Observation of self-generated magnetic fields due to laser-plasma resonance absorption

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(Received 18 July 1979)

This paper is concerned with broad-scale studies of self-generated magnetic fields by use of the magnetic-tape method. A refined technique which enables a sensible and fine-structure observation is described. In a large-cone-angle experiment parity existence is verified by using convergent and divergent laser beams. In a small-cone-angle experiment it is shown that negative and positive magnetic fields cross the resonance region; the existence of parity is demonstrated by reversing the sign of the incident angle. These observations strongly support resonance absorption as the mechanism of field generation.

I. INTRODUCTION

Self-generated megagauss dc magnetic fields were observed in laser-plasma interaction experiments in 1971.[1] Fields of this magnitude can have a substantial effect on both absorption[2] and transport properties.[3] This effect could have important consequences for our understanding of the physics of laser-plasma interaction, in particular, the laser fusion problem. Most theoretical work on this subject has concentrated on fields due to the thermoelectric current[1,4] and resonance absorption.[5,6] The diagnostic methods used to observe the magnetic fields have been restricted to magnetic probes,[1] Faraday rotation,[7-9] and current probes.[10] They have provided measurements of the magnitude of the fields mainly in vacuum, but not the detailed geometry near the source region. Knowledge of the field geometry may provide important insights into the proposed generation mechanism. Experiment to reveal the field geometry has been limited to microwave simulation using a divergent beam.[11,12]

In our first paper,[13] we conceived a very simple and effective diagnostic method of using audio magnetic tape and provided the first observation of the two-dimensional distribution of self-generated magnetic fields near the resonance region. There we showed the fields' properties: the orthogonality both to the density gradient and incident laser polarization, the s and p polarization dependence, and the angular dependence of p polarization. All point to the observed magnetic fields as being generated by resonance absorption.

In this paper we extend broad-scale studies of self-generated magnetic fields. In Sec. II, we will describe a refined observation technique to examine the fine structure of the fields. In Sec. III, we will show the first experimental evidence of parity existence of the fields, an essential feature of resonance absorption, by using convergent and divergent laser beams in a large-cone-angle experiment. We will also show that the observed direction of the magnetic fields does not contradict that found with other diagnostic methods. In Sec. IV, we will reveal the first observation of negative and positive magnetic fields below and above the cutoff density in a small-cone-angle experiment. We will also demonstrate the existence of parity arising from reversal of the sign of the incident angle of laser beam. These facts are intrinsic properties of resonance absorption. Furthermore, we will clarify the mechanism of lobe rotation mentioned in the previous paper.

II. EXPERIMENTAL PROCEDURE

A laser irradiation apparatus consists of a neodymium-yttrium aluminum garnet (Nd–YAG) mode-locking oscillator, a single-pulse selector and two-stage Nd-glass amplifiers. The laser gives a single pulse of 30 ps duration (full width at half maximum) at a wavelength of 1.064 μm. It was focused on the target through an aspheric lens with a focal length and focal spot diameter of 37 mm and 20 μm, respectively. We used a small full-cone angle of 6°. The typical laser energy was 5–10 mJ, with a corresponding power density of $(5-10)\times 10^{13}$ W/cm^2 in the focal spot. A large full-cone angle of 30° was also used in the experiment by inserting a concave lens to expand the laser beam. The two-dimensional field distribution was obtained by using the same audio recording magnetic tape as a target as was mentioned in the previous paper. The vacuum chamber containing the target was evacuated to 1×10^{-3} Torr.

The magnetic tape consisted of a ferromagnetic film 6 μm in thickness and polyester base 12 μm in thickness. The ferromagnetic film was made of γ-Fe_2O_3 particles. The mean size of the particles was 0.1 μm in diameter and 0.5 μm in length. The width of the tape was 3.81 mm, which was large enough to detect the field distribution. The small anisotropic sensitivity did not affect the essential features of our data. The ferromagnetic response was more than 30 MHz. As in Ref. 13, after laser irradiation the magnetic tape was inserted in the homogeneous external magnetic field of a little more than 250 Oe, sprinkled over by magnetic-tape developer, and dried in order to identify the field direction. This technique will be designated a dry-pattern method. Once inserted into an external magnetic field of this magnitude, part of the self-generated magnetic fields was modified and could not be reclaimed. Moreover, the dry-pattern method sometimes smeared out the microscopic field distribution. In an effort to improve these defects, we improved the observation method. We used a glass cell containing the magnetic tape dipped in the magnetic-tape developer. We could easily observe the field distribution, which we call a wet pattern, through a microscope. The magnetic-tape developer contained iron particles with diameters ranging from 1 to 2.5 μm suspended in trichlorotrifluoroethane. Particles of this size were suitable for our panoramic observation of their stretching in a row along the magnetic lines of force. To identify the polarity of the magnetic field, a small bar magnet was used instead of homogeneous external magnetic field. As an N pole of the magnet was approaching, some parts of the field were attracted and others repelled. We could view the instant movement like a motion picture. The slight movement enabled us to identify the field polarity more sensitively. This removed field pattern was designated a magnet pattern. The magnetic flux density produced by the bar magnet was about 10 G at the tape position, which was small enough to modify the self-generated magnetic fields. As the magnet withdrew, the removed pattern returned to the original wet pattern. This refined method of using the wet pattern and the magnet pattern gave the fine structure of the magnetic lines of force, which we had not observed in the previous paper using the dry pattern. The sensitivity was also improved by about a factor of 10.

III. LARGE-CONE-ANGLE EXPERIMENT

A large full-cone angle of 30° was selected because there exists an optimum angle 15° of resonance absorption within this angle.[13] The ferromagnetic film of the magnetic tape was irradiated by the laser beam at normal incidence. The y and z axes correspond to the laser electric field of plane polarization and the laser propagation direction. The tape was moved back and forth along the z axis across the focal position $z = 0$ to form a divergent and a convergent beam. When placed at $z = 400$ μm, it was irradiated by the divergent laser beam. The burned area about 200 μm in diameter was equal to the irradiated spot, at a laser energy of 10 mJ. The area was discolored to dark brown in contrast to the brown color of the surrounding original tape. The wet pattern is shown in Fig. 1(a) in the case of a divergent beam. It indicates the clear appearance of four magnetic poles from which the magnetic lines of force emerge or enter. Some asymmetry of strength of the poles was inferred, owing to some spatial distortion of the laser beam. In the magnet pattern as shown in Fig. 1(b), the polarities of N and S of each pole were identified. The lobe structure which we described in Ref. 13 was registered in the dry-pattern observation, as shown in Fig. 1(c). The orientation of the lobes was perpendicular to the incident laser electric field as stated in the previous paper. With respect to the sensitivity, it could be said that the large part of these patterns were induced by self-generated magnetic fields more than 250 Oe in intensity, because the coercive force of the tape had this value.

If resonance absorption is the generation mechanism, the parity of the self-generated magnetic fields must exist.[6] In attempting an analytic

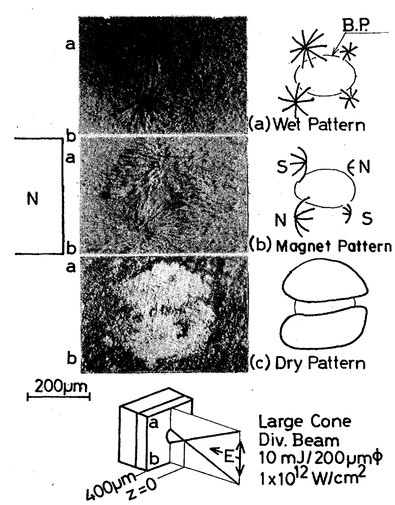

FIG. 1. Example of self-generated magnetic fields using a divergent beam with a cone angle of 30° at normal incidence. The magnetic tape was placed at $z = 400$ μm. The mean diameter of the laser-irradiated area and the observed burned pattern (B.P.) was 200 μm. The laser energy was 10 mJ, with a corresponding power density of 1×10^{12} W/cm^2.

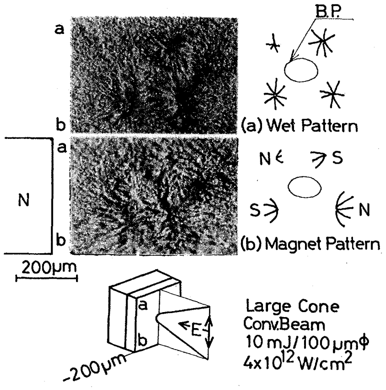

FIG. 2. Example of the self-generated magnetic fields using a convergent beam with a cone angle of 30° at norm-normal incidence. The magnetic tape was placed at $z = 200\ \mu m$. The mean diameter of the laser-irradiated area and the observed burned pattern (B.P.) was 100 μm. The laser energy was 10 mJ, with a corresponding power density of 4×10^{12} W/cm^2.

explanation of this parity existence, we used a convergent laser beam. The observed wet and magnet patterns are shown in Figs. 2(a) and (b). Parity existence was clear in the observed inverse polarities of N and S poles in comparison with those in the divergent laser case.

The explanation of these patterns is given according to the illustration in Fig. 3. Since the laser beam is polarized in the plane of incidence, plasma waves are generated at the cutoff density surface, where they feed energy into the plasma. This dissipation introduces a phase lag between the electron oscillatory motion and the wave, causing the electrons to experience a time-averaged force and to form electric currents along the y axis. From Ampere's law the negative and

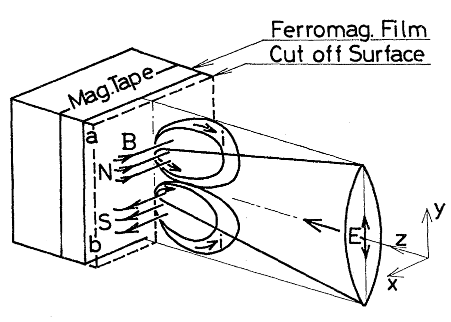

FIG. 3. Illustration showing the qualitative explanation of the self-generated magnetic fields. The laser E field is along the y axis. A convergent laser beam is irradiated at normal incidence on the ferromagnetic film. Self-generated electric currents and magnetic fields are indicated as i and B, respectively. N and S poles are registered on the film.

positive magnetic fields are produced across the cutoff density surface. It is an important point to notice whether the obtained patterns of the film were produced by the fields behind the sheet currents or ahead of them. It is reasonable to explain the obtained patterns if the former situation is considered. Since the convergent laser beam irradiates the film, two points exist at which maximum resonance absorption occurs. The electric currents flow upward and downward, respectively, as shown by the arrows. These sheet currents expand into the vacuum space preferentially to form double loops. The self-generated magnetic fields are interlinked across these current loops. These magnetic fields leave four magnetic poles in the film. The N and S combinations correspond to our experimentally obtained pattern.

To confirm that the position of the sheet currents is ahead of the film, another type of laser irradiation was conducted. A polyester sheet 12 μm thick was attached to the film. The front surface of sheet was painted black to absorb the laser energy easily. Thus the magnetic tape was separated from the field source region. The magnetic tape was not burned or discolored by this irradiation. The measured polarities of N and S poles were consistent with our prediction that the sheet currents are ahead of the film.

Now let us compare our data with other experiments using conventional focused- or convergent-laser-beam methods. In the Faraday rotation measurements,[7-9] the clockwise direction of the magnetic fields around the z axis is expressed, though they can detect only the x component in our coordinate system. If this x component is considered, it is consistent with our convergent-beam data. Spot to spot observation by means of magnetic probes indicates the same direction of the fields.[1] For the electric current configuration, our model agrees with the current-probe data where the electric currents flow into the target material.[10]

IV. SMALL-CONE-ANGLE EXPERIMENT

A small full-cone angle of 6° was adopted. The laser beam was incident at an angle of 15°, at which resonance absorption was a maximum.[13] The tape was placed at the focal position. The burned pattern of 50 μm diameter was registered, accompanied by a drilled hole of 20 μm diameter. In the wet pattern shown in Fig. 4(a), we can observe a pair of bold ranges on the inside and a pair of faint ones on the outside. These faint ranges were observed only for this refined observation method. The orientations of these ranges

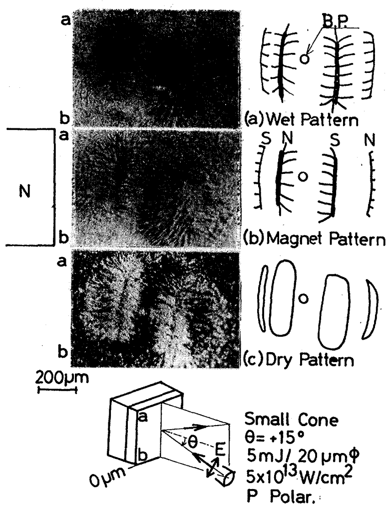

FIG. 4. Example of the self-generated magnetic fields using a cone angle of 6° at the positive incidence angle 15°. The magnetic tape was placed at the focal position $z=0$. The focal diameter was 20 μm. The observed diameter of the burned pattern (B.P.) was about 50 μm. The laser energy was 5 mJ, with a corresponding power density of 5×10^{13} W/cm^2.

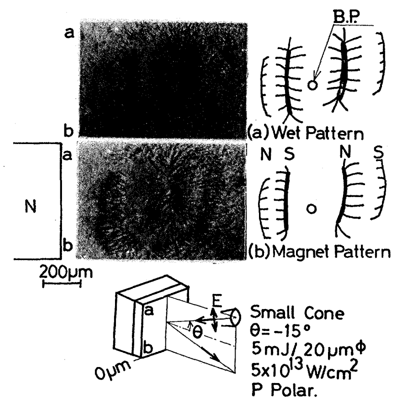

Fig. 5. Example of the self-generated magnetic fields using a cone angle of 6° at the negative incidence angle 15° degrees. The magnetic tape was placed at focal position $z=0$. The focal diameter was 20 μm. The observed diameter of the burned pattern (B.P.) was about 50 μm. A laser energy was 5 mJ, with a corresponding power density of 5×10^{13} W/cm^2.

were parallel to the applied laser electric field. We can observe the magnetic lines of force emerge or enter at each point of these ranges. The orientation of the lines of force is perpendicular to the laser electric field. The magnet pattern is shown in Fig. 4(b), where we find that these ranges correspond to N and S poles. After the developer was evaporated, the dry pattern shown in Fig. 4(c) was obtained. It could be recognized that these ranges changed to the lobes mentioned previously. The lobes rotated to 90° in comparison with the large-cone-angle case.

Parity existence was also verified in the small-cone-angle case by changing the sign of the incident angle, as shown in Figs. 5(a) and 5(b). The observed signs of the N-S poles were inverted, in contrast to the positive-incident-angle case. No parity was observed according to our prediction whether the convergent or divergent beam was used.

The appearance of two pairs of N-S poles and their polarities can be explained if we consider the situation as shown in Fig. 6. It must be assumed the cutoff density surface resides within the ferromagnetic film, contrary to the large-cone-angle case. A sheet current is excited along this surface and forms a single loop, which produces solenoidal magnetic fields around it. These magnetic fields can be considered to produce a pair of N-S poles on the front surface and S-N poles on the rear surface of the film. It can be considered that the former N-S poles correspond to the observed bold ranges and the latter to the faint ones.

In order to confirm the field reversal across the cutoff density, we performed another experiment using the polyester-sheet–magnetic-tape combination as stated in Sec. III. The large sheet thickness of 140 μm was employed. The magnetic tape registered the field distribution without any burned or discolored pattern. This pattern can be considered to be produced by the self-generated magnetic fields behind the cutoff surface. The observed N-S polarities, though they were rather vague, were considered to correspond with those of the faint range where the magnetic tape was

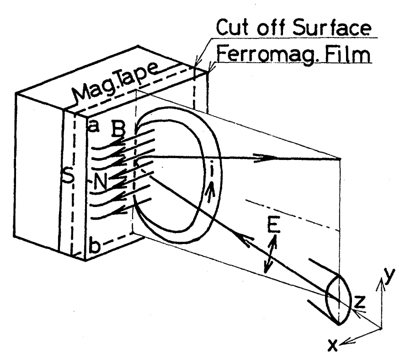

FIG. 6. Illustration showing the qualitative explanation of the self-generated magnetic fields. The laser E field is along the yz plane. A focused laser beam is irradiated at a positive incidence angle on the ferromagnetic film. Self-generated electric current and magnetic fields are indicated as i and B, respectively. N and S poles are registered on the film.

irradiated directly by the laser beam. This observation supports the argument for field reversal across the cutoff surface. This field reversal is an intrinsic property of the resonance absorption, as predicted in Refs. 5 and 6.

One question remains: why does the cutoff surface reside within the ferromagnetic film in the small-cone-angle case in contrast to the large-cone case? This can be explained by its small cone angle and hence its higher power density, which may be apt to lead to self-focusing of the laser beam. Plasma formation within a target by self-focusing was measured by the time-resolved optical methods of the authors,[14,15] where it has been shown that the threshold power density of the self-focusing was 5×10^{12} W/cm^2. In this experiment, by using a power density well above 5×10^{12} W/cm^2, self-focusing can produce a cutoff surface within the film and give the field distribution mentioned above.

An experiment was carried out using the small cone angle and power density of 2×10^{12} W/cm^2, which is below the threshold value. It was observed that the direction of the obtained fields changed, contrary to the higher-power-density case.

Finally we will mention the observation of the s-polarized laser case. In this case, the wet pattern never revealed the straight ranges as in the p-polarization case but showed four to six magnetic poles of the N-S combination. The number of poles, the polarities of the poles, and the direction of the magnetic fields were rather irregular in the shot to shot laser irradiations. These phenomena can be explained if a ripple or cavity at the critical density surface is induced rather randomly to meet the conditions for resonance absorption.

V. SUMMARY AND CONCLUSION

This broad-scale study of self-generated magnetic fields made use of the magnetic-tape method. A refined observation method using dipped tape approaching a bar magnet yielded the wet and magnet patterns, which gave the correct and fine structure of the magnetic field distribution.

A large full-cone angle of 30° at normal incidence gave a pair of self-generated magnetic fields perpendicular to the incident electric field. Parity existence was also verified by means of a divergent beam.

A small full-cone angle of 6° with an incident angle of 15° to the p-polarized laser beam indicated negative and positive magnetic fields across the resonant region. The magnetic fields were perpendicular to the electric field. The parity existence was also verified by reversing the sign of the incident angle. An s-polarized laser beam never gave the regular field distribution as in the p-polarization case.

All these observations strongly suggest that resonance absorption is attributable to the generation mechanism.

ACKNOWLEDGMENTS

We would like to thank J. J. Thomson of Lawrence Livermore Laboratory for valuable suggestions and discussions during his stay in Japan. We would also like to acknowledge the continuing encouragement of Professor I. Arima. We were lucky to have the assistance of S. Nagao throughout this study.

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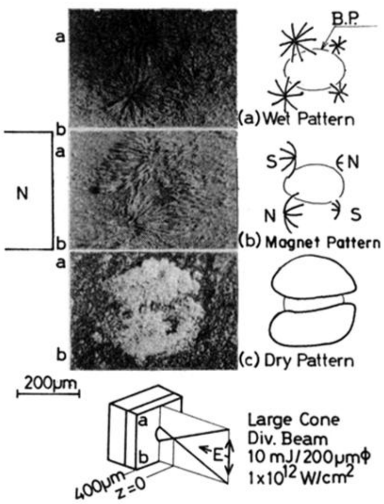

FIG. 1. Example of self-generated magnetic fields using a divergent beam with a cone angle of 30° at normal incidence. The magnetic tape was placed at $z = 400$ μm. The mean diameter of the laser-irradiated area and the observed burned pattern (B.P.) was 200 μm. The laser energy was 10 mJ, with a corresponding power density of 1×10^{12} W/cm^2.

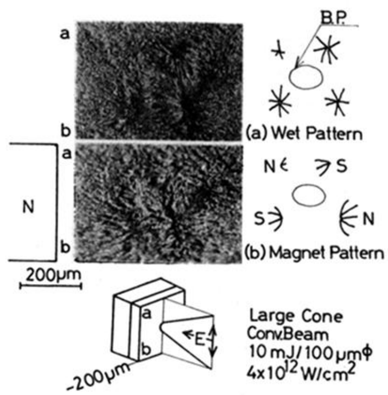

FIG. 2. Example of the self-generated magnetic fields using a convergent beam with a cone angle of 30° at norm-normal incidence. The magnetic tape was placed at $z = 200\ \mu$m. The mean diameter of the laser-irradiated area and the observed burned pattern (B.P.) was 100 μm. The laser energy was 10 mJ, with a corresponding power density of 4×10^{12} W/cm^2.

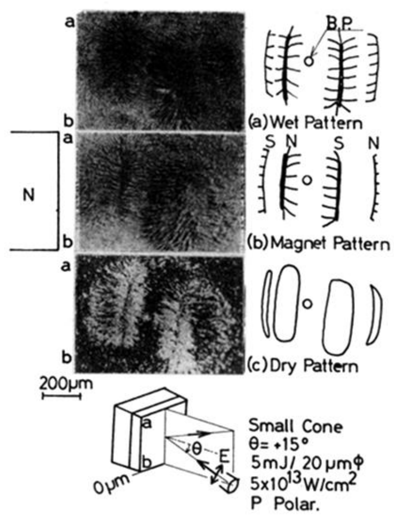

FIG. 4. Example of the self-generated magnetic fields using a cone angle of 6° at the positive incidence angle 15°. The magnetic tape was placed at the focal position $z=0$. The focal diameter was 20 μm. The observed diameter of the burned pattern (B.P.) was about 50 μm. The laser energy was 5 mJ, with a corresponding power density of 5×10^{13} W/cm^2.

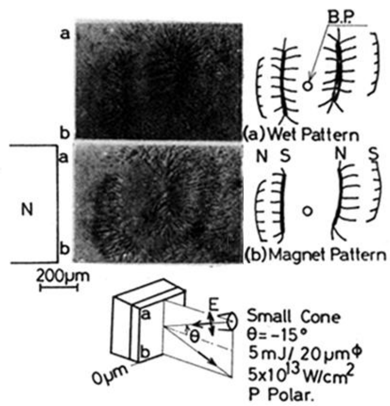

Fig. 5. Example of the self-generated magnetic fields using a cone angle of 6° at the negative incidence angle 15° degrees. The magnetic tape was placed at focal position $z = 0$. The focal diameter was 20 μm. The observed diameter of the burned pattern (B.P.) was about 50 μm. A laser energy was 5 mJ, with a corresponding power density of 5×10^{13} W/cm^2.