Evolution of the Electron Distribution Function in the Presence of Inverse Bremsstrahlung Heating and Collisional Ionization

A. L. Milder,[1,2] H. P. Le,[3] M. Sherlock,[3] P. Franke,[1,2] J. Katz,[1] S. T. Ivancic,[1] J. L. Shaw,[1] J. P. Palastro,[1] A. M. Hansen,[1,2] I. A. Begishev,[1] W. Rozmus,[4] and D. H. Froula[1,2]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Department of Physics & Astronomy, University of Rochester
[3]Lawrence Livermore National Laboratory

The picosecond evolution of non-Maxwellian electron distribution functions was measured in plasmas generated by the Multi-Terawatt laser using collective electron plasma wave Thomson scattering. During the laser heating, the distribution was measured to be approximately super-Gaussian due to inverse bremsstrahlung heating. After the heating laser turned off, collisional ionization caused further modification to the distribution function while increasing electron density and decreasing temperature.

Electron velocity distributions govern most fundamental processes in plasma physics. Models of these processes often take the electron distribution function to be Maxwellian or impose small deviations from a Maxwellian. While this assumption can lead to significant errors, any significant deviation from a Maxwellian requires a kinetic understanding, which is often prohibitively challenging. As computational resources improve and experiments begin to isolate kinetic effects an understanding of non-Maxwellian electron distribution functions is becoming more tractable.

In laser-produced plasmas, inverse bremsstrahlung heating,[1–3] thermal transport,[4,5] laser–plasma instabilities,[6] and ionization recombination[7] all provide competing mechanisms that govern the shape of the electron distribution function. A recent computational study has shown the impact of atomic kinetics on inverse bremsstrahlung heating and nonlocal thermal transport, through modifications of the electron distribution function.[7] In a separate study, non-Maxwellian electron distribution functions driven by thermal transport were shown to modify Landau damping of electron plasma waves and enhance their corresponding instabilities.[5] Furthermore, most atomic physics models used to calculate x-ray emission for plasma characterization are built assuming a Maxwellian electron distribution function and deviation from a Maxwellian modifies these calculations.[2]

Although there have been numerous computational studies of kinetic effects in hydrodynamics over the last 40 years,[8] experiments have been challenged to isolate changes to the electron distribution function. In the 1990s, microwaves were used in low-temperature (~1 eV), low-density ($<10^{17}$ cm^{-3}) plasmas to investigate changes to the electron distribution function introduced by inverse bremsstrahlung heating.[9] Later in the decade, initial studies in laser plasmas suggested the existence of non-Maxwellian electron distribution functions using Thomson scattering.[10] More recently, Thomson-scattering experiments were able to show the effect of nonlocal thermal transport on electron distribution function.[4]

This research presents the first measurements of the interplay between inverse bremsstrahlung heating and ionization kinetics on the electron distribution function.[11] An ultrafast Thomson-scattering system was used to collect the electron plasma wave spectrum, which enabled the picosecond evolution of the non-Maxwellian electron distribution function to be measured in a laser-produced plasma (Fig. 1). The preferential heating of the slow electrons by the laser beam with an intensity of 2.5×10^{14} W/cm^2, coupled with atomic kinetics, resulted in a non-Maxwellian electron distribution function. The shape of the electron distribution function, 60 ps into the plasma formation, was measured to be approximately a super-Gaussian of the order of 3.4. After the laser turned off, the electron density continued to increase by 15% over the next 40 ps (~25 electron–ion collision times) due to collisional ionization.

Over this time, the electron temperature decreased from 400 eV to 300 eV [Fig. 1(c)], which is consistent with the energy required for ionization to increase the density [Fig. 1(d)]. To determine the electron distribution functions consistent with the measured Thomson-scattered spectra in this rapidly evolving plasma, Vlasov–Fokker–Planck simulations using the code K2 (Ref. 12), which included both laser heating and ionization, were required. Laser heating was found to have the largest effect on the shape of the distribution function, while atomic kinetics provided a smaller effect and allowed matching of the evolution of plasma conditions.

Figures 1(c) and 1(d) show that it is necessary to include ionization in the K2 calculations in order to match the measured plasma conditions. Including ionization also improved agreement with the Thomson-scattering spectra by altering the electron distribution function. While Fig. 1(b) shows the need for non-Maxwellian distributions driven by inverse bremsstrahlung heating to reproduce the spectra, the electron density and temperature [Figs. 1(c) and 1(d)] reveal the need to include an atomic physics model. In simulations without ionization, it is possible to alter the initial plasma conditions to achieve better agreement with the temperature, but this results in distribution functions that generate spectra with poor agreement with the measured Thomson-scattering spectra.

To determine the impact of ionization on the electron distribution function, an atomic physics model was coupled to K2. An inelastic collsional operator, sometimes called a Boltzmann operator, was used to model the changes to the distribution resulting from all atomic processes. The time evolution of the atomic states was determined through a set of coupled rate equations. The collisional rates that enter the rate matrix were obtained from direct integration of the actual distribution. The atomic data (energy levels and cross sections) were constructed based on a screened hydrogenic model using the code Cretin.[13] While the model used for these simulations includes different types of collisional and radiative processes (both bound–bound and bound–free), collisional ionization was identified as the main atomic process affecting the distribution function.[7] The simulations were performed using the experimental laser conditions. Simulations performed without the atomic physics model used a preionized plasma with an electron density of 2.2×10^{19} cm^{-3} (corresponding to an average ionization state of 9.1) and an electron temperature of 10 eV. When using the atomic physics model, ionization was self-consistently included and the simulations were initialized with a neutral density of 2.4×10^{18} cm^{-3}.

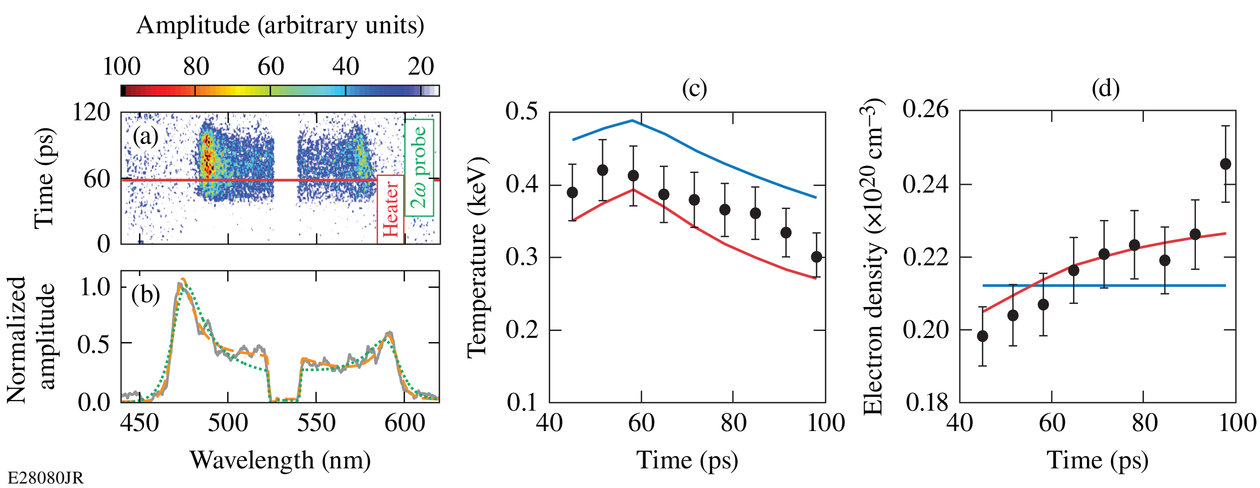

Figure 1
(a) Thomson-scattering spectrum measured from a plasma heated by an intensity of 2.5×10^{14} W/cm^2. The heater beam begins at $t = 0$ ps and the probe beam at $t = 40$ ps (inset). (b) The measured spectrum at 58 ps (solid gray curve) plotted with a spectrum calculated using Maxwellian (dotted green curve) and non-Maxwellian (dashed orange curve) electron distribution functions. The best-fit spectra determined $T_e = 428$ eV, $n_e = 2.12 \times 10^{19}$ cm^{-3}, and $m = 2$ (Maxwellian); and $T_e = 412$ eV, $n_e = 2.13 \times 10^{19}$ cm^{-3}, and $m = 3.1$ (non-Maxwellian). (c) Temperature and (d) density at nine times through the measurement are shown as solid black circles compared to K2 simulation results. The uncertainty, shown as black error bars, in the measured temperature (c) and density (d) results from repeated fitting within the noise on the spectra. The results of a K2 simulation without atomic kinetics are shown as a solid blue line. The results of a K2 simulation with atomic physics are shown as red curves.

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