shifts are not peculiar to Rydberg states but that the blackbody fields will affect all low-frequency transitions and may be particularly important for high-resolution measurements.

We would like to acknowledge helpful discussions with D. L. Huestis, P. F. Liao, P. Lambropoulos, D. C. Lorents, and R. E. Olson, and we are grateful to F. Gounand for his calculations of alkali lifetimes. This work was supported by the U. S. Air Force Office of Scientific Research under Contract No. F44620-74-0059.

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# Two-Dimensional Distribution of Self-Generated Magnetic Fields near the Laser-Plasma Resonant-Interaction Region

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(Received 6 November 1978)

The two-dimensional distribution of self-generated magnetic fields near the laser-plasma interaction region is observed for the first time by the very simple method of laser irradiation of audio magnetic tape. The lobe structure is a maximum at the incident angle of 10° to 15° for $p$-polarized laser light. The direction of the fields is perpendicular to the density gradient and to the incident $p$-polarization plane. These observations support resonance absorption as the field-generation mechanism.

Self-generated dc megagauss magnetic fields have recently been observed in laser-plasma interaction experiments.[1] Fields of this magnitude can have a substantial effect both on the absorption[2] and transport properties.[3] The original work on this subject concentrated on thermoelectric sources for the magnetic fields.[1,4] Recently, the dc magnetic fields generated concomitantly with the resonance-absorption process have been studied theoretically.[5,6] The diagnostic tools to observe the magnetic fields have been restricted up to now to magnetic probes,[1] Faraday rotation,[7,8] and current probes.[9] They provided measurements of the magnitude of the fields mainly in the vacuum space, but not the detailed geometry near the source region. Knowledge of the field geometry may lend important insight into the proposed generation mechanism. Experiments to reveal the field geometry have been limited to microwave simulations using a divergent beam.[10]

In the experiments reported here, we show the first observation of the two-dimensional distribution of the self-generated magnetic fields near the resonant region by a very simple method. We also show the field-generation mechanism to be attributable to resonance absorption.

The laser irradiation facility at Gifu University consists basically of a neodimium–yttrium aluminum garnet (Nd-YAlG) mode-locked oscillator, a single-pulse selector, and two staged Nd:glass amplifiers. The laser gives a single pulse of 30-ps duration at a wavelength of 1.064 $\mu$m. It was focused on the target through an aspheric lens with a focal length and focal-spot diameter of 37 mm and 20 $\mu$m, respectively. The maximum laser energy was 20 mJ with a corresponding power density of $2\times10^{14}$ W/cm$^2$ in the focal spot. Full cone angles of 6° and 20° were used in the experiments. In the latter case a concave lens was inserted to expand the laser beam.

The two-dimensional field distribution was obtained by using an audio-recording magnetic tape as a target material. The ferromagnetic tape consisted of $\gamma$-$Fe_2O_3$ particles. The mean size of the particle was 0.1 $\mu$m diameter and 0.5 $\mu$m length. The film of thickness 6 $\mu$m was supported by a 12-$\mu$m-thick polyester base. The width of the tape was 3.81 mm which was large enough to register the field distribution. The tape had isotropic sensitivity to the field direction. Spatial resolution was about 2 $\mu$m. The ferromagnetic responsivity was more than 30 MHz. To visualize the field distribution, the Bitter-pattern method[11] was employed; this method is mainly used to ascertain the ferromagnetic domain of steel. In our case, liquid containing magnetite $Fe_3O_4$, the mean diameter of which was 100 Å, was poured onto the laser-irradiated magnetic tape. As the liquid evaporated, the residual magnetite displayed the field pattern. For convenience, a commercially available magnetic-tape developer was used at the sacrifice of spatial resolution and quality of the picture.

In Fig. 1, the two-beam focusing system for $p$ and $s$ polarization is shown. The magnetic tapes could be tilted in the chamber to vary the incident angle. The chamber was evacuated to $1\times10^{-3}$ Torr. A set of calorimeters monitored the incoming laser energy. The distance between two tapes was 10 mm, which was large enough to prohibit the occurrence of cross talk.

In Fig. 2, an example of the field distribution is shown. In Fig. 2(a) the burning pattern is shown before use of the Bitter-pattern method. In Fig. 2(b) the lobe pattern of the self-generated magnetic fields is represented by sprinkling the magnetic-tape developer over the film. The lobe pattern observed is typical for resonance absorption, in contrast to the toroidal geometry caused by the thermoelectric mechanism. The resonance absorption of energy concentrated in lobes was shown theoretically for the first time by Thomson and co-workers.[12,13] The magnetic fields frozen into the expanding, hot plasma can survive on a nanosecond time scale. Perhaps the observed magnetic fields are due to currents induced on the surface of the exposed tape adjacent to the focal spot.

In Fig. 3 the procedure to visualize and identify the field direction is shown. In the upper figure the $B$-$H$ curve of the magnetic tape is shown. The origin corresponds to the initial state. The horizontal axis shows the applied magnetic field intensity upon the tape, and the vertical axis shows the response of the tape. The saturation magnetic flux density, residual magnetic flux density, and the coercive force were 1000 G, 800 G, and 250 Oe, respectively. As the self-generated magnetic field intensity by laser shot was much greater than 250 Oe, labeled 1 in the figure, the tape records the field distribution at 800 G corresponding to state 2. To determine the direction of the self-generated magnetic field, the tape, after the laser shot as shown in Fig. 2(a), was inserted in a homogeneous external magnetic

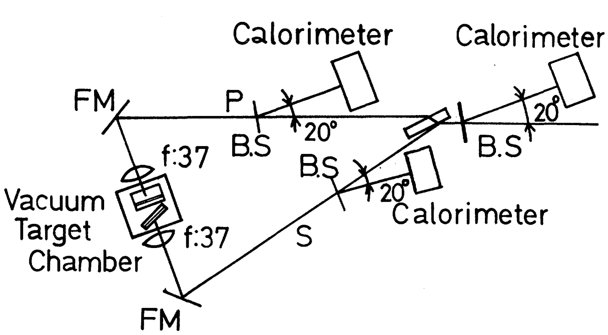


FIG. 1. Two-beam focusing system.

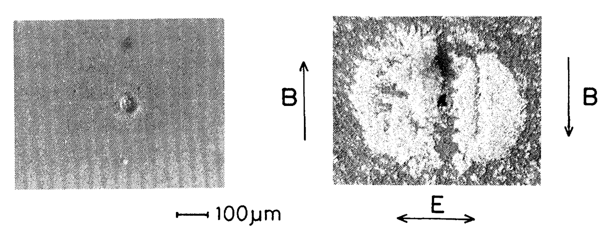


FIG. 2. An example of the self-generated magnetic field distribution for a laser energy of $6\times10^{13}$ W/cm$^2$ incident at 0° with a cone angle of 20°. (a) Burning pattern before use of the Bitter-pattern method; (b) field distribution by the Bitter-pattern method.

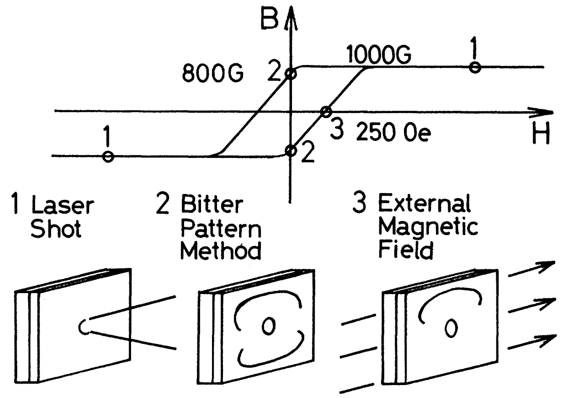


FIG. 3. The procedure to visualize the field pattern and identify the field direction.

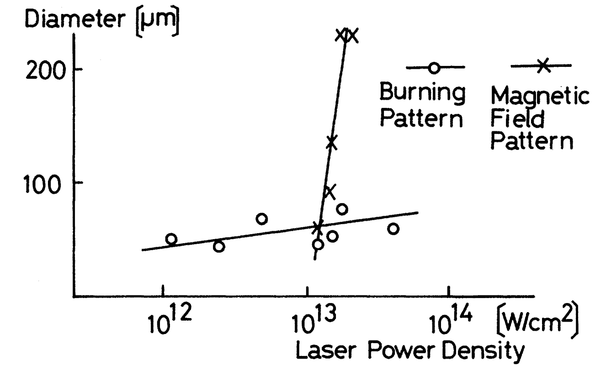


FIG. 4. The diameters of burning pattern and field pattern vs incident laser power density. Cone angle, 20°; incident angle, 0°.

field of a little more than 250 Oe. This state is labeled 3 in the figure. The field pattern, the orientation of which was parallel or antiparallel to the external magnetic field, remained or disappeared correspondingly. Applying an external magnetic field along the direction of the original laser electric field did not produce a strong lobe asymmetry in the direction perpendicular to the electric field. It was found from this method that the magnetic field was almost orthogonal to the $p$-polarized electric field of the laser. The measured direction of the magnetic fields is shown in Fig. 2 by arrows.

The diameters of the burning pattern and the residual magnetic field pattern versus laser power density are plotted in Fig. 4. The diameter of the burning pattern gradually increased, whereas the diameter of the field increased markedly for incident laser energy above $10^{13}$ W/cm$^2$. The field increase above $10^{13}$ W/cm$^2$ corresponds to the magnetic-probe data mentioned in Ref. 3.

The incident-angle dependence of the self-generated magnetic field using a $p$-polarized laser beam was investigated. In this case a cone angle of 6° was employed to make a thin beam. In Fig. 5 typical examples are shown using magnetite in the Bitter-pattern method. In the case of incident angles of 10° to 15°, the lobe structure at large diameters was clearly observed. At the other angles the structure was obscure. The incident angle of 15° corresponding to the absorption maximum for $p$ polarization coupled with Ginzburg's resonance absorption function[14] implies a scale length of $L=(0.7/\sin\theta)^3/k$, where $k$ is the wave number in the vacuum. The gradient scale length estimated by isothermal expansion is given by $L=c_s t$. The estimated temperature of 0.5 keV gives an expansion velocity $c_s$ of $1.5\times10^7$ cm/s. With substitution of 30 ps, the pulse length, for $t$, one gets the scale length of 4 $\mu$m, which agrees

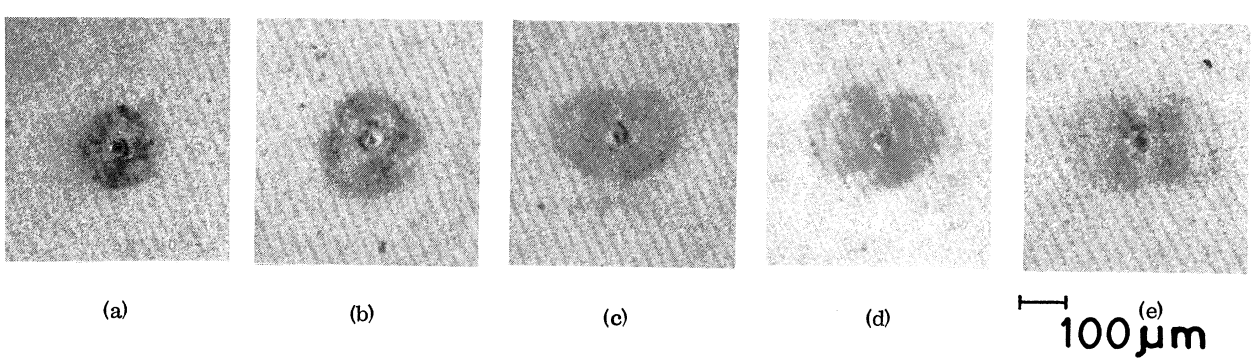


FIG. 5. Incident-angle dependence of the self-generated magnetic fields using $p$-polarized laser beam. The laser energy is $2.4\times10^{13}$ W/cm$^2$ and the cone angle is 6°. The incidence angles are (a) 0°, (b) 5°, (c) 10°, (d) 15°, and (e) 20°.

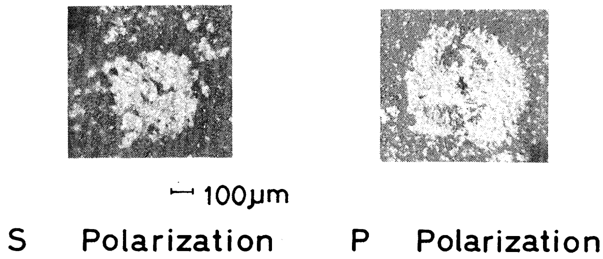


FIG. 6. $s$- and $p$-polarization dependence of the self-generated magnetic fields. The laser energy is $5\times10^{13}$ W/cm$^2$ incident at 10° with cone angle 6°.

with the experimentally obtained value.

In Fig. 6 the $s$- and $p$-polarization dependence is shown using magnetic-tape developer, where the two-beam focusing system was employed to equalize the incoming laser power densities. The cone and incident angles were 6° and 10°, respectively. Only the $p$-polarization case shows a large lobe structure.

Some comments must be added on the lobe structure in the case of the cone angle. The direction of the field was perpendicular to the incident $p$ polarization, but the lobe rotated to 90°. The lobe rotation occurred because of the different illumination geometry. At normal incidence using a 20° cone angle, the incoming and reflected laser beams exist in the same cone. In the case of the 6° cone angle and some incident angles, the reflected beam does not come back into the same cone. Further experiments are being made now.

In summary, we wish to emphasize the use of magnetic tape as a diagnostic. This experiment shows how very simple and effective it can be. The two-dimensional distribution of self-generated magnetic fields near the laser-plasma resonant-interaction region was observed for the first time. The lobe structure, the orthogonality both to the density gradient and to the incident laser polarization, the $s$- and $p$-polarization dependence, and the angular dependence in $p$ polarization, all point to the observed magnetic fields as being generated by resonance absorption.

The authors would like to thank J. J. Thomson of Lawrence Livermore Laboratory for valuable discussions during his stay in Japan. They also would like to acknowledge the continuing encouragement of Professor I. Arima. This work was supported in part by a Grant-in-Aid for Developmental Scientific Research.

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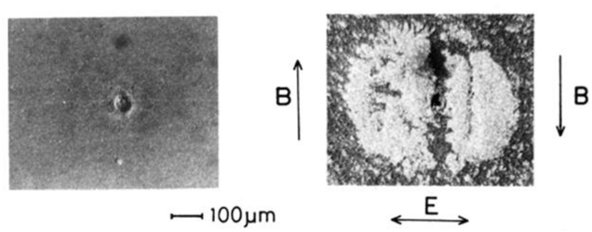


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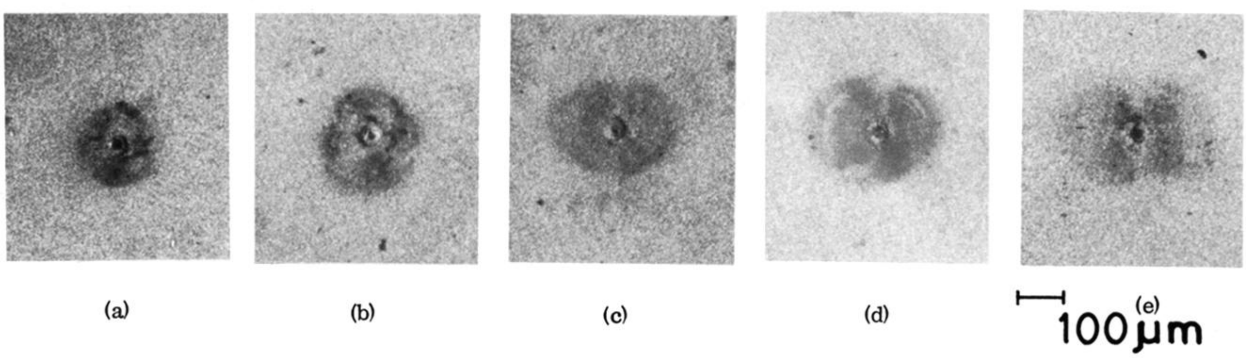


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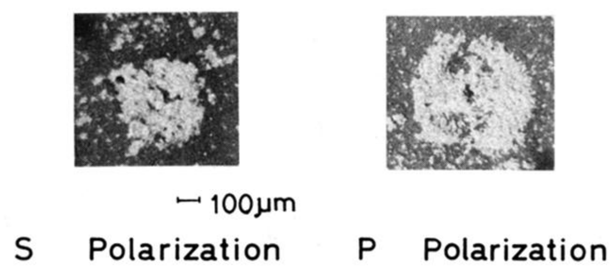


FIG. 6. $s$- and $p$-polarization dependence of the self-generated magnetic fields. The laser energy is $5\times10^{13}$ W/cm$^2$ incident at 10° with cone angle 6°.