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Features and Limiting Characteristics of the Heating of a Substance by a Laser-Accelerated Fast Electron Beam

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The features of plasma formation in a substance heated by a laser-accelerated fast electron beam have been studied. These features are related to the ratio of the heating rate to the rate of energy loss because of radiation processes and electronic thermal conductivity, which are governed by the dependence of the energy of the heating beam particles on the beam intensity, which is characteristic of laser-driven electron acceleration. It has been shown that energy losses increase with the beam intensity and significantly limit the maximum temperature of the formed plasma. The possibility of generating an intense γ-radiation pulse of a nonnuclear origin because of the bremsstrahlung of laser-accelerated electrons has been discussed.

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1. Laser-plasma acceleration of charged particles allows generating electron or ion beams with a record energy flux density under laboratory conditions, corresponding to the intensity of the laser pulse acting on the target. In combination with the ability of charged particles to efficiently transfer their energy to a solid in Coulomb collisions, this determines the unique capabilities of laser-accelerated charged particle beams to create a high-temperature dense plasma [1–4]. In the case of laser-accelerated electron beams, this possibility is being actively investigated to generate intense shock waves with a pressure of hundreds or even thousands of megabars [2] to study the equation of state of matter. Heating by a nonrelativistic fast electron beam formed in a target exposed to a laser pulse with an interaction parameter of $I\lambda^2 \approx 10^{16}$–$10^{17}$ W μm^2/cm^2 (I and λ are the intensity and wavelength of the laser radiation, respectively) can provide pressures up to 1 Gbar [1, 2]. A further increase in pressure up to tens of gigabars can be achieved using a relativistic electron beam accelerated at an interaction parameter exceeding 10^{18} W μm^2/cm^2 [2]. Another reason for applied interest is the possibility of generating an intense hard X-ray pulse when heating heavy elements by a laser-accelerated electron beam.

The theory of pulsed plasma formation through heating light elements by a nonrelativistic laser-accelerated electron beam was developed in [1, 2, 5, 6]. The aim of this work is to theoretically study the features of plasma formation in a substance heated by a fast electron beam, including the case of relativistic electrons, taking into account the energy losses, which are typical of, e.g., the plasma of heavy elements. The mechanisms of such energy losses are primarily the radiation cooling of the plasma, as well as electronic thermal conductivity and bremsstrahlung of the heating electron beam itself. Heating of the plasma with a density close to the initial density of the substance is investigated. Such a plasma of light elements corresponds to the maximum pressure, whereas the plasma of heavy elements in addition ensures the maximum conversion of the energy to the energy of hard X rays. We find the extreme plasma temperatures determined by the above-mentioned energy loss mechanisms, including heating by a relativistic electron beam accelerated at laser pulse intensities of 10^{19}–10^{20} W/cm^2, achieved in existing experiments.

2. It is well known that the efficiency η of the conversion of the laser energy to the energy of fast electrons and the characteristic energy E of laser-accelerated electrons increase with the parameter $I_L\lambda^2$. A significant degree of conversion of the laser energy to the fast electron energy is achieved when the parameter $I_L\lambda^2$ exceeds 10^{16} W μm^2/cm^2. Numerous experiments indicate that the degree of conversion η ranges from 10 to 30% at the radiation intensity of the main harmonic of the Nd laser of 10^{16}–10^{19} W/cm^2. Unfortunately, reliable quantitative data on the dependences of the degree of conversion η on the intensity and wavelength of laser radiation are currently absent. For this reason, the ratio of the intensities of the heating fast electron beam and the accelerating laser pulse $\eta = I_b/I_L$ will be used in this work as a parameter of the problem whose values lie in the range mentioned above. At the same time, sufficiently reliable dependences are available for the characteristic energy of electrons accelerated by the laser pulse with a relatively short wavelength corresponding to the radiation of the first, second, and third harmonics of the Nd laser. Combining experimental data and theoretical models, these dependences can be represented in the form [7, 8]

$$E_{\rm MeV} \approx 0.45(I_{\rm L(19)}\lambda^2)^{1/3} \quad \text{at} \quad I_{\rm L(19)}\lambda^2 < 0.1, \qquad (1)$$

$$E_{\rm MeV} \approx 1.2(I_{\rm L(19)}\lambda^2)^{1/2} \quad \text{at} \quad I_{\rm L(19)}\lambda^2 > 1, \qquad (2)$$

where $I_{\rm L(19)}$ is the laser radiation intensity in units of 10^{19} W/cm^2, λ is the wavelength in microns, and $E_{\rm MeV}$ is the energy of the fast electron in MeV.

We consider the heating of the half-space of an incompressible substance by a monoenergetic electron beam whose energy depends on the intensity of the laser pulse accelerating the electrons according to Eqs. (1) and (2). The formation of a plasma with a maximum initial density equal to the initial density of the substance occurs in a time interval during which the heated substance can be considered static. The duration of this interval or the ablative loading time $t_{\rm h}$ (the term introduced in [1]) is approximately the time during which the rarefaction wave from the outer surface of the half-space propagates toward the inner surface of the heated substance layer. Taking into account that the fractions of the thermal and kinetic energies for a plane isothermal expansion are equal to each other according to the self-similar solution [9], the following solution is obtained for the plasma temperature that is reached in the time $t_{\rm h}$ [2]:

$$T_{\rm h} = \frac{1}{C_V}\left[\frac{9}{16(\gamma-1)}\right]^{1/3}\left(\frac{I_{\rm ab}}{\rho}\right)^{2/3}, \quad t \le t_{\rm h}. \qquad (3)$$

Here, $I_{\rm ab}$ is the absorbed energy flux density; ρ is the initial density of the heated substance; $C_V = (Z+1)k_{\rm B}/(\gamma-1)Am_p$ is the specific heat, where Z is the degree of ionization, $k_{\rm B}$ is the Boltzmann constant, γ is the adiabatic index, A is the atomic number of plasma ions, and m_p is the proton mass; and

$$t_{\rm h} = \frac{\mu}{\rho V_{\rm s}}. \qquad (4)$$

Here, $V_{\rm s} = [(\gamma-1)C_V T_{\rm h}]^{1/2}$ is the isothermal speed of sound and μ is the mass range of a fast electron with the initial energy E, which increases with the energy E according to the quadratic and linear laws in the cases of the nonrelativistic and relativistic electrons, respectively. Involving the data from [5, 10] on the stopping power of the plasma caused by the binary and collective interactions of the fast electron with the electronic component of the plasma and scattering on plasma ions, the calculation of the mass range of the fast electron in the aluminum plasma at the degree of ionization $Z = 11$, for which numerical estimates will be made in this work, gives the results

$$\mu = \mu_{\rm nr}E^2 \approx 0.8E_{\rm MeV}^2 \quad \text{and} \quad \mu = \mu_{\rm r}E \approx 0.9E_{\rm MeV} \qquad (5)$$

in grams per square centimeter. The purpose of this work is to find the extreme temperature $T_{\rm h}$, which is determined by the energy loss mechanisms listed above. The energy fluxes of the bremsstrahlung of the plasma and beam electrons are given by the expressions $I_{\rm rp} = W_{\rm rp}\mu/\rho$ and $I_{\rm rb} = W_{\rm rb}\mu/\rho$, respectively, where $W_{\rm rp}$ and $W_{\rm rb}$ are the emissivities of the plasma and beam electrons at scattering on plasma ions, respectively. The emissivity of plasma electrons is given by the known expression [11]

$$W_{\rm rp} = 1.73\times10^{24}\left(\frac{Z}{A}\right)^2 ZT^{1/2}\rho^2, \ \text{erg/(cm}^3\ \text{s)}, \qquad (6)$$

where T and ρ are the temperature and density of the plasma measured in keV and grams per cubic centimeter, respectively.

Following the theory of bremsstrahlung [11], an expression similar to Eq. (6) is obtained for the emissivity of the beam electron, where the density $n_{\rm b} = I_{\rm b}/vE$ and velocity v of beam electrons should be substituted for the density and thermal velocity of the plasma electrons, respectively. This expression has the form

$$\begin{aligned} W_{\rm rb} &= \frac{16\pi^2}{3^{3/2}}\frac{Z^2e^6n_i}{m_ec^3h}\frac{I_{\rm b}}{E} \\ &\approx 1.7\times10^{23}Z\left(\frac{Z}{A}\right)\frac{\rho I_{\rm b}}{E_{\rm MeV}}, \ \text{erg/(cm}^3\ \text{s)}, \end{aligned} \qquad (7)$$

where m_e and e are the mass and charge of the electron, respectively; c is the speed of light; h is the Planck constant; n_i is the concentration of plasma ions; and $I_{\rm b}$ is measured in 10^{19} watts per square centimeter.

The energy flux caused by the electronic thermal conductivity is approximately written as $I_{\rm c} = \kappa T^{5/2}{\rm grad}\,T \approx \kappa T^{7/2}\rho/\mu$ using the known result [12, 13]

$$\kappa \approx 8\times10^{19}(Z+3.3)^{-1}, \ \text{erg/(cm s keV}^{7/2}). \qquad (8)$$

Substituting $I_{\rm ab} = I_{\rm b} - I_{\rm rp} - I_{\rm rb} - I_{\rm c}$ into Eq. (3), we obtain the following approximate equation for the extreme temperature T_*:

$$1 - \left(\frac{T_*}{T_{\rm h0}}\right)^{3/2} - \frac{I_{\rm rp}}{I_{\rm b}}\left(\frac{T_*}{T_{\rm h0}}\right)^{1/2} - \frac{I_{\rm rb}}{I_{\rm b}} - \frac{I_{\rm c}}{I_{\rm b}}\left(\frac{T_*}{T_{\rm h0}}\right)^{7/2} = 0, \qquad (9)$$

where T_{h0} is the temperature T_h in the absence of energy losses (when $I_{ab} = I_b$ in Eq. (3)) and I_{rp}, I_{rb}, and I_c are the fluxes calculated from the parameters of the plasma in the absence of energy losses.

The second term in Eq. (9) is the fraction of the energy of the heating electron beam that is spent directly on the heating of the substance, whereas the third, fourth, and fifth terms are the fractions of energy related to losses because of the bremsstrahlung of plasma electrons, the bremsstrahlung of beam electrons, and the electron thermal conductivity, respectively.

Using Eqs. (1)–(3) and (5)–(8) at $\gamma = 5/3$, we obtain

$$\frac{I_{rp}}{I_b} = 0.2\times Z\left(\frac{Z}{A}\right)^2\left(\frac{A}{Z+1}\right)^{1/2} \times\frac{\rho^{2/3}}{\eta^{2/3}}\begin{cases}0.23\mu_{nr}\lambda^{4/3}, & I_{L(19)}\lambda^2 < 0.1,\\ 1.2\dfrac{\mu_r\lambda}{I_{L(19)}^{1/6}}, & I_{L(19)}\lambda^2 > 1,\end{cases} \tag{10}$$

$$\frac{I_{rb}}{I_b} = 8\times10^{-4}Z\left(\frac{Z}{A}\right) \times\begin{cases}\mu_{nr}(I_{L(19)}\lambda^2)^{1/3}, & I_{L(19)}\lambda^2 < 0.1,\\ 1.25\mu_r, & I_{L(19)}\lambda^2 > 1,\end{cases} \tag{11}$$

$$\frac{I_c}{I_b} = 75\frac{\eta^{4/3}}{(Z+3.3)\rho^{4/3}} \times\left(\frac{A}{Z+1}\right)^{7/2}\begin{cases}\dfrac{I_{L(19)}^{2/3}}{\mu_{nr}\lambda^{4/3}}, & I_{L(19)}\lambda^2 < 0.1,\\ 0.53\dfrac{I_{L(19)}^{5/6}}{\mu_r\lambda}, & I_{L(19)}\lambda^2 > 1.\end{cases} \tag{12}$$

Let us discuss the extreme characteristics of plasma heating by a laser-accelerated fast electron beam by the example of solving Eq. (9) with Eqs. (10)–(12) for the aluminum plasma ($Z = 11$, $\mu_{nr} = 0.8$, and $\mu_r = 0.9$) and the accelerating laser pulse of the first harmonic of the Nd laser radiation ($\lambda = 1.06$ μm) at the conversion rate $\eta = 0.2$. Aluminum is often used as a reference material in experiments to study the equation of state. Trends in the influence of various energy loss mechanisms can be understood by analyzing Eqs. (10)–(12). The ratio I_{rp}/I_b for nonrelativistic electrons does not depend on the intensity of the laser pulse and is about 0.4. The effect of energy losses on the bremsstrahlung of the electron beam and the electron thermal conductivity increases with the laser intensity as $I_L^{1/3}$ and $I_L^{2/3}$, respectively. At an intensity of 10^{17} W/cm^2, the ratio I_c/I_b is about 0.35, whereas the ratio I_{rb}/I_b is as small as 0.0007. The solution of Eq. (9) for nonrelativistic electrons shows that the ratio T_*/T_{h0} varies slightly depending on the intensity of the laser pulse and is about 0.75. At the same time, the dominant mechanism of energy losses is the bremsstrahlung of the plasma, responsible for loss of about 35% of the input energy; the thermal conductivity is responsible for about 5%; and the bremsstrahlung of the beam is responsible for tenths of a percent.

For relativistic electrons, the fraction of energy losses due to the electronic thermal conductivity increases. The ratio I_{rp}/I_b decreases slightly as $I_L^{-1/6}$ with increasing laser pulse intensity, whereas the ratio I_c/I_b increases as $I_L^{5/6}$ with increasing laser pulse intensity. However, as in the case of nonrelativistic fast electrons, the dominant loss mechanism remains the plasma bremsstrahlung. The ratio I_{rb}/I_b for the bremsstrahlung of the beam reaches a constant value, but remains, as before, a small value of 0.004. The solution of Eq. (9) for relativistic electrons at $I_L \geq 10^{20}$ W/cm^2 shows that the ratio T_*/T_{h0} hardly depends on the laser intensity, remaining equal to approximately 0.28. The total energy losses to the bremsstrahlung of the plasma and the thermal conductivity also change slightly. They constitute about 80% of the input energy for a relativistic beam. At the same time, as mentioned above, the relative contribution of the thermal conductivity to energy losses increases with the laser intensity: they are about 10 and 35% of the input energy at $I_L = 10^{20}$ and 10^{21} W/cm^2, respectively.

According to Eqs. (10)–(12), the ratio I_{rp}/I_b decreases and the ratio I_c/I_b increases with a decrease in the wavelength of laser radiation in the case of both relativistic and nonrelativistic laser-accelerated electrons. As a result, in the case of the third harmonic pulse of the Nd laser radiation, the energy losses due to the bremsstrahlung of the plasma and the electronic thermal conductivity are comparable: they are 18 and 12%, respectively, in the case of nonrelativistic electrons and are 15 and 45%, respectively, in the relativistic case. At the same time, the temperature decrease is less because energy losses is less: the ratio T_*/T_{h0} is about 0.8 for the nonrelativistic case and 0.35 for the relativistic case.

The results obtained above make it possible to improve the estimates in [2] concerning heating by a nonrelativistic electron beam and to estimate the plasma temperature at heating by a relativistic electron beam. In the case of the first harmonic of the Nd laser radiation, the temperatures of the aluminum plasma heated by the nonrelativistic beam with the intensity $I_L = 10^{17}$ W/cm^2 and by the relativistic beam with the intensity $I_L = 10^{20}$ W/cm^2 are expected to be 1.2 and 33 keV, respectively, which correspond to pressures of about 0.7 and 20 Gbar, respectively. Conversion of a significant part of the energy of the fast electron beam to X rays of the plasma means the generation of an intense hard X-ray pulse. In particular, according to the above estimates, the plasma of an aluminum target heated by the relativistic electron beam accelerated by the first harmonic of the Nd laser with the intensity $I_L = 10^{20}$ W/cm^2 is a source of hard X rays with the upper limit of the photon energy about 30 keV and with an intensity of about 10^{18} W/cm^2. In addition, although the efficiency of converting the energy of the relativistic electron beam decelerated in the plasma to radiation energy is as low as 0.4%, the γ-radiation pulse of a nonnuclear origin with the upper limit of the photon energy of several MeV at $I_L = 10^{20}$ W/cm^2 can reach an intensity of about 10^{16} W/cm^2. It is important to note that, as the atomic number of the target substance increases, the intensity of the X rays caused by the bremsstrahlung of plasma and beam electrons increases linearly with the degree of plasma ionization. The calculations within the model described in this work show that up to 90% of the energy of the fast electron beam in a gold plasma will be converted to the energy of bremsstrahlung with the upper limit of the photon energy of about 5 keV. The intensity of γ radiation caused by the deceleration of the fast electron beam in the gold plasma is a factor of 2–3 higher than that for the aluminum plasma and at a laser intensity of $I_L = 10^{20}$ W/cm^2 can exceed 10^{17} W/cm^2.

3. The main conclusions of the work are as follows. The extreme temperature of heating of a substance by an electron beam accelerated by a laser pulse with an intensity exceeding 10^{17} W/cm^2 is largely determined by energy losses caused by the bremsstrahlung of the plasma. Energy losses increase with the intensity of the heating electron beam. For aluminum plasma, these losses are about 40 and 80% in the cases of a nonrelativistic and relativistic electron beams, respectively. Heating of the plasma by the laser-accelerated relativistic electron beam is responsible for the generation of an intense hard X-ray pulse with the upper limit of the photon energy of several tens of keV with an intensity exceeding 10^{18} W/cm^2 and an intense γ-radiation pulse of a nonnuclear origin with the upper limit of the photon energy of several MeV with an intensity exceeding 10^{16} W/cm^2.

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