# Self-excitation of magnetic fields in a laser plasma

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It is shown that the generation of spontaneous magnetic fields when plasma waves are resonantly excited by intense electromagnetic radiation takes the form of a magnetic plasma instability that manifests itself in an exponentially rapid self-excitation of the magnetic field.

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Recently, in connection with experiments on laser-mediated thermonuclear fusion, interest has greatly increased in the generation of spontaneous magnetic fields in a plasma acted upon by high-power electromagnetic radiation. This interest is due primarily to the fact that the resultant strong magnetic field can greatly influence the character of the penetration of the light into the plasma and the rate at which transport phenomena take place in the plasma.

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The question of generation of spontaneous magnetic fields in a plasma irradiated by an electromagnetic field was first investigated in Refs. 1 and 2. At the present time the most extensively discussed are two causes of magnetic-field generation, namely thermoelectric power[3] and the presence of a $p$ component of the electric field in the laser radiation,[4] which lead to the presence of a field-generation source that acts constantly in time.

In the present communication we call attention to the possibility of an exponentially rapid self-excitation of the magnetic field as a result of the instability of a plasma situated in an electromagnetic-radiation field. We point out that the onset of a magnetic field was considered, from the point of view of instability development in a plasma, in Refs. 5 and 6 for the case when the source is of the thermoelectric current type, and in Ref. 7 for a turbulent plasma.

Consider a plasma situated in the field of an electromagnetic pumping wave $\widetilde{\mathbf{E}}_0(\mathbf{r},t) = \frac{1}{2}[\mathbf{E}_0(\mathbf{r},t)\exp(-i\omega_0 t) + \text{c.c.}]$ of frequency $\omega_0$. This field produces in the plasma rapidly alternating variations of the electron density $\tilde{n}_E$ and of the velocity $\tilde{\mathbf{v}}_E$ at the frequency $\omega_0$. If $\Omega_e \ll \omega_0$ ($\Omega_e$ is the gyrofrequency of the electrons), their amplitudes $n_E$ and $\mathbf{v}_E$ are connected with the amplitude $\mathbf{E}_0$ of the pump wave by the following equations of motion and continuity

$$\mathbf{v}_E = i\frac{e}{m\omega_0}\mathbf{E}_0 , \quad i\omega_0 n_E = \operatorname{div} n_e \mathbf{v}_E . \tag{1}$$

Here $e$, $m$, and $n_e$ are the charge, mass, and density of the electrons. The presence of rapidly alternating components of the electron density and velocity leads to the onset of a slowly varying (within the period of the oscillations of the pump wave) nonlinear current

$$\mathbf{j}_E = e\langle \tilde{n}_E \tilde{\mathbf{v}}_E \rangle = \frac{e}{2}\operatorname{Re}(n_E \mathbf{v}_E^*), \tag{2}$$

where the angle brackets denote averaging over the period of the field $\widetilde{\mathbf{E}}_0$.

Inclusion of the nonlinear field (2) in Maxwell's equations for slowly-varying fields yields the following equation for the magnetic field generated in the plasma

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{c}{\sigma}\operatorname{rot}\mathbf{j}_E . \tag{3}$$

Here $\sigma = e^2 n_e/m\nu_{ei}$ is the electric conductivity of the plasma, $\nu_{ei}$ is the electron–ion collision frequency, $c$ is the speed of light, and the density of the nonlinear current can, according to (1) and (2), be written in the form

$$\mathbf{j}_E = \frac{e}{2\omega_0}\operatorname{Im}(\mathbf{v}_E^* \operatorname{div} n_e \mathbf{v}_E). \tag{4}$$

To obtain a closed system of equations, relation (3) must be supplemented by an equation for $\mathbf{E}_0$. This can be the well known (see, e.g., Ref. 8) equation for the amplitude of a high-frequency field in a plasma in the presence of a magnetic field $\mathbf{B}$.

Assume for simplicity that the plasma density $n_e$ depends only on the coordinate $x$. The "$x$" axis is chosen to coincide with the direction of propagation of the pump wave, which will be assumed in vacuum to be $x$-polarized in a direction coinciding with the "$y$" axis. We then have for the magnetic-field component $B_z$

$$\frac{\partial B_z}{\partial t} = \frac{e}{2m}\frac{c\,\nu_{ei}}{\omega_0^3\,\omega_{Le}^2}\operatorname{Im}\left(\frac{\partial}{\partial X}E_{oy}^*\frac{\partial}{\partial X}\omega_{Le}^2 E_{ox}\right), \tag{5}$$

where $\omega_{Le}$ is the electron Langmuir frequency.

The $E_{0x}$ component of the electric pump field ($p$ component) in (5) is produced in turn in an inhomogeneous plasma because of the magnetic field and is connected with the $E_{0y}$ component by the relation

$$\frac{E_{0x}}{E_{0y}} = -i\frac{\Omega_e}{\omega_0}\frac{\omega_{Le}^2}{\omega_0^2 - \omega_{Le}^2 - \Omega_e^2 + i\nu_{\text{eff}}\omega_0}. \tag{6}$$

According to (6), the $p$ component of the field is most effectively excited in the density region where $\omega_0^2 \approx \omega_{Le}^2 + \Omega_e^2$, and corresponds to the onset of upper-hybrid oscillations. The quantity $\nu_{\text{eff}}$ characterizes the maximum possible value of $E_{0x}$ in the region of the plasma resonance. Since the right-hand side of (5) depends on the magnetic field, the onset of the latter has the character of self-excitation and is accompanied by an exponential growth of the initial perturbations. We note that a formula similar to (5) was obtained in Ref. 4. It was assumed here that the components of the field $E_{0x}$ and $E_{0y}$ are constant quantities, which are determined by the polarization of the pump wave in vacuum and do not depend on the magnetic field intensity. The generation of the magnetic field in this case was due to the presence of a constant source in the right-hand side of (5) and was not of instability type.

From formula (5) we obtain for the characteristic growth time $t \sim \gamma^{-1}$ of the magnetic field ($\lambda\!\!\!^{-}_0 = c/\omega_0$)

$$\gamma \sim \frac{q_0}{q_c}\left(\frac{\lambda\!\!\!^{-}_0}{L}\right)\left(\frac{\omega_0}{\nu_{\text{eff}}}\right)^3 \nu_{ei}, \tag{7}$$

where $q_0$ is the pump energy flux density in vacuum, $L$ is the characteristic dimension of the plasma density inhomogeneity, $q_c = n_e mc^3 \approx 3\times 10^{17}\lambda_0^{-2}$ W/cm$^2$ ($\lambda\!\!\!^{-}_0$ is in $\mu$m). For example, if the limitation of the amplitude of $p$ component of the field in the region of the plasma resonance is imposed by outflow of the waves, the quantity $\nu_{\text{eff}}$ turns out to be $\nu_{\text{eff}} = (v_{Te}^2\omega_0/L^2)^{1/3}$, where $v_{Te}$ is the thermal velocity of the electrons. In this situation we obtain for $\gamma$

$$\gamma \sim \frac{q_0}{q_c}\left(\frac{L}{\lambda\!\!\!^{-}_0}\right)^{1/3}\left(\frac{c}{v_{Te}}\right)^2 \nu_{ei}. \tag{8}$$

It follows from (8) that under typical laser-plasma conditions, effective generation of magnetic fields is possible during the time of action of the pulse. For example, at $T_e \sim 1$ keV, $L \sim 10\ \mu$m, $q_0 \sim 10^{15}$ W/cm$^2$, and $\lambda\!\!\!^{-}_0 = (1/2\pi)\ \mu$m we get from (8) a magnetic-field characteristic growth time is $\sim 10^{-11}$ sec. We note also that this time is comparable with the characteristic time $\nu_{ei}Ll/v_{Te}^2$ ($l$ is the characteristic dimension of the plasma inhomogeneity and under typical laser-plasma conditions $l \gg L$) of the development of the magnetic-thermal instability.[5]

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