# Measurements of Inverse Faraday Effect and Absorption of Circularly Polarized Laser Light in Plasmas

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Measurements of the inverse Faraday effect and of the absorption of circularly polarized laser light in plasmas are reported. The experiments were performed with a Nd:YAG laser system. For the laser irradiance range studied here, $9 \times 10^{13}-2.5 \times 10^{14}$ W/cm$^2$, the absorption of circularly polarized light was higher by 14% relative to the absorption of linear polarized light. It is suggested that the above increase in the laser absorption is related to the axial magnetic field in the plasma created by the circularly polarized laser light. Axial magnetic fields of tens of kilogauss were measured at irradiances in the range of $10^{12}-10^{13}$ W/cm$^2$ using the Faraday rotation diagnostic. [S0031-9007(97)02545-3]

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Large (megagauss) magnetic fields are produced by laser-plasma interaction when a high irradiance laser pulse is focused on a solid target. The relevance of these magnetic fields to inertial confinement fusion depends on the numerous ways in which they can affect the laser-plasma interaction and the resulting plasma. Many theoretical studies have dealt with a variety of generation mechanisms [1] and with the associated transport and instability phenomena. One of the most studied processes inducing self-generated magnetic fields in laser-plasma interaction is the $\nabla n \times \nabla T$ mechanism [2] which creates a toroidal magnetic field as a result of the current loop produced by the ejected hot electrons.

Recently the production of an axial magnetic field by circularly polarized laser light (CPLL), the inverse Faraday effect, is of much interest. A new concept of hot plasma confinement in a miniature magnetic bottle induced by CPLL was suggested [3–6]. This concept relies on the hybrid use of inertial and magnetic confinements and megagauss field generation by CPLL. The schematic structure of this configuration is as follows: A DT plasma is created inside a cylindrical or spherical heavy conductor (or superconductor) shell with a hole. The plasma is irradiated by an intense circularly polarized laser beam. The CPLL creates a toroidal current in the plasma, which in turn induces an opposite current in the wall. The currents induce axial magnetic fields inside and outside the plasma, in addition to the toroidal magnetic field created, for example, by the $\nabla n \times \nabla T$ mechanism [2]. The plasma is heated resonantly by the CPLL to several keV during a time of a few ns. An estimation of the time scales describing the plasma confinement in this configuration showed [5] that the Lawson criterion may be fulfilled for $3\omega$ CPLL created plasma with a density of $5 \times 10^{21}$ cm$^{-3}$ and a confinement time of 20 ns.

The investigation of the interaction between CPLL and plasmas is also motivated by the possibility of fast ignition [7]. The idea of fast ignition for the direct drive implosion is that a capsule is first imploded as in the conventional approach to inertial fusion to assemble a high density fuel configuration. Second, a hole is bored through the capsule corona composed of ablated material, as the critical density is pushed close to the high-density core of the capsule by the pondermotive force associated with high-intensity laser light. Finally, the fuel is ignited by suprathermal electrons, produced in high-intensity laser plasma interactions, which then propagate from critical density to this high-density core. This scheme may drastically reduce the difficulty of uniform compression. One of the boring schemes suggested lately is circularly polarized laser light [8,9]. In this scheme, an ultraintense magnetic field as large as hundreds of MG for relativistic laser intensities is obtainable in an overdense plasma where the wave can propagate owing to the induced transparency [8], boring a much deeper hole. For example, at an intensity of about $10^{19}$ W/cm$^2$, the cutoff density of the plasma is increased by a factor of 3.

In this paper the interaction between plasmas and CPLL is considered at moderate intensities in the range $9 \times 10^{13}-2.5 \times 10^{14}$ W/cm$^2$. The absorption fraction of a Nd:YAG, 1.06 $\mu$m, 7 ns laser pulse in the plasma was measured for circular and linear polarization. The experiments show that the absorption fraction is increased by 14% for circular polarization. The CPLL induced axial magnetic field was measured using the Faraday rotation diagnostic.

The experimental setup for measurements of the laser absorption fraction is shown in Fig. 1. The main laser system is based on a Continuum NY-60 Nd:YAG oscillator followed by one triple passed and one double passed amplifier. The laser yields up to 100 J, in 7 ns FWHM pulses focused at the target by a F/5 lens.

By introducing a $\lambda/4$ plate, the laser polarization is changed from circular to linear. The degree of the linear polarization is 99.99% (the polarization is determined by two polarizers, each with a contrast of 100). The quality of polarization change by the $\lambda/4$ plate is better than 99%, therefore the degree of the circular polarization is

  

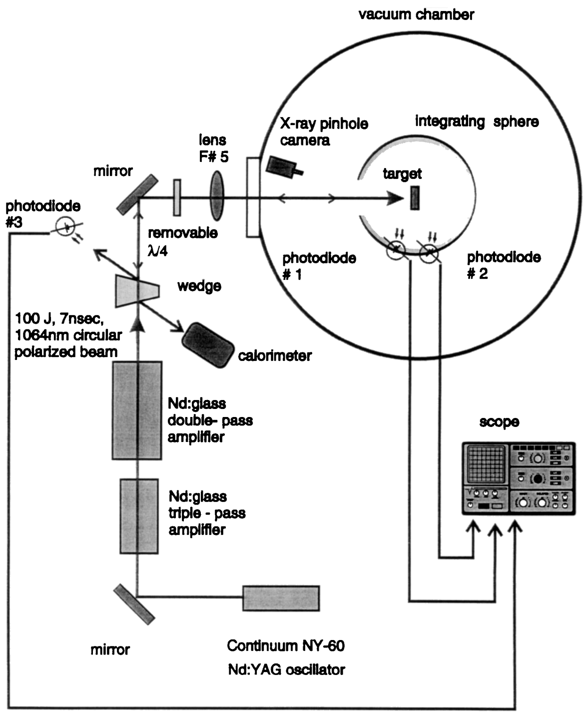


FIG. 1. The experimental setup for measurements of laser absorption.

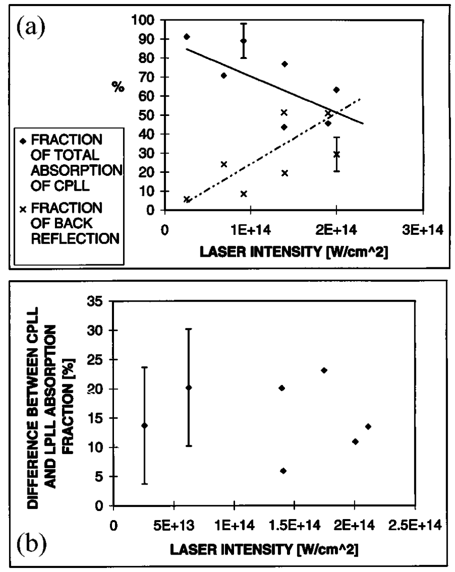


FIG. 2. (a) The measured total and the back reflected fraction of the circularly polarized laser light as a function of the laser irradiance. (b) The difference of the absorption fractions of circularly polarized and linearly polarized laser light as a function of the laser irradiance.

99%. An aluminum target is mounted inside an integration sphere, which is placed in a vacuum chamber. The incident laser energy is measured with a calorimeter. The laser absorption fraction is obtained from the measurement of the total energy reflected from the plasma. The radiation generated by the laser-target interaction is diffusely reflected from the highly reflective inside surface of the integration sphere and measured with photodiodes 1 and 2. The use of two photodiodes allows an increase in the dynamical range of the detection method. In addition to the measurement of the total energy reflected from the plasma, the back reflection of the radiation from the plasma was recorded by photodiode 3. The dimensions of the plasma were measured with a pinhole camera. The experiments were performed with thick aluminum targets. The photodiodes 1 and 2 were calibrated by measuring the reflected light of the oscillator NY-60 (1.06 $\mu$m, 100 mJ) passing through different filters to a mirror mounted inside the integration sphere. The whole calibration laser radiation is reflected from the mirror to the integration sphere. The measurements were performed within the linear range of the photodiodes.

Figure 2(a) displays the measured total and the back reflected fraction of the circularly polarized laser light absorption as a function of the irradiance. Figure 2(b) shows the difference of the absorption fractions of CPLL and the linearly polarized laser light (LPLL) as a function of the irradiance. The results show an increase of about $(14 \pm 9)\%$ in the absorption fraction for the CPLL case. Experiments with circular and linear polarization at the same laser irradiance displayed in Fig. 2(b) were performed one after the other, in pairs, by introducing the $\lambda/4$ plate.

The axial magnetic field induced by the circularly polarized laser light was measured by the Faraday rotation diagnostic. This method is based on the rotation of the plane of polarization of a double frequency $(2\omega)$ linear polarized probe electromagnetic beam propagating along a magnetic field. The angle of rotation is given by

$$\phi(\text{deg}) = 3.02 \times [\lambda_p(\mu\text{m})]^2 \times \int_0^L \frac{n(\text{cm}^{-3})B_z(\text{MG})dz(\mu\text{m})}{10^{21}\sqrt{1 - n/n_{cp}}}. \quad (1)$$

$z$ is the distance along the ray path, $L$ is the plasma length, as measured by the pinhole, $B_z$ is the magnetic field component along the path, $\lambda_p$ is the wavelength of the probe beam, $n$ is the density of the plasma, and $n_{cp}$ is the critical density for the probe beam.

The experimental setup for measuring the axial magnetic field is shown in Fig. 3. The main laser beam, 7 ns, 70 J, 1.06 $\mu$m irradiates the target and creates the plasma and the axial magnetic field. The probe beam, 5 ns, 50 mJ, 0.532 $\mu$m, collinearly with the main beam propagates into the plasma, reflects from the critical surface, and than is directed by a beam splitter into an analyzer system. This system includes a $\lambda/2$ plate, a beam splitter, a polarizer, and two photodiodes.

The angle of rotation of the polarization of the probe beam, after propagating through the plasma, is determined by the ratio of the signals of the two photodiodes and a calibration curve of the analyzer. The calibration of the

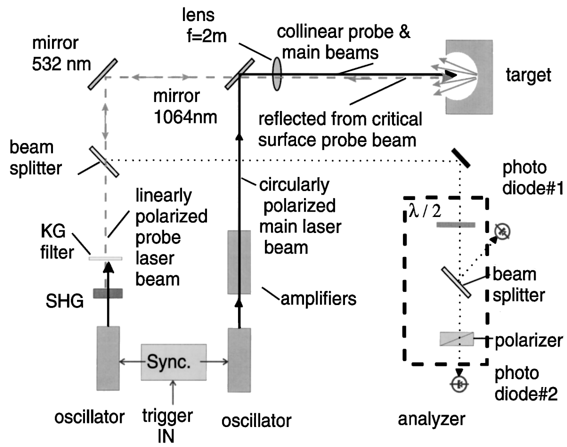


FIG. 3. The experimental setup for measuring the inverse Faraday effect.

analyzer was done by reflecting the probe beam from a perfect mirror, located at the place of the target. The $\lambda/2$ plate was rotated to simulate the rotation of the polarization plane of the probe beam due to the axial magnetic field. We measured the ratio of the signal of the two photodiodes as a function of the rotation angle of the $\lambda/2$ plate. By using this calibration method, one eliminates all the undesired components of the linearly polarized probe beam. The calibration curve has a parabolic shape with a distinct minimum. In the experiment the perfect mirror is removed and the Al target is placed in the focus of the F/20 lens. The $\lambda/2$ plate in the analyzer is adjusted to the angle that corresponds to the minimum of the calibration curve. By reading the output signals of the photodiodes and using the calibration curve, the rotation angle is found.

The experiments were performed for both circularly and linearly polarized light. A rotation angle of $(3 \pm 0.3)^\circ$ was obtained for a CPLL at an irradiance of $6.4 \times 10^{12}$ W/cm$^2$ and a plasma length measured by the pinhole camera of 400 $\mu$m. Assuming a linear density profile, by unfolding the integral in (1) a magnetic field of 16 kG was obtained. For exponential density profiles the estimated value of the magnetic field may change by less than 30%.

The Faraday rotation probe beam diagnostics was also used for plasmas created by linearly polarized laser light. The plane of polarization of the probe beam did not rotate in these experiments, implying that the axial magnetic field was not induced by linearly polarized laser light.

Calculations of the axial magnetic field created by the interaction of CPLL with plasmas was done by several models. The dispersion relation of a circularly polarized relativistic wave was determined based on the magnetic dipoles related to the circular motion of single electrons [10]. The axial magnetic field induced by CPLL was estimated in Refs. [4,5] by calculating the toroidal current in the plasma. Recently [8] the magnetic field generation was calculated in a self-consistent way, considering two sources: One source is related to the circular motion of single electrons in the wave which is equivalent to a magnetic dipole. The second source is related with the inhomogeneity of both the electron density and the intensity of the laser beam. The magnetic field generation and laser front wave distortion were calculated with 2D particle-in-cell simulation [9]. Similar relations between the laser intensity and the magnetic field strength are obtained in the above calculations. We chose to compare the measured magnetic field in the experiments reported here with [8]

$$B = \frac{1}{2}\left(\frac{eE_0}{m\omega c}\right)^2\left(\frac{\omega_p^2}{\omega^2}\right)\left(1 + \frac{L_a^2}{L_a^2 + L_n^2}\right) \times \exp\left[-\left(\frac{r^2}{L_a^2} + \frac{r^2}{L_n^2}\right)\right]. \tag{2}$$

$E_0$ is the electric field of the laser, $\omega$ is the laser frequency, $m$ and $e$ are the electron mass and charge, $c$ is the light velocity, $L_a$ and $L_n$ describe the laser and plasma profiles: $E(r) = E_0 \exp(-r^2/L_a^2)$, $n(r) = n_0 \exp(-r^2/L_n^2)$. $\omega_p = 4\pi n_0 e^2/m$ is the classical plasma frequency at the center of the plasma distribution. The magnetic field measured in our experiments was larger by a factor of 50 than the theoretical estimation of Eq. (2). This discrepancy in the magnetic field may be caused by convection effects from the critical surface to the ablative surface [11,12].

It is suggested to describe the enhancement of the absorption of CPLL in plasma at nonrelativistic intensities by two models: (1) a macroscopic semiclassical model, based on angular momentum transferred to the plasma electrons [3] and (2) a microscopic model based on resonant absorption via the excitation of upper hybrid oscillations [13–16] induced by the self-generated axial magnetic field.

According to a semiclassical model, the circularly polarized photons are imagined to give up a fraction of their angular momentum to the plasma. A laser pulse of energy density $W_L = E^2/4\pi$ contains angular momentum density in the laser propagation direction $z$, $L_L = W_L/\omega$. The angular momentum density of the electrons in the $z$ direction is $L_e = -m/e\mathbf{r} \times \mathbf{J} \cdot \mathbf{z}$, $r$ is the radius of the electron orbits and $J$ the current density. Replacing $\mathbf{J} = (c/4\pi)\nabla \times \mathbf{B}$ and averaging over the plasma volume, an average angular momentum density is obtained, $L_e = (mc/4\pi e)B$. Assuming that the angular momentum density acquired by the electrons is some fraction $\eta_L$ of the photon angular momentum density, and using (2) we obtain that at the center of the plasma

$$\eta_L = \frac{1}{2}\left(\frac{\omega_p^2}{\omega^2}\right)\left(1 + \frac{L_a^2}{L_a^2 + L_n^2}\right). \tag{3}$$

This fraction can attain large values, depending on the laser wavelength and the pulse and plasma profiles.

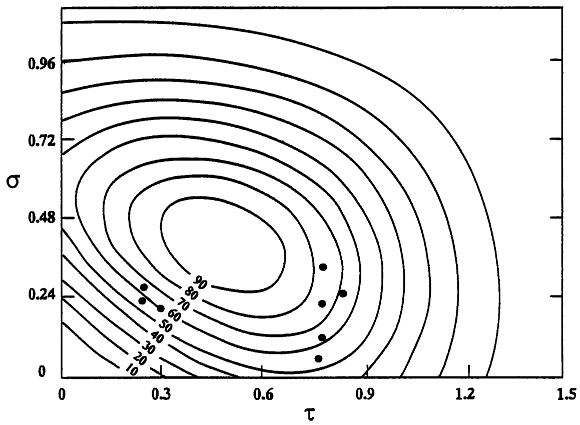


FIG. 4. Contours of equal laser absorption fraction (in percent) in a magnetized plasma calculated in Ref. [13] and the experimental results reported here as a function of the parameters $\tau$ and $\sigma$ (see text).

From solving the equations of propagation of an electromagnetic wave in plasma in the presence of an external magnetic field [13–16] it was shown that the fraction of laser absorption via excitations of upper hybrid oscillations can be characterized by two dimensionless parameters. The parameter $\tau$ is related to the density gradient and the angle of incidence $\theta$ of light at the reflection point,

$$\tau = (2\pi L/\lambda)^{1/3} \sin\theta . \tag{4}$$

$L$ is the density scale length. The second parameter $\sigma$ is related to both the density gradient and the magnetic field,

$$\sigma = (2\pi L/\lambda)^{2/3}(\omega_{ce}/\omega) . \tag{5}$$

$\lambda$ is the laser wavelength and $\omega_{ce} = eB/mc$.

Figure 4 shows the absorption at oblique incidence as a function of $\tau$ and $\sigma$. The contours of equal absorption were taken from Ref. [13]. The points represent the experimental results reported here. The density scale length used for calculating $\tau$ and $\sigma$ was measured in the experiments $L = 100$ $\mu$m. Two sets of experiments were performed, with $\theta_1 = 2°$ and $\theta_2 = 5°$. The magnetic field used in the calculation of $\sigma$ was taken from the experimental measurements conducted in the region of laser irradiances of $6 \times 10^{12}$ W/cm$^2$ and the extrapolation using the scaling law of Eq. (2). (Because of the small plasma dimension in the experiments performed at laser irradiances of about $10^{14}$ W/cm$^2$ we had alignment difficulties in measuring the inverse Faraday effect.) The experimental points for the CPLL case in Fig. 4 range from 55% to 75%, which is in a reasonable agreement with the absorption fraction measurements. However, these data do not explain the 14% higher absorption of CPLL in comparison to LPLL. This problem is intrinsic to this "resonant" theory, which can induce up to 99% absorption without taking into account the inverse bremsstrahlung absorption.

In summary, measurements of the self-generated axial magnetic field created by the interaction of CPLL with plasma at laser irradiances about $10^{13}$ W/cm$^2$ and CPLL laser absorption at about $10^{14}$ W/cm$^2$ laser irradiances were performed. The results show an enhancement of the laser absorption of about 14% for CPLL relatively to circular polarized light.

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