Laser induced heating and emission of electrons from metallic targets

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Abstract

A high power laser incident on a metallic target heats the electrons in the skin layer within a few ps. For a specific dependence of electron-phonon collision frequency on electron temperature, $\nu \propto T_e^{1/2}$, the steady state electron temperature profile turns out to be an exponential function of depth. The heated electrons raise the rate of thermionic emission. When the laser is significantly converted into a surface plasma wave the rate of heating and emission is considerably enhanced.

1. Introduction

Laser ablation of materials has been a fascinating field of study in recent years [1–8]. In case of a metallic target laser penetrates into the skin layer and heats the electrons. The heated electrons transfer energy to the lattice and cause melting, evaporation and ablation of the material on a longer time scale. When pulse duration is short, thermionic emission of heated electrons could be an important process. In semiconducting targets also one may observe electron emission when laser pulse is strong enough to produce high concentration of electron-hole pairs. A more interesting situation would arise when laser gets mode converted into a surface plasma wave and the latter heats the electrons far beyond the spot size of the laser.

In this note we study the heating of electrons by a laser and mode converted surface plasma wave in a metallic target. A quasisteady state for electron temperature is achieved as a balance of heating rate by the energy loss rate through collisions and thermal conduction. In Section 2 we study the electron and thermionic emission of heated electrons in a target when a laser is normally incident on it. In Section 3 we study the problem when laser is mode converted into a surface plasma wave. The results are discussed in Section 4.

2. Laser induced electron heating and emission

Consider a high power laser incident on a metallic target, located at $z > 0$. The incident laser field
\( z < 0 \) is \( E_0 = i \delta \epsilon_0 \exp[-i(\omega t - (\omega/c)z)] \) whereas the transmitted field is
\[
E_T = i \delta \epsilon_0 e^{-\delta z} e^{-i\omega t}
\]
where
\[
A_T = \frac{2 \epsilon_0 \omega_0^2}{1 + e^{1/z}}, \quad \epsilon = \epsilon_L - \left( \frac{\omega_0^2}{\omega^2} \right) (1 - \nu/\omega),
\]
\[
\delta = \frac{\omega_0}{c} \left( 1 - \epsilon_L \frac{\omega_0^2}{\omega^2} \right)^{1/2},
\]
\( \epsilon_L \) is lattice permittivity and \( \omega_0 \) and \( \nu \) are electron plasma and collision frequencies respectively. The laser induces an oscillatory velocity on electrons,
\[
\nu = \frac{eE_T}{m(\omega + i\nu)},
\]
where \( -e \) and \( m \) are electronic charge and mass, and heats them at a rate \( -\frac{1}{2} \epsilon_0 \omega_0^2 \nu e^{-2\delta z} \), \( \nu \) denotes complex conjugate. A steady state is reached when heat generation is balanced by the energy loss rate through electron–phonon collisions and thermal conduction,
\[
\frac{2e^2 \lambda_T \nu e^{-2\delta z}}{m \omega^2 ||1 + e^{1/z}||^2} - \frac{d}{dz} \left( \frac{\delta}{\gamma_0} \frac{d}{dz} \frac{1}{\gamma_0} \right) - \frac{1}{2} \nu \Delta (T_L - T) = 0,
\]
where \( \lambda_T = \nu \omega_0 / \nu \) is electron thermal conductivity \( v_0 \) is electron thermal speed, \( T_L \) is lattice temperature and \( \Delta \) is the mean fraction of excess electron energy lost in a collision. Here we have assumed \( \nu \ll \omega_0^2 \).

For \( \nu = \nu_0 (T_L / T_0)^{1/2} \), i.e., assuming electron–phonon collision cross-section to be independent of electron energy. Eq. (3) takes the following form:
\[
\frac{d^2 \psi}{dz^2} + \alpha_1 \psi^{1/2} (\psi^{2/3} - 1) = \alpha_2 \psi^{1/3} e^{-2\delta z},
\]
where
\[
\psi = (T_L / T_0)^{3/2}, \quad \alpha_1 = \frac{9}{4} \frac{\nu_0 \Delta}{\chi_0},
\]
\[
\alpha_2 = \frac{2 \epsilon_0 \omega_0^2}{\nu_0 \lambda_T ||1 + e^{1/z}||^2} \cdot \nu_0 = eA_0 / m \omega_0.
\]

\( \nu_0, \chi_0 \) and \( \nu_0 \lambda_T \) are the values of \( \nu, \chi_0 \) and \( \nu_0 \) at \( T_L = T_0 \). Near the surface if one assumes \( \psi \ll 1 \), then Eq. (4) offers a solution,
\[
\psi = \alpha_3 e^{-2\delta z},
\]
where
\[
\alpha_3 = \left( \frac{\alpha_2}{\alpha_1 + 9 \delta^2} \right)^{3/2}.
\]

The electron temperature can be written as
\[
T_T = \frac{8 m \nu_0^2}{9 \chi_0 ||1 + e^{1/z}||^2} \Delta \gamma_0 \lambda_0 \delta^3.
\]

where, \( \Lambda _m = \nu_0 / v_0 \) is the electron mean free path at \( T_L = T_0 \). As one goes deeper into the metal, \( \psi \) is no longer much greater than 1, and Eq. (7) is not valid. In fact \( \psi \) would asymptotically approach 1 with large \( z \). We have solved Eq. (4) numerically to obtain \( T_L(z) \). For \( z > 3 \delta^{-1} \) we have neglected the thermal conduction first term in Eq. (4), hence \( T_L / T_0 = 1 + \alpha_2 / \alpha_1 e^{-2\delta z} \). Then we proceed backwards, using the Range–Kutta technique to obtain \( T_L(z) \) closer to surface, using Eq. (4). We have plotted, in Fig. 1, the variation of \( T_L / T_0 \) as a function of dimensionless distance \( \delta z \) for \( \alpha_2 / \delta^3 = 1, \alpha_3 / \alpha_1 = 10, 40 \).

The rate of thermionic emission of electrons per unit area per second is given by the Richardson formula,
\[
1 = C T^2 \epsilon^{-2} \psi / e,
\]
3. Surface plasma wave induced heating

A metal-free space interface supports a surface plasma wave (SPW) with electric field

\[ E = A(z) e^{-i\omega t - k_x x}, \quad k_x = \frac{\omega}{c} \left( \frac{\epsilon}{1 + \epsilon} \right)^{1/2}, \tag{9} \]

where \( \epsilon < 1 \), i.e., \( \omega \rho > \omega(1 + \epsilon)^{1/2} \). In regions I \((z < 0, \text{ free space})\) and II \((z > 0)\), \( A \) is

\[ A = A_1 \left( \frac{x + ik_x}{\delta_1} \right) e^{i \delta_1 z}, \quad z < 0 \]

\[ A = A_1 \left( \frac{x + ik_x}{\delta_2} \right) e^{-i \delta_2 z}, \quad z > 0 \tag{10} \]

where \( \delta_1 = \frac{\pi}{\epsilon} |1 + \epsilon|^{1/2}, \delta_2 = \frac{\pi}{\epsilon} |1 + \epsilon|^{1/2} \).

The power flow density per unit \( y \)-width is

\[ P_y = \frac{c}{8\pi} \int E^*_y H_y dx. \]

\[ P_y = \frac{c^2}{10 \pi \omega} |1 + \epsilon|^{1/2} |1 + \epsilon|^{1/2} (1 + 1/\epsilon^2). \tag{11} \]

Let the surface plasma wave be produced by a laser of rectangular spot size, large \( y \)-width and \( x \)-width \( r_0 \). The incident laser power flow per unit \( y \)-width is \( P_0 = (cA_0^2)/8\pi r_0 \). If \( \beta \) is fraction of laser power is converted into the surface wave then

\[ A_1^2 = A_0^2 \left( \frac{2 \omega r_0 \beta}{c} \right), \tag{12} \]

where \( \Phi = (1 + 1/\epsilon|1 + 1/\epsilon^2|1 + \epsilon|\epsilon|^{1/2})^{-1} \).

In Fig. 2 we have plotted \( \Phi \) as a function of \( \epsilon \). We have also plotted \( \delta_x/\delta \), the ratio of laser skin depth to the depth of the surface wave, as a function of \( \epsilon \). As \( \epsilon \) goes from \(-10 \) to \(-4 \), i.e., as the electron density rises, \( \Phi \) varies from \( 0 \) to \( 0.2 \) whereas \( \delta_x/\delta \) varies from \( 0 \) to \( 1.15 \). For a typical value of \( \beta = 0.1, A_0 = 100, \epsilon = -2, A_1^2/\delta = 120, A_0^2/\delta_x/\delta = 1.4 \), i.e., laser driven surface plasma wave is as effective in electron heating as laser of 120 times more power would be. The thickness of the surface layer heated by the SPW is 1.4 times less than the skin depth but the surface plasma wave spreads over a much wider surface area than the laser spot size.

The equation governing the electron temperature is the same as given in Section 2 with \( A_0^2 \) replaced by
The present treatment is valid when electron-phonon collision cross-section is constant. This is reasonable when electron-acoustical phonon collisions dominate. At high lattice temperature electron-optical phonon collisions become important and one should invoke temperature dependent collision cross-section. The treatment is also restricted to steady state, which is realized in a time of the order of a few ps, determined by thermal conduction.

References