Theory of inverse Faraday effect in an inhomogeneous plasma

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The generation of quasi-steady-state magnetic fields in an inhomogeneous plasma, which is subjected to the influence of circularly polarized electromagnetic radiation, is proved theoretically.

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A great deal of attention has recently been directed to studying the mechanisms for the excitation of spontaneous magnetic fields in a plasma in the field of linearly polarized electromagnetic radiation (see, for example, Ref. 1). The current interest in the formation of strong magnetic fields is due primarily to their controlling influence on the absorption of the pumping wave[2] and on the rate at which the transport processes occur in a plasma.[3]

The generation of quasi-steady-state magnetic fields in an inhomogenous plasma as a result of the influence of a circularly polarized, homogeneous electric field (known in a solid as the inverse Faraday effect[4]) has been explained analytically by us for the first time. It must be noted that the inverse Faraday effect does not exist in a homogeneous plasma, contrary to the erroneous statement made in Ref. 5. The theory developed below is in good agreement with the known experimental results,[6] in particular with those that indicate the absence of a spontaneous magnetic field in a plasma irradiated by a linearly polarized, homogeneous electric wave.

We examine an inhomogeneous electron plasma with a density $n_e(\mathbf{r})$ in a homogeneous high-frequency electric field

$$\mathbf{E}(t) = E_0\{\mathbf{e}_x \cos\omega_0 t + \lambda\mathbf{e}_y \sin\omega_0 t\}. \tag{1}$$

Here E_0 and ω_0 are the amplitude and frequency of the electric field $\mathbf{e}_x$ and $\mathbf{e}_y$ are the unit vectors of the x and y axes, $\lambda = 1$ for right-hand polarization, and $\lambda = -1$ for left-hand polarization. To describe the generation process of quasi-steady-state magnetic fields, we used the system of collisional-hydrodynamics equations of a cold plasma in an HF electric field and the system of Maxwell equations.[1] Thus, the space and time evolution of the magnetic field is described by the following equation:

$$\frac{\partial\mathbf{B}}{\partial t} + \mathrm{rot}\left(\frac{c^2}{4\pi\sigma}\,\mathrm{rot}\,\mathbf{B}\right) = \frac{c}{e}\,\mathrm{rot}\,\mathbf{F}_E + c\,\mathrm{rot}\left(\frac{\mathbf{j}_E}{\sigma}\right), \tag{2}$$

where $\sigma = e_2 n_e/m_e\nu_{\text{eff}}$ is the static conductivity of the plasma, ν_{eff} is the effective frequency of electron collisions, and e and m_e are the charge and mass of the electron. The quantities $\mathbf{F}_E$ and $\mathbf{j}_E$ are, respectively, the radiation-pressure force and the nonlinear current, which are defined by the formulas

$$\mathbf{F}_E = \lambda \frac{m_e}{2} \frac{\nu_{\text{eff}}}{n_e} r_E' V_E \left\{ \mathbf{e}_x \frac{\partial}{\partial y} - \mathbf{e}_y \frac{\partial}{\partial x} \right\} n_e, \qquad (3)$$

$$\mathbf{j}_E = \lambda \frac{e}{2} r_E' V_E \left\{ \mathbf{e}_x \frac{\partial}{\partial y} - \mathbf{e}_y \frac{\partial}{\partial x} \right\} n_e. \qquad (4)$$

In relations (3) and (4) $r_E = eE_0/m_e\omega_0^2$ and $V_E = r_E\omega_0$ are the amplitude and velocity of the electron oscillations in the field (1). It must be noted that Eq. (2) is valid for the conditions

$$\nu_{\text{eff}} \gg \Omega_e,\ \tau^{-1},$$

where $\Omega_e = eB/m_e c$ is the electron cyclotron frequency and τ is the characteristic time of the magnetic-field variation. The steady-state solution of Eq. (2) with allowance for Eqs. (3) and (4) for the condition $n_e = n_e(x, y)$ has the form

$$\mathbf{B}(x, y) = \lambda \frac{4\pi e}{c} r_E' V_E n_e(x, y) \mathbf{e}_z. \qquad (5)$$

We note that the produced magnetic field, as in the experiment,[6] is directed perpendicularly to the polarization plane of the external radiation and reverses its direction with the reversal of the rotation direction of the electric-field intensity vector. The magnetic field is not excited for linear polarization of the external radiation [$\lambda = 0$ in Eq. (1)]. We point out that the sources of magnetic-field generation (3) and (4) vanish in a homogeneous plasma; this corresponds to a mutual compensation of the circular electron currents, which also occurs in the case of plane, circularly polarized, electromagnetic radiation. The numerical estimate of the magnetic field $B \sim 0.5 \times 10^{-2}$ G in a laboratory plasma, which follows from Eq. (5), is in quantitative agreement with the results of Ref. 6.

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