Temperature relaxation in hot spots in a laser-produced plasma

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The study of temperature relaxation and ion acoustic wave excitation in localized regions of intense laser field (hot spots) has been carried out for the conditions of inhibited electron thermal transport. We consider the fast energy deposition in a single cylindrical hot spot and describe the following temperature and density relaxation using a perturbation approach and the nonlocal electron transport equations. We find a significant increase in the temperature relaxation time for hot spots with sizes comparable to the electron mean free path. Thermal decay of the hot spot together with the pondermotive effect of the laser field on ions could also be a source of large density fluctuations in currently exploited laser-produced plasmas. [S1063-651X(97)06312-5]

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I. INTRODUCTION

Laser-beam-smoothing techniques are being used these days to control unavoidable nonuniformities present in a laser beam to achieve efficient coupling of laser-driver energy to the target and uniform compression of the spherical fuel shell in inertial confinement fusion (ICF). Commonly used smoothing techniques involve random-phase plates to produce spatial incoherence and fibers and temporal modulators to increase the spectral width of a laser beam [1,2]. The basic idea of beam smoothing is to divide the incident laser beam into several sufficiently small beamlets and randomly assign them phase shifts on their way to a target. The constructive interference of these beamlets in the focal spot region results in a large number of short-lived speckles or laser hot spots. Although the energy deposition in a plasma is strongly inhomogeneous leading to these hot spots, it is believed that thermal relaxation eventually leads to uniform pressure applied to the ablation surface of the target if the time scale of thermal transport is smaller than the hydrodynamical time scale. Although experiments indicate a significant suppression of hydrodynamic and parametric instabilities in a smoothed laser beam, this result is not yet completely understood because the level of fluctuations in a plasma remains unknown.

In order to understand better the physics of thermal smoothing under actual experimental conditions we have carried out a detailed study of this problem theoretically assuming the hot spot lifetime to be shorter than the characteristic relaxation time and the hot spot radius to be comparable to the electron mean free path. These are conditions where a laser driver can be treated in terms of the initial perturbation and the nonlocal transport effects increase significantly the amplitude of the temperature and density perturbations and the temperature relaxation time. For relatively large size hot spots this time might be within the resolution limits of current diagnostic techniques, offering a way for direct measurements of the nonlocal heat conductivity.

We separate the main contents of our paper into two parts. In Sec. II we consider the electron temperature relaxation that occurs for a short-time scale when the ions of the plasma do not move. Section III is devoted to the study of density perturbations excited by the hot spot thermal decay and an initial momentum deposited by the ponderomotive force. We conclude with a discussion and summary in Sec. IV.

II. ELECTRON TEMPERATURE RELAXATION

In this section we consider the relaxation of relatively large hot spots, with the characteristic radius R comparable to the electron mean free path λ_{ei}. We will demonstrate later that the density perturbations are relatively small and the electron thermal conductivity dominates the relaxation for this parameter domain. The relaxation of the hot spot is described using the nonlocal electron transport theory as per Ref. [3], where an appropriate set of hydrodynamiclike equations has been derived for small-amplitude perturbations of an arbitrary scale length. A cylindrical hot spot is considered in a Gaussian form in the radial direction:

$$\delta T_0(r)=\delta T_0 \exp\left(-\frac{r^2}{R^2}\right), \tag{1}$$

with initially small temperature perturbation $\delta T_0 \ll T_e$, where T_e is the electron temperature of an ambient plasma. The magnitude of δT_0 is determined by inverse bremsstrahlung heating in a laser hot spot: $\delta T_0(r) =(2\nu_{ei}/3n_c c)\int_0^{\tau_p} I dt$, where n_c is the critical density, $I(r,t)$ is the laser intensity, τ_p is the hot spot lifetime, and ν_{ei} is the electron-ion collision frequency.

Once this perturbation is applied to a homogeneous plasma, we proceed to obtain solutions to the equation of temperature relaxation

$$\frac{\partial \delta T}{\partial t}=-\frac{2}{3n_e}\nabla\cdot\mathbf{q}, \tag{2}$$

where $\mathbf{q}=-\kappa\nabla\delta T$ is the electron heat flux and the thermal conductivity κ is the integral operator defined in Fourier space. The result of the calculation of its wave-number dependence $\kappa(k)$ over the entire range of plasma collisionality

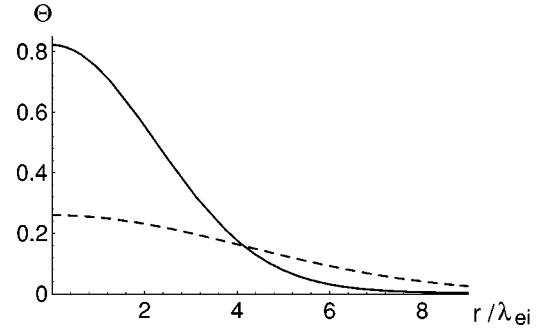

FIG. 1. Radial distribution of the temperature perturbation $\Theta = \delta T(r,t)/\delta T_0$ for $\nu_{ei}t=1$ in a plasma with $Z=5$ and $R/\lambda_{ei}=3$. The dashed line demonstrates the reference case with the classical heat conductivity.

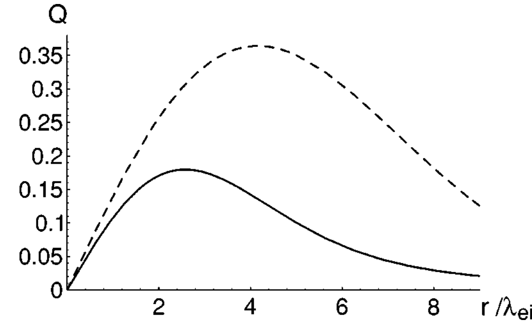

FIG. 2. Radial distribution of the normalized electron heat flux $Q=q(r,t)/n_e v_{Te}\delta T_0$ for $\nu_{ei}t=1$ in a plasma with $Z=5$ and $R/\lambda_{ei}=3$. The dashed line demonstrates the reference case with the classical heat conductivity.

parameter $k\lambda_{ei}$ is illustrated by Fig. 11 in Ref. [3], but we use here a simple analytical formula that gives an accurate interpolation of κ for $k\lambda_{ei}\gtrsim 1$ [3]:

$$\kappa(k)=\frac{\kappa_0}{1+(10\sqrt{Z}k\lambda_{ei})^{0.9}}, \quad \kappa_0=\frac{128}{3\pi}n_e v_{Te}\lambda_{ei}\zeta(Z), \tag{3}$$

where v_{Te} is electron thermal velocity and $\lambda_{ei}=v_{Te}/\nu_{ei}$ is the electron mean free path. The function $\zeta(Z)\approx(0.24+Z)/(2.4+Z)$ accounts for the electron-electron collisions in the classical electron thermal conductivity [6]. Equation (3) provides a good description of the exact result of the nonlocal [3,4] as well as the numerical result of kinetic calculations [5] for not too strong plasma inhomogeneity.

A. Classical temperature relaxation

Equation (2) with classical heat conductivity κ_0 can be solved analytically and one readily obtains the temperature profile

$$\delta T(r,t)=\frac{\delta T_0}{1+t/\tau_0}\exp\left(-\frac{r^2}{R^2(1+t/\tau_0)}\right), \tag{4}$$

where $\tau_0=3n_eR^2/8\kappa_0=0.028R^2/v_{Te}\lambda_{ei}\zeta$ is the characteristic time of temperature relaxation. According to Eq. (4), the radius of the heated region increases as a square root of time while the temperature in the center decreases inversely proportional to t. The characteristic time of relaxation is very small for the case of current experiments with laser-produced plasmas [7,8]. For the plasma with the electron density $n_e=10^{21}\text{ cm}^{-3}$, the ion charge $Z=5$, and the electron temperature $T_e=0.7$ keV, the electron mean free path is 2.2 μm and the relaxation time for $R=3\lambda_{ei}$ is about 0.07 ps. The initial amplitude of the temperature perturbation is 12% for the laser intensity 10^{15} W/cm^2 at the wavelength 0.5 μm and the hot spot lifetime $\tau_p=0.5$ ps. However, for such scales the nonlocal effects are already important because the characteristic wave number $k\sim 2/R$ is comparable to the inverse of the electron mean free path.

B. Nonlocal effects in the temperature relaxation

Equation (2) with the nonlocal heat conductivity has been solved using the Fourier transform in space and then solving the ordinary differential equation for Fourier components in time. After the inverse Fourier transformation one can find the evolution of the temperature perturbation and the heat flux

$$\delta T(r,t)=\delta T_0\frac{R^2}{2}\int \exp\left(-\frac{k^2R^2}{4}-\frac{2\kappa k^2}{3n_e}t\right)kJ_0(kr)dk,$$

$$q(r,t)=\delta T_0\frac{R^2}{2}\int \exp\left(-\frac{k^2R^2}{4}-\frac{2\kappa k^2}{3n_e}t\right)\kappa k^2J_1(kr)dk. \tag{5}$$

The electron temperature distribution around the speckle and the evolution of the electron heat flux are shown in Figs. 1 and 2, respectively. They are normalized by δT_0 and $n_e v_{Te}\delta T_0$. The results for the classical transport are also shown for comparison with dashed lines. One can see that the heat flux and temperature perturbation for the classical case have broader spatial profiles and decrease in time faster compared to the nonlocal case. Note that the nonlocal theory predicts a smaller electron heat flux than the classical theory does. This is a consequence of the electron flux inhibition due to the nonlocal character of energy transfer. According to Ref. [3], Eqs. (2) and (3) are equivalent to the electron kinetic equation and therefore describe hot-electron penetration to an ambient plasma from the speckle.

Figure 3 illustrates the dependence of the characteristic relaxation time $t_{1/2}$ (which is the time when the temperature in the center drops two times compared to the initial value)

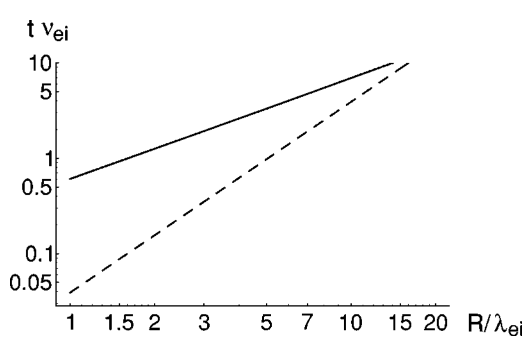

FIG. 3. Temperature relaxation time $\nu_{ei}t_{1/2}$ as a function of the normalized hot spot radius R/λ_{ei} for a plasma with $Z=5$. The dashed line demonstrates the reference case with the classical heat conductivity.

on the hot spot radius. This time is normalized by the electron-ion collision frequency. One can see that the relaxation time for the nonlocal case is significantly higher than the classical one τ_0 for practically interesting scales $R \lesssim 10\lambda_{ei}$. The essential contribution to the temperature profile comes from Fourier harmonics with $kR \sim 2$. Therefore, the following estimate for the temperature relaxation time can be written:

$$t_{1/2} = 0.028\frac{R^2}{v_{Te}\lambda_{ei}\zeta}\left[1+\left(20\sqrt{Z}\frac{\lambda_{ei}}{R}\right)^{0.9}\right]. \tag{6}$$

It is in reasonable agreement with exact calculations. In particular, for the example given above in Sec. II A, this formula predicts enhancement of the hot spot relaxation time about 12 times. That brings the relaxation time to the value $t_{1/2} \approx 0.9$ ps, which could be measured in an experiment. Formula (6) provides also the condition on the hot spot lifetime $\tau_p < t_{1/2}$, which allows us to treat the laser energy deposition in a hot spot as an initial condition.

III. EXCITATION OF DENSITY PERTURBATIONS

The above consideration does not take into account the plasma motion and because of this it cannot describe the density perturbation. The ion motion has a negligible effect on the temperature relaxation in a hot spot with $R \gtrsim \lambda_{ei}$ and therefore we consider the hydrodynamic equations for the ion density perturbation δn and velocity u assuming that the temperature perturbations are already found from Eq. (2):

$$\frac{\partial \delta n}{\partial t} = -n_e \nabla \cdot \mathbf{u}, \quad \frac{\partial \delta \mathbf{u}}{\partial t} = -c_s^2 \nabla\left(\frac{\delta n}{n_e} + \frac{\delta T}{T_e}\right), \tag{7}$$

where c_s is the ion acoustic velocity. The pondermotive force of the laser beam produces an initial acceleration of ions in the radial direction. Therefore, to the end of the hot spot lifetime ions acquire the velocity $u_0(r) = -(Z/2m_i n_c)(\partial/\partial r)\int_0^{\tau_p} I dt$. We use u_0 and $\delta n(t=0)=0$ as the initial conditions for Eqs. (7), which have been solved together with Eq. (2). Note that nonlocal effects can increase the magnitude of the pondermotive force [9]. However, this effect is not too significant for $R \sim \lambda_{ei}$ and we neglect it here. Thus the following relation between the initial velocity and temperature perturbations holds: $u_0 \approx -(3/4)(c_s^2/\nu_{ei})(d/dr)\delta T_0/T_e$.

For times $t \ll R/c_s$ shorter than the ion acoustic transit time across the hot spot, the density perturbation can be neglected in the second of Eqs. (7) and for the case of classical heat conductivity the density perturbation reads

$$\frac{\delta n}{n_e} = -3\frac{\delta T_0}{T_e}\frac{c_s^2 t}{R^2 \nu_{ei}}\left(1 - \frac{r^2}{R^2} + \frac{4}{3}\nu_{ei}\tau_0\right)\exp\left(-\frac{r^2}{R^2}\right). \tag{8}$$

This expression is valid for $t \gg \tau_0$ and the term $\sim \nu_{ei}\tau_0$ in parentheses accounts for the contribution from temperature perturbations in Eqs. (7); the other two terms come from the initial conditions. For typical plasma parameters $R < 10\lambda_{ei}$, the effect of the temperature perturbation on plasma density is small, manifesting an almost independent evolution of the

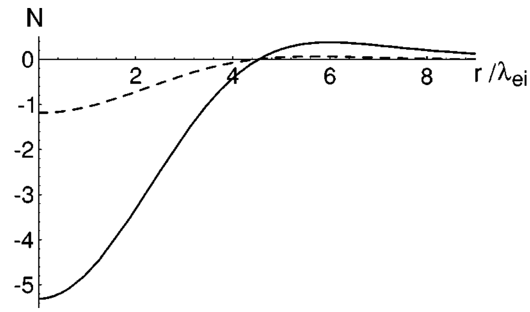

FIG. 4. Radial distribution of the normalized ion density perturbation for the time $\nu_{ei}t = 150$ (which corresponds to the maximum density depletion in the center) in a plasma with $Z=5$, $c_s/v_{Te} = 1.4\times 10^{-2}$ and $R/\lambda_{ei}=3$. Here $N = [\delta n(r,t)/n_e](v_{Te}/c_s)(T_e/\delta T_0)$; the dashed line demonstrates the reference case with the classical heat conductivity.

temperature and density in a classical hot spot, each of these quantities being defined by their own initial conditions.

Equation (8) demonstrates a linear growth in time of the density perturbation until saturation becomes important. The latter corresponds to $t \sim R/c_s$ when the ion acoustic wave forms and escapes from the hot spot. To estimate the level of the density perturbation one can substitute $t \sim R/c_s$ and $r \sim R$ into Eq. (8) to get $\delta n/n_e \sim (\delta T_0/T_e)(c_s/R\nu_{ei})$. The last factor is the ratio of the electron-ion collision time to the ion acoustic transit time, which is a small parameter less than 10^{-2} for the case discussed above in Sec. II A. Therefore, the amplitude of the ion acoustic wave is of the order of 10^{-3}, and we conclude that for the classical transport case the thermal relaxation proceeds without significant density perturbations.

The heat flux inhibition slows down the temperature relaxation rate and leads to enhancement of the ion acoustic wave amplitude. To demonstrate this effect we have solved Eqs. (7) using the Fourier transform in space and then solving the ordinary differential equation for Fourier components in time. The temperature perturbation was taken from Eq. (5). After the inverse Fourier transform one finds the following formula for the evolution of the density perturbation for $t \gg t_{1/2}$:

$$\frac{\delta n(r,t)}{n_e} = -\frac{3}{4}\frac{c_s R^2}{\nu_{ei}}\frac{\delta T_0}{T_e}\int_0^\infty dk J_0(kr)\exp\left(-\frac{k^2R^2}{4}\right)\left(k^2 + 2\frac{n_e\nu_{ei}}{\kappa}\right)\sin k c_s t. \tag{9}$$

The characteristic ion acoustic wave amplitude follows from this equation: $\delta n/n_e \sim (\delta T_0/T_e)(c_s/R)(1/\nu_{ei} + t_{1/2})$. Comparing this formula with the estimate from the classical theory, one can see that the enhancement of the ion acoustic wave amplitude takes place for $\nu_{ei}t_{1/2} > 1$, where the temperature relaxation time is larger than the electron-ion collision time. Figure 4 demonstrates the radial distribution of the density perturbations for inhibited and classical cases at time $\nu_{ei}t = 150$ when the density depletion in the center of the hot spot achieves its maximum. This time is about 30 ps for the parameters taken in Sec. II A and is much longer than the temperature relaxation time $t_{1/2}$. The enhancement of the density fluctuations about five times for the nonlocal case is evident in Fig. 4.

IV. SUMMARY

We summarize the results that are presented in this paper as follows. Relaxation of a single hot spot in a laser-produced plasma has been described by using the small perturbation approach in nonlocal electron transport theory for a cylindrically symmetrical speckle with the characteristic radius comparable to or larger than the electron mean free path. The time evolution of the electron temperature and density perturbations has been investigated for short-lived hot spots $\tau_p < t_{1/2}$. The relaxation time $t_{1/2}$ has been obtained and compared with the result of classical transport theory. A significant enhancement of the relaxation time due to the heat flux inhibition is found. For typical plasma and laser parameters the temperature relaxation time (6) could be about 1 ps. This is already within the time resolution of current optical instruments, which opens the possibility for direct measurements of the electron heat transport coefficients. The nonlocal effects result also in enhancement of the amplitude of density perturbation generated in a hot spot and propagated outward as an ion acoustic wave. It appears much later in time than the temperature perturbation and has a significantly longer lifetime of the order of the ion acoustic damping time (which is about $100R/c_s$ or 1 ns for typical plasma conditions).

The detailed study of a single hot spot relaxation in laser-produced plasmas carried out in this paper constitutes a necessary background for the consideration of multiple hot spots in the target volume being generated in typical ICF experiments employing the laser-beam-smoothing technique. One can use the statistical properties of hot spots as described in Ref. [10] to construct a fluctuation theory of a plasma driven by a randomized laser beam.

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