Effect of intense ultrashort light pulses on a substance

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The processes which occur during the application of an intense subpicosecond laser pulse to a condensed-matter target are discussed. Under certain conditions, a new, nonhydrodynamic interaction of the light with the substance sets in. Under these conditions the plasma can serve as a source of an intense pulse of hard x radiation.

Lasers which are capable of generating subpicosecond pulses in the 1-μm wavelength region with high intensities (above 10^{18} W/cm^2) have now been developed.[1] The electric field of such a pulse is considerably stronger than an atomic field, and the electron oscillation energy in the field of the pulse reaches the rest energy of an electron. The pulse is so short that the motion of the matter during the pulse is inconsequential. For these reasons, the nature of the interaction of the laser light with the target and the properties of the plasma which is produced are quite different from those which have been studied well at lower intensities and at nanosecond pulse lengths.[2] Our purpose in the present letter is to work from an analysis of the processes by which the light is absorbed, by which the heating occurs, and by which the energy is redistributed between electrons and ions to evaluate the properties of the plasma which is produced and to discuss possible applications of this plasma.

If the laser energy flux density q_0 exceeds $q_B = ce^2/8\pi a_B^4 = 3.5\times 10^{16}$ W/cm^2 (a_B is the first Bohr radius, c is the velocity of light, and e and m_e are the charge and mass of an electron), the electron will acquire an energy greater than the binding energy in the atom over a distance a_B. The ionization probability $w \sim e^2/\hbar a_B \sim 10^{17}$ s^{-1} turns out to be extremely high under these conditions and is independent of q_0 (Ref. 3). Over a time $\sim w^{-1}$, photoelectrons with a density $n_e \gtrsim n_a$ will be produced in a condensed-matter target (with a density of atoms $n_a \sim 10^{23}$ cm^{-3}). These photoelectrons will in turn cause an additional ionization by impact. Using the expressions for the impact-ionization cross section, we find the estimate that over a time of 10^{-14}–10^{-15} s the degree of ionization will increase to $Z \sim 10$–30, and the electron density will correspondingly reach $n_e \gtrsim 10^{24}$ cm^{-3}.

The electron plasma frequency, $\omega_{pe} \gtrsim 5\times 10^{16}$ s^{-1}, turns out to be substantially higher than the laser frequency: $\omega_0 \lesssim 0.1\omega_{pe}$. The electromagnetic field penetrates a depth equal to the skin layer, l_s, into the target. In the stage in which the ionization is terminated, the average energy of the electrons is on the order of 1 keV; the electron-ion collision rate is $\nu_{ei} \sim 10^{16}$ s$^{-1} > \omega_0$; and there is a normal skin effect, with $l_s = (c/\omega_{pe})(\sqrt{\nu_{ei}/\omega_0})$. The power dissipated per unit volume of the plasma, $Q = (\omega_0 E_0^2/4\pi) = (\omega_0/c)q_0$ (E_0 is the electric field amplitude of the pulse in vacuum), does not depend on the energy of the electrons. It thus follows from the energy balance equation $n_e(d\epsilon_e/dt) = Q$ that the electron energy $\epsilon_e = \dot{\epsilon}_e = t$ increases linearly over time. The heating rate $\dot{\epsilon}_e = \omega_0 q_0/n_e c$ for $q_0 \approx 10^{18}$ W/cm^2 and at $\lambda_0 = 0.5$ μm is ~ 1 MeV/ps.

Later on, the collision rate decreases because of the increase in the energy of the electrons, and at ϵ_e on the order of a few kiloelectron volts there will be a transition from a normal skin effect to an anomalous one, with[4] $l_s = (c^2 v_{Te}/\omega_0\omega_{pe}^2)^{1/3}$. The rate at which electrons acquire energy in the case of the anomalous skin effect remains the same, but the time dependence of the absorption coefficient $A \approx Q l_s/q_0$ changes. While we have $A \propto t^{-3/4}$ (a decrease over time) in the normal skin effect, in the case of the anomalous skin effect there is an increase in $A \approx (\omega_0/\omega_{pe})^{2/3}(v_{Te}/c)^{1/3} \propto t^{1/6}$, which reaches $A \approx (\omega_0/\omega_{pe})^{2/3} \sim 10\%$ at $v_{Te}/c \sim 1$.

The estimates above were based on the linear theory of the absorption of electromagnetic waves in a plasma. The distortion of the electron distribution function which accompanies the anomalous skin effect may lead to a change in the heating rate. Furthermore, nonlinear processes involving the excitation of plasma waves may occur in the skin layer. The velocity of the relative motion of the electrons and ions in the field of the light (under the conditions of the anomalous skin effect),

$$v_E \approx eE_0/m_e\omega_0(v_{Te}/c)^{1/3}(\omega_0/\omega_{pe})^{2/3} \sim 0.1 \text{ s}, \tag{1}$$

is comparable to the electron thermal velocity. We can thus expect the excitation of parametric instabilities with growth rates $\gamma \sim \omega_{pi} \sim 10^{15}$ s^{-1} (Ref. 5). Over a time $\Delta t \gtrsim \gamma^{-1}$, the evolution of these instabilities leads to the appearance of a turbulence and to an effective electron collision rate $\nu_{ef} \sim \gamma \sim \omega_{pi}$.

The linear growth of the energy of the electrons over time may be stopped because the electrons escape from the skin layer. We can find the limiting energy by equating the absorbed energy flux Aq_0 to the energy flux of the heated electrons, $fn_e v_{Te}\epsilon_e$, where f is the thermal-conductivity limitation coefficient. In a laser plasma at energy flux densities $q_0 \gtrsim 10^{15}$ W/cm^2 we would have[6] $f \sim 0.01$–0.03; this figure is well below the classical value $f \approx 0.6$. The reasons for this result are that the distribution function is not Maxwellian, there are intense quasistatic electric and magnetic fields, and there is a high level of plasma turbulence. All these factors come into play in the case under consideration here. Assuming $f \lesssim 0.01$, we see that the removal of energy by electrons does not prevent the heating of electrons to relativistic energies.

A more important factor limiting the heating of the electrons is the acceleration of the ions by the ambipolar electric field produced by the electrons emitted from the target. In this field, an ion of charge Z acquires an energy[7] $\epsilon_i \approx Z\epsilon_e$. Correspondingly, the skin layer expands over the time required for the passage of a rarefaction wave, $\Delta t_r \sim l_s/v_i$, where $v_i = (Z\epsilon_e/m_i)^{1/2}$. Using for l_s the expression for the case of the anomalous skin effect, along with expression (1), we find the lifetime of the ultradense plasma to be

$$\Delta t_r \approx \omega_0^{-1}\left(\frac{q_0}{n_c m_e c^3}\right)^{-1/4}\left(\frac{m_i}{Zm_e}\right)^{3/8} \propto \lambda_0^{1/2} q_0^{-1/4}, \tag{2}$$

where $n_c = m_e \omega_0^2 / 4\pi e^2$ is the critical density. For the conditions of interest here we would have $\Delta\tau_r \sim 10^{-13}$ s. Over a time Δt_r the electrons would acquire an energy

$$\epsilon_{e,\,max} \approx m_e c^2 \left(\frac{q_0}{m_e n_c c^3}\right)^{3/4} \left(\frac{\omega_0}{\omega_{pe}}\right)^2 \left(\frac{m_i}{Z m_e}\right)^{3/8} \propto \lambda_0^{-1/2} q_0^{3/4}, \qquad (3)$$

which corresponds to 100 keV. With decreasing wavelength of the laser light, there would be an increase in $\epsilon_{e,\max}$.

After the rarefaction wave has passed through the skin layer, the region in which the laser light is absorbed moves, along with the expanding plasma, in the direction opposite the laser beam. The plasma density in the absorption region decreases, and the familar hydrodynamic regime[2] sets in over a time $t \gg \Delta t_r$.

In summary, the interaction of an ultrashort ($\tau \lesssim \Delta t_r$) laser pulse with a condensed-matter target is of a qualitatively different—nonhydrodynamic—nature. The plasma density reaches a level which is more than two orders of magnitude above the critical density, and the average electron energy can reach 100 keV. Such a plasma is an intense source of hard x radiation. Using the expression for the power of the bremsstrahlung of electrons from a unit volume, $P = (e^2/\hbar c) \nu_{ef}\, n_e (\epsilon_e^2 / m_e c^2)$, along with (1) and (3) in the case of an anomalous skin effect and Coulomb electron-ion collisions ($\nu_{ei} \sim 10^{13}$ s at $\epsilon_e \sim 100$ keV), we find the brightness of the x radiation, $J = P l_s$, to be $\sim 10^{14}$ W/cm^2. This estimate is a lower limit. Incorporating the effective collision rate $\nu_{ef} \sim \omega_{pi}$ which would arise because of the plasma turbulence, would increase this estimate of the brightness of the x radiation by two orders of magnitude; i.e., the conversion of laser light into x radiation could reach $\gtrsim 1\%$.

We note in conclusion that the possibility of a generation of high-energy electrons and ions and of hard x radiation qualifies the plasma produced during the application of intense ultrashort pulses to condensed-matter targets as a new and interesting subject for research.

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