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Ultra-power shock wave driven by a laser-accelerated electron beam

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Abstract

This review is presented on modern research to achieve in a laboratory experiment the new level of shock-wave pressure of a few hundred or even thousands of Mbar when a substance is exposed to a stream of laser-accelerated fast electrons. The applications associated with the use of ultra-power shock waves as the ignition driver of inertial fusion targets as well as the tool in studying the equation of a state of a matter are discussed.

Keywords: shock wave, fast electrons, ablation pressure, shock ignition, equation of state

1. Introduction

Interest in the problem is related, on the one hand, to the study of fundamental phenomena of high-energy density physics and, on the other hand, to topical applications to develop the methods of ultra-power shock wave generation with respect to inertial confinement fusion (ICF), as well as investigation of extreme states of matter in the laboratory experiment. The action of a laser pulse, capable of providing a high concentration of energy at the target, is currently the most effective method to generate a powerful shock wave. For ICF, irradiation of a spherical target by a laser beam with an intensity of $I_L \approx 10^{13-14}\,\mathrm{W\,cm^{-2}}$ provides the pressure in the evaporated part of the target (ablation pressure) of a few tens of Mbar. Such a pressure is able to compress the target so as to create a thermonuclear plasma (hot spot) in its central area (see, for example, [1, 2]). Under the action of a laser beam with such an intensity on a plane target, record pressures of shock waves (about 100 Mbar) are obtained in experiments that investigate the equation of state (EOS) of matter (see, for example, the review [3]). In this case, an ablation pressure is created when laser radiation is absorbed, mainly in the region of plasma with the critical density ρ_{cr}, which corresponds to equality of the plasma frequency and the laser radiation frequency: $\rho_{cr} \approx 1.83 \cdot 10^{-3} A Z \lambda^{-1}\,\mathrm{g\,cm^{-2}}$. ($A$ and Z are, respectively, the atomic number and average charge of plasma ions, and λ is the wavelength of laser light.) The scale of pressure is determined by critical density ρ_{cr} and sound velocity $V_s \propto (I_L/\rho_{cr})^{1/3}$: $P \propto \rho_{cr}^{1/3} I_L^{2/3}$.

Unlike laser light, the fast-charged particles have the ability to heat the substance with an initial solid-state density ρ_0, owing to the transfer of their energy in Coulomb collisions, mainly with hermal electrons of substance. Therefore, the charged particle beam is able to provide the ablation pressure, which is, approximately, $(\rho_0/\rho_{cr})^{1/3}$ times larger than the pressure produced by a laser beam of the same intensity. Keeping in mind, for example, the Nd-laser basic harmonic radiation with a wavelength of $\lambda \approx 1.06\,\mu\mathrm{m}$ ($\rho_{cr} \approx 3.6 \cdot 10^{-3}\,\mathrm{g\,cm^{-3}}$) and the aluminum target ($\rho_0 \approx 2.7\,\mathrm{g\,cm^{-3}}$), such an increase is about 10 times the pressure. The density of the energy flux on a target surface, which is comparable to the intensity of laser beam, can be provided by the beam of laser-accelerated charged particles. In modern experiments on laser interaction with matter (including the use of a petawatt laser), the fast electron and ion energies larger than 1 MeV and 100 MeV/nucleon, respectively, are reached at the efficiency of laser energy conversion into accelerated particle energy equal to, respectively, 20–30% and 7–10% (see, for example, reviews [4–6]). Considering further the fast electrons as the most effectively accelerated particles, it should be noted that the scale of their energy for all known mechanisms of generation is the average energy of electron oscillations in a laser field. That energy increases with increasing the coupling parameter $I_L\lambda^2$. The spectrum of laser-accelerated fast electrons from a plane target usually is closed to the Maxwellian distribution, and the divergence of the fast electron stream does not exceed 30°.

Significant transformation of laser energy into fast electron energy begins when the coupling parameter is larger than 10^{14} W μm^2 cm^{-2} [5, 6]. When $I_L\lambda^2 > 10^{15}$ W·μm^2 cm^{-2}, fast electron energy becomes equal to several tens of keV, and fast electron energy transfer to the dense part of target plays a dominant role in the formation of ablation pressure [7]. The last requirement for the Nd-laser basic harmonic radiation means the intensity must be larger than 10^{15} W cm^{-2}. And, if $I_L\lambda^2 > 10^{15}$ W μm^2 cm^{-2}, an ablation pressure of several hundred or even thousands of Mbar can be achieved.

In ICF, the generation of such a powerful shock wave is the key element of shock ignition [8, 9], which is one of the promising methods of thermonuclear ignition. This method is the version of spark ignition approach using the profiling laser pulse. In fact, such a pulse consists of two parts. The first one, of nanosecond duration with an intensity of $10^{13–14}$ W cm^{-2}, should be used to preliminarily compress the target, while the second part, with a duration of a few hundred picoseconds and an intensity of $10^{15–16}$ W cm^{-2}, should be used to launch a strong shock wave converging at the center of target and creating a hot spot there. A hot spot of a small fraction of total thermonuclear fuel mass should have an areal density (product of density and dimension) of 0.2–0.3 g cm^{-2} and a temperature of more than 5 keV. The pressure of the igniting shock wave should exceed 300 Mbar, and the duration of its propagation into the targets should be not less than 0.3 ns. A shock-wave EOS experiment at the gigabar level of pressure [10] means a transition of EOS investigation to a new level of pressure that will be one order of magnitude larger than the pressure available today. It should be noted that the characteristics of a shock wave driven by a fast electron stream depend on the spectrum of fast electrons. The spectrum determines the distribution of fast electron energy between the processes of ablation of some part of a target and preliminary heating of the solid part of the target before the arrival of the shock wave (preheating). The first process determines the pressure of the shock wave, and the second one determines the degree of compression of the material behind the wave front.

The review is devoted to the current state of studies in the field of physics of an ultra-power shock wave driven by laser-accelerated fast electrons. The second section is devoted to the physics of high-energy electron beam interaction with matter, including the energy transfer by these particles as well as the formation of high-temperature plasma and ablation pressure. In the third section, the results of studies of a shock wave driven by a fast electron stream are presented, including the applications related to shock ignition of an ICF target and the EOS investigation.

2. Powerful laser-accelerated electron stream interaction with plasma

The problem of fast electron influence on hydrodynamic processes in laser-produced plasma have, traditionally, attracted considerable attention, especially in studies of spherical target compression in relation to ICF research (see reviews [1, 2, 11]). As a result, the limiting value of a coupling parameter was found, amounting to the value of about 10^{14} W μm^2 cm^{-2}, below which the preheating by fast electrons has an insignificant effect on the hydrodynamics of laser-produced plasma, owing to the insignificant level of fast electron generation itself. This result was the basic argument to use in ICF research on short-wavelength laser radiation, particularly the radiation of the first three harmonics of an Nd-laser ($\lambda = 1.06 - 0.353$ μm).

The results of experiments [12] on spherical target compression by a nanosecond pulse of long-wavelength CO_2-laser radiation ($\lambda = 10, 6$ μm) with an energy of 3–5 kJ and an intensity of $10^{13–14}$ W cm^{-2} (performed in the early 1980s) had great importance for understanding the role of energy transfer by fast electrons. The interaction of laser radiation with plasma when the coupling parameter was equal to $10^{15–16}$ W μm^2 cm^{-2} occurred at intense generation of fast electrons. Since the critical density corresponding to CO_2-laser wavelength is two orders of magnitude lower than that corresponding to Nd-laser radiation, a distinctive feature of these experiments was a low density of subcritical plasma. In such conditions, the contribution of inverse bremsstrahlung absorption of laser radiation in the subcritical plasma was negligible in comparison with a resonant absorption in the region of near critical density, where almost all of the absorbed laser energy is transformed into the energy of fast electrons. The experiments were carried out with targets, which were glass shells with a constant diameter of 300 μm and a thickness of 1 μm, containing deuterium–tritium (DT) gas with a density of about 6 mg cm^{-3}. The shells were coated with a layer of plastic (CH). The thickness of the plastic layer varied from 1–100 μm. The main result was a significant (order of magnitude) reduction in the density of the compressed target in comparison with experiments on irradiation of spherical targets of the same design by short-wavelength radiation of an Nd-laser with similar values of energy and intensity. Using the results of one-dimensional (1D) numerical simulation has shown that the reason for such a significant reduction in compression is preheating the target material by fast electrons before the arrival of the shock wave [12, 13]. In this regard, [14] should be noted, where, on the basis of numerical simulation, the approximation formulas were concluded for the energy of a fast electron stream of Maxwellian spectrum in dependence on the thickness of the traversed layer of different materials. These data, in particular, are a useful tool for evaluating the fast electron energy spent for preheating.

The strong effect of preheating observed in the experiments in [12] has stimulated intensive studies of energy transfer by fast electrons in laser-produced plasmas. In [15–18], a theoretical analysis was made of fast electron energy transfer not only in a compressed part of the target, which leads to the negative effect of preheating, but also in the evaporated part of the target (corona) with supercritical density. In these papers, the analytical model of a steady-state corona created by fast electrons that were produced by a nanosecond laser pulse was developed [15], and 1D numerical simulations of spherical target compression, taking into account the heating of the target ablator by monoenergetic fast electrons, were carried out [16]. It was shown that the fast electron energy transfer in the target corona plays a positive role and leads to an increase in the ablation pressure. In these papers, the problem of the effect of the initial spectrum of fast electrons on ablation pressure and preheating was indicated [17]. As a result, the requirements were formulated to match the target ablator thickness and laser pulse parameters so that the preheating effect can be suppressed at the significant contribution of fast electron energy transfer to an ablation pressure formation [16, 18]. Namely, such a matching is the basis of the shock ignition approach in ICF.

A non-stationary model of a target corona created by fast electron heating was proposed in [19]. It is based on the self-similar solution [20] of a plane isothermal expansion of a given mass of substance. This solution is fully adequate to the phenomenon of thermal expansion of plasma heated by a fast electron stream, because the Coulomb mean free pass of the fast electrons depends only on its initial energy. In [21, 22], the model has been developed as a superposition of the self-similar solutions of isothermal expansion of a given mass of substance and the isothermal rarefaction wave. Such a model proved to be highly useful for calculation of the ablation pressure created by heating the substance with a fast electron stream in the conditions of powerful shock wave generation for shock ignition and for EOS studies that will be discussed in the next section of this review. According to this model, the temperature, density, and pressure on the ablation surface (the boundary of vaporized material and the solid part of the target) are:

$$T = \frac{I_b t}{a C_V \mu},$$
$$\rho = \rho_0 \times \begin{cases} 1, & t \leqslant t_h \\ \left(\dfrac{t_h}{t}\right)^{3/2}, & t \geqslant t_h \end{cases},$$
$$P = P_h \times \begin{cases} \dfrac{t}{t_h}, & t \leqslant t_h \\ \left(\dfrac{t_h}{t}\right)^{1/2}, & t \geqslant t_h \end{cases} \tag{1}$$

where I_b is the intensity of the fast electron stream; the constant a is equal to 1.25; $C_V = (Z+1)k_B/A(\gamma-1)m_p$ is specific heat; k_B is the Boltzmann constant; m_p is a proton mass; γ is the adiabat exponent; t_h is the loading time, which is the time of unloading wave propagation through the heated layer of target

$$t_h = \frac{a^{1/3}\mu}{(\gamma - 1)\rho_0^{2/3} I_b^{1/3}}; \tag{2}$$

P_h is the maximal pressure attained in the moment of $t = t_h$

$$P_h = a^{-2/3} \rho_0^{1/3} I_b^{2/3}; \tag{3}$$

μ is the Coulomb mass range of fast electron with initial energy E_0, which for a non-relativistic electron in low-Z plasma is (see, for example [6, 23, 24],)

$$\mu_e = \frac{E_0^2 \cdot A \cdot m_p}{4\pi e^4 \cdot Z \cdot \Lambda} \approx 5.2 \cdot 10^{-7} \frac{A}{Z} E_{keV}^2, \ \text{g cm}^{-2}; \tag{4}$$

E_{keV} is the initial energy of fast electron measured in keV, which can be evaluated with use of formula for the average energy of non-relativistic laser-produced fast electrons [25, 26]

$$E \approx 21.6 \left(I_{15} \lambda_\mu^2\right)^{1/3}, \ \text{keV}; \tag{5}$$

e is the electron charge; Λ is the Coulomb logarithm; and I_{15} is the fast electron stream intensity measured in units of 10^{15} W cm^{-2}. $\lambda\mu$ is measured in μm.

The efficiency of heating stream energy transformation to shock wave energy is calculated as

$$\eta = \eta_h \times \begin{cases} \left(\dfrac{t}{t_h}\right)^{3/2}, & t \leqslant t_h \\ 10\left(\dfrac{t_h}{t}\right)^{3/4} - 9\dfrac{t_h}{t}, & t \geqslant t_h \end{cases} \tag{6}$$

where:

$$\eta_h = \frac{2}{5a}\left(\frac{\gamma + 1}{2}\right)^{1/2}.$$

According to (1–5), the ablation pressure exceeding 1 Gbar, for example, in the case of an aluminum target, may be created as a result of target irradiation by the first Nd-laser harmonic pulse with intensity of 10^{16} W cm^{-2}, capable of providing the conversion of 20% of its energy to fast electrons with an average energy of 40 keV. The loading time in this case is only 15 ps.

The effect of increasing the ablation pressure due to fast electron energy transfer in a target irradiated by a laser pulse was first confirmed in the experiments of [27] and investigated in detail in experiments [7, 28]. The experiments were performed with a PALS iodine laser pulse of 250 ps duration (full width at half maximum) and of 290 J energy. The objective was to measure the energy of a shock wave excited in the solid part of a plane target (made from aluminum) at the various regimes of its irradiation by laser beam, which correspond to the conditions of high and low intensity of fast electron generation. The large and small values of the coupling parameter were achieved by using, respectively, the first and third harmonic of iodine laser radiation as well as by varying the laser beam intensity and varying the radius of the focal spot on the target surface from, respectively, 40 to 160 μm. In the experiments with the first harmonic radiation, the coupling parameter was changed from $4 \cdot 10^{16}$ W μm^2 cm^{-2} at $R_L = 40\,\mu$m to $2.4 \cdot 10^{15}$ W μm^2 cm^{-2} at $R_L = 160\,\mu$m. In the experiments with the third harmonic radiation, the coupling parameter was changed from $4.4 \cdot 10^{15}$ W μm^2 cm^{-2} at $R_L = 40\,\mu$m to $2.6 \cdot 10^{14}$ W μm^2 cm^{-2} at $R_L = 160\,\mu$m. The energy of the shock wave was determined by measuring the volume of a crater produced on the target surface. Figure 1 illustrates the processes providing the main contribution to

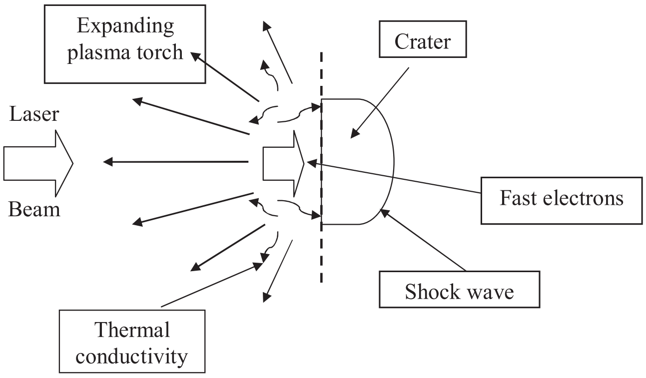

Figure 1. The scheme of the main physical processes responsible for the creation of laser-produced plasma under the conditions of intensive fast electron generation.

laser-produced plasma evolution under the conditions of the experiments [7, 27, 28]. They are the energy transfer by fast electrons and the electron thermal conductivity, as well as longitudinal and transverse thermal expansion of matter. The main result consisted in the opposite dependences of the fraction of laser energy transmitted to the shock wave on laser beam radius (laser intensity) in the experiments with the first and third harmonic radiation.

The reduction of the radius from 160 μm to 40 μm (that means increasing the intensity from $1.4 \cdot 10^{15}$ W cm^{-2} to $2.3 \cdot 10^{16}$ W cm^{-2}) in the case of the third harmonic leads to a monotonic decrease of this fraction from 2.2% to 1%, due to enhancing the effect of transverse expansion of the plasma torch, while in the case of the first harmonic, this fraction, on the contrary, increases from 2.1% to 4.7%, in spite of the effect of transverse expansion. The numerical modeling of PALS experiments was carried out by using the two-dimensional (2D) hydrodynamic code ATLANT-HE [29], which includes a unit for calculating the resonant absorption of laser radiation and energy transfer by fast electrons. According to the numerical simulations, the fractions of the laser energy absorbed by the resonance mechanism and transformed into the energy of fast electrons in experiments with both radiation harmonics were close to each other and varied slightly with changing the radius of the laser beam, remaining in the range of 8–10%. However, the average energy of fast electrons in the case of the first harmonic experiments was much larger than in the case of the third harmonic experiments. In the first harmonic case, it increased from 20 to 100 keV with decreasing the radius from 160 to 40 μm, while in the third harmonic case it increased from only 3 to 20 keV. As a result, the dominant mechanism of the heating of a substance and its subsequent ablation in the case of the third harmonic was a thermal conductivity wave, while in the case of the first harmonic, it was energy transfer by fast electrons.

Under the conditions of the discussed experiments, a transverse thermal expansion had a significant value. It is interesting to note that this effect plays a role of a peculiar filter, which emphasizes the effect of energy transfer by fast electrons. In the absence of transverse expansion, the efficiency of energy transfer to the shock wave in the case of the third harmonic would increase (although not as fast as in the case of the first harmonic) with decreasing the radius of the beam, due to increasing the velocity of the thermal conductivity wave with increasing the intensity of heating radiation. That is, the effect of transverse expansion leads to the opposite character of the dependences of energy transfer efficiency on laser beam radius in the cases of the first and third harmonics. This effect weakens, but does not suppress completely, the growth of the energy transfer efficiency with decreasing the radius in the case of the first harmonic, and not only inhibits the growth of this characteristic, but changes it to a decreasing function with the decreasing of the radius.

The model of high-temperature laser-produced plasma of a flat target irradiated by laser beam of a given radius, taking into account the effect of transverse thermal expansion, has been proposed in [27, 28] and was elaborated in a complete form in [29]. This 2D model is also based on the self-similar solution for isothermal expansion of a given mass of substance. The expressions of the model for the temperature, density, and, consequently, the pressure are presented as a superposition of self-similar solutions for the plane and spherical geometries of expansion:

$$T = \frac{T_1}{\left(2 - \Psi^{-1}\right)}, \quad \rho = \rho_1 \Psi^{-2},$$
$$P = P_1 \left[\Psi (2\Psi - 1)\right]^{-1} \tag{7}$$

where T_1, ρ_1, and P_1 are, respectively, temperature, density, and pressure of the self-similar solution for the plane geometry, and Ψ is the factor of decreasing of temperature and density at the transition to spherical expansion ($\gamma = 5/3$):

$$\Psi = \left(1 + \frac{2^{3/4}}{3\pi^{1/4}} \frac{\xi}{R}\right) \tag{8}$$

and

$$\xi = \left(\frac{I}{\mu}\right)^{1/2} \cdot t^{3/2}.$$

I is the intensity of absorbed heating radiation.

The solution of interest is the solution at the ablation surface:

$$T_1 = \frac{1}{2C_V} \frac{It}{\mu}, \quad \rho_1 = \frac{3}{2^{1/2}\pi} \frac{\mu^{3/2}}{I^{1/2} t^{3/2}},$$
$$P_1 = \frac{1}{2^{1/2}\pi} \frac{I^{1/2}\mu^{1/2}}{t^{1/2}} \tag{9}$$

which corresponds exactly to solution (1) at $t \gg t_h$.

As the areal density of evaporated substance μ, the larger quantity is used between the specific mass (4) heated by fast electrons (mass per unit surface that is the mass range of fast electrons) and the specific mass heated by thermal conductivity. The last value is

$$\mu_c = 3.6 \cdot 10^{-3}\left(\frac{f}{Z+3.3}\right)^{1/3} \times \left(\frac{A}{Z+1}\right)^{7/6} \delta_a^{2/3} I_{15}^{2/3} t_{ns}^{2/3},\ \text{g cm}^{-2}, \quad (10)$$

where f is the limiting factor of thermal conductivity flow, which is 0.06 – 0.01 for laser intensities of 10^{14}–10^{15}W cm^{-2}; δ_a is the absorption coefficient of laser radiation; t_{ns} is the time measured in nanoseconds; and I_{15} is the intensity of absorbed laser radiation measured in 10^{15} W cm^{-2}.

The calculations made with a 2D model have shown that ablation density and pressure are significantly larger in the case of first harmonic irradiation (when energy transfer is due to fast electrons) in comparison with the case of third harmonic irradiation (when energy transfer is due to thermal conductivity). Furthermore, these values grow rapidly in the case of the first harmonic and weakly change in the case of the third harmonic with increase of the laser intensity, due to decreasing the beam radius. When a beam radius decreases from 160 μm down to 40 μm, ablation density increases five times, from 0.07 g cm^{-3} to 0.35 g cm^{-3}, and the pressure increases four times from 30 Mbar to 120 Mbar in the case of the first harmonic, in despite of the transverse expansion effect. In the case of the third harmonic, the ablation density decreases from 0.08 g cm^{-3} to 0.06 g cm^{-3}, and the ablation pressure increases only 1.4 times from 50 Mbar to 70 Mbar. The efficiency of energy transmission to shock wave is greater, the larger the ratio of the ablation density to the target density. Under the plane approximation, such an efficiency is $\eta \propto (\rho/\rho_s)^{1/2}$ [30]. Therefore, the large ablation density due to fast electron energy transfer is the cause of much higher transmission of laser pulse energy into shock wave energy in the case of the first harmonic in comparison with the case of the third harmonic, registered in the experiments [7, 27, 28]. In the case of the first harmonic, the five-fold increase in the ablation density leads to a 2.2-fold increase in the energy transmission to shock wave, which agrees well with the experimental data.

3. Ultra-power shock wave driven by energetic electron stream for shock ignition and EOS investigation

The shock wave driven by a laser-accelerated fast electron stream related to the shock ignition approach has been investigated in the papers [21, 22], based on the model in (1–6) and on numerical simulations made using the 1D version of the CHIC code containing the kinetic unit for calculation of fast electron transport. These studies have shown that a shock wave with an amplitude of pressure of 0.4–2 Gbar, undamped within 0.3 – 1 ns, can be generated when a solid target is exposed by fast electrons with energies of 30–100 keV, generated under the action of a laser pulse with an intensity of 10^{16}–10^{17} W cm^{-2}, at the efficiency of energy conversion to fast electrons of 10%. Such a shock wave is able to provide the shock ignition. According to the data of numerical simulations, the pressure of the shock wave, which is excited in a semi-space filled with a DT-substance with a density of 10 g cm^{-3} by the heating stream of monoenergetic fast electrons with intensity of 10^{15} W cm^{-2} and the electron energy of 30 keV, reaches 410 Mbar during the period of 14 ps. At the fast electron stream intensity of 10^{16} W cm^{-2} and electron energy of 100 keV, the pressure reaches about 2 Gbar during the period of 70 ps. Note that the non-stationary model (1–6) agrees very well with the numerical results. The differences in the values of loading time and pressure do not exceed 10%.

Properties of a shock wave that can be applied to EOS experiments must meet the specific requirements. These requirements are that the shock wave should remain flat and quasi-stationary during the period of measurements. Moreover, the wave should propagate over a tested target at a distance exceeding at least the spatial resolution of used diagnostic methods during a time greater than at least the temporal resolution. Theoretical justification of the possibility to generate a fast electron-driven shock wave with a gigabar pressure for EOS investigations using the recent lasers has been done in [10].

The non-stationary model (1–6) of the plasma heated by a monoenergetic fast electron stream was also used in [10]. The requirement of a plane wave means that the laser beam radius $R_{\rm L}$ must exceed the dimension of ablation region, where the pressure is created during the laser pulse duration τ. This requirement can be written, according to (1–3), in the form of inequality

$$R_{\rm L} > \frac{\mu}{\rho_0} + \frac{2}{3}\left[\frac{(\gamma-1)\beta I_L(\tau - t_h)^3}{a\mu}\right]^{1/2},\ \tau \geqslant t_h, \quad (11)$$

where β is the efficiency of laser energy conversion to fast electron energy. According to (1), for the formation of pressure close to the maximum value, the duration of the laser pulse should exceed the ablation loading time. At the same time, this excess should not be significant for the quasi-stationary character of a shock wave. However, the last requirement is not fundamental, because the pressure after the achievement of the maximum value P_h decreases quite slowly with the time (as $P \propto t^{-1/2}$). In addition, the pressure can be maintained at a level of P_h, choosing a time profiling of a laser pulse with the law of $I_{\rm L} \propto t^3$. Finally, the distance covered by a strong shock wave during the period of laser pulse duration exceeds the limit associated with the spatial resolution δ if

$$\left[\frac{(\gamma+1)}{2}\right]^{1/2}\left(\frac{\beta I_{\rm L}}{a\rho_0}\right)^{1/3}(\tau - t_h) \gg \delta,\ \tau \geqslant t_h. \quad (12)$$

The parameters of a laser beam with an intensity of $I_{\rm L} = 5 \cdot 10^{16}$ W cm^{-2}, which is able to ensure the generation of a shock wave with a pressure of several Gbar, satisfying the requirements of the EOS experiment, have been calculated in [10]. These evaluations were performed under the assumption that the laser energy conversion efficiency in the fast electron energy is $\beta = 0.2$ when, therefore, the intensity of fast electron stream is $I_b = 10^{16}\,\mathrm{W\,cm^{-2}}$. Aluminum was considered as a material of target. According to (1), selected parameters correspond to the pressure of about $P_h = 2.5$ Gbar and a shock wave velocity of about $3.5{\cdot}10^7\,\mathrm{cm\,s^{-1}}$. According to (5), the energies of fast electrons generated by the first and third harmonics of the Nd-laser pulse with the intensity of $I_\mathrm{L} = 5 \cdot 10^{16}\,\mathrm{W\,cm^{-2}}$ are 40 and 20 keV, respectively. According to (4), the mean free paths of electrons with these energies in aluminum are 24 and 6 μm, respectively. So, formula (3) gives, in these cases, loading times equal to $t_h = 115$ and 29 ps, respectively. When the first harmonic is used, a value of 200 ps can be chosen as a minimum duration of the laser pulse. In this case, the dimension of the pressure formation region is 44 μm, and the shock wave propagates at a distance of 30 μm, which is acceptable at a spatial resolution of several microns. Thus, the beam radius should be no less than 150 μm. In the case of the third harmonic and $\tau = 100$ ps, the dimension of the pressure formation region is 33 μm, and the shock wave propagates at a distance of 25 μm. In this case, $R_\mathrm{L} = 150\,\mu$m should also be chosen. Thus, at $I_\mathrm{L} = 5 \cdot 10^{16}\,\mathrm{W\,cm^{-2}}$, the minimum energies of the first and third harmonics of the Nd-laser pulses, which can ensure the generation of fast electron driven shock wave with a pressure of 2 Gbar, are 7 kJ and 3 kJ, respectively.

The spectrum of non-relativistic laser-accelerated fast electrons is close to a Maxwellian distribution. Such a spectrum corresponds to the spatial distribution of a heated layer temperature with a negative gradient along the direction of a heating beam propagation. The general problem of the generation of a shock wave in a medium with a decreasing temperature profile and the criterion of shock wave generation in these circumstances have been formulated in [10]. Figure 2 shows a qualitative scheme of shock wave generation in a medium with a falling temperature profile. Fast electrons of the low-energy part of the spectrum, which transfer their energy in the region with a coordinate less than the ablation surface coordinate x_a, provide the creation of ablation pressure and, ultimately, the generation of a shock wave propagating in the region with $x > x_a$. Fast electrons of the high-energy part of the spectrum, which transfer energy to the region with $x > x_a$, are responsible for preheating the material ahead of the shock wave front.

From the general requirement of shock wave generation, according to which the velocity of a piston should be larger than the speed of sound in the unperturbed material, the criterion of shock wave generation on the descending temperature profile $T(x)$ was written in [10] as

$$\int_0^{x_a} [T(x)]^{1/2}\mathrm{d}x \geqslant (\gamma + 1)^{1/2} x_a \left. T^{1/2}\right|_{x = x_a}. \tag{13}$$

Here x_a is the coordinate at which a shock wave is formed (the ablation boundary).

The solution of the relativistic kinetic equation for fast electrons of an arbitrary spectrum, decelerated in plasma semi-space with arbitrary density profile, was found in [31] to find the temperature profile of the medium, heated by a stream of fast electrons of an arbitrary spectrum. In the case of a non-

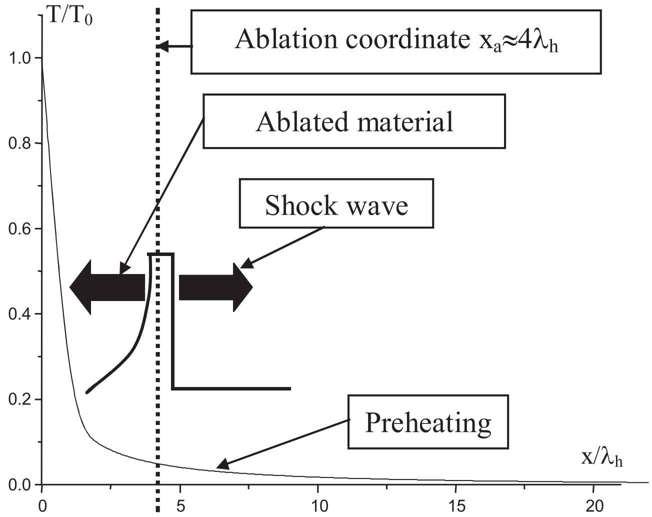

Figure 2. The scheme of the regions of ablation and shock wave generation under the conditions of target temperature distribution, with negative gradient along the heating fast electron beam propagation.

relativistic Maxwellian spectrum of fast electrons, this solution has the form

$$f(x, p) = \frac{2}{\pi^{1/2}} \frac{n_b}{p_h} \exp\left\{ -\left[\left(\frac{p}{p_h} \right)^4 + \frac{x}{\lambda_h} \right]^{1/2} \right\}$$
$$\times \left[1 + \left(\frac{p_h}{p} \right)^4 \frac{x}{\lambda_h} \right]^{-1/2}. \tag{14}$$

In expression (14), the stopping length

$$\lambda_h = \frac{p_h^4}{4 g_0 \rho m_e}$$

is introduced for a non-relativistic fast electron beam with the 'thermal' momentum $p_h = (2kT_h m_e)^{1/2}$, $g_0 = 4\pi e^4 m_e Z/A m_p$, m_e is the electron mass, and n_b is the concentration of fast electrons at the semi-space boundary.

Solution (14) satisfies to the boundary condition

$$f|_{x=0} = n_b S(p)$$

where the initial spectrum is

$$S(p) = \frac{2}{\pi^{1/2} p_h} \exp\left[-\left(\frac{p}{p_h} \right)^2 \right].$$

The temperature profile calculated on the basis of this solution has the form

$$T(x) \approx T_0 \exp\left[-\left(2\frac{x}{\lambda_h} \right)^{1/2} \right] \tag{15}$$

where T_0 is the temperature at the boundary where the heating beam enters the medium ($x = 0$). Expression (15) gives the result close to the data of numerical calculations [14]. Using (15), the criterion (13) gives the equation for a thickness of the ablation layer

$$\exp(\chi_a) = \frac{1}{2}(\gamma + 1)^{1/2}\chi_a^2 + \chi_a + 1,$$
$$\chi_a = \left(\frac{x_a}{2\lambda_h}\right)^{1/2}. \qquad (16)$$

When $\gamma = 5/3$, the approximate solution of equation (16) is $x_a \approx 4\lambda_h$. Since the Coulomb stopping length of a non-relativistic fast electron increases with its initial energy as $\lambda \propto E^2$, it follows that the electrons with energies $E < 2T_h$ respond for the ablation process and the generation of a shock wave, and the electrons with energies $E > 2T_h$ respond for preheating. It means that the ratio of the energy flux at the ablation surface to the initial intensity of fast electron stream is $I_b(x_a)/I_{b0} \approx 0.8$, and, therefore, about 80% of the Maxwellian fast electron energy is spent for creating the ablation pressure, and 20% is spent for preheating.

According to (1), the ratios of the pressures and loading times in the cases of Maxwellian and monoenergetic beams are $\left[I_b(x_a)/I_{b0}\right]^{2/3} \approx 0.86$ and $(x_a/\lambda_h)\left[I_b(x_a)/I_{b0}\right]^{-1/3} \approx 4.3$, respectively. These results are in good agreement with numerical calculations [32, 33] of an igniting shock wave driven by a beam of non-relativistic fast electrons with a Maxwellian spectrum. The decrease of the pressure in the case of a Maxwellian spectrum is small enough. The spectrum effect on the space – time characteristics of the generation of a shock wave is much stronger. For the igniting shock wave, the effect of increasing the ablation region thickness is the most important. It requires a modification of shock-ignited target design so that the areal mass of the pre-compressed target should be larger by a factor of 4 in comparison with a target designed for a mono-energetic igniting beam. In the case of a shock wave for EOS investigation, the increase of the ablation region thickness and the loading time, respectively, four and 4.3 times leads to a significant increase in the laser pulse energy required to generate a shock wave with a gigabar pressure.

Under the above conditions of gigabar wave generation, in the case of a Maxwellian spectrum, the thickness of the ablation layer is 100, and 25 μm for the first and third harmonics, respectively, and the loading time is 500 and 125 ps, respectively. As the result, the duration of the first harmonic radiation pulse should be no less than 700 ps. In this case, the dimension of the pressure formation region would be 125 μm, and the distance of the shock wave propagation would be about 70 μm. The corresponding radius of the beam should be no less than 300 μm. The duration of the third harmonic radiation pulse should be increased to $\tau \approx 300$ ps. In this case, the dimension of the pressure formation region would be 70 μm, and the distance of shock wave propagation would be about 60 μm. The corresponding radius of the laser beam can be 250 μm. Thus, the energy of a laser pulse in the case of the Maxwellian spectrum of fast electrons necessary for the generation of a gigabar shock wave for EOS experiments increases by an order of magnitude, to 90 kJ and 30 kJ for the first and third harmonics of the Nd-laser pulse, respectively. Nevertheless, these energies are significantly lower than the energy of the largest operating [34] and created [3, 35] megajoule facilities for ICF research. Let us note that the higher pressures of the shock wave (10 Gbar and larger) can be reached by using the relativistic fast electron beam, which could be generated at the laser pulse intensity larger than 10^{18} W cm^{-2}. However, taking into account the requirements of a shock-wave EOS experiment, the energy of the laser pulse in this case should be 1 MJ and larger.

There are else two other effects that influence the properties of a powerful shock wave driven by a stream of laser-accelerated fast electrons. They are the divergence of the fast electron beam and the density gradient at the boundary of the target. In respect to the divergence, its effect is expected to be insignificant under the conditions of the irradiation regimes discussed above. According to (3), it can reduce the pressure by a factor of $\left(1 + d \tan\theta/R_{\rm L}\right)^{4/3}$, where d is the distance from the region of generation of fast electrons to the surface of the solid part of the target and θ is the divergence angle of the beam of laser-accelerated electrons. Even at the maximum possible d value equal to the dimension of the region of a high-temperature plasma and at $\theta = 30°$ (see introduction), the decrease in the pressure owing to divergence in the proposed irradiation regimes is no more than 20%. The density gradient effect in the case of a shock wave for EOS research can only be due to the existence of a pre-pulse creating the plasma near the target boundary; it doesn't lead to the generation of fast electrons. This effect can be eliminated by using the laser pulse with a high contrast in intensity. In terms of shock ignition, the density gradient is an essential aspect of the problem, since it is formed during the compression target under the action of the nanosecond part of the pulse. Numerical calculations performed in [33] indicate that this effect can be very significant and results in a reduction in shock wave pressure by a factor of 2–3. Investigation of the role of this effect in a shock ignition requires further theoretical as well as experimental studies.

4. Conclusion

Using the beam of laser-accelerated fast electrons, including the beam with a Maxwellian spectrum of particles, is an effective way to generate an ultra-power shock wave. Energy transfer by fast electrons at the irradiating of the target by laser pulse with an intensity of about 10^{16} W cm^{-2} can ensure the generation of a shock wave with a pressure of 400–700 Mbar, satisfying the requirements of shock ignition. Using the beam of fast electrons generated under the action of a laser pulse with an intensity of 10^{17-18} W cm^{-2} can ensure the generation of a flat, quasi-stationary shock wave with a pressure of a few Gbar. It opens up the possibility of a great transition of a laboratory shock-wave EOS experiment from the current level of pressure of 100 Mbar to a higher level of pressure of an order of magnitude of several Gbar.

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