Electron transport anomaly in a plasma in an intense radiation field

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It is shown that in an intense radiation field the electron friction force resulting from electron–ion collisions becomes an electron accelerating force on account of absorption of radiation by electrons. It is pointed out that the thermal conductivity increases. © 1996 American Institute of Physics.

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Interest in the kinetics of plasma in an intense radiation field arose in connection with the development of high-power short-pulse lasers. Such lasers have made it possible to realize, not only in the microwave range but also in the laser range, conditions under which the velocity $v_E = eE/m\omega$ of electron oscillations in a radiation field with frequency $\omega$ is much greater than the thermal velocity. Such conditions first attracted attention in connection with the problem of collisional absorption of intense radiation (see also Ref. 2 and the literature cited therein). In Ref. 3 the effect of a radiation field on temperature relaxation was studied. In the present Letter, electron momentum relaxation in a completely ionized plasma is studied. It is shown that in the case of sufficiently powerful radiation the electron–ion collisions result not in the retardation of electrons but rather in the acceleration of the electrons on account of the absorption of radiation by the electrons.

To determine the anomalous properties of plasma, we shall employ a very simple model in which the radiation possesses the following elliptical polarization: $E = (E_x, E_y, E_z) = E(-\cos \alpha \sin \omega t, \sin \alpha \cos \omega t, 0)$. In such a radiation field an electron oscillates with the velocity $u_E(t) = v_E(\cos \alpha \cos \omega t, \sin \alpha \sin \omega t, 0)$. We shall assume that the amplitude $v_E$ of the electron velocity oscillations is much higher than the electron thermal velocity $v_T = \sqrt{\kappa_B T/m}$. In the light of the conditions of Ref. 1, it is convenient to employ instead of the conventional distribution function $f(v, r, t)$ the function $F(u, r, t) = f(v, r, t)$, where $u = v - u_E(t)$. Then we obtain the following transport equation for the function $\langle F \rangle = F_0(u, r, t)$, averaged over a period of the fast oscillations, in the case of a field which varies slowly over a distance of the order of the amplitude $a_E = v_E/\omega$ of the electron position oscillations:

$$
\frac{\partial F_0}{\partial t} + u \frac{\partial F_0}{\partial r} + \left( \frac{e}{m} E_0 - \frac{e^2}{4m^2\omega^2} \frac{\partial |E|^2}{\partial r} \right) \frac{\partial F_0}{\partial u} = (J_{cl}[u + u_E(t), F_0(u)]) + J_{el}[F_0, F_0].
$$

(1)

where $E_0$ is the quasistatic (slowly varying over a period of $2\pi/\omega$) electric field.
electron–ion $J_{ei}$ and electron–electron $J_{ee}$ collision integrals can be used in the Landau form. The electron oscillations do not affect the relative motion of electrons colliding with one another, but they do affect the electron–ion collisions. Neglecting infinitesimals of the order of the ratio of the electron and ion masses, to describe the relaxation of the electron momentum we employ

$$\langle J_{ei}[u + u_E(t), F_0(u)] \rangle = A \frac{\partial}{\partial u_k} \langle D_{kj}(u + u_E(t)) \rangle \frac{\partial F_0}{\partial u_j}.$$  \hspace{1cm} (2)

Here $A = 2\pi e^2 e_i^2 n_i \Lambda_{ei} / m^2$, where $n_i$ is the ion number density and $\Lambda_{ei}$ is the Coulomb logarithm, the form of which in an intense radiation field is discussed in Ref. 4. Finally,

$$\langle D_{kj}(u + u_E(t)) \rangle = \langle \{ (u + u_E)^2 \delta_{kj} - (u + u_E)_k(u + u_E)_j \} | u + u_E |^{-3} \rangle.$$  \hspace{1cm} (3)

The question of electron–ion momentum relaxation, which is the topic of interest, can be answered simply in the five-moment approximation of Grad’s moment method, in which the local Maxwellian electron distribution function shifted by the ordered electron velocity $u^0$ is used. This gives the equation of motion (cf. Ref. 5)

$$mn \left( \frac{\partial u^0}{\partial t} + \left( u^0 \frac{\partial}{\partial r} \right) u^0 \right) + \frac{\partial p}{\partial r} - n \left( e E_0 - \frac{e^2}{4m\omega^2} \frac{\partial |E|^2}{\partial r} \right) = R_{ei}.$$  \hspace{1cm} (4)

Here $n$ is the electron number density, $p = n k_B T$ is the electron pressure, and $R_{ei}$ in Grad’s method is called the friction force:

$$R_{ei} = m \int d u (u - u^0) \langle J_{ei}[u + u_E(t), F_0(u)] \rangle.$$  \hspace{1cm} (5)

Linearizing this expression with respect to the velocity $u^0$ of the ordered motion of the electrons, we obtain

$$(R_{ei})_k = -mn v_{kj} u_j^0.$$  \hspace{1cm} (6)

In the case of elliptical polarization, which we are considering, the tensor $v_{kj}$ of the effective collision frequency is diagonal. It is especially simple to illustrate the anomalous property of the electron momentum relaxation in the case of nearly linear polarization of the radiation, when $\sin \alpha \ll 1$. However, we shall assume here that

$$eE \sin \alpha \gg m\omega v_T.$$  \hspace{1cm} (7)

We then have

$$v_{xx} = -\bar{v}(E) \left\{ \ln \frac{4}{\sin \alpha} - 1 \right\},$$

$$v_{yy} = -\bar{v}(E) \left\{ \frac{1}{\sin^2 \alpha} - \frac{1}{2} \ln \frac{4}{\sin \alpha} + \frac{5}{4} \right\},$$

$$v_{zz} = \bar{v}(E) \left\{ \frac{1}{\sin^2 \alpha} + \frac{1}{2} \ln \frac{4}{\sin \alpha} + \frac{1}{4} \right\},$$  \hspace{1cm} (8)

where

$$22 \hspace{1cm} \text{JETP Lett., Vol. 64, No. 1, 10 July 1996} \hspace{1cm} \text{V. P. Silin} \hspace{1cm} 22$$