Effect of electron dragging by photons in a laser plasma

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The dragging of a charge by light in a fully ionized plasma is considered. It is shown that in a laser plasma the drag current and the photo-emf can reach appreciable values.

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It is known that the effect of dragging of a charge by light is a unique manifestation of light pressure when light flux is absorbed in a medium with participation of free carriers. In the optical region of the spectrum, it was first experimentally observed and explained for the case of absorption of light by free carriers in semiconductors.[1–3] When light is absorbed in intraband (free-free) transitions the absorbed photon momentum is transferred to the system of free carriers and produces a directed flow of carriers, i.e., a drag current. Investigation of this effect in semiconductors not only yielded a number of new interesting physical results, but also led to the development of low-inertia broadband IR receivers with large dynamic ranges.[4]

Since light is absorbed in a fully ionized plasma also mainly as a result of free-free transitions (inverse bremmstrahlung), the electron-dragging effect should manifest itself in this case to a full degree. We deem it important therefore to analyze this effect when laser radiation interacts with a plasma. This may turn out to be useful in connection with the intensive development of methods for laser diagnostics of plasma and the large expansion of work aimed at producing a high-temperature dense plasma with the aid of lasers.[5]

Consider a layer of a uniform plasma with electron density n_e and temperature T_e, in which a photon flux I of laser radiation of frequency ν propagates. The photon flux αI absorbed per unit time and per unit volume imparts to the electrons a momentum

$$n_e m\Delta v = \frac{h\nu}{c}\,\alpha I\,,$$

where h is Planck's constant and α is the light absorption coefficient. The resulting drag-current density is:

$$j = en_e v_{\text{dr}} = \frac{eh\nu\alpha I\tau}{mc}\,, \tag{1}$$

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Here τ is the current relaxation time, which in the case of a fully ionized plasma is simply th electron-ion collision time[6] $\tau_{ei}=0.4T_e^{3/2}/Z_i n_e \ln\Lambda$. Using the expression for the light absorptio coefficient in a plasma under the assumptions $k\nu \lll kT_e$ and $\nu<\nu_p$ (where the plasma frequency i $\nu_e \approx 10^4\sqrt{n_e}$,[6] $\alpha=10^{-2}Z_i n_e^2 \ln\Lambda/\nu^2 T_e^{3/2}$, and the expression given above for τ_{ei}, we obtain fron (1):

$$j = 4\times 10^4 \frac{en_e J}{mc\,\nu^2} = 2.4\times 10^2 \frac{n_e J}{\nu^2}\ [\text{A/cm}^2]. \qquad (2$$

The radiation flux density J is given here in W/cm². Naturally, the equivalent electric fiel intensity E and the induced dragging photo-emf in a plasma layer of thickness l can be obtained b equating the drag current to the corresponding conduction current $E=j/\sigma$. Since $\sigma=10^{-5}T_e^{3/2}/Z$ [Ω-cm^{-1}], we get from (2)

$$E = 4\times 10^9 \frac{en_e Z_i J}{mc\,\nu^2 T_e^{3/2}} \approx 2.4\times 10^7 \frac{n_e Z_i J}{\nu^2 T_e^{3/2}}\quad [\text{V/cm}]. \qquad (3$$

To obtain the photo-emf it is necessary to integrate (3) with allowance for the dependence of th flux J on x, namely $J=J_{oe}^{-\alpha x}$; this yields:

$$V = 4\times 10^9 \frac{en_e Z_i J_o}{amc\,\nu^2 T_e^{3/2}} [1 - e^{-ae}]. \qquad (4$$

We get therefore in two limiting cases

$$V = 2.4\times 10^7 \frac{n_e Z_i J_o l}{\nu^2 T_e^{3/2}}\ [\text{V}] \qquad \text{if } al \ll 1, \qquad (5$$

$$V = 2.4\times 10^8 J_o/n_e\ [\text{V}] \qquad \text{if } al \gg 1. \qquad (6$$

It is interesting to note that according to (2) and (6) both the drag-current density and th photo-emf are independent of the plasma temperature if the light is sufficiently fully absorbed i the layer. Consequently, heating the plasma directly by the laser radiation does not influence thes parameters. From (2)–(6) we can see clearly how to use this effect for plasma diagnostics.

Let us estimate the characteristic parameters of the quantities involved in the experiments o the interaction of laser radiation with plasma. If a pulsed nanosecond neodymium-glass lase ($\nu=3\times 10^{14}$ sec^{-1}) is used, the characteristic radiation flux is $J_0=10^{12}$ W/cm², and the characteris tic plasma density is of the order of the critical density $n=10^{21}$ cm^{-3} for the given frequency (whe $\nu_p\approx\nu$). In this case we get from (2) and (6) $j=2.7\times 10^6$ A/cm² and $V=0.24$ V.

For picosecond laser pulses, the region of interest is $J=10^{16}$ W/cm². In this case the drag current and the photo-emf can reach quite large values, $j=2.7\times 10^{10}$ A/cm² and $V=2.4\times 10^3$ V (A natural limitation on j is $j_{\text{lim}}=en_e v_{\text{ther}}\approx 10^{-13}n_e\sqrt{T_e}$ [A/cm²], which holds true in most cases.

It follows from the estimates that the drag current must be taken into account when analyzin kinetic processes in a laser plasma. In particular, it can be one of the sources of spontaneou magnetic fields that are observed in a laser plasma and manifest themselves as electromagneti radiation in the plasma.

In addition, the dragging effect can be used here, too, both for the diagnostics of the plasm parameters and to determine the structure of the laser fluxes in the plasma. This effect can occur i the photosphere of stars, in the ionosphere of planets, and in outer-space plasma.

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