Investigation of Picosecond Thermodynamics in a Laser-Produced Plasma Using Thomson Scattering

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The rapid evolution of electron density and temperature in a laser-produced plasma was measured using collective Thomson scattering. Picosecond time resolution, enabled by a pulse-front-tilt–compensated spectrometer, revealed a transition in the plasma-wave dynamics from an initially cold evolving state to a quasi-stationary equilibrium state. The equilibrium temperature was found to match the generalized heat equation's predicted scaling $T_e \propto n_e^{2/5}$ and $T_e \propto I^{1/5}$. The plasma evolution was compared to Raman gain bandwidth calculations and showed a time-dependent resonance detuning that would limit the transfer efficiency of a Raman plasma amplifier in the linear regime.

Endeavors to engineer plasmas for a number of applications rely critically on plasma conditions. Optimizing plasma devices, including laser amplifiers,[1–5] laser compressors,[6] wave plates,[7,8] polarizers,[9,10] Q plates,[11] particle accelerators,[12,13] photon accelerators,[14] high-order frequency conversion,[15,16] and photon–electron light sources,[17,18] require an accurate knowledge of plasma density and temperature dynamics. Engineering plasmas to create a laser amplifier and compressor is of particular interest because a plasma-based device can avoid the optical damage thresholds that currently limit the maximum intensity of chirped-pulse–amplification systems.[19]

A Raman plasma amplifier seeks to amplify and compress an ultrashort pulse by transferring energy from a long (tens of picoseconds), energetic pump pulse to a short (tens of femtoseconds), intense seed pulse. Raman amplification is a three-wave interaction, in which two counter-propagating laser pulses of different frequencies form a beat wave that drives an electron plasma wave through the ponderomotive force. The plasma wave facilitates the energy transfer from the higher- to the lower-frequency beam.[1] Pulse compression and efficient energy transfer require the pump pulse amplitude to be depleted within the seed pulse duration, known as the π-pulse or nonlinear regime.[6] Depleting the pump pulse amplitude within the duration of the seed requires a rapidly growing and large-amplitude plasma wave that typically forms when the Langmuir frequency is resonant with the beat frequency produced by the pump and seed beams. In the linear regime, the frequency, growth rate, and maximum amplitude of an electron plasma wave are dependent on the instantaneous electron temperature and density. Accurate prediction of the linear growth of the electron plasma wave in a Raman amplifier has been impeded by the lack of measured plasma conditions over this regime.

In a laser-produced plasma, the electromagnetic fields generate dynamic plasma conditions that evolve rapidly over the initial 50 ps. This evolution is comparable to pump durations (10 to 20 ps) that have typically been used in plasma devices. Therefore, the plasma conditions vary over the course of these experiments. During the transit of a high-intensity pump pulse through a gas, the photoionized electrons are liberated with minimal kinetic energy, resulting in an initially cold plasma. The energy supplied to the electrons by the electromagnetic field, through inverse bremsstrahlung, causes the temperature to rise rapidly until the collisionality of the plasma reduces the heating rate to a level comparable to the cooling mechanisms. Measurements of these early plasma dynamics on application-relevant time scales have been previously unattainable.

Optical Thomson scattering is a powerful diagnostic that can accurately measure plasma conditions.[20–26] A Thomson-scattering diagnostic can be used to determine localized plasma conditions by calculating the time-resolved spectra from laser light scattered off of plasma waves. The diagnostic requires a spectrometer streak-camera system to provide spectral and temporal resolution of the scattered spectra. Thomson-scattering diagnostics have not had sufficient temporal resolution to characterize the dynamics of plasma devices. Temporal resolution (>50 ps) for Thomson-scattering systems has been limited by the diagnostic's pulse-front tilt, which is inherent in the angular dispersion of the spectrometer.[27,28] In a conventional system, this pulse-front-tilt–limited resolution is more than an order of magnitude larger than the temporal resolution of present-day streak cameras (~1 ps).

Figure 1 shows measurements of the picosecond evolution of the electron temperature and density in a laser-produced plasma. The measurements were obtained by an ultrafast high-throughput spectrometer[29] that provided unprecedented temporal resolution of the electron plasma waves in the Thomson-scattering spectra.[30] These spectra were used to extract the picosecond evolution of the electron temperature and density. Hydrogen gas was ionized at an intensity near 10^{14} W/cm^2, where the electron plasma temperature was measured to rise from an initial partially ionized cold (~3-eV) plasma to a fully ionized plasma at a quasi-steady-state equilibrium temperature over ~25 ps. Figure 2 shows that the equilibrium temperatures were found to increase with higher densities and laser intensity. The measured thermodynamics were compared to generalized heat equation calculations of the equilibrium temperature. Measurements agreed with calculated equilibrium temperatures to within 15%, and the plasma condition's dependence on the density and intensity matches the heat equation's predicted scalings $T_e \propto n_e^{2/5}$ and $T_e \propto I^{1/5}$, respectively. The temporal evolution of the temperature measurements was also compared to heat equation calculations (Fig. 1), but the heating rate of the measurements was found to be slower compared to the calculations, suggesting the need to include ionization physics in the model.[31] The time dynamics of the electron plasma waves were compared to calculations of the Raman backscatter dispersion relation of the gain bandwidth. The comparisons show that the picosecond plasma evolution results in a time-dependent resonance detuning in a Raman plasma amplifier. This detuning would significantly limit transfer efficiencies in the linear regime.

The picosecond thermodynamics presented here are relevant to engineering optimum plasmas for a Raman plasma amplifier. The frequency-matching conditions necessary for laser amplification in the linear regime are dependent on the instantaneous

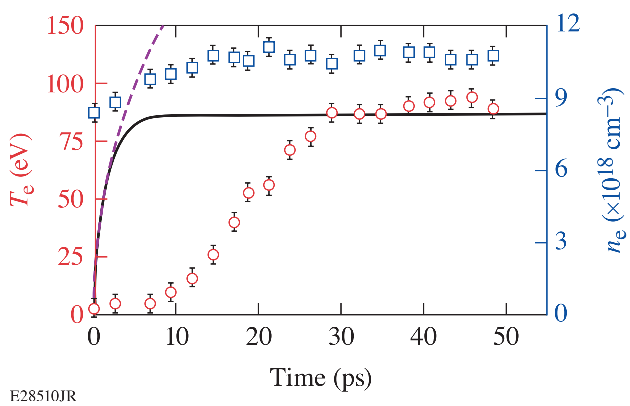

Figure 1
The measured (red circles, left axis) and calculated (solid black curve) electron temperatures are compared. The measured electron density (blue squares, right axis) is plotted as a function of time. The calculated temperature (dashed purple curve) is plotted as a function of time when the heat conduction and ion-heating terms are dropped from the generalized heat equation.

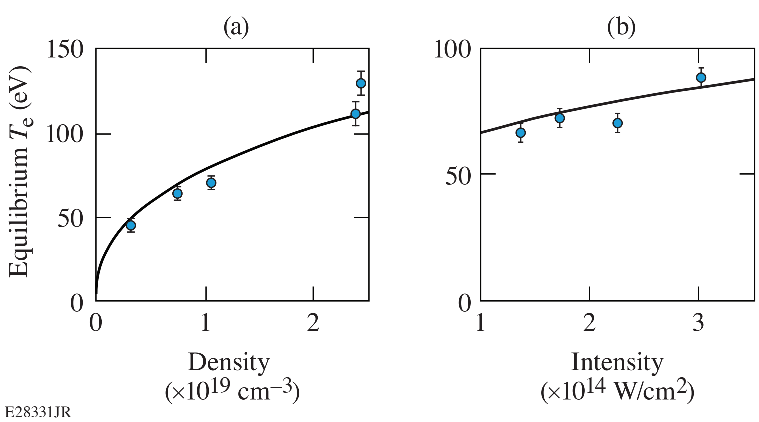

Figure 2
(a) The measured (circles) and calculated (solid curve) equilibrium temperatures are plotted versus the plasma density for an intensity of 2.2×10^{14} W/cm^2. (b) The measured (circles) and calculated (solid curve) equilibrium temperatures are plotted versus laser intensity for a density of 1.0×10^{19} cm^{-3}.

density and temperature conditions, as indicated by the Langmuir frequency. When accounting for the detuning introduced by the evolving plasma conditions (Fig. 1), the amplification regime is limited to a finite temperature range (~60 eV to ~120 eV, when the laser frequencies are chosen to be resonant at the equilibrium temperature). Outside the amplification zone, there will be zero gain due to the temperature detuning. By comparing this amplification zone to the measured temperature evolution shown in Fig. 1, it is apparent that the time dynamics of the electron plasma wave would result in time-dependent resonance detuning in a Raman plasma amplifier. In this example, the amplifier would experience zero gain until after the first 25 ps. If an 8-mm plasma channel was used to match the pump pulse duration, the first 4 mm would be wasted and the maximum possible transfer efficiency would be <50%. This example illustrates the importance of taking the plasma evolution into account when designing a Raman amplification experiment; these results can help guide future endeavors.

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