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On the Possibility of Laboratory Shock Wave Studies of the Equation of State of a Material at Gigabar Pressures with Beams of Laser-Accelerated Particles

S. Yu. Gus'kov

Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia
e-mail: guskov@sci.lebedev.ru

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The possibility of laboratory shock wave studies of the equation of state of a material with beams of laser-accelerated charged particles at pressures an order of magnitude higher than those reached in current experiments has been discussed. The possibility of the generation of a plane quasistationary shock wave with a pressure of several gigabars behind its front at the irradiation of a target by a laser beam with an energy of several kilojoules and an intensity of about 10^{17} W/cm^2, which is accompanied by the generation of fast electrons with an average energy of 20–50 keV, has been justified.

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The action of a laser pulse that can ensure a high energy concentration on a target is the most efficient method of the generation of a high-power shock wave in a laboratory experiment for studying the equation of state of a material (see, e.g., review [1]). Such experiments with a nanosecond laser pulse with an intensity of $I_L = 10^{13}$–10^{14} W/cm^2 are performed at various laboratories at pressures below 100 Mbar [1]. The ablation pressure induced by the laser pulse with the indicated intensity is formed owing to the absorption of radiation in the region of the formed plasma with the critical density ρ_{cr} and to the energy transfer by an electron heat conduction wave. The scale of a pressure is determined by the density ρ_{cr} and speed of sound $(I_L/\rho_{cr})^{1/3}$: $P \propto \rho_{cr}^{1/3} I_L^{2/3}$. In contrast to laser radiation, charged particles can heat a material with the initial solid-state density ρ_0 by transferring energy in Coulomb collisions. For this reason, a charged-particle beam can ensure the pressure on a target that is approximately a factor of $(\rho_0/\rho_{cr})^{1/3}$ higher than that induced by a laser beam with the same intensity. This factor in the case of the first harmonic of a Nd laser with the wavelength $\lambda \approx 1.06$ μm ($\rho_{cr} \approx 3.6 \times 10^{-3}$ g/cm^3 for the fully ionized plasma) and an aluminum target ($\rho_{cr} \approx 2.7$ g/cm^3) is about 10.

The energy flux density on the surface of the target comparable with the intensity of a laser beam can be ensured by beams of laser-accelerated charged particles. The energies of fast electrons and ions reached in current experiments on the interaction of laser radiation (including petawatt radiation) with matter exceed 1 MeV and 100 MeV/nucleon, respectively, and the degrees of transformation of the energy of laser radiation to the energy of these particles are 20–30 and 7–10%, respectively (see, e.g., reviews [2–4]). Fast electrons will be considered below as the most efficiently accelerated particles. The scale of their mean energy at all known mechanisms of generation is the average energy of oscillations of an electron in a laser radiation field, which increases with the parameter $I_L\lambda^2$. The spectrum of fast electrons appearing at the incidence of a laser pulse on a flat target is usually close to a Maxwellian distribution and the divergence of the beam is no more than 30°. The transformation of the energy of laser radiation to the energy of fast electrons becomes significant when the parameter $I_L\lambda^2$ becomes larger than 10^{14} W μm^2/cm^2 (see, e.g., monographs [5, 6]). At $I_L\lambda^2 > 10^{15}$ W μm^2/cm^2, when the energy of fast electrons reaches several tens of keV, the transfer of their energy to the dense part of a target dominates in the formation of ablation pressure [7]. The last condition for the first harmonic of the Nd laser means the intensity $I_L > 10^{15}$ W/cm^2. The effect of energy transfer by fast electrons at the formation of ablation pressure was detected in experiments [8, 9], where a planar aluminum target was irradiated by the first harmonic of an iodine laser ($\lambda \approx 1.315$ μm) and the ablation pressure increased from 10 Mbar at $I_L = 5 \times 10^{14}$ W/cm^2 to 150 Mbar at $I_L = 5 \times 10^{16}$ W/cm^2.

In this work, the possibility of the generation of a shock wave with a gigabar pressure whose properties satisfy the requirements of a shock wave experiment on studying the equation of state at the action of a flow of laser-accelerated fast electrons is justified. A transition to such a pressure will be a serious step in the development of laboratory studies of the equation of state.

An nonstationary model of a high-temperature plasma formed at the action of a monoenergetic beam of fast electrons on a half-space of completely ionized matter was developed in [10, 11]. This model is based on a self-similar solution of the problem of the isothermal expansion of a given mass of matter [12]. In this problem, the mass of expanded matter is determined by the mass mean free path μ of a fast electron with the initial energy E_0. The temperature, density and pressure of the plasma at the boundary with the solid part of a target are given by the expressions

$$T = \frac{I_b}{\xi C_V \mu},$$
$$\rho = \rho_0 \begin{cases} 1 & \text{at} \quad t \le t_h \\ \left(\frac{t}{t_h}\right)^{3/2} & \text{at} \quad t \ge t_h, \end{cases} \tag{1}$$
$$P = P_h \begin{cases} \frac{t}{t_h} & \text{at} \quad t \le t_h \\ \left(\frac{t_h}{t}\right)^{1/2} & \text{at} \quad t \ge t_h. \end{cases}$$

Here, I_b is the intensity of the fast electron beam; $\xi = 1.2$; $C_V = (Z + 1)k_B/A(\gamma - 1)m_p$ is the specific heat, where Z and A are the charge and atomic numbers of the material of the target, γ is the heat capacity ratio, k_B is the Boltzmann constant, and m_p is the mass of the proton; t_h is the ablation loading time, which is the time of the propagation of a unloading wave over the heated layer of the material:

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

and P_h is the maximum pressure appearing at the time $t = t_h$:

$$P_h = \xi^{-2/3}\rho_0^{1/3} I_b^{2/3}. \tag{3}$$

According to Eq. (3), a pressure of 1 Gbar corresponds to the intensity of the fast electron beam about 10^{16} W/cm^2. The parameters of a laser pulse that can ensure the generation of a fast electron beam with such an intensity will be determined below taking into account the requirements of a shock wave experiment for studying the equation of state. According to these requirements, the shock wave should remain plane and quasistationary during the entire time of measurements. Furthermore, the wave should propagate in the target at a distance exceeding at least the spatial resolution of diagnostic methods in a time exceeding at least their time resolution. The condition of a plane shock wave means that the radius of the laser beam R_L should exceed the dimension of the pressure formation region during the action time of a laser pulse τ. According to Eq. (1), this requirement can be represented in the form of the inequality

$$R_L > \frac{\mu}{\rho_0} + \frac{2}{3}\left[\frac{(\gamma-1)\beta I_L(\tau - t_h)^3}{\xi\mu}\right]^{1/2}, \quad \tau \ge t_h, \tag{4}$$

where β is the efficiency of the transformation of the energy of laser radiation to the energy of fast electrons. According to Eq. (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 quasistationary character of the 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 owing to the weak profiling of a laser pulse by the law $I_L \propto t^{3/4}$. Finally, the distance covered by a strong shock wave in the time of pulse action exceeds the limit associated with the spatial resolution δ if

$$\left(\frac{\gamma+1}{2}\right)^{1/2}\left(\frac{\beta I_L}{\xi\rho_0}\right)^{1/3}(\tau - t_h) \gg \delta, \quad \tau \ge t_h. \tag{5}$$

We take $I_b = 10^{16}$ W/cm^2, $\beta = 0.2$, and, therefore, $I_L = 5 \times 10^{16}$ W/cm^2. We consider an aluminum target for estimates. The chosen parameters correspond to the pressure $P_h = 2.5$ Gbar, at which the velocity of the shock wave is about 3.5×10^7 cm/s. Then, we use the known scaling law [13] for the mean energy of fast electrons:

$$E_h \approx 22(I_L\lambda^2)^{1/3} \text{ [keV]}, \tag{6}$$

where I_L and λ are measured in 10^{15} W/cm^2 and μm, respectively. According to Eq. (6), the energies of fast electrons generated by the first and third harmonics of the Nd laser with the intensity $I_L = 5 \times 10^{16}$ W/cm^2 are 40 and 20 keV, respectively. According to [11], the mean free paths of electrons with these energies in aluminum are 24 and 6 μm, respectively. Formula (2) gives $t_h = 115$ and 29 ps, respectively. When the first harmonic is used, a value of 200 ps can be chosen for the 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 radius of the beam 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, $R_L = 150$ μm should also be chosen. Thus, at $I_L = 5 \times 10^{16}$ W/cm^2, the minimum energies of pulses of the first and third harmonics of the Nd laser that can ensure the generation of a shock wave with a pressure on the level of 2 Gbar owing to the energy transfer by fast electrons are 7 and about 4 kJ, respectively.

It is important that the spectrum of laser-accelerated fast electrons could be Maxwellian. Such a spectrum corresponds to the formation of the spatial distribution of the temperature with a negative gradient along the direction of the propagation of the heating beam. In the case of a monoenergetic spectrum, the energy of all fast electrons is spent on the formation of ablation pressure. In the case of a Maxwellian spectrum, only electrons in the low-energy part of the spectrum are involved in the ablation of the target. Electrons in the high-energy part of the spectrum can transfer their energy to the region ahead of the shock wave front and, thereby, they heat the material before its compression (preheating). At a given temperature profile of the material, the boundary energy of these two spectral groups of electrons is determined by the thickness of the ablation layer. From the general condition of the generation of a shock wave according to which the velocity of a piston should be higher than the speed of sound in the unperturbed material, the criterion of the generation of a shock wave on the descending temperature profile $T(x)$ can be written in the form

$$\int_0^{x_a}[T(x)]^{1/2}dx \geq (\gamma+1)^{1/2}x_a T^{1/2}\big|_{x=x_a}. \tag{7}$$

Here, x_a is the coordinate at which the shock wave is formed (boundary of the ablation region). As the function $T(x)$, it is possible to use the following approximation of numerical calculations performed in [14]:

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

where T_0 is the temperature at the entry of the beam to the material ($x = 0$) and λ_h is the deceleration length of an electron with the average energy corresponding to the temperature of fast electrons. Then, according to Eq. (7), the following equation is obtained for the thickness of the ablation layer:

$$\exp\chi_a = \frac{1}{2}(\gamma+1)^{1/2}\chi_a^2 + \chi_a + 1, \quad \chi_a = \left(\frac{x_a}{2\lambda_h}\right)^{1/2}. \tag{8}$$

Equation (8) at $\gamma = 5/3$ has the approximate solution $x_a \approx 4\lambda_h$. Since the Coulomb deceleration length of a nonrelativistic electron increases with its initial energy as $\lambda \propto E_0^2$, fast electrons with the energies $E < 2T_h$ are responsible for the ablation process, whereas electrons with the energies $E > 2T_h$ induce preheating. This means that the ratio of the energy flux on the ablation surface to the initial energy flux of fast electrons at the irradiation boundary is $I_b(x_a)/I_{b0} \approx 0.8$. Thus, about 80% of the energy of the fast electron beam with a Maxwellian spectrum is spent on the formation of ablation pressure and 20% is spent on preheating.

According to Eq. (1), the ratios of the pressures and pressure formation times in the cases of Maxwellian and monoenergetic beams are $[I_b(x_a)/I_{b0}]^{2/3} \approx 0.86$ and $(x_a/\lambda_h)\ [I_{b0}/I_b(x_a)]^{1/3} \approx 4.3$, respectively. The decrease in the pressure in the case of a Maxwellian spectrum is small. The effect of the spectrum of the beam on the space–time characteristics of the generation of a shock wave is much stronger. Indeed, under the conditions of the generation of a gigabar wave in the case of the Maxwellian spectrum of the beam considered above, the thickness of the ablation layer increases to 100 and 25 μm for the first and third radiation harmonics, respectively, and the formation time of ablation pressure increases to 500 and 125 ps, respectively. As a result, the duration of the pulse of the first harmonic should be no less than 700 ps. In this case, the dimension of the pressure formation region would be 125 μm and the length of the propagation of the shock wave would be about 70 μm. Hence, the corresponding radius of the beam should be no less than 300 μm. The duration of the pulse of the third harmonic should be increased to $\tau \approx 300$ ps. In this case, the dimension of the pressure formation region would be 70 μm and the length of the propagation of the shock wave 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 in experiments on studying the equation of state increases by an order of magnitude: to 90 and 30 kJ for the first and third harmonics of the Nd laser, respectively. Nevertheless, this energy is significantly lower than the energy of the largest operating and created megajoule facilities for studies of laser fusion (see, e.g., [4]).

Under the conditions of the irradiation regimes discussed above, the effect of divergence of the beam of laser-accelerated electrons is expected to be insignificant. According to Eq. (1), it can reduce the pressure by a factor of $(1 + d\tan\theta/R_L)^{4/3}$, 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 above), the decrease in the pressure owing to divergence in the proposed irradiation regimes is no more than 20%.

In the case of beams of relativistic fast electrons corresponding to the irradiation of the target by a laser pulse with the intensity $I_L > 10^{18}$ W/cm^2, higher pressures of the shock wave (10 Gbar or above) can be reached. However, taking into account the requirements of a shock wave experiment on studying the equation of state, the energy of the laser pulse in this case should be 1 MJ or higher.

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