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Spontaneous Magnetic Fields in Laser-Produced Plasmas

J. A. Stamper, K. Papadopoulos, R. N. Sudan,* S. O. Dean, and E. A. McLean
U. S. Naval Research Laboratory, Washington, D. C. 20390

and

J. M. Dawson
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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Spontaneously generated magnetic fields of the order of a kilogauss have been observed in a laser-produced plasma, using a variety of targets and background pressures. The generation of these magnetic fields is explained in terms of thermoelectric currents associated with large temperature gradients near the target.

A dense, energetic plasma can be produced by focusing the pulse from a Q-switched laser onto a small solid target located in a background gas. We have observed the generation of large magnetic fields in such a laser plasma in the absence of any applied fields.

In our experiment, the target was located at the center of a large (12-in. i.d. × 54-in. long) Pyrex tube containing an ambient gas. A lens, located at the end of the tube, was used to focus the laser beam onto the target. A neodymium-doped glass laser was used to produce the laser plasma. It had an output of 60 J in 30 nsec with a beam diameter of 32 mm and a full-angle, half-power beam divergence of 200 μrad.

Magnetic probes were inserted radially through small side tubes near the target. The probe supports were in a plane perpendicular to the tube axis and made an angle of 45° with the vertical fiber target. They could be oriented so as to record the time derivative $\dot{B}$ of either the axial (B_z) or azimuthal (B_φ) (with respect to the laser beam) component of the magnetic field. The probes consisted of small (diameter <1 mm) coils of wire. They were connected via 50-Ω coaxial signal cables to an oscilloscope which recorded $\dot{B}$. Several steps were taken to insure that the data was accurate and meaningful. The probes were calibrated for orientation and sensitivity in a fast probe calibrator. A probe was considered to be operating satisfactorily, in the experiment, only when signals were accurately reversed when the probe was rotated through 180°. This simple test[1] insures against spurious electrostatic signals. Replacement of probes was necessary, at times, since they were easily damaged by the intense laser plasma. The magnetic field was mapped on a shot-by-shot basis with good reproducibility (~10%). The spontaneous magnetic fields were observed with a variety of probes. These included glass and epoxy-coated probes, single and double probes, and probes which were either open or closed to plasma penetration into the interior of the coils. A large (~1-cm-diam) probe, having a turns-area parameter over twenty times greater than the probes normally used, was used to measure the fields at large radii ($r \geqslant 4$ cm). The field intensities in this range could not be accurately measured on the small probes but, nevertheless, there was agreement to within a factor of 2 or 3 for the two probes.

The target in most of our studies was a 250-μm-diam fiber of Lucite ($C_5H_8O_2$). This was approximately the diameter of the laser focal spot. Lucite was chosen because it produced an energetic laser plasma absorbing more than 95% of the incident radiation, while the carbon and oxygen provided opportunity for doing spectroscopic studies. The studies indicate a peak electron temperature in the laser plasma of about 100 eV. Experiments were also made using aluminum and silver surfaces as targets. The aluminum and silver disks ($\frac{1}{16}$ in. thick$\times\frac{3}{4}$ in. diam) were supported by an insulator. Most of the data were taken in a nitrogen background. The background gas was photoionized by energetic photons from the laser plasma. This photoionization is complete out to a radius of several millimeters and then decreases as the inverse square of the radius. Spectroscopic studies give an electron temperature for the background plasma of about 3 eV and a degree of ionization of about 5% at $r=0$, $z=-2$ cm for a Lucite target in a 200-mTorr background of nitrogen[2] (see insert in Fig. 1). The expanding laser plasma couples strongly to the background. An interaction region or front is observed,[3] by means of image converter photography and shadowgraphy, to travel outward with an initial veloctiy of $(1\text{-}5)\times10^7$ cm/sec.

Magnetic fields were observed as pulses which propagated with the same velocity as the fronts observed by optical means. The pulses became diffuse, with a spatial extent of the order of the radius at which they were observed. The magnitude of the spontaneous fields was insensitive to background pressure. The fields in a 200- and a 50-mTorr background of nitrogen were, within experimental error, the same, and the fields in a background of 6×10^{-3} mTorr of air (base pressure) were only down by a factor of 3 or 4. The fields for $r>1$ cm, $z<0$ were primarily in an

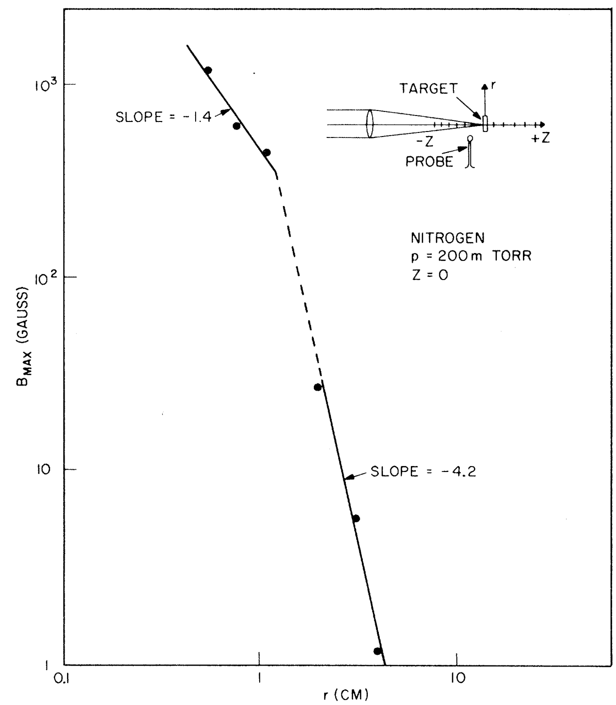

FIG. 1. Radial variation of spontaneous fields.

azimuthal direction but, for a Lucite target, showed a comparable axial component for $r\leqslant1$ cm, $z=0$. The polarity of the azimuthal fields implied conventional current flow in the direction of the laser beam. Figure 1 shows the radial variation of the maximum azimuthal field observed in the midplane ($z=0$) for a Lucite target in a 200-mTorr background of nitrogen with 10% hydrogen added for diagnostics. For $r<1$ cm, $B\propto r^{-1.4}$. In this range, the front passes the probe while the laser pulse is still incident on the target. For $r>1$ cm, $B\propto r^{-4.2}$. Here, the laser pulse is over before the front reaches the probe. A typical $\dot{B}$ oscillogram is shown in Fig. 2 for the same target and background as Fig. 1. The probe was at $r=1$ cm, $z=0$. The maximum field in this pulse is 450 G.

The Lucite laser plasma showed anisotropies of the order of 2 in the velocity of early expansion. A horizontal velocity twice that of the vertical velocity was, presumably, due to the presence of fiber above and below the target region. A preferred expansion velocity back toward the laser was always present. If the laser pulse hit the target at one side there was a perferred expansion to that side.

Data were also taken using aluminium and silver surfaces as targets. The conducting-plane boundary allows comparison with the solutions of

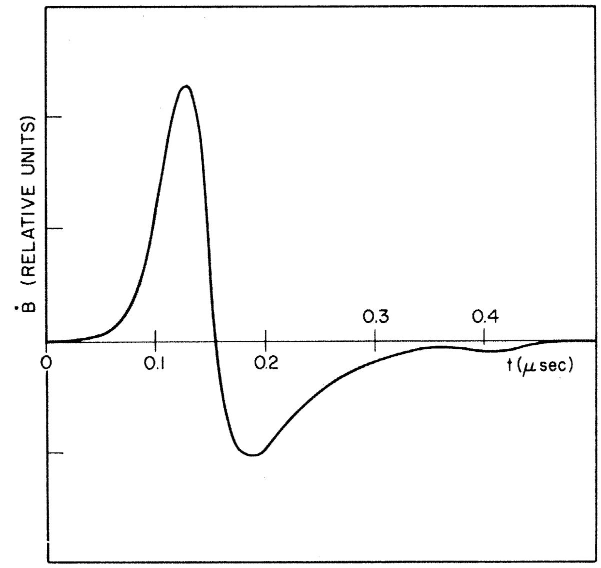

FIG. 2. Typical $\dot{B}$ oscillogram.

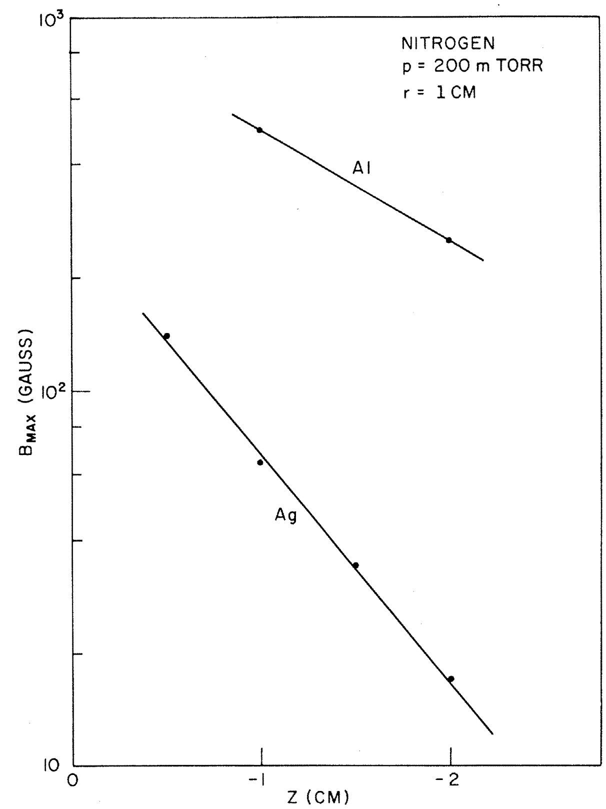

FIG. 3. Axial variation of spontaneous fields.

boundary-value problems. A more complete set of data with respect to axial position was taken in these experiments. Figure 3 gives the axial variations of the maximum fields in the pulse. The fields for an aluminum target were appreciably larger than for silver. This could be a result of the larger radiative energy loss from a silver target. The fields were, within experimental error, in an azimuthal direction about the incident laser beam for all probe positions. This is expected since the only anisotropy for a surface target is a higher expansion velocity back toward the laser.

The spontaneous generation of a magnetic field requires the presence of an initial solenoidal electric field. Near the focus there are large gradients in temperature. We consider the plasma and the target to form a thermoelectric junction with the laser focus as the hot junction. For the initial evolution of the laser-generated plasma and before any interaction occurs with the background plasma, one can apply a simple two-fluid model of a collision-dominated plasma since the plasma density near the focus is very large.

The generalized Ohm's law, neglecting electron inertia and ion pressure, is given by

$$\vec{J} = \sigma(\vec{E} + \vec{v}_e \times \vec{B}/c + \nabla P_e/n_e e - \overleftrightarrow{\alpha}\cdot\nabla T) = (c/4\pi)\nabla\times\vec{B}, \tag{1}$$

where $\overleftrightarrow{\alpha}$ is the plasma thermoelectric tensor; P_e, T, and n_e are, respectively, the electron pressure, temperature, and density; and the other quantities have their conventional meaning. For a circuit moving with velocity $\vec{v}_e$, the rate of change of magnetic flux Φ over a surface S spanning it is given by

$$d\Phi/dt = \int_S [\partial\vec{B}/\partial t - \nabla\times(\vec{v}_e\times\vec{B})]\cdot d\vec{S} = c\oint_C (\nabla P_e/n_e e + \overleftrightarrow{\alpha}\cdot\nabla T - \overleftrightarrow{\sigma}^{-1}\cdot\vec{J})\cdot d\vec{S}. \tag{2}$$

The sources for the flux are the thermoelectric term $\overleftrightarrow{\alpha}\cdot\nabla T$ and, if $\nabla n\times\nabla T\neq 0$, the term with ∇P_e. These can be considered as an equivalent "battery" which drives the currents needed to produce the magnetic field. The thermoelectric contribution would vanish if $\overleftrightarrow{\alpha}$ were a scalar independent of position, i.e., if there were no discontinuities or junction contacts. From Eq. (1) and Faraday's law, assuming scalar conductivity, we obtain

$$\partial\vec{B}/\partial t = \nabla\times(\vec{v}_e\times\vec{B}) + (c^2/4\pi\sigma)\nabla^2\vec{B} + \vec{S}(\vec{r}, t), \tag{3}$$

where $\vec{S}$ is the source term.

Since we are interested in times and distances before any interaction with the background plasma occurs, the plasma conductivity will be given by the Spitzer formula.[4] The diffusion time for a length L is given by $\nu_{\text{coll}}\tau_{\text{diff}} = (L\omega_p/c)^2$. For the plasma in this experiment, τ_{diff} exceeds the experimental times for distances larger than a few millimeters. Therefore neglecting the diffusion term in Eq. (3), the azimuthal component of the magnetic field is given in spherical coordinates (ρ, θ, φ) by

$$\partial B_\varphi/\partial t + \rho^{-1}\partial(\rho v_\rho B_\varphi)/\partial\rho = S(\vec{r}, t). \quad (4)$$

In Eq. (4), we assume a spherically symmetric expansion of the laser plasma. The source term can be approximated at the focus of the laser by

$$S(\vec{r}, t) = (ckT_0/e)[\delta(\rho)/\rho]f(t). \quad (5)$$

$S(\vec{r}, t)$ will, in general, depend on θ, but the explicit dependence has been ignored here. T_0 is the source electron temperature and $f(t)$ is the shape of the laser pulse in time. We can solve Eqs. (4) and (5) for B_φ, assuming that $v_\rho = v_0 U(t - \int_0^\rho d\rho/v_0)$:

$$B_\varphi(\rho, t) = (c/e)(kT_0/v_0\rho)f(t - \int_0^\rho d\rho/v_0), \quad (6)$$

where U is the Heaviside unit step function.

Such a profile for the magnetic field appears to be consistent with the experimental observations at early times. The magnetic front propagates with the plasma expansion front as observed, and the duration is the approximate duration of the laser pulse. The maximum field falls off as $1/r$ which agrees approximately with experimental observations, Fig. 1, for $r < 1$ cm. The maximum field at any point r can be estimated from Eq. (6) if we take $T_0 \sim 100$ eV and $v_0 \sim 10^7$ cm/sec:

$$B_\varphi \approx (10^3/\rho) \text{ G},$$

which agrees in order of magnitude with the observations for a constant-velocity profile. The duration of the B pulse, at early times, is approximately that of the laser pulse, in agreement with (6). The above analytical treatment aims at describing the main characteristics of the observations and has a number of shortcomings of detail. However, we think it covers the main effect both qualitatively and quantitatively.

At later times and longer distances, because of the momentum coupling of the expanding plasma with the background plasma, the simplified model presented above would need re-examination. Detailed study of the processes connected with the formation of a high-Mach-number shock are in progress.

In the course of writing the manuscript, our attention was called to the work of Korobkin and Serov[5] who observed a small spontaneous magnetic moment $[(3\text{-}5)\times10^{-2}$ Oe cm$^3]$ in the laser induced breakdown of a gas. Because of the meager data and sketchy description given, we cannot make a comparison between the two experiments.

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*On leave of absence from Cornell University.

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