Spontaneous magnetic fields with dipole structure in a laser plasma

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We identified a magnetic moment that occurs in a laser plasma during the interaction of laser radiation with matter in the case when axial symmetry in the distribution of n and T gradients is disturbed.[1)]

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The proposed mechanism for the generation of spontaneous magnetic fields (SMF)[1,2] is associated with a lack of parallelism between the n and T gradients which occurs in a plasma in a region of the focal spot at the onset of the laser action. Under the traditional formulation of an experiment involving a magnetic pickup, direct registration of such fields is impossible since in the axisymmetric case SMF should be characterized by a closed toroidal configuration and the pickup must be placed directly in a region where laser radiation interacts with matter. In view of this, magnetic pickups were used extensively[3–6] to register SMF away from the focal spot after extinction of the laser pulse (or at an instant close to termination). It was concluded[5,6] that the observed fields are directly related to SMF that are generated directly in the focal region and which depend on the diffusion of SMF in the residual-gas plasma and convection with the scattering laser plasma. As we see it, this conclusion is far from unique since, on the one hand, SMF generated in the focal region should rapidly attenuate upon termination of the laser pulse due to Joule losses[7] and, on the other hand, generation of the magnetic field in a scattering plasma also occurs after termination of the laser pulse.[8–13] However, if the axial symmetry of n and T gradient distribution is upset, the corresponding perturbation of the toroidal symmetric distribution of closed-loop currents in the focal region (which occur as a result of lack of parallelism of the n and T gradients) should lead to the formation of "non-compensated" current loop and the occurrence of a magnetic moment whose field may be also recorded outside the plasma region. In this work, we describe detection of such a field. Figure 1(a) shows a diagram of the experimental setup. A 20-nsec (FWHA) 1–3-J laser (TEM$_{00}$, $\lambda = 1.06\ \mu$m) was focused in a vacuum chamber on a target by means of an $f = 25$-cm lens. A magnetic pickup[14] was placed near the target emitting a signal proportional to $2B/\partial t$ which was recorded by a C1–11 oscillograph. The pickup could be moved at will along r and z both in front of ($z > 0$) and behind ($z < 0$) the target, and it could be rotated around the axis through the pickup coil diameter (coil diameter was 1 mm). Rotation of the pickup by 180° caused the observed signal to change polarity which attested to its magnetic nature.

Above all we should note that the magnitude of SMF is strongly attenuated in the region behind the target ($z < 0$) when the latter is axisymmetrically illuminated. Thus, at $P = 10^{-4}$ tor and a power density at the target 2×10^{12} W/cm^2 the SMF attained 10^3

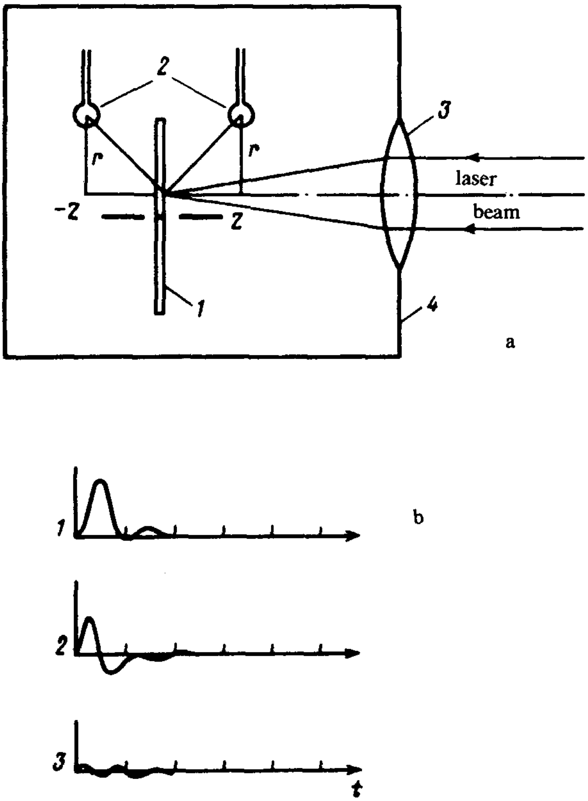

FIG. 1. (a) 1—dielectric target (disc, 30 mm in diameter and 1 mm thick); 2—magnetic pickups; 3—focusing lens; 4—vacuum chamber. (b) 1—laser pulse; signal behind dielectric target ($z < 0$) for nonsymmetric (2) and symmetric (3) illumination. Sensitivity, 0.12 V/cm. Scale, t—50 nsec.

gauss at a point with coordinates $r = 1.3$ mm and $z = 1.3$ mm. At a point with symmetrical coordinates ($r = 1.3$ mm and $r = -1.3$ mm), the SMF amplitude was more than 2×10^3-fold smaller; moreover, it was verified that the experimental targets failed to impede transmission of the electromagnetic radiation in a spectral region characteristic for SMF. A strong field decrease at $z < 0$ indicates that the toroidal SMF configuration is closed with a high degree of accuracy. This condition provides a means for observing a comparatively weak dipole field behind the target that is symmetrically illuminated (see Fig. 1b).[2] Asymmetric illumination was produced in three ways. In one case, a composite target was used which consisted of two variable–density dielectrics (vinyl-teflon) (Fig. 2). Target preparation technique was such that the gap between dielectrics was eliminated. Laser radiation through the precise lens center was focused at 90° to the plane surface of the composite target at a distance Δ from a boundary between the two dielectrics. The magnetic pickup was placed behind the target. Figure 2 shows the dependence of the maximum signal amplitude recorded by the pickup on the displacement Δ. The distribution halfwidth obtained in this manner is 50 μm which is below the value of radial density distribution halfwidth in the focal

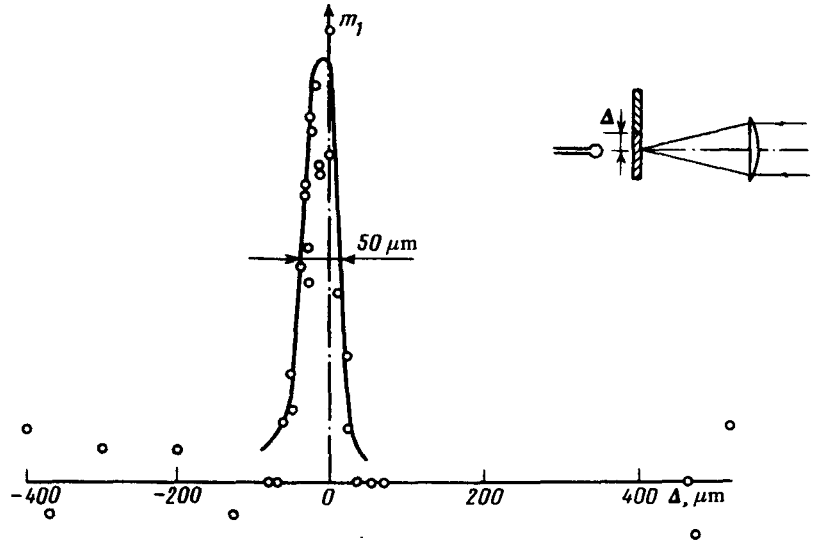

FIG. 2. Dependence of m_1 in arbitary units on distance Δ between focal spot center and dielectric boundary.

region. These measurements lead to the conclusion that the observed moment $\mathbf{m}_1$ occurs at the boundary between dielectrics and is confined to a region where the radiation interacts with a spatially-nonhomogeneous plasma. The resultant magnetic moment is parallel to the vector $[\boldsymbol{\rho}_1, k]$, where k is the wavevector of the incident radiation and $\boldsymbol{\rho}_1$ is a vector in the target plane which is directed perpendicularly to the boundary from the target with lower density to high density. When the positions of target dielectrics are switched, the magnetic moment changes its sign. The value of $\mathbf{m}_1$ is 0.1 CGS for a laser power density of 5×10^{11} W/cm^2. It should be noted that the occurrence of a strong magnetic field in a plasma was considered theoretically for the case where laser radiation was focused on a composite target[15]; this study was based on the mechanism of SMF generation due to the nonparallelism of the n and T gradients. The field direction predicted in Ref. 15 coincides with the direction of the magnetic moment recorded in our work.

Secondly, the axisymmetric distribution of the n and T gradients could be achieved by oblique illumination of a plane homogeneous target by laser radiation[3] (see Fig. 3). Measurements of the spatial SMF distribution behind the target at the incidence angle $\beta \neq 0$ showed that the magnetic moment $\mathbf{m}_2$ is localized in the focal spot region and is directed along the vector $[k, \boldsymbol{\rho}_2]$, where $\boldsymbol{\rho}_2$ is a vector of a normal to the target drawn from the focal spot toward the focusing lens. It can be readily seen that the direction of the magnetic moment $\mathbf{m}_2$ is in opposition to the direction that could occur under these conditions as a result of flow of closed-loop currents due to light pressure. Measurements showed that as β increases, the magnetic moment intensifies continuously and attains a maximum at $\beta = 45°$ (see Fig. 3). It should also be noted that $\mathbf{m}_2$ is independent of the aximuth angle α of the polarization plane of laser radiation: $\alpha = 0$ (s-polarization), $\alpha = 45°$ and $\alpha = 90°$ (p-polarization). Independence

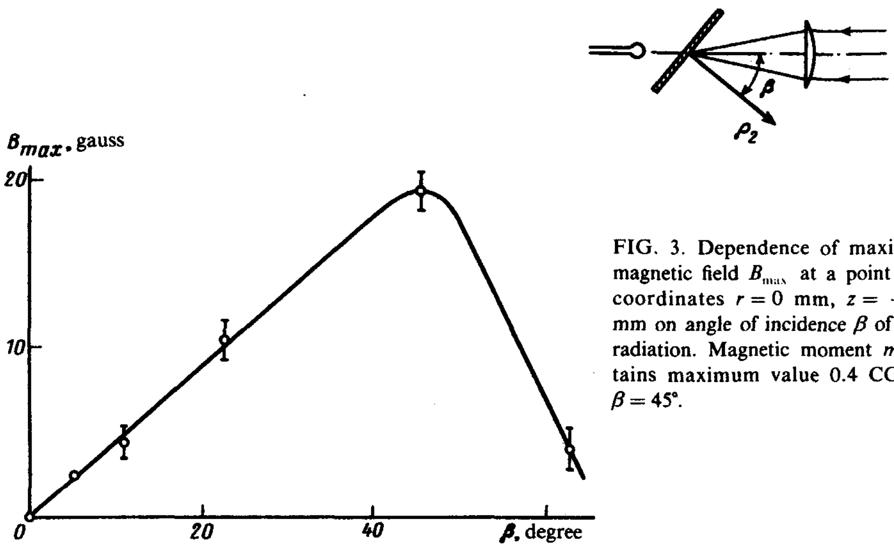

FIG. 3. Dependence of maximum magnetic field B_{max} at a point with coordinates $r = 0$ mm, $z = -2.8$ mm on angle of incidence β of laser radiation. Magnetic moment m_2 attains maximum value 0.4 CGS at $\beta = 45°$.

of $\mathbf{m}_2$ from α leads to the conclusion that in these experiments the contribution of resonant absorption of plane-polarized radiation[17] to SMF generation is insignificant.

Another mechanism for disturbing the axisymmetric distribution of the n and T gradients in a laser plasma is the occurrence of abberations that lead to perturbation of the axisymmetric distribution of laser radiation intensity in the focal region. Measurements showed that beam displacement from the lens center gives rise to a coma and the occurrence of the magnitude moment $\mathbf{m}_3$ which is directed along the vector $[k, \boldsymbol{\rho}_3]$, where $\boldsymbol{\rho}_3$ is a vector that originates at the lens center and terminates on the beam axis. A 5-mm displacement results in the value of $\mathbf{m}_3 = 0.03$–0.04 CGS.

It should be noted that the moments, $\mathbf{m}_1$, $\mathbf{m}_2$, $\mathbf{m}_3$ are practically independent of residual-gas pressure. Thus, when the pressure changes from 10^{-4} to 15 tor, the moments vary by not more than 20–30%. Furthermore, $\mathbf{m}_1$, $\mathbf{m}_2$ and $\mathbf{m}_3$ occur simultaneously with the arrival of the laser pulse at a target. We believe, that the mechanism for the occurrence of the observed moments is identical in all three cases and is associated with perturbation of the axisymmetric distribution of the n and T gradients in a laser plasma, which leads to a distortion of the toroidally-symmetric configuration of closed-loop currents and the occurrence of an "uncompensated" current loop that produces dipole radiation.

In conclusion, based on the experimental results for a composite target, we shall evaluate the strength of the magnetic fields in a region where the magnetic moment $\mathbf{m}_1$ is localized. As is known, the magnetic field at the center of a rectangular frame (with sides a and b) with a current is expressed by $B = 8m(a^2 + b^2)^{1/2}/(ab)^2$, where m is the magnetic moment of a frame. In the case of a composite target, the overall width of localization is 100 μm. If the length b is ~ 300 μm, a dimension approximately corresponding to to the length of a laser plasma, we get $B \sim 3 \times 10^5$ gauss.

[1)] Results of this work were presented at the 12th European Conference on the Interaction of Laser Radiation with Matter, Moscow, 1970.

[2)] It should be noted that placing a pickup behind a dielectric target is also effective in other experiments, where SMF recorded by a pickup at $z > 0$ are noise. Examples of this are observation of the diamagnetic effect, the magnetic moment in a plasma during absorption of circularly-polarized radiation (inverse Faraday effect), etc.

[3)] It should be noted that oblique incidence on a target was assumed in Ref. 16 where the observed SMF were explained as a result of light pressure effect.

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