Penetration of weak electromagnetic radiation into a superdense plasma acted upon by powerful short-wave radiation

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We consider the possibility of an electromagnetic wave penetrating into a superdense plasma that is simultaneously irradiated by a circularly-polarized wave of higher frequency. The penetration is due to the constant magnetic field induced by the high-frequency wave as a result of the inverse Faraday effect. Quantitative estimates are presented as applied to the case when the two waves are the emissions of a CO_2 and an Nd laser, respectively.

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It is known (see, e.g.,[1]) that when a sufficiently strong constant magnetic field H_0 is applied to a plasma there can propagate in the plasma, in a quasilongitudinal direction, an electromagnetic wave of a definite type at an arbitrarily high electron density, i.e., at an arbitrarily large ratio ω_p/ω (ω is the wave frequency and $\omega_p=\sqrt{4\pi e^2N_e/m}$ is the plasma frequency). More accurately speaking, this propagation is possible if

$$(\omega_H/\omega)\cos\phi > 1, \tag{1}$$

where $\omega_H=ecH_0/mc$ is the gyromagnetic frequency and ϕ is the angle between the wave propagation direction and the field H_0. It was proposed in[2] to use this effect to introduce radiation into a superdense laser plasma when $(\omega_p/\omega)>1$. Its realization in laser experiments, however, encounters great technical difficulties connected with the need for producing superstrong magnetic fields. For a CO_2 laser ($\lambda=10.6$ μ), e.g., the required intensity is $H_0 \gtrsim 10^7$ G.

We consider in this article the possibility of realizing the "penetration effect" not by applying an external field H_0, but by simultaneously acting on the plasma with a sufficiently strong shorter-wavelength circularly polarized radiation. It is important here that the weak (long wave) radiation can penetrate into the plasma to higher electron densities than the high-power radiation that makes this penetration possible.

In our case the penetration of a weak wave of frequency ω_2 is due to the fact that the strong wave propagating in the same (or opposite) direction, with frequency ω_1, induces in the plasma via the inverse Faraday effect a constant magnetic field parallel to the wave propagation direction and equal to

$$H_{ind} = 4\pi N_e \mu = 4\pi N_e (er^2 \omega_1 / 2c) = H^0_{ind} \, (\omega_p/\omega_1)^2 (\gamma^2 - 1)/\gamma^2. \quad (2)$$

Here μ is the magnetic dipole moment of an electron moving in the strong-wave field on a circular orbit having a radius $r = (c/\omega_1)\sqrt{\gamma^2 - 1}/\gamma$ that depends on the wave intensity E_1 via the relativistic factor $\gamma = (1 - v^2/c^2)^{-1/2}$, in accordance with the equation (see[3])

$$eE_1 = mc\,\omega_1 \sqrt{\gamma^2 - 1}\left[1 + \frac{1}{2}\left(\frac{\omega_p}{\omega_1}\right)^2 \frac{\gamma^2 - 1}{\gamma^3}\right]; \quad (3)$$

$H^0_{ind} = \pi mc^2/e\lambda_1$ ($\lambda_1 = 2\pi c/\omega_1$ is the wavelength). For example, for neodymium-laser emission ($\lambda_1 = 1.06\ \mu$) we have $H^0_{ind} \approx 1.7 \times 10^7$ G. In fact, the field H_{ind} can be even stronger if the wave ω_1 has a "relativistic" intensity, corresponding to the condition $\gamma > 1$. At these intensities, the wave propagation becomes nonlinear and the critical electron density increases. It is easy to show on the basis of the results of[3] that in the general case, when account is taken of the relativistic correction to the mass and of the influence exerted on the wave ω_1 by the field H_{ind}, the critical density is determined from the equation

$$(\omega_p/\omega_1)^2 = 2\gamma^3/(\gamma^2 + 1), \quad (4)$$

and consequently, according to (2), the field H_{ind} can reach values $2H^0_{ind}\gamma(\gamma^2 - 1)/(\gamma^2 + 1)$. In such fields, the penetration condition (1) for the weak wave ω_2 takes the form

$$\frac{\omega_H}{\omega_2}\cos\phi = \frac{eH_{ind}}{\gamma m \omega_2}\cos\phi = \frac{\gamma^2 - 1}{\gamma^2 + 1}\frac{\omega_1}{\omega_2}\cos\phi > 1. \quad (5)$$

If the wave propagates in the direction of increasing electron density (a typical situation for laser-plasma experiments), then the strong wave reaches only the point determined by Eq. (4), whereas the weak wave should penetrate to higher values of the electron density, because the induced field H_{ind}, like a solenoid field, preserves its intensity over distances $l \lesssim d$, where d is the diameter of the ω_1 wave beam.

Let us estimate now the strong-wave intensity I_1 necessary to realize the considered effect. According to[3], E_1 and I_1 are connected in the nonlinear approximation by the usual relation for plane waves

$$I_1 = cn_1 E_1^2/4\pi, \quad (6)$$

where n_1 is the refractive index. For an inhomogeneous plasma this relation can obviously be used so long as geometric optics holds, i.e., so long as

$$\frac{\lambda_1 |\nabla n_1|}{2\pi n_1^2} \sim \frac{\lambda_1}{4\pi n_1^3 \Delta z} \ll 1, \quad (7)$$

where Δz is the space scale over which the electron density drops from the critical value to zero. In laser experiments we have $\Delta z \sim \min\{d, v_T t\}$, where v_T is the average ion thermal velocity ($\sim 10^8$ cm/sec), and t is the time of exposure of the plasma to the high-power radiation. Condition (7) determines the minimum value $(n_1)_{min}$ at which (6) is still valid. In the plasma region where $(n_1)_{min} \ll 1$, the ratio (ω_p/ω_1) is connected with γ by Eq. (4), and we obtain for this region on the basis of (3), (4), and (6)

$$I_1 = (n_1)_{min}\frac{4\gamma^4(\gamma^2 - 1)}{(\gamma^2 + 1)^2} I_o, \quad (8)$$

where $I_0 = \pi m^2 c^5/e^2\lambda_1^2 \approx 2.7 \times 10^{18}/\lambda_1^2$ (micron)(W/cm^3). Let us estimate the intensity I_1 needed to satisfy conditions (5), when the strong and weak waves are produced by a neodymium and CO_2 laser, respectively ($\omega_1/\omega_2 = 10$). It is necessary here to have $\gamma > \sqrt{11/3} = 1.1$, and we obtain $I_1 > 6.5(n_1)_{min} \times 10^{17}$ W/cm^2. The value of $(n_1)_{min}$, according to (7), depends on the experimental conditions. Putting $\Delta z \approx 10^{-2}$ cm ($t \approx 10^{-10}$ sec, $d \gtrsim 10^{-2}$ cm), we obtain on the basis of (7) $(n_1)_{min} \approx 0.1$ and $I_1 > 6.5 \times 10^{16}$ W/cm^2. It is precisely these intensities that are realized and being planned in future experiments on laser thermonuclear fusion. The weak CO_2-laser radiation can be used here for diagnostics by means of scattering of the superdense nucleus of the plasma target, and also to complete the heating of the nucleus during the last irradiation stage.[1)] The penetration coefficient depends on the angle aperture ϕ_0 of the CO_2 beam that converges on the plasma, and turns out to be not small if (see[1])

$$\phi_o \lesssim \frac{2}{\pi}(1 - \omega_2/\omega_H)^{3/4}(\lambda^2/\Delta z)^{1/2}. \quad (9)$$

At $\Delta z \approx 10^{-2}$ cm and $(\omega_2/\omega_H) = 1/2$ this yields $\phi_1 \lesssim 7°$.

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[1)]The intensity I_2 of the "weak radiation" should only satisfy the condition $I_2 \ll \pi m^2 c^5/e^2\lambda_2^2$, which yields for the case of a CO_2 laser $I_2 \ll 2.3 \times 10^{16}$ W/cm^2.

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