electron distribution functions recovered the amplitude of observed scattering features at all positions

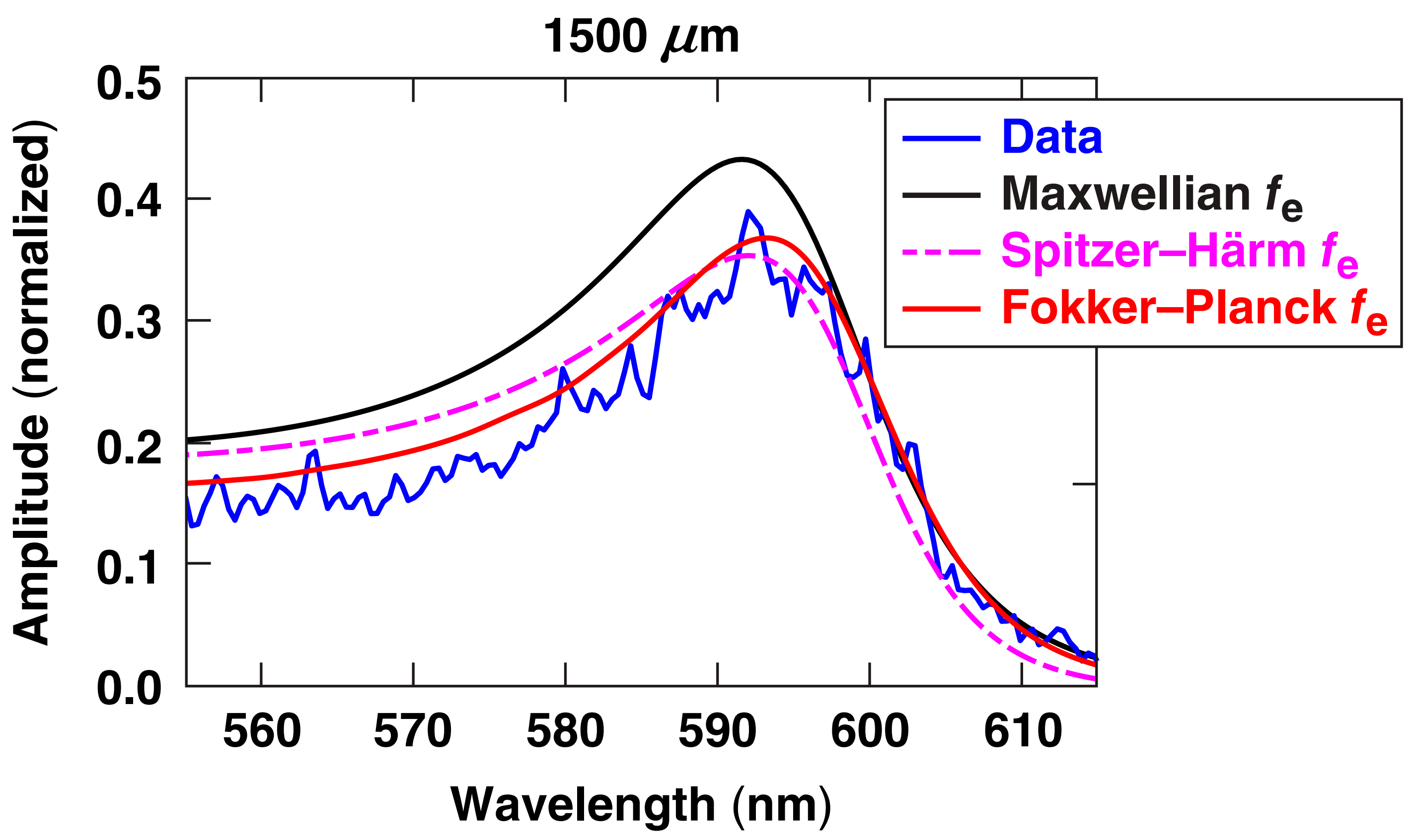


The excellent agreement between calculated and measured spectra provided a path to measure heat flux.

E27794

In the most nonlocal conditions, the calculated spectra reproduce the amplitude of the scattering peaks, but underestimate the width





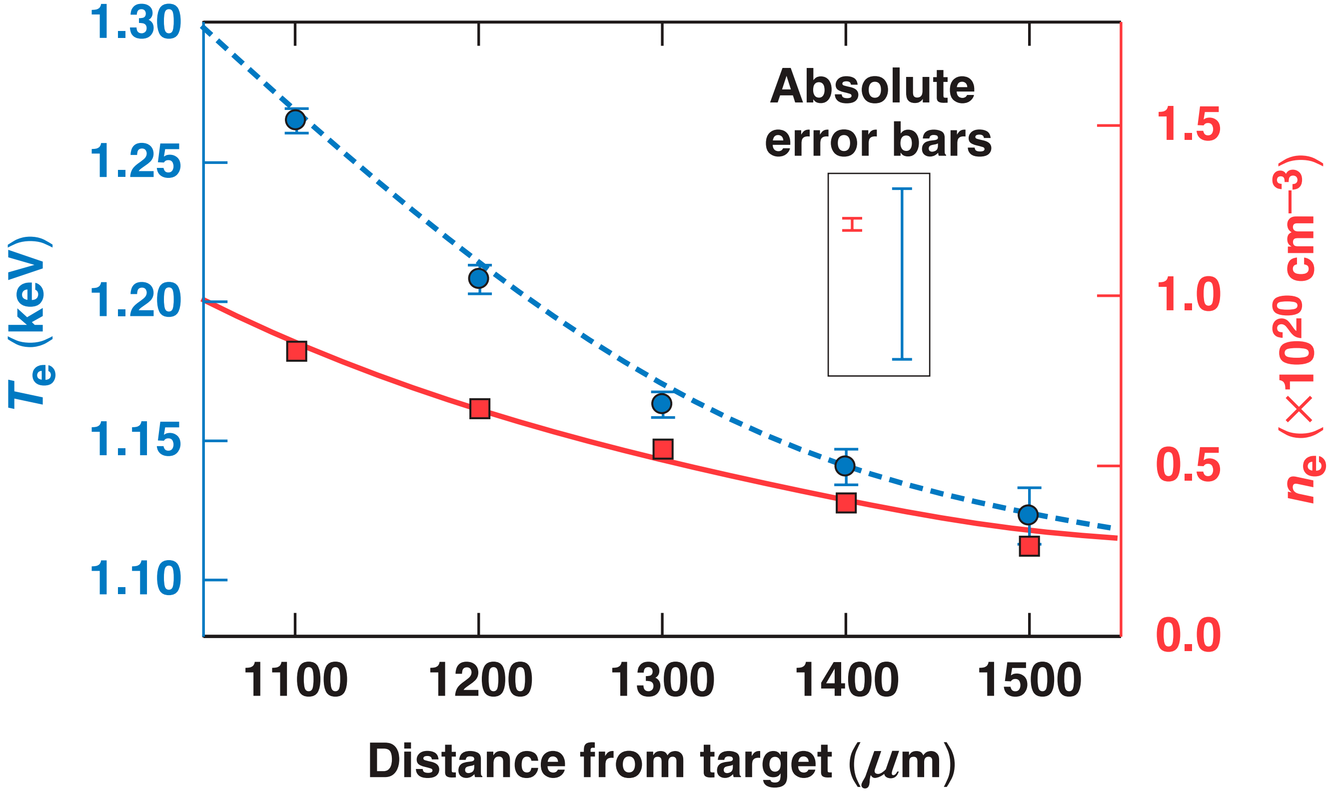
Spectra calculated using multiple heat-flux models at the most collisional location (1500 μm) show good agreement with the data.

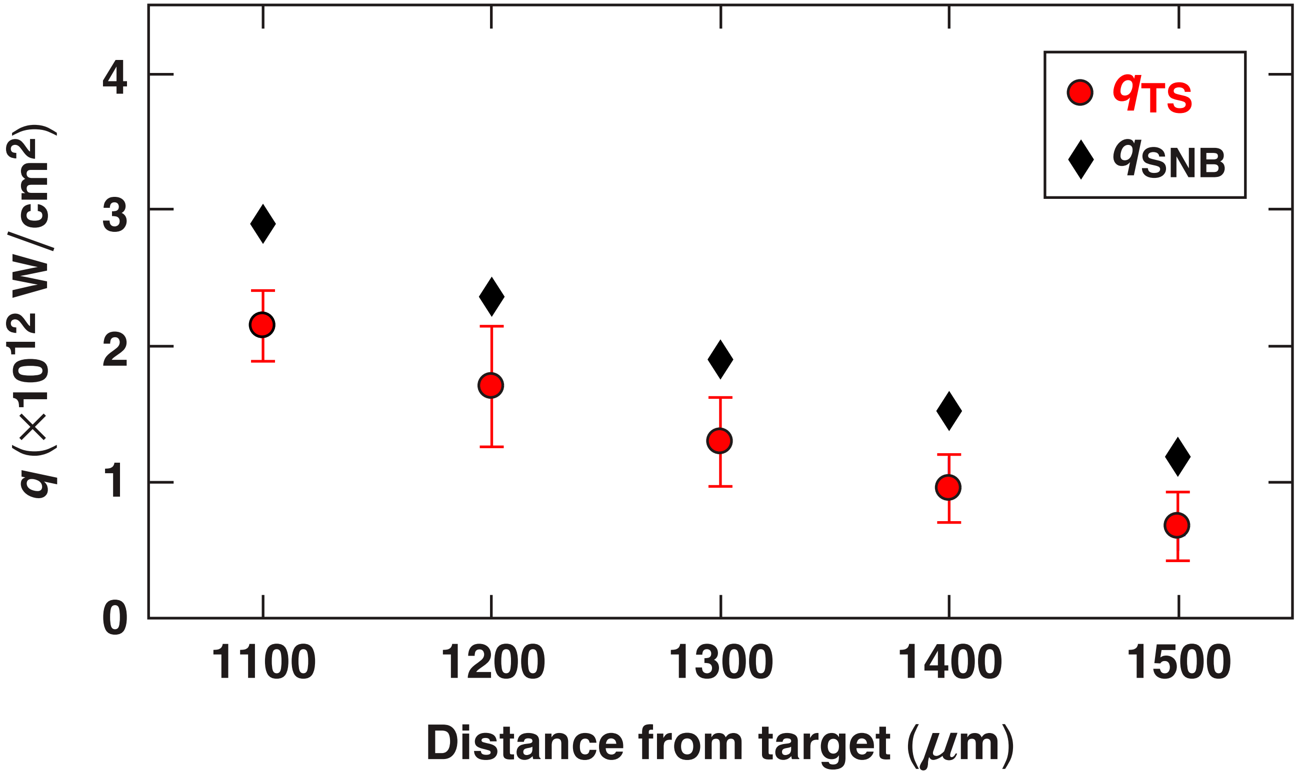
E27734a

The SNB* model is a computationally efficient method that uses multigroup diffusion to calculate nonlocal heat flux

$$q(\vec{r}) = q_{SH}(\vec{r}) - \sum_g \frac{\lambda_g(\vec{r})}{3} \nabla H_g(\vec{r})$$

$$H_g(\vec{r}) = \int_{4\pi} q_g(\vec{\Omega}, \vec{r})\, d^2\vec{\Omega}$$



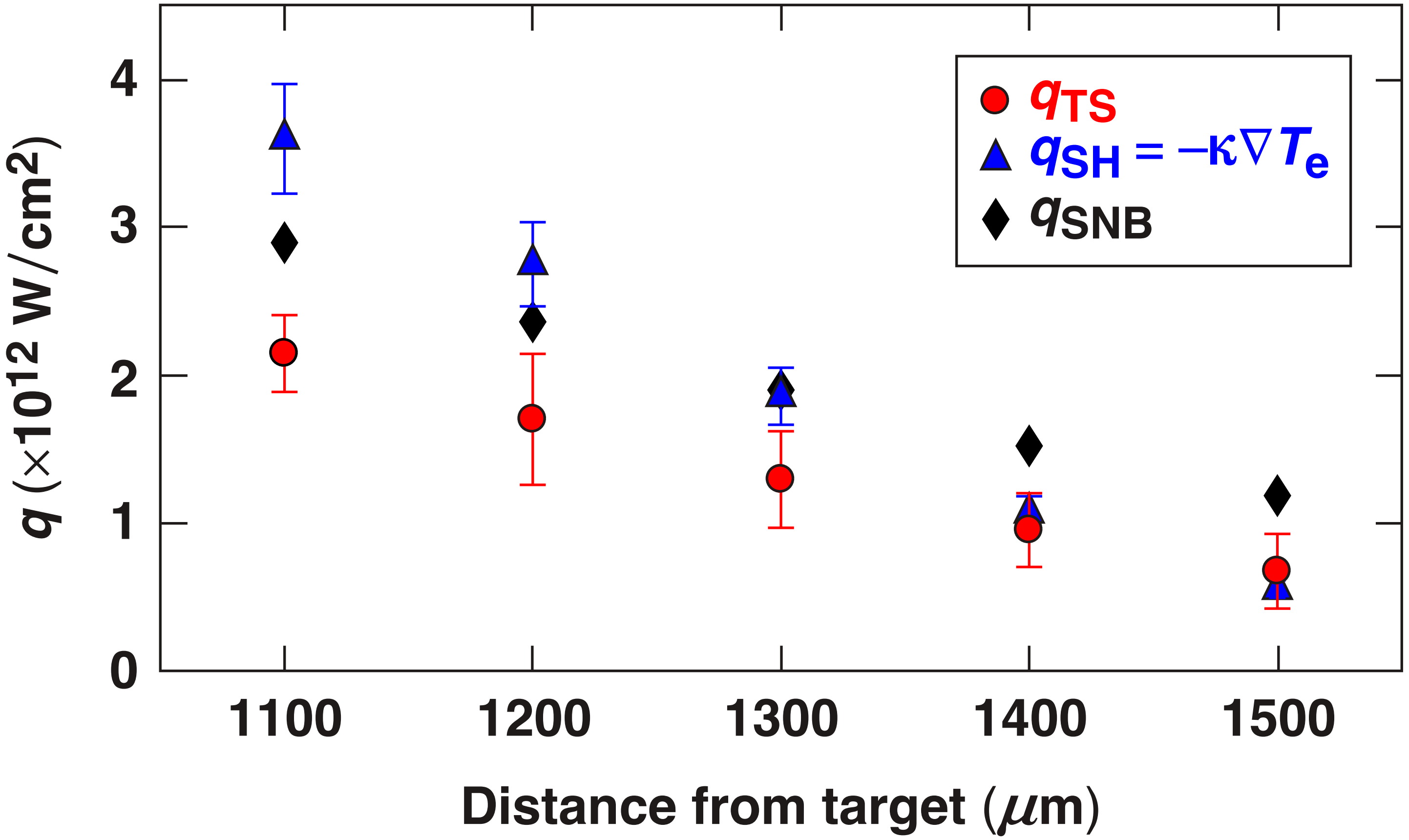


The SNB model overestimates the heat flux at all measured locations.

E27795

*G. P. Schurtz, Ph. D. Nicolaï, and M. Busquet, Phys. Plasmas 7, 4238 (2000).

The measured heat flux is reduced from values predicted by classical theory in the nonlocal regions and agrees with classical theory in small-gradient regions



These results highlight the need to include physics often missing from computationally efficient models (i.e., high-order polynomials to properly resolve velocity space.)

E27294

Nonlocal heat flux was measured using Thomson scattering from electron plasma waves

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R. J. Henchen *et al.*, Phys. Rev. Lett. 121, 125001 (2018).