# Detection of spontaneous magnetic fields in a laser plasma in the Del'fin-1 device

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(Submitted 13 January 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 4, 173–176 (25 February 1987)

Spontaneous magnetic fields have been detected during multibeam bombardment of shell targets at power densities $\sim 8\times 10^{13}$ W/cm$^2$. These fields were detected from the Faraday rotation of the polarization plane of a probing beam at the doubled frequency, $2\omega_0 = 353$ nm. The faradaygrams found provide evidence of a complex field structure under these experimental conditions.

In this letter we are reporting the first detection of spontaneous magnetic fields in a laser plasma in the Del'fin-1 device. We will offer an interpretation of the results. The output from a neodymium laser in six composite beams, each consisting of 18 beams, with a total energy $\sim 1$ kJ, a power density $\sim 8\times 10^{13}$ W/cm$^2$, and a pulse

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length $\sim 5$ ns, is focused on a target. The target is a spherical glass shell $2R_0 = 400$–$600\ \mu m$ in diameter with a wall thickness $\Delta R_0 = 1$–$3\ \mu m$. The spontaneous magnetic fields are measured by making use of the Faraday rotation of the polarization plane of a probing beam.[1,2] A diagnostic complex assembled for this purpose includes a stand for producing probing beams at the frequencies $2\omega_0$ and $3\omega_0$ and polarimetric, shadow, and interferometric detection channels. This complex makes it possible to measure the rotation angle of the probing beam with spatial resolution over the target and the plasma density profile. This information is required for reconstructing the strength of the spontaneous magnetic fields.

The "faradaygrams" of the plasma recorded in completely crossed polarizers demonstrate that the magnetic fields in the spherical targets have a complex structure during multibeam bombardment. On one of the faradaygrams (for a target with $2R_0 = 410\ \mu m$ and $\Delta R_0 = 1\ \mu m$) the angle through which the polarization plane rotates descreases from $1°$ at the density $n_e = 10^{20}\ cm^{-3}$ to the smallest value that can be measured, $12'$ (this sensitivity is set by the polarizer contrast $\sim 10^{-5}$), at a distance $\sim 800\ \mu m$ from the center of the target (Fig. 1). In addition to the large-scale changes in teh rotation angle, there is also a small-scale structure of size $\sim 100\ \mu m$ on the faradaygrams. The faradaygram in Fig. 1 was obtained during probing of the plasma at the frequency $2\omega_0$, so that the bright inner region, corresponding to the initial size of the target, is due to the intrinsic emission from the plasma at twice the laser frequency. This emission arises near the critical surface, with the density $n_e \sim 10^{21}\ cm^{-3}$, as a result of a linear conversion of the laser light into plasma waves.

Calculations show that the primary mechanism for the generation of a magnetic field under these experimental conditions is the mechanism involving the thermal emf,

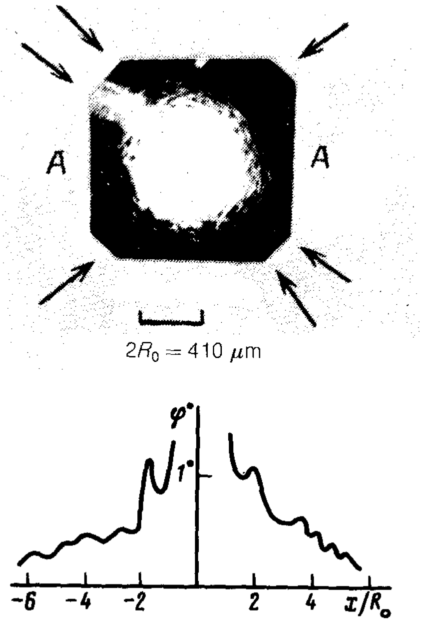


FIG. 1. Faradaygram and plot of the rotation angle of the polarization plane of the probing beam along the coordinate $x/R_0$ corresponding to a diametric cross section of the faradaygram (A–A). The arrows show the directions of the constituent heating beams.

which is driven by noncollinear gradients of the temperature and density of the plasma. The density gradient $\hat{\nabla} n_e$ is directed along the target radius, while the temperature gradient $\hat{\nabla} T_e$ is directed along the target surface. Temperature variations are determined by the nonuniformity of the illumination during the multibeam heating of the target. Over times shorter than the laser pulse, a quasisteady magnetic field is established. This field is determined by the equation (we are assuming that Joule heating is the primary relaxation mechanism, and we are ignoring the removal of field along with the plasma)[3]

$$\Delta \mathbf{B} = -\frac{4\pi\sigma}{ce}[\nabla T_e \times \nabla \ln n_e] \,. \tag{1}$$

Here $\sigma$ is the conductivity, $\mathbf{B}$ is the magnetic induction, and $e$ is the electron charge. In the case with $\hat{\nabla} \ln n_e \| \mathbf{r}$, and $T_e = T(\theta,\varphi)$, the magnetic field has only the components $B_\theta$ and $B_\varphi$ (Fig. 2). Since the temperature distribution in the corona is an alternation of maxima and minima, associated with the multibeam nature of the illumination, the magnetic field alternates in sign along the surface of the corona, as can be seen from (1). This circumstance can apparently explain the small-scale structure on the experimental faradaygrams, which indicates a substantial change in the magnetic field over a distance $\sim 100\,\mu$m. The resultant rotation of the polarization plane of a probing laser beam sent through the corona due to the Faraday effect may be simply zero, if there is an even number of spatial modes of the field along the beam path. The effects of fields of different signs on the beam cancel each other out. In the case of an odd number of modes, the effective rotation angle of the polarization plane is acquired along a path length $y$, equal to the scale of the change in the sign of the field, i.e., equal to the scale of the spatial variations in the illumination, which is $\sim 100\,\mu$m, according to both experiments and numerical calculations.[4] Adopting these assumptions and substituting the measured value of the largest rotation angle of the polarization plane of the probing beam, $\alpha \sim 1°$, and densities $n_e \sim 10^{20}$ cm$^{-3}$ into the well-known formula for the Faraday effect,

$$B[\mathrm{G}] = \frac{2m_e c^2}{e} \frac{n_c}{n_e} \frac{\alpha[\mathrm{rad}]}{Y[\mathrm{cm}]} \,, \tag{2}$$

we find the average magnetic field to be $\sim 60$ kG. This figure can apparently be

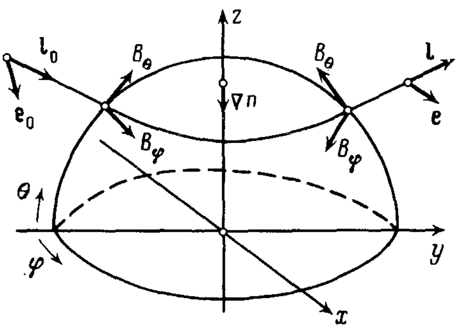


FIG. 2. Qualitative diagram of the propagation of an electromagnetic wave through a spherical plasma corona in which a magnetic field $\mathbf{B} = (0, B_\theta, B_\varphi)$ has been produced by the thermal-emf mechanism.

regarded as a lower estimate, since on the final part of the path of the probing beam, which determines the detected rotation angle $\alpha$, the plasma density must be below $10^{20}$ $cm^{-3}$. Furthermore, only the component of the magnetic field along the probing direction is found from expression (2).

There is another circumstance to be noted. A factor which may cause a rotation of the polarization plane of the probing beam, in addition to the Faraday effect ($\mathbf{l}\|\mathbf{B}$) and the weaker Cotton-Mouton effect ($\mathbf{l}\perp\mathbf{B}$), is a nonuniformity of the plasma, even in the absence of a magnetic field. It can be shown that in the geometric-optics approximation [$\lambda/L \ll 1$, where $\lambda$ is the wavelength of the probing beam, and we have $L = (\nabla n_e/n_e)^{-1}$ under the condition $n_e/n_c < 1$ (when refraction is slight)] the angle through which the polarization of a probing beam is rotated in an inhomogeneous magnetized plasma is the sum of the rotations due to the Faraday effect, $\alpha_B$, and due to the inhomogeneity of the plasma density, $\alpha_{\nabla n_e}$:

$$\alpha = \alpha_{\nabla n_e} + \alpha_B = -\int_0^Y d\zeta\,(\mathbf{e}_0\vec{\kappa}(\zeta))\int_0^\zeta d\zeta'([\mathbf{l}_0\mathbf{e}_0]\vec{\kappa}(\zeta')) - \frac{1}{2c}\int_0^Y d\zeta'\,\frac{n_e(\zeta')}{n_c}(\mathbf{l}_0\vec{\Omega}(\zeta'))\,. \tag{3}$$

Here $\mathbf{e}_0$ and $\mathbf{e}$ are unit polarization vectors ($\mathbf{e} = \mathbf{E}/E$), $\mathbf{l}_0$ and $\mathbf{l}$ are unit vectors along the directions ($\mathbf{l} = \mathbf{k}/k$) of the incident and transmitted waves, respectively, $\kappa = \frac{1}{2}\nabla \ln n_e$, $n_e(\zeta)$ is the electron density on the path of the probing beam, and $\mathbf{\Omega} = e\mathbf{B}/m_e c$.

For a plasma which is inhomogeneous in one dimension, along the $x$ axis [$\kappa_x = -\frac{1}{2}(n_e/n_c)(1/L)$], and which has a thickness $Y$ along the $y$ axis, and for a probing beam which is incident along the $y$ axis, with a polarization plane which makes an angle $\psi$ with the $(x,y)$ plane, we easily find from (3) (under the assumption $\mathbf{B}\|y$)

$$\alpha = \alpha_{\nabla n_e} + \alpha_B = \frac{\sin 2\psi}{16}\,\frac{Y^2}{L^2}\left(\frac{n_e}{n_c}\right)^2 + \frac{Y\Omega}{2c}\,\frac{n_e}{n_c}\,. \tag{4}$$

It follows that the Faraday effect is greater than the rotation of the polarization plane due to the plasma inhomogeneity under the condition

$$\frac{\Omega L}{c} > \frac{Y}{8L}\,\frac{n_e}{n_c}\,. \tag{5}$$

It can be seen from (5) that for the parameter values given above ($Y \simeq 100$ $\mu$m, $n_e \sim 10^{20}$ $cm^{-3}$) and for $L \simeq 30$ $\mu$m, this inequality holds at $B > 25$ kG. Consequently, under our experimental conditions these two effects may give rise to comparable rotations of the polarization plane of the probing beam.

[1]J. A. Stamper and B. H. Ripin, Phys. Rev. Lett. **34**, 138 (1975).
[2]A. Raven *et al.*, Phys. Rev. Lett. **41**, 554 (1978).
[3]Yu. V. Afanas'ev, E. G. Gamaliĭ, I. G. Lebo, and V. B. Razanov, Zh. Eksp. Teor. Fiz. **74**, 516 (1978) [Sov. Phys. JETP **47**, 271 (1978)].

[4]V. B. Rozanov and N. N. Demchenko, Kvant. Elektron. (Moscow) **12**, 1895 (1985) [Sov. J. Quantum Electron. **15**, 1251 (1985)].

Translated by Dave Parsons