Structure of spontaneous magnetic field in a laser plasma

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We investigated experimentally the spontaneous magnetic fields produced when a powerful laser beam interacts with a metallic target. It was observed that the signal consists of two components, fast ($\dot{B}_1$) and slow ($\dot{B}_2$). It was established that $\dot{B}_1$ is due to electron emission. The mechanism that produces $\dot{B}_2$ is governed by the interaction of the expanding plasma with the residual gas.

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The important role played by magnetic fields in laser plasma is by now universally recognized. However, notwithstanding the large number of papers published after the first report of registration of the spontaneous magnetic field[1] (see, e.g., [2–6] no final conclusion can be drawn concerning the mechanisms of this phenomenon. At present, at least four possible mechanisms for the generation of the spontaneous magnetic field can be proposed: 1) the flux of charged particles emitted from the plasma; 2) the charge separation produced when the plasma interacts with the residual gas; 3) the thermoelectric power produced when ∇T is not parallel to ∇n in the plasma; 4) the pressure of the light.

The purpose of the present paper was to ascertain the mechanisms whereby spontaneous magnetic fields are generated at laser-radiation densities 5×10^{11}

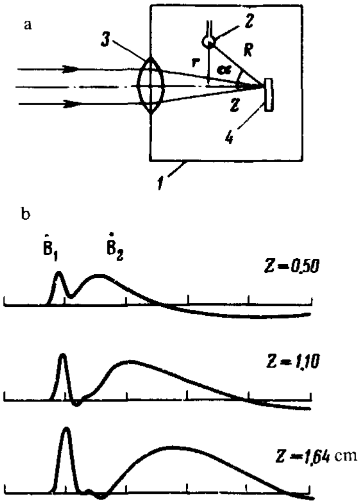

FIG. 1. a) Experimental setup: 1—vacuum chamber, 2—magnetic pickup, 3—focusing lens, 4—target. b) Oscillograms of pickup signal for three different positions along the z axis, at a fixed residual gas pressure 0.1 Torr. The time scale is 100 nsec per division.

W/cm^2. We used a neodymium-glass laser operating in one axial mode and one angle mode TEM$_{00}$. The output energy reached 2 J at a pulse duration 30 nsec. The radiation was focused into a vacuum chamber by a lens of $f = 24$ cm. We used metallic targets (iron, copper, and aluminum) electrically connected to the vacuum chamber. The derivative $\dot{B}$ of the magnetic field was measured with a pickup constituting a coil of 2.5 mm diameter. The signal from the pickup was fed to a type S1-11 oscilloscope. The time constant of the entire registration system was 3.5 nsec. The construction of the vacuum chamber was such that the pickup could be moved relative to the plasma in the r and z directions (see Fig. 1a) and rotated through any angle about an axis passing through its diameter. The criterion establishing the magnetic nature of the signal was the reversal of its polarity following 180° rotation of the pickup, and also the vanishing of the total integral of the signal. At a residual gas pressure P in the range 10^{-1}—10^{-4} Torr and at a distance $R \geqslant 0.5$ cm between the center of the pickup and the focal spot, two components of the $\dot{B}$ signal are clearly seen. Typical oscillograms for the different positions of the pickup are shown in Fig. 1b. The signal components $\dot{B}_1$ and $\dot{B}_2$ differ in character. We note first that they depend in different manners on the residual-gas pressure in the chamber (see Fig. 2). Thus, when the pressure changes from 10^{-4} to 10^{-2} Torr, $\dot{B}_1$ increases threefold whereas $\dot{B}_2$ increases by more than two orders

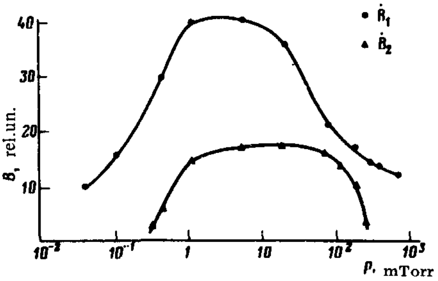

FIG. 2. Dependence of the signals $\dot{B}_1$ and $\dot{B}_2$ on the residual-gas pressure.

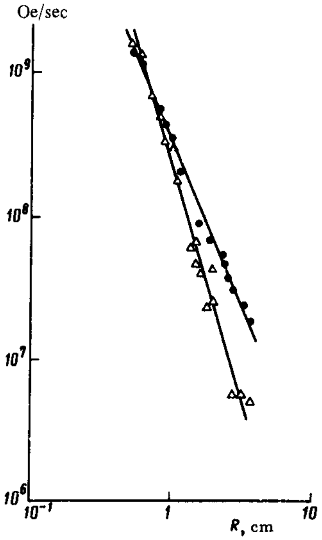

FIG. 3. Spatial dependences of the signals. Experimental points: triangles—$\dot{B}_2$; circles—$\dot{B}_1/\sin\alpha$. Extrapolation: $\dot{B}_2 \sim R^{-3.2\pm0.15}$; $\dot{B}_1/\sin\alpha \sim R^{-2.2\pm0.1}$.

of magnitude. With further increase of pressure, $\dot{B}_1$ decreases slowly (by a factor of three at 1 Torr), while $\dot{B}_2$ vanishes at 0.3 Torr. At a pressure less than 10^{-4} Torr, only $\dot{B}_1$ exists. It follows therefore that the principal mechanism responsible for the appearance of $\dot{B}_2$ is the interaction of the expanding plasma with the residual gas. The most probable is the onset of a dipole as a result of charge separation on the front of the expanding plasma. The observed polarity of the signal shows that the electrons are in the lead, as they should be in the case of ambipolar diffusion. The $\dot{B}_2$ component is delayed relative to $\dot{B}_1$ by a time t depends on the pickup position (see Fig. 1b). The value $z/t = 1.2\times10^7$ cm/sec is in satisfactory agreement with the average rate of expansion of the laser plasma (see e.g., [7]). It should be noted that the pressure dependence was measured with the pickup in a fixed position at $r = 1.0$ cm and $z = 1.5$ cm.

As to the component $\dot{B}_1$, the principal mechanism responsible for its appearance is electron emission from the laser plasma. We note above all that the $\dot{B}_1$ pulse duration, which is 30 nsec at half-height, agrees well with the duration of the laser pulse and does not depend on the pickup position; the amplitude of $\dot{B}_1$ is satisfactorily described by the Biot-Savart law, as it should be in the case of a current element. The measured dependence is of the form $\dot{B}_1 \sim \sin\alpha/R^{2.2}$ (see Fig. 3). In addition, the experiments have shown that in the case of a dielectric target or in the case of a sufficiently small metallic target insulated from the walls of the vacuum chamber, the former component decreases by at least a factor of 100. An explanation of this fact is the onset of a strong space charge that retains the electrons near the focal region. The polarity of the signal $\dot{B}_1$ confirms that it is precisely the electrons which are emitted. (The component $\dot{B}_2$ was not investigated in detail for dielectric or small metallic targets).

The magnetic field, B_1 as well as B_2, has cylindrical symmetry with respect to the laser-beam axis. The magnetic-field vector lies in a plane perpendicular to this axis. In our experiment we did not register magnetic-field components parallel to the beam axis. The maximum field intensity registered in our experiment is 100 Oe at a distance 5 mm from the focal region.

We note that direct extrapolation of the results to the dimensions of the focal spot could yield fields on the order of 10^6 Oe. Such an extrapolation, in our opinion, can be carried out only up to the boundaries of the region occupied by the plasma for B_2 and up to the boundaries of the electron cloud for B_1, which in our conditions are much larger than the dimensions of the focal spot. It appears that the largest magnetic fields in our experiment were several kilooersteds.

It can thus be stated that at flux densities 5×10^{11} W/cm^2 the principal mechanisms whereby spontaneous magnetic fields are generated in a laser plasma are the emission of electrons and the separation of the charges at the boundary of the expanding plasma.

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