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High-intensity laser radiation on solid targets

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Abstract

The interaction of the laser radiation with solid targets is analyzed. Bulk and surface plasmons are derived in this context, as well as surface uni-polar currents. Far from resonance the motion of the charges in solid targets is non-relativistic, up to pretty high intensities. For higher intensities, or close to resonance, the motion becomes relativistic and charges may be violently ejected from target.

The interaction of the laser radiation with solid targets may provide accelerated chrages, like electrons, protons, ions, as well as short pulses of ultraviolet radiation and X-rays. We consider a laser radiation with optical frequency $\omega = 10^{15}s^{-1}$ (photon energy $\simeq 1eV$, wavelength $\lambda \simeq 2\times 10^{-4}cm$) in contact with thin solid targets, as in usual experiments. Let d be the dimension of the laser pulse, whose duration is $\tau = d/c$, c being the speed of light in vacuum, and let I be the intensity of the laser radiation. The energy of the pulse is $E = Id^2\tau = Id^3/c$. Let a be the mean inter-separation distance of the ions (and electrons) in the target; in the pulse volume d^3 there are $N = (d/a)^3$ particles in the target. Assuming that all the pulse energy would be given to the target, we get an energy per particle $e = E/N = Ia^3/c$; for $a = 5\text{Å}$ this energy is $e(eV) \simeq 2\times 10^{-14}I(w/cm^2)$. The non-relativistic regime for electrons would impose the inequality $e \ll mc^2 \simeq 500keV$, where m is the electron mass, which restricts the intensities to $I < 10^{19}w/cm^2$ (for protons this limit increases to $\simeq 10^{22}w/cm^2$).

Another way of estimating the energy of a charge in a radiation field is to start with the potential energy $e = qA_0$, where q is the electrical charge and A_0 is the amplitude of the potential vector; since $A_0 = cE_0/\omega$, where E_0 is the amplitude of the electric field, we get $e = qcE_0/\omega \simeq qE_0\lambda$. We can see that this is the mechanical work done by the field on the charge, when the latter is displaced by a wavelength. We can estimate the electric field from the intensity $I = cE_0^2/8\pi$, which leads to $e = q\sqrt{8\pi cI}/\omega$. Making use of the numerical data given above we get the non-relativistic imit $I < 10^{18}w/cm^2$ (which agrees accidentally with the former estimate).

We should note that neither the total energy of the radiation field is transferred to the charges, nor the displacement of the charges are as large as the wavelength. We expect the non-relativistic regime to hold beyond the limits given here.

The best way of getting an estimate for the limit of the non-relativistic regime is to start with the non-relativistic equation of motion of the charges in the radiation field and impose the limit upon the results.

Under the action of the laser radiation the electrons suffer a displacement $\mathbf{u}$ with respect to the ions (relative displacement); we neglect the ionic displaceemnt, in view of the much larger ionic mass in comparison with the electron mass. In the non-relativistic regime this displacement obeys Newton's equation of motion with Lorentz force. We assume that the velocity $\dot{\mathbf{u}}$ is much smaller than c, such that we may negelct the magnetic part of the Lorentz force; similarly, we assume that an intrinsic magnetization is too small to be included. In these conditions, the equation of motion reads

$$m\ddot{\mathbf{u}} = q\mathbf{E} + q\mathbf{E}_i \ \ , \tag{1}$$

where $\mathbf{E} = \mathbf{E}_0 \cos(\omega t + \mathbf{kr})$ is the external electric field of the laser radiation ($\mathbf{k}$ being the wavevector) and $\mathbf{E}_i$ is the internal (de-polarizing field); for small distances r we may neglect also the spatial phase $\mathbf{kr}$ in the electric field (the so-called dipole approximation), but, as long as we envisage here distances much longer than the wavelength, we keep this spatial phase. However, it gives only a slow varying envelope, whose contribution to the motion may be neglected. The displacement $\mathbf{u}$ produces a density imbalance $\delta n = -ndiv\mathbf{u}$, such that the internal field is given by

$$div\mathbf{E}_i = -4\pi nq div\mathbf{u} \ . \tag{2}$$

In order to account for the presence of the (plane) surface at $z = 0$, we write $\mathbf{u} = \mathbf{v}\theta(z)$, where $\theta(z)$ is the step function; equation (2) becomes

$$div\mathbf{E}_i = -4\pi nq div\mathbf{v} \cdot \theta(z) - 4\pi nq v_{sz}\delta(z) \ \ , \tag{3}$$

where v_{sz} is v_z for $z = 0$; for $z \geq 0$ this equation has the solution $\mathbf{E}_i = \mathbf{E}_{ib} + \mathbf{E}_{is}$, where

$$div\mathbf{E}_{ib} = -4\pi nq div\mathbf{v} \ , \ z > 0 \tag{4}$$

and

$$E_{isz} = -2\pi nq v_{sz} \ z = 0 \ . \tag{5}$$

The field $\mathbf{E}_{ib}$ is the internal bulk field, while the field $\mathbf{E}_{is}$ is the surface field ($z = 0$); the latter is reduced to its z-component; from the first equation (3) we get $\mathbf{E}_{ib} = -4\pi nq\mathbf{v}$ (for $z > 0$). The equation of motion (1) leads to

$$\ddot{\mathbf{v}} + \omega_p^2\mathbf{v} = \frac{q}{m}\mathbf{E} \ , \ z > 0 \tag{6}$$

and

$$\ddot{v}_{sz} + \frac{1}{2}\omega_p^2 v_{sz} = \frac{q}{m}E_{sz} \ , \ z = 0 \ \ , \tag{7}$$

where $\omega_p = \sqrt{4\pi nq^2/m}$ is the (bulk) plasma frequency and $\omega_p/\sqrt{2}$ is the frequency of the surface plasmons; in addition, $E_{sz} = E_0 \cos(\omega t - \mathbf{KR})$, where $\mathbf{K}$ and $\mathbf{R}$ are the projections of $\mathbf{k}$ and $\mathbf{r}$ on the surface, respectively. The solutions of equations (6) and (7) can be obtained immediately as

$$\begin{aligned} \mathbf{v} &= -\tfrac{q\mathbf{E}}{m}\tfrac{1}{\omega^2-\omega_p^2} \ , \ z > 0 \ , \\ v_{sz} &= -\tfrac{qE_{sz}}{m}\tfrac{1}{\omega^2-\omega_p^2/2} \ , \ z = 0 \ . \end{aligned} \tag{8}$$

For a mean inter-atomic separation 5Å the plasma frequency is $\omega_p \simeq 4.8 \times 10^{15}s^{-1}$; it is close to the excitation frequency ω, such that we may expect a resonance from equations (8), plasma instabilities and ejection of electrons and ions (through Coulomb repulsion) from the target's surface (especially through the action of the surface plasmons). However, this plasmonic resonance is very sharp, and, very likely, the process of plasma excitation is a regular one, with a displacement amplitude of the order $qE_0/m\omega_p^2$ and a velocity of the order $\omega qE_0/m\omega_p^2$. In these conditions, non-linearities may appear in plasma oscillations, which may lead to emission of ultraviolet radiation or X-rays.

The validity of these results requires $\dot{u}/c \ll 1$, *i.e.* $qE_0\omega/mc\omega_p^2 \ll 1$, which indicates a non-relativistic limit $E_0 < 10^9 esu$, an intensity $I < 10^{20} w/cm^2$ and a limit of displacement amplitude $\simeq 10^{-5} cm$. We can see that this limit is given by $(qA_0/mc^2)\frac{\omega^2}{\omega_p^2-\omega^2} \ll 1$ (or with ω_p^2 replaced by $\omega_p^2/2$ for the surface plasmons). Close to resonance the motion of the charges become relativistic. We note that the displacement amplitude becomes larger than the mean inter-ionic separation $a = 5Å$ for $E_0 > 10^6 esu$ ($I > 10^{14} w/cm^2$), where we expect to start the ejection of charges from the target (although, the energy perturbation in this case is sufficiently low to be relaxed (dissipated) in the body). Of course, for higher intensities we have violent charge ejection. The relativistic motion of the charges in this context can be treated as the relativistic motion of free charges. This point raises no special interest. The rate of fast emission of charges under the action of high-intensity radiation fields have been analyzed in Ref. [2].

We note that surface plasmons are excited on a plane surface by an electric field perpendicular to that surface. In order to have them excited by a laser pulse propagating perpendicular to the surface, a surface grating is employed.

A special feature occurs in the electromagnetic fields in finite bodies, related to the surface motion. The magnetic field is given by the Maxwell equation

$$curl\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{1}{c}\frac{\partial \mathbf{E}_i}{\partial t} + \frac{4\pi}{c}\mathbf{j}_i \quad , \tag{9}$$

where $\mathbf{j}_i = nq\dot{\mathbf{u}}$ is the internal current density (we neglect intrinsic magnetization). For volume charges and currents $\mathbf{j}_i = nq\dot{\mathbf{v}}$ and $\mathbf{E}_i = -4\pi nq\mathbf{v}$ (as derived above), such that the internal contribution $\partial\mathbf{E}_i/\partial t + 4\pi\mathbf{j}_i$ in equation (9) is vanishing; the magnetic field is not affected by the internal polarization. This reflects the charge conservation inside the body. On the contrary, on the surface $j_{isz} = nq\dot{v}_{sz}$ and $E_{isz} = -2\pi nqv_{sz}$ and equation (9) becomes

$$(curl\mathbf{H})_{sz} = \frac{1}{c}\frac{\partial \mathbf{E}_{sz}}{\partial t} + \frac{4\pi}{c}nq\dot{v}_{sz} = \frac{4\pi}{c}\left(\frac{1}{2}j_{isz}\right) \quad ; \tag{10}$$

This equation shows that surface currents appear in the body, and a related surface magnetic field, as a consequence of the fact that charges that oscillate below the surface ($z < 0$) are not anymore in the body; and the surface charge is not conserved in the body. Since these curents arise from oscillating charges at the surface they are called uni-polar currents. They generate radiation field.

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References

[1] A. Macchi, "Surface plasmons in superintense laser-solid interactions", Phys. Plasmas **25** 031906 2018).

[2] M. Apostol, "Fast ionization in strong electromagnetic radiation", Z. Naturforschung **A73** 461 (2018).