Measurements of Non-Maxwellian Electron Distribution Functions and Their Effect on Laser Heating

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Statistical mechanics governs the fundamental properties of many-body systems, and the corresponding velocity distributions dictate most material properties. In plasmas, a description through statistical mechanics is challenged by the fact that the movement of one electron effects many others through their Coulomb interactions, leading to collective motion. Although most of the research in plasma physics assumes equilibrium electron distribution functions, or small departures from a Maxwell–Boltzmann (Maxwellian) distribution, this is not a valid assumption in many situations. Deviations from a Maxwellian can have significant ramifications on the interpretation of diagnostic signatures and, more importantly, in our ability to understand the basic nature of plasmas. Uncertainties in the distribution function have implications across many areas of plasma physics including magnetic and inertial confinement fusion, astrophysics, and space sciences. The uncertainty in modeling of high-velocity electrons, including their nonlocal behavior, combined with the lack of experimental constraints has led to fundamental questions about the shape of electron velocity distributions.

In this summary, we present the first measurements of complete electron distributions without any assumptions on their shape or the underlying physics that produced them. A corresponding reduction in laser absorption, compared to classical absorption, of up to 37% was measured when the electron distributions were determined to be super-Gaussian. At these conditions the inverse bremsstrahlung heating dominated over thermalization by electron–electron collisions, and the measured absorption was in reasonable agreement with analytic predictions[1] that are commonly used in hydrodynamic modeling. To enable single-shot temporally and spatially resolved measurements of the electron distribution function over several orders of magnitude, an optical diagnostic was invented that uses the angular dependence of scattering to simultaneously access the noncollective and collective nature of plasmas. This first-principles measurement showed that during significant heating by the laser beams, the distributions had a super-Gaussian shape in the bulk ($v < 3\ v_{\mathrm{th}}$) with a Maxwellian tail ($v > 3\ v_{\mathrm{th}}$). The super-Gaussian bulk is associated directly with the inverse bremsstrahlung heating and is well reproduced by the previous computational work.[2] The departure from super-Gaussian at high velocities was predicted by Fourkal *et al.*,[3] but these measurements show this deviation at a higher velocity. Particle simulations show improved agreement and demonstrate the importance of isotropic heating in accurately predicting the high-velocity tail.

Figure 1 shows the electron distribution function that was measured while five ultraviolet laser beams, with an overlapped intensity of $I_{\mathrm{UV}}^{\mathrm{total}} = 2.8 \times 10^{15}\ \mathrm{W/cm^2}$, uniformly heated an ~1-mm^3 volume of gas through inverse bremsstrahlung absorption. As predicted by theory,[1] the measurements show that slow electrons are preferentially heated to form a super-Gaussian electron distribution [Fig. 1(b)]. The measured electron distribution functions are well reproduced in the bulk by the heuristic scaling determined from early Fokker–Plank simulations,[2] where the electron distribution functions were parameterized by

$$f_m(v) = C_{\mathrm{m}} \exp\left[-\left(\frac{v}{a_{\mathrm{m}} v_{\mathrm{th}}}\right)^m\right] \tag{1}$$

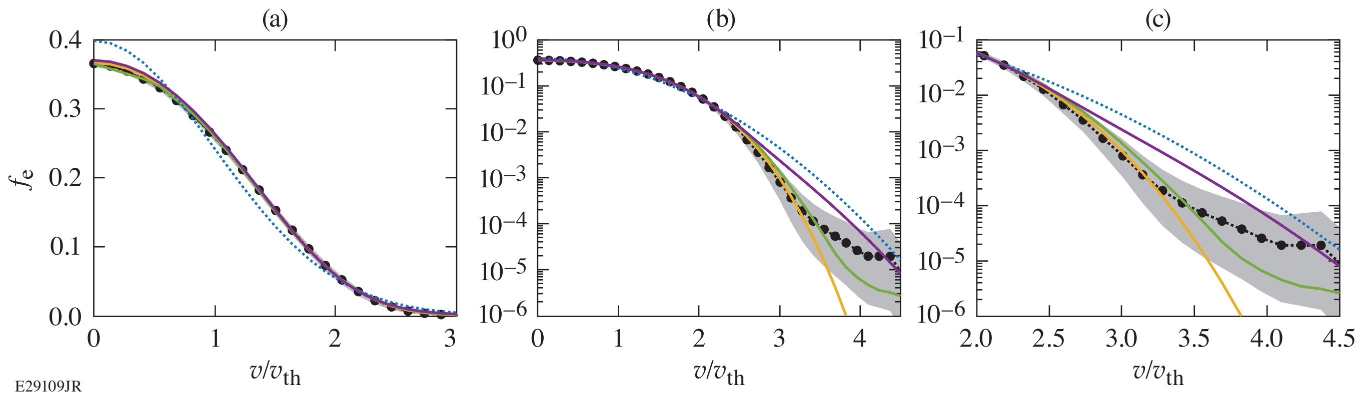

Figure 1
Electron distributions on (a) linear and logarithmic scales where (b) shows the complete velocity range, while (c) reduces the range to highlight the differences in the tails of the electron distribution functions. While the laser beams are heating the krypton plasma, the measured distribution (black points) is well reproduced in the bulk by a super-Gaussian function (orange curve) consistent with Matte *et al.*[2] [Eq. (2), $m = 3.9$]. A formalism describing the Maxwellian tail from Fourkal *et al.*[3] (purple curve), a Maxwellian distribution (blue curve), and results from particle simulation (green curve) are shown. The 90% confidence interval on the measured distribution function (gray region) is shown.

with super-Gaussian order

$$m(\alpha) = 2 + \frac{3}{1 + 1.66 \big/ \alpha^{0.724}}, \tag{2}$$

where $\alpha = Z v_{osc}^2 \big/ v_{th}^2$ is the ratio of the inverse bremsstrahlung heating rate to the electron–electron collision rate and Z is the ionization state. Normalization constants (C_m, a_m) maintain the standard definitions of the first three moments of the distribution function. For the results shown in Fig. 1, the calculated electron distribution function [Eq. (1)] is in excellent agreement with the measurements for velocities less than $\sim 3v_{th}$ when using the overlapped intensity and the measured plasma conditions. The plasma conditions ($T_e = 1.16$ keV, $Z = 25$) were obtained from the simultaneous measurement of the angularly resolved electron plasma wave features and collective ion-acoustic wave features.

Figure 1(c) shows that the measured electron distribution transitions from a super-Gaussian to a Maxwellian shape at $\sim 3v_{th}$, whereas the theory from Fourkal *et al.*[3] predicts an earlier transition around $\sim 2.5v_{th}$ and more electrons in the tail. This departure of Fourkal from a super-Gaussian distribution was calculated considering a single plane-wave electromagnetic source, where electrons oscillating in the laser field collide with electrons in the tail, modifying the distribution function at high energies. By introducing five overlapped beams, consistent with the experimental configuration, particle simulations using the code *Quartz* show that the number of electrons in the tail exceeds the super-Gaussian for velocities in the range $3.5v_{th} < v < 4.5v_{th}$, qualitatively consistent with the enhancement above super-Gaussian observed in the data. These results suggest that the increased uniformity due to multiple overlapped beams reduced the energy transferred to the high-velocity electrons.

Figure 2 shows that the measured laser absorption was significantly less than the absorption calculated assuming a plasma with a Maxwellian electron distribution. The absorption rapidly drops to ~60% of the Maxwellian expectation as the relative heating rate increases $\left(\text{large } Z v_{osc}^2 \big/ v_{th}^2\right)$. When the inverse bremsstrahlung heating rate dominates over the electron–electron collision rate, the reduction in absorption is in reasonable agreement with the original predictions.[1]

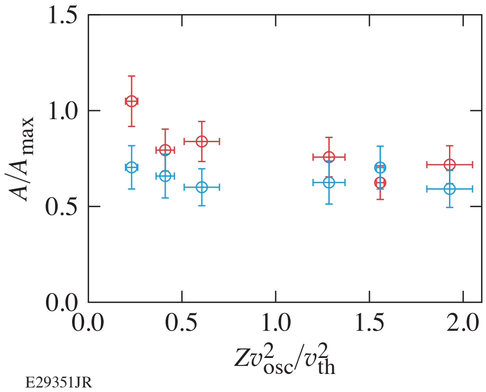

Figure 2
The measured (red circles) and calculated (blue circles) absorption, normalized to the absorption calculated assuming a Maxwellian electron distribution function, is plotted as a function of the ratio of the inverse bremsstrahlung heating rate to the electron–electron collision rate determined from the measured plasma conditions at the center of the plasma. Error bars represent one standard deviation propagated from uncertainties in the measured plasma conditions.

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3. E. Fourkal *et al*., Phys. Plasmas **8**, 550 (2001).