Generation of a quasi-static magnetic field in a plasma by a high-intensity electromagnetic wave

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The appearance of a quasi-static magnetic field as a result of interaction of a high-intensity electromagnetic wave with a plasma is studied experimentally. It is shown that the magnetic field is produced by a flux of electrons accelerated by an rf field.

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1. The appearance of a quasi-static magnetic field (QMF) as a result of interaction of high-intensity radiation with a plasma was first observed in experiments using a laser controlled thermonuclear fusion system.[1,2] Similar experiments, which were performed in the microwave range, made it possible to investigate the QMF and its dependence on the radiation power.[3,4] The known[5] mechanisms of QMF generation—electron entrainment due to momentum transfer by electrons from the electromagnetic wave as a result of its absorption in the plasma, and the excitation of a current because of the nonparallel orientation of ∇n and ∇T_e—were used in these investigations to explain the experimental results.

Our experiments were initiated by studies in which a high-intensity nonisotropic flux of accelerated electrons with a preferential direction of acceleration along the electric field of an incident wave was observed.[6,7] The geometry of the current in the plasma was such that the magnetic field excited by it had a configuration corresponding to the field distribution measured in Ref. 4.

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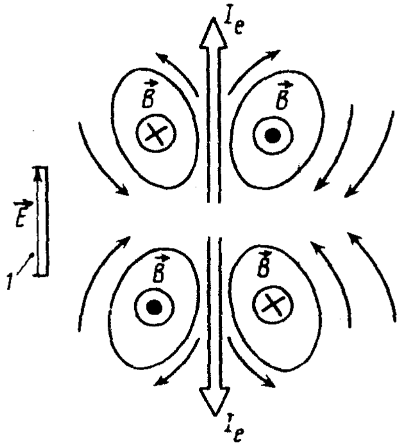

FIG. 1. Configuration of generated magnetic field and currents in plasma (1, emitter).

2. The experiments were performed using an apparatus that was described in detail in Ref. 6. We shall briefly review its basic characteristics: a plasma layer with a diameter of 50 cm and a thickness of 30 cm was formed inside a vacuum chamber in which a pressure of 3×10^{-4} Torr was maintained. The plasma density at the center of the layer reached a value $n = 1.5\ n_c$ (n_c is the critical density). The temperature T_e of electrons in the plasma was equal to 10 eV and that of the ions was equal to 0.5 eV. A 10-cm-band electromagnetic wave was emitted from the open end of a waveguide with dimensions $(1.5\times1.5)\lambda_0$ (λ_0 is the length of the microwave in a vacuum), which was located on the axis of the plasma layer 20-cm from its center. The duration of the radiation pluse was $\tau_i = 10\ \mu$sec. The controlled radiation power made it possible to perform experiments using the parameter $\eta = E_0^2/8\pi n T_e$ (E_0 is the field in the absence of the plasma) in the range of 10^{-3} to 7.5×10^{-1}. The QMF was measured using a 180-turn, 2-cm-diam shielded coil. The accelerated electron flux was studied using a collimated electrostatic analyzer. The current in the plasma was measured by a Rogowski loop.

3. The measurements showed that the magnetic field had an octupole structure similar to that obtained in Refs. 3, 4. The field geometry is shown schematically in Fig. 1. Figure 2a shows the dependence of the magnetic field on the parameter η. As seen from the graph, the three characteristic regions can be easily identified on the curve. At sufficiently small values of η, $\eta < \eta_c \approx 10^{-2}$ the dependence $B(\eta)$ is $\sim\eta^{1/2}$. At $\eta_c < \eta < \eta_H B(\eta)$ is proportional to η and then begins to saturate at $\eta > \eta_H$. We also found that the field maximum begins to move to the region of higher plasma densities in the region of η corresponding to the linear dependence of the magnetic field $B(\eta)$ (Fig. 2b).

At the same time we studied the QMF generation, we measured the flux of electrons accelerated in the direction of the field of an incident wave. The dependence of this flux on the parameter η is shown in Fig. 2a. A simultaneous analysis of both curves showed that a definite relationship exists between the electron flux and the QMF generated at radiation power corresponding to the parameter $\eta > \eta_c$. This is

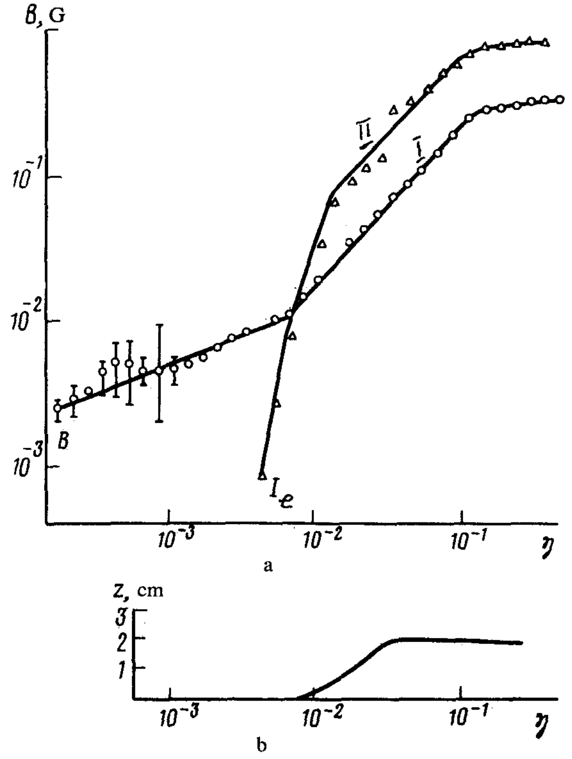

FIG. 2. (a) I, Dependence of the magnetic field on η; II, dependence of the accelerated electron flux on η (normalized to $I_e^{\max}$); (b) dependence on η of the coordinate for the location of the magnetic-field maximum.

indicated by the following facts. First, the threshold of the accelerated electrons[1)] coincides with the first break in the $B(\eta)$ dependence at $\eta = \eta_c$. Second, the dependence of the accelerated electron flux for $\eta_c < \eta < \eta_H$ has the same linear character as $B(\eta)$. Third, at $\eta > \eta_H$ the accelerated electron flux like the QMF, is saturated. Fourth, there is a definite time correlation between the magnitude of the accelerated electron flux and the QMF intensity (Fig. 3).

The measured flux values make it possible to approximately estimate the induced QMF. For $\eta = 2.8 \times 10^{-1}$ the current measured by a Rogowski loop (with a diameter $D = 5$ cm) was $I_e = 2.8$ A. We can easily estimate the generated QMF from this current $B \sim 4\, I_e/cD = 0.22$ G, in satisfactory agreement with the experimental value of $B = 0.35$ G.

4. The flux of fast electrons can be explained as follows. If the threshold of the modulation instability $\eta > v/\omega$ is exceeded, then a small-scale stratification of the plasma will occur along the rf electric field and the electrons will be accelerated by the produced structure in the vicinity of the critical layer $n = n_c$.

We should mention that the magnetic field was present before the appearance of fast electrons flux. The mechanism of its generation at low power levels can be ex-

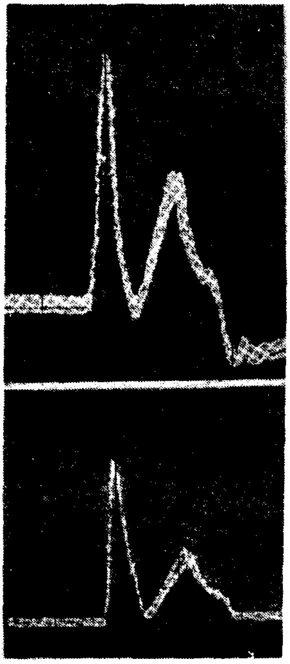

FIG. 3. Oscillograms of the magnetic field and of the current from the electrostatic analyzer, obtained during one electromagnetic radiation pulse.

plained by the entrainment current $j_{e\ \mathrm{ent}} = e\langle n\mathrm{V}\rangle$ (the thermo emf mechanism $\nabla n \times \nabla T_e$ in this case is not important because of the small temperature-redistribution time).

In conclusion, we note that the QMF generation in a laser plasma may also be due to a flux of accelerated electrons produced as a result of a parametric instability. For a crude estimate of the QMF we assume that the electrons in the field of an s-polarized wave are accelerated in the direction of the electric field of the wave in a layer of thickness $d = 3\,l\,(k_0 l)^{-2/3}$ (d is the width of the first maximum of the Airy function and l is the characteristic scale of plasma inhomogeneity). If the density of accelerated electrons is equal to a few percent of the unperturbed density $n_g = (0.01$–$0.03)n_0$ (for a neodymium laser $n_0 = 10^{21}$ cm^{-3}) and their energy is $W_g = 10$ keV, then we can obtain the values that fit the magnetic fields measured experimentally $B \sim 10^6$ G by estimating the QMF from the formula $B = 2\pi e n_g v_g / c \cdot \mathrm{d}$.

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[1)] The electrons with energies $W_1 > 30$ eV were recorded in the experiments.

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