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Faraday-Rotation Measurements of Megagauss Magnetic Fields in Laser-Produced Plasmas*

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Magnetic fields in the megagauss range have been observed in the laser-produced plasma near the focus of a high-power laser pulse. Faraday-rotation measurements utilizing the light of a probing beam and the specularly reflected laser light both show the presence of these large fields.

We report here the first direct observations of spontaneous megagauss magnetic fields in laser-produced plasmas. Spontaneous magnetic fields have previously been measured in laser-produced plasmas formed when a high-power laser pulse was focused onto a solid target,[1-3] or into a gas.[4] The earlier measurements were made with magnetic probes at some distance from the laser focus. Although these fields, measured in the expanding plasma, were as large as a kilogauss,[2] theory[2,5-7] predicts that very large fields (megagauss) exist in the focal region. The megagauss fields may be of considerable importance since they can affect the physics of laser fusion in a variety of ways.[8-11] The direct observation of large magnetic fields should stimulate further theoretical studies of their effect on laser fusion.

It has been recognized that measurements of magnetic fields in the focal region require optical techniques since magnetic probes cannot give reliable data closer than 3 or 4 mm from the focus.[11] In this Letter, we describe two independent measurements involving Faraday rotation of electromagnetic waves. One method uses a probing beam of second-harmonic light (0.53 μm) with the data recorded on film. The other method uses the light (1.06 μm) which is specularly reflected from the critical surface of the plasma and depends on measuring (with photodiodes) both components emerging from a polarizing prism. The methods are thus independent and complementary. Analysis shows that the results of both methods are consistent with magnetic fields in the megagauss range. A brief theoretical discussion is given which shows that megagauss magnetic fields in the observed direction are expected for the reported experimental conditions.

The laser system used in these studies consists of a Nd-doped, mode-locked, mode-selected, yttrium-aluminum-garnet oscillator with a Nd-doped–glass amplifier chain.[11] The pulse width for the studies reported here was 100 psec; pulse energy was typically 2 J. The laser beam was focused with a 3-in.-diam, $f/14$ lens producing an irradiance of about 10^{15} W/cm^2. Targets were located in a vacuum chamber having a base pressure around 10^{-4} Torr.

The experimental arrangement for studies using a probing beam are shown in Fig. 1(a). The probing beam was obtained by splitting off part

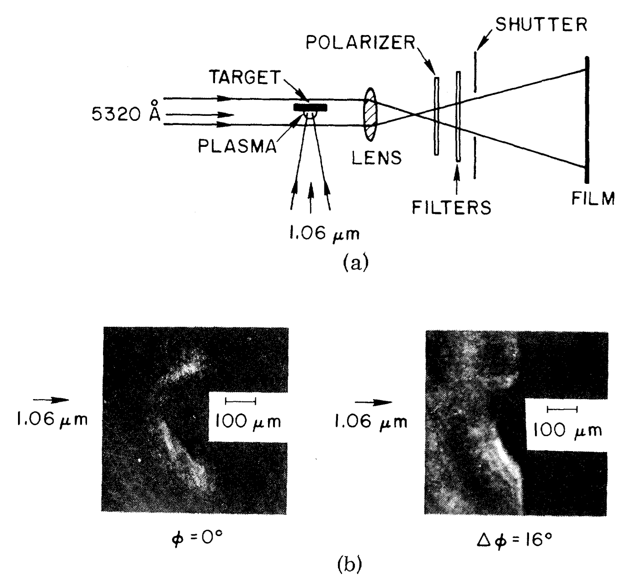

FIG. 1. Measurements of Faraday rotation of a probing beam. (a) Arrangement for detecting the rotation of polarization. (b) Sample photographs as a function of polarizing-sheet orientation.

of the main laser beam and frequency doubling it to 0.53 μm. This green probing beam was passed parallel to the target surface and timed to arrive around 200 psec after the main laser pulse (which arrives at normal incidence onto a slab target). The probing beam and the main laser beam were vertically polarized. That portion of the probing beam which passes through the laser-produced plasma was focused, with a 4:1 magnification, onto photographic film. The film was protected against room light by opening a shutter only a few seconds before firing the laser. Plasma light was discriminated against by using a broad-band blocking filter and a narrow-band interference filter (50-Å width centered at 0.53 μm).

Exposures were taken of the probing beam with a polarizing sheet placed in front of the shutter. As expected, with no main laser beam, the film was dark when the polarizing sheet was oriented horizontally. The effect of plasma light was checked by taking exposures with the probing beam blocked and was found to be negligible. However, when the probing beam was passed through the laser-produced plasma in the focal region, a distinct lighted pattern could be seen on the film. See Fig. 1(b) for data for an aluminum target.

The lighted pattern is what one would expect for green light rotated by the spontaneous magnetic fields so that it can pass through the polarizing sheet. These fields are primarily in an azimuthal direction about the target normal with a maximum off-axis (since the maximum gradients are off-axis). The central region at the target surface is dark since refraction and reflection prevent light from passing through the high-density region. For azimuthal magnetic fields due to thermal sources, the magnetic field above focus is parallel to the probing beam and that below center is antiparallel.[2] One would thus expect an up-down asymmetry in the lighted pattern when the polarizing sheet is rotated. Rotation of the polarizing sheet, Fig. 1(b) (right-hand side), was in the direction to enhance the transmission of light which had been given a Faraday rotation of positive helicity. The fact that the lighted region was at the bottom is consistent with fields generated from thermal sources. By rotating the polarizing sheet until the background exposure (for probing beam only) is comparable with that of the lighted region, we estimate a typical rotation angle to be about 0.2 rad.

We can estimate the magnetic field magnitude required for this Faraday rotation from the expression for the rate of change of rotation angle φ with respect to distance z along the propagation direction,

$$d\varphi/dz = \tfrac{1}{2}(\omega_p/\omega)^2\omega_{cz}/c, \tag{1}$$

where ω_p and ω are, respectively, the plasma and laser frequencies. The magnetic field dependence, ω_{cz}/c, is given in inverse centimeters by $0.586B_{\parallel}(kG)$, where $B_{\parallel}=B_0\cos\theta$, and where the angle between the magnetic field and propagation direction of the electromganetic wave is denoted by θ. We have tried a variety of density and magnetic field variations guided by experimental results, simple models, and computer calculations. The implied magnetic fields agree within a factor of 3 or 4. For example, assume that the density varies down from the critical density (10^{21} cm^{-3}) at a 35-μm focal radius and that the probing light passes 100 μm (radius of lighted region) from the focal center. Then, if we assume that the density decreases exponentially with radius from the critical surface and that the field varies inversely as the radial position,[2] a rotation angle of 0.2 rad corresponds to a maximum field of 4.8 MG. The scale length (35 μm) for density variation was obtained from interferometry.

The other experimental method utilized the laser light specularly reflected from the critical surface of the plasma. Large gradients in the electron pressure and the laser intensity occur in the critical region and, since these are involved in the field generation, the largest fields occur near the critical region. Hence, the specularly reflected light is inherently timed and positioned to sample the large magnetic fields. However, the specularly reflected light sampled by our detector involves some spatial and temporal averaging which limits the magnetic field information.

The experimental arrangement for the specular-reflection measurements is shown in Fig. 2(a). The laser light is focused onto a target inclined at 45° to the laser beam. Laser light specularly reflected from the critical surface is thus centered at 90° to the incident beam.[12] This light is analyzed with a polarizing prism. Each component of polarization is measured with a photodiode-oscilloscope system having a 2-nsec response. The data are thus time integrated for the 100-psec laser pulses used.

Some experimental results are shown in Fig. 2(b). On some shots (left-hand side) with the de-

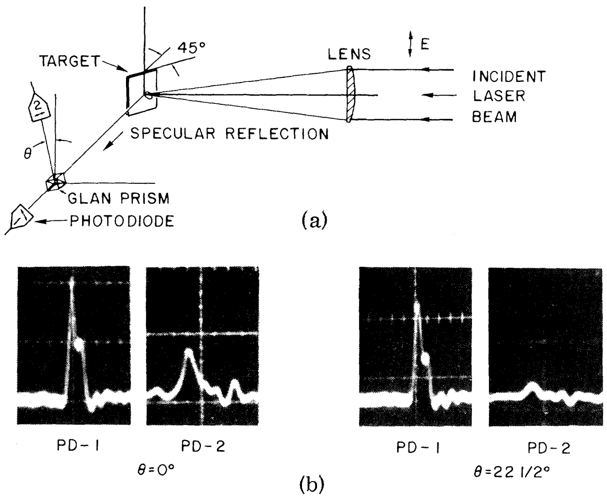

FIG. 2. Measurements of Faraday rotation of specularly reflected light. (a) Arrangement for detecting the rotation of polarization. Arrows indicate the directions of polarization (mutually perpendicular). The whole detector can be rotated by an angle θ. (b) Photodiode outputs for detector assembly set at $\theta = 0$ (left-hand side) and at $\theta = 22\frac{1}{2}°$ (right-hand side).

tector assembly oriented vertically, appreciable signals are observed on both channels. This suggests rotation but could also be due to depolarization. Some depolarization is expected from Faraday rotation because of the mixing of signals implied by space and time averaging. Clear evidence of a net rotation requires that a high degree of polarization be observed with the detector assembly rotated away from the vertical. Shot-to-shot variation of this rotation angle was such that the detector-assembly rotation coincided sufficiently close to the Faraday angle only in a minority of shots. However, on some shots with the detector assembly rotated, we did observe a rather high degree of polarization and were thus able to get an accurate measurement of the rotation angle. The signals on the right-hand side in Fig. 2(b) were for a detector set at $22\frac{1}{2}°$ and thus imply a rotation of about that angle. Typical observed rotations were approximately this value.

Equation (1) can be used to estimate the magnetic field required to produce a $\pi/8$-rad rotation in the specularly reflected light.[13] A rough estimate can be made by assuming that the laser light comes in and out of the critical region along a radius and that the density and magnetic field have particular radial variations. For example, with the assumption that $\cos\theta$ has a value of 0.2 (discussed below) and that the density and magnetic field have the variations used previously, then a $\pi/8$ rotation corresponds to a 1.6 MG magnetic field. A number of reasonable density and magnetic field variations have been assumed as a test. We find that the implied magnetic fields agree with this value to within a factor of 3 to 4.

Magnetic fields of a few megagauss are expected from numerical studies[5,6] and simple models.[7] The numerical studies, utilizing two-dimensional computer codes, have been based on thermal source terms. Here the magnetic source term $\vec{S}$ or time rate of change of the field is given by $(ck/ne)\nabla T \times \nabla n$. Since the density gradient has a large component normal to the target surface and the temperature gradient has a large component radially outward, the initial fields are, as observed, clockwise in an azimuthal direction about the target normal. For a 1-keV temperature, with temperature and density length scales of 35 μm, $|\vec{S}|$ is about 10 MG/nsec. Thus fields in the megagauss range can be generated during the 100-psec laser pulse.

Since thermally generated fields for 45° incidence onto the target will be primarily in an azimuthal direction about the normal to the target, the specularly reflected light from the central part of the critical region will be almost perpendicular to the thermally generated fields. At 10^{15} W/cm^2 the magnetic fields generated from the plasma thermal energy are dominant. However, since the specularly reflected light samples only a small component of this field it also may be affected by fields generated by radiation pressure and polarization effects.[7] Radiation pressure at 10^{15} W/cm^2 is about one-tenth of the electron pressure at 1 keV and 10^{21} cm^{-3}. These effects complicate the field geometry. For example, polarization effects produce a field component along the propagation direction even for normal incidence onto the target. From these considerations, a typical angle between the field and the propagation direction is taken as 80° so that $\cos\theta$ was taken as 0.2 in the example cited. The average $\cos\theta$ sampled by the detected light should agree with this value within a factor of 2.

In summary, we have described two independent measurements of the magnetic fields generated at the focus of a high-power laser pulse interacting with a solid target. These measurements depend upon Faraday rotation of plane-polarized electromagnetic radiation traversing the region of high fields. Taken together, the measurements demonstrate that megagauss magnetic fields do exist in the local region.

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Neutron Production and Second-Harmonic Generation in Laser-Target Experiments

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Experimentalists studying the interaction of strong electromagnetic radiation with plasma have reported scattered asymmetric lines with frequency $2\omega_0$. This line and the neutron yield are correlated as a function of the peak intensity on the plasma profile. I show how the observed correlations between the $2\omega_0$ radiation and the neutron production can be explained by considering parametrics and linear effects in an inhomogeneous plasma. Scattered radiation and neutron output are discussed.

Harmonic generation in a laser-created plasma has been observed in the laboratory.[1] Bobin *et al.*[1] observed the light emitted from the interaction of a Nd-glass laser and a target (H_2 or D_2). Intense lines were found at $2\omega_0$ and at $\frac{3}{2}\omega_0$. These have a line shape broadened toward lower frequency. The polarization of the wave in the backward direction is the same as for the incident. Furthermore, they have measured the intensity of these lines as a function of the position of the focal spot on the target. The neutron production is then correlated with the $2\omega_0$ line.

In this Letter, I propose a mechanism to explain the backscattered radiation and neutron production. A parametric, nearly forward, Brillouin decay produces radiation at $\omega_0 - \omega_a$, where ω_0 is the pump frequency and ω_a is the ion-wave frequency. Because of the density gradient, linear wave conversion produces the backscattered light at $\omega_0 - \omega_a$, and the harmonic at $2(\omega_0 - \omega_a)$ is then generated by a nonlinear effect. The strong pump drives the low-frequency modes ω_a producing a broad spectrum of them. The spatial domain where these waves are produced goes up to the critical density where, through the electron-ion decay, the pump also drives a broad

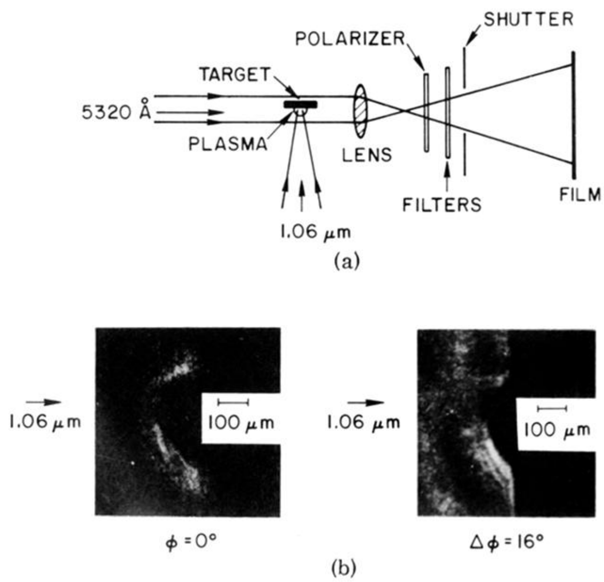

FIG. 1. Measurements of Faraday rotation of a probing beam. (a) Arrangement for detecting the rotation of polarization. (b) Sample photographs as a function of polarizing-sheet orientation.

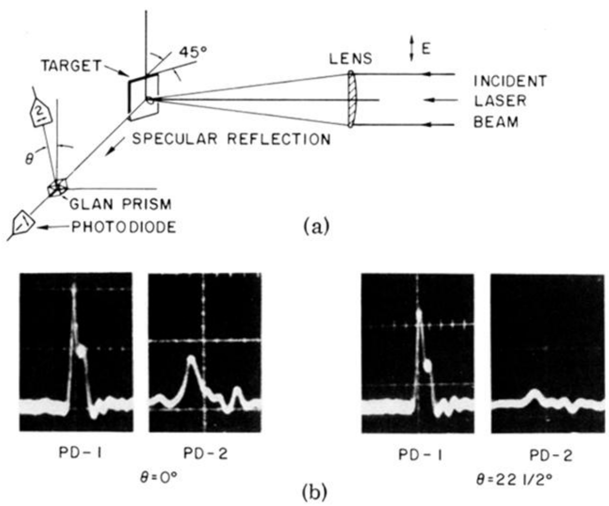

FIG. 2. Measurements of Faraday rotation of specularly reflected light. (a) Arrangement for detecting the rotation of polarization. Arrows indicate the directions of polarization (mutually perpendicular). The whole detector can be rotated by an angle θ. (b) Photodiode outputs for detector assembly set at $\theta = 0$ (left-hand side) and at $\theta = 22\frac{1}{2}°$ (right-hand side).