Measuring Heat Flux from Collective Thomson Scattering with Non-Maxwellian Distribution Functions

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Thermal transport in plasmas is of particular interest to inertial confinement fusion, where a correct description of heat flux is crucial to modeling the absorption of incident laser beams used to implode fusion targets. Electron thermal transport is a fundamental process in plasma physics that becomes difficult to calculate since even in the most modest conditions, classical theory tends to break down. Extensive work has attempted to determine the nonlocal heat flux that is responsible for transporting thermal energy over large distances but quantitative experiments are required.

In laser-produced plasmas, where energy is primarily deposited locally at the critical density, temperature gradients inherently drive non-Maxwellian electron distribution functions as electrons carry the heat down the temperature gradient and slower electrons carry a return current up the temperature gradient to maintain neutrality. A consequence of heat flux, and the ensuing distortion of the distribution function, is to change the partition of energy between the thermal electrons and the thermal fluctuations. This has a particularly large effect on the amplitude of the fluctuations that have phase velocities near the velocity of the heat-carrying electrons. The heat flux modifies both the number of electrons and the slope of the distribution function, which directly changes the local Landau damping of ion-acoustic and Langmuir waves.

Collective Thomson scattering measures the fluctuation spectrum, and when probing electron plasma fluctuations with phase velocities in the region of heat-carrying electrons, the spectrum can be used to determine the heat flux.[1] The first-order effect of the electron distribution function on the Thomson-scattering spectrum can be observed in the dependence of the peak power scattered into the electron plasma wave feature,

$$P_{\text{peak}} \propto \left. \frac{f_{\text{e}}(v)}{\left[\text{d}f_{\text{e}}(v)/\text{d}v\right]^2} \right|_{v=v_\phi}, \tag{1}$$

where $f_{\text{e}}(v)$ is the electron distribution function and $\text{d}f_{\text{e}}(v)$ is elevated at the phase velocity v_ϕ.

We present the direct measurement of heat flux using collective Thomson scattering from a laser-produced coronal plasma. The heat flux was measured in two ways that were used to experimentally determine the validity of classical thermal transport. The first measurement of heat flux used the classically derived non-Maxwellian electron distribution functions to reproduce the electron plasma wave Thomson-scattering spectra, while the second method used the measured plasma conditions to calculate the classical heat flux. Figure 1(a) shows the experimental setup, where six 351-nm laser beams created a blowoff aluminum plasma. A 526-nm Thomson-scattering probe beam was used to scatter light from five locations in the coronal plasma. At each location the complete collective Thomson-scattering spectrum was measured and used to determine the electron temperature (T_e) and density (n_e) profiles. These plasma conditions were used to calculate the classical heat flux ($q = -\kappa \nabla T_e$), where κ is the classical thermal conductivity that depends only on the local electron temperature and density.

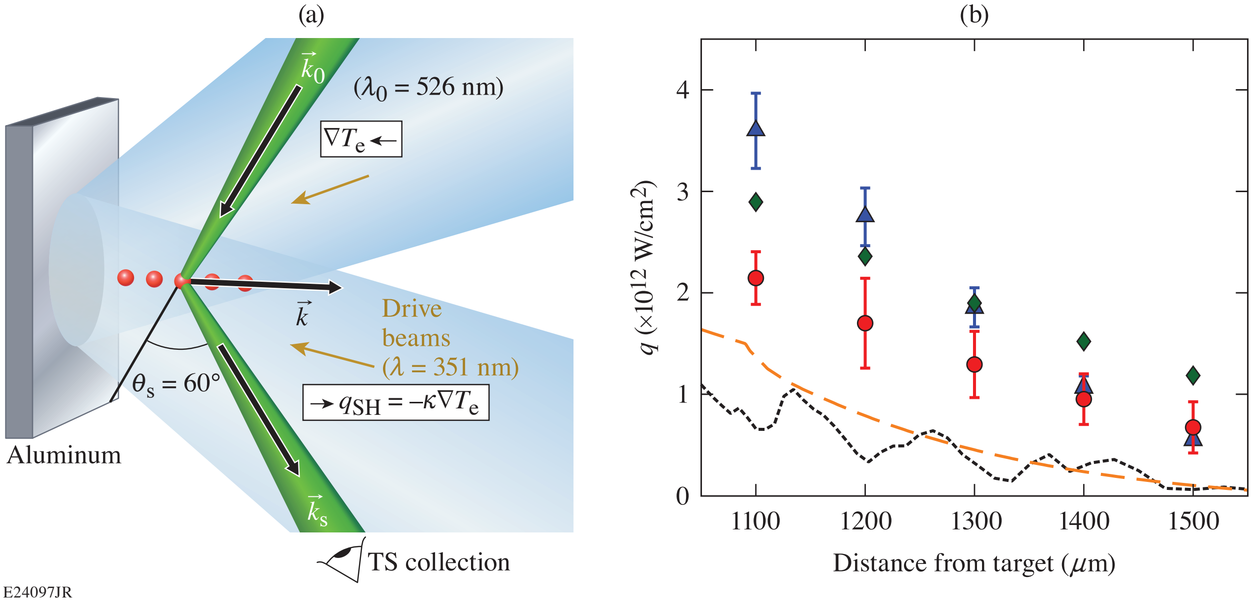

Figure 1
(a) The experimental setup is shown where six beams (blue) produced a blowoff plasma from a planar target (gray). A Thomson-scattering probe beam (green) with wave vector $\vec{k}_0$ was oriented relative to the target to probe plasma waves $(\vec{k})$ along the central axis, where the temperature gradient is the largest. Five Thomson-scattering locations (red) along the target normal provided measurements of plasma parameter profiles (T_e, n_e, ∇T_e). (b) Heat-flux measurements (red circles) are shown at t = 1.5 ns after the start of the $\lambda_{3\omega}$ beams as a function of distance from the initial target surface. Classical heat-flux values determined from the measured plasma parameters (blue triangles) are included along with results from full-scale SNB (black dotted line) and *FLASH* (orange dashed line) simulations in addition to 1-D SNB calculations using the measured plasma profiles (green diamonds).

Figure 1(b) shows that in regions where the electron–ion mean free path is small compared to the temperature gradients $\left(\lambda_{ei} / \left| L_T \right| < 7 \times 10^{-3}\right)$, the two heat-flux measurements agreed (red and blue symbols), which demonstrates the validity of the classical Spitzer–Härm theory. For larger relative temperature gradients (i.e., closer to the intial target surface, <1500 μm), the flux determined from non-Maxwellian electron distribution functions derived from classical theory was not consistent with the heat flux determined from measurements of the plasma conditions. This experimentally demonstrated that in plasmas with steep relative temperature gradients, the classical thermal transport theory is not valid. To determine the flux in this region, non-Maxwellian electron distribution functions consistent with nonlocal thermal transport were used to fit the Thomson-scattering spectra. At the steepest relative temperature gradient (1100 μm), the nonlocal heat-flux measurements were up to 1.5× smaller than the flux determined from classical theory. One-dimensional calculations using the Schurtz–Nicolaï–Busquet (SNB) model (diamonds), initiated with the measured plasma conditions, show a reduced heat flux compared with the classical theory but overestimated the flux at all locations compared with the nonlocal measurements.

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