ELECTRON-ION RELAXATION IN A PLASMA PRODUCED BY ULTRASHORT LASER PULSES

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Focusing of ultrashort pulses ($\tau = 10^{-11} - 10^{-12}$ sec) of powerful laser radiation on a solid target is one of the effective methods of obtaining a dense high-temperature plasma [1]. Let us consider ion heating in such a plasma in the case when the electronic heat conduction can be neglected.

The initial dimension x_0 of the produced plasma, as a rule, greatly exceeds τv_s, where v_s is the ionic speed of sound. The gasdynamic expansion during the time of action of the ultrashort pulse can therefore be neglected. The laser-pulse energy is transferred during the time τ to the plasma electrons. This energy is then transferred to the ions by collision, is radiated out of the plasma, and is transformed into translational particle motion. In this case τ is usually much shorter than the characteristic plasma times, such as the time τ_{ei} of equalization of the electron and ion temperatures (relaxation), the time τ_{rad} of plasma radiation, or the time τ_{gd} of gasdynamic expansion. For example, for an LiD plasma with electron density $n_0 = 10^{21}$ cm^{-3}, a temperature $T_0 = 200$ eV, and $x_0 = 1\times10^{-2}$cm we get $\tau_{ei} \sim 10^{-10}$ sec [2], $\tau_{rad} \sim 5\times10^{-10}$ sec, and $\tau_{gd} \sim 10^{-9}$ sec. The electron-electron relaxation time, however, is $\tau_{ee} \sim 10^{-13}$ sec. We are therefore justifying in assuming that the electrons are instantaneously heated to a temperature T_0. The electron heat conduction can be neglected if $T_0 < T_k = 1.5\times10^{-10}(n_0x_0)^{1/2}$ (keV). ($T_k \simeq 500$ eV for $n_0x_0 = 10^{19}$ cm^{-2}.) The plasma is then insulated energywise from the remainder of the target during the initial stage of expansion. We are interested in the region $T_0 > 100$ eV, when the plasma is fully ionized and its radiation is of the bremsstrahlung type. The ion temperature at the initial instant is $T_i(0) \ll T_0$ and can be set equal to zero.

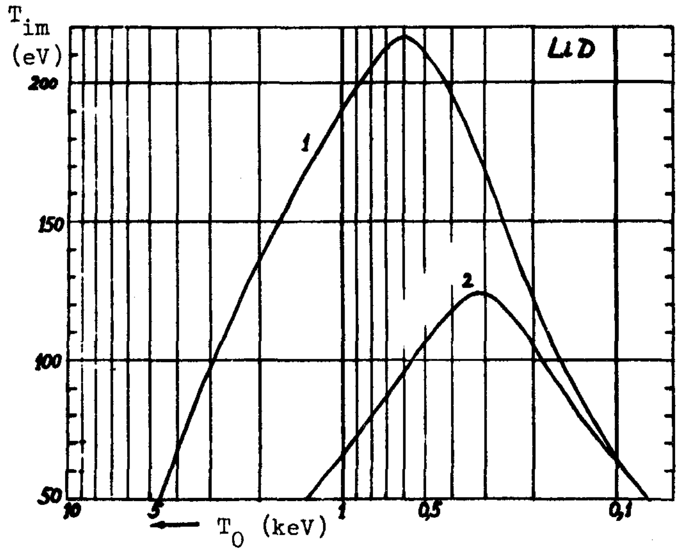
The plasma is not homogeneous at the instant of formation and during the course of expansion. Its temperature and density are characterized by a certain spatial distribution. Let us consider the volume-averaged parameters, in order not to make any arbitrary assumptions concerning the concrete forms of the indicated profiles, which are not sufficiently well known under real conditions. Such an approximation is justified also because in most experiments one measures volume-averaged plasma characteristics. A consistent application of this approach makes it necessary to exclude from consideration the process of absorption of the laser radiation and to operate with the energy absorbed in the plasma, or with the temperature T_0 at specified n_0 and x_0. The arbitrariness of T_0 presupposes a small optical thickness of the plsma layer at the laser frequency, but this does not influence the main conclusions. The solutions will be applicable in full to the heating of an isolated small particle in a thin foil. For the case of planar expansion, the equations of plasma motion, of energy conservation with allowance for radiation, and for the electronic relaxation per ion are written in the form

$$zT_e + T_i = m_i x\ddot{x}, \tag{1}$$

$$-\frac{3}{2}\frac{d}{dt}(zT_e + T_i) = \frac{m_i}{2}\frac{d}{dt}\dot{x}^2 + \xi\frac{x_0 T_e^{1/2}}{x}, \tag{2}$$

$$\frac{dT_i}{dt} = \kappa\frac{x_0}{x}\frac{T_e - T_i}{T_e^{3/2}} - \frac{2}{3}m_i\dot{x}\ddot{x}\frac{T_i}{zT_e + T_i} \tag{3}$$

subject to the initial conditions $T_e(0) = T_0$, $T_i(0) = 0$, $x(0) = x_0$, and $n_e(0) = n_0$. The following notation is used: z and m_i - average charge and mass of ions, $\xi = 1.35\times10^{-19}z^2n_0$, $\kappa = 5.33\times10^{-50}(z^2n_0/m_i)$, $\dot{x} = dx/dt$, $\ddot{x} = d^2x/dt^2$, and T is expressed in energy units. Similar



Maximum attainable ion temperature T_{im} vs. initial electron temperature T_0 for LiD plasma at $n_0x_0 = n_0r_0 = 10^{19}$ cm^{-2}. For a plasma with a different composition and different initial conditions, multiply the ordinate scale by $[3z/2(1 + z)]^{1/2}L$, and the abscissa scale by $[3(1 + z)/2z]^{1/2}L$, where

$$L = \left(\frac{8 m_H}{m_i}\right)^{1/4} \frac{z^{3/4}}{2,25} \sqrt{\frac{n_0 x_0}{10^{19}}}.$$

1 - planar expansion, 2 - spherical expansion.

equations can be written for spherical expansion. The contribution to the increment of the expansion energy is proportional to $zT_e/(zT_e + T_i)$ and $T_i(zT_e + T_i)$ for electrons and ions, respectively, since we are dealing with a collision plasma and the electrodynamic acceleration of the ions by the electrons on the edge of the freely expanding plasma can be neglected. For example, for LiD at $n = 10^{21}$ cm^{-3} and $T_0 = 200$ eV, the electron mean free path is $\ell_e \sim 5\times10^{-5}$ cm, and the Debye radius, which determines the volume involved in the acceleration, is $\ell_D \sim 3\times10^{-7}$ cm [3]. The $T_i(t)$ dependence has a maximum T_{im} at $t = r_m$, determined by the initial conditions. The growth of T_i due to electron-ion relaxation then gives way to a drop as a result of the conversion of the heat into expansion energy. The solution is sought in the form of the dependence of T_{im} on the initial data, since T_{im} is of greatest interest and determines, for example, the neutron yield.

The system (1 - 3) was solved approximately, but the estimate of the possible errors does not exceed 20%. The results can be represented in the form of a $T_{im}(T_0)$ plot (see the figure). In the region of low T_0 the temperature equalization occurs earlier than the gasdynamic expansion. With increasing T_0, the rleaxation occurs during the course of the expansion, and the growth of T_{im} slows down. At large T_0 the plasma expands under the influence of the internal electron pressure more rapidly than the exchange of heat between the electrons and the ions, and T_{im} decreases with increasing T_0. We note that radiation, being a process slower than the relaxation, exerts little influence. At a specified T_0, the maximum attainable ion temperature depends on n_0x_0. If we define T_0^* at constant n_0x_0 as the temperature at which the $T_{im}(T_0)$ reaches a maximum value T_{im}^*, then we get $T_0^* \sim (n_0x_0)^{1/2}$. The temperature T_0^* depends little on the ion mass (like $m_i^{1/4}$) and depends more strongly on z. At n_e = const we have $T_0^* \sim z^{3/4}$.

Thus, in the case of an isolated plasma (n_0x_0 = const) it is impossible to obtain an ion temperature higher than a certain value T_{im}^*. Moreover, passage through T_0^* leads to a drop of the ion temperature. However, if n_0x_0 is increased with increasing T_0, then further growth of T_i becomes possible. This situation can be realized under the influence of very powerful pulses incident on a massive target. The number of heated particles is then increased as a result of heat conduction. In this case heat conduction is not a useless process that leads to undesirable losses, but a mechanism that contributes to attainment of higher ion temperatures.

[1] N. G. Basov, S. D. Zakharov, P. G. Kryukov, Yu. V. Senatskii, and S. V. Chekalin, ZhETF Pis. Red. 8, 26 (1968) [JETP Lett. 8, 14 (1968)].
[2] L. Spitzer, Physics of Fully Ionized Gases, Interscience, 1962.
[3] Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, Academic Press, 1966.