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

Paul Kolodner and Eli Yablonovitch
Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138
(Received 19 June 1979)

In a beautiful recent experiment Sakagami *et al.* have recorded, on magnetic tape, the spatial field distribution produced in laser-plasma interaction. The standard infinite-plane theory of magnetic field produced by resonance absorption is unable to explain their experimental observations. This Letter proposes that finite geometry effects in resonance absorption produce a new magnetic field contribution which is responsible for their results.

In a beautiful recent experiment, Sakagami *et al.*[1] have recorded the magnetic fields of laser-plasma interaction on magnetic recording tape. The distribution of field which they observe has the characteristic signature of resonance absorption.[2] That is, the geometry of the magnetic field is dependent on the p or s polarization of the light wave, and the effect is maximum at a finite (nonzero) angle of incidence.

The authors of Ref. 1 invoke the standard theory[3,4] of resonance-absorption–produced magnetic fields to explain their results. These models, however, predict a magnetic field symmetry which is different from what was actually observed. We are particularly concerned with the alternation in sign of magnetic field on opposite sides of the target focal spot and the appearance of a node in between. While such an observation seems reasonable at normal incidence with a wide cone-angle focused laser beam, it is very puzzling with narrow cone-angle beams at large angles of incidence.

In the model[3,4] of magnetic field production by resonance absorption near the critical layer, the dc currents and magnetic fields carry the symmetry of the angle of incidence. The field directions become opposite for positive and negative angles of incidence. Indeed, this has been directly confirmed in microwave resonant plasma experiments.[5] According to this picture, the magnetic field should *not* alternate in sign or have a node with narrow cone-angle beams at large angles of incidence. Furthermore, our usual models predict a narrow[4] magnetic field region near the critical layer, whereas Sakagami *et al.*[1] observed magnetic fields well outside the focal spot. Therefore our standard models do not correspond to the observations of Ref. 1.

In this Letter, we describe a new mechanism for the generation of magnetic fields in resonance absorption. Let us remember that in resonance absorption, the incoming electromagnetic waves are linearly converted to outgoing plasma waves near the critical layer.[6] These, in turn, transfer their energy to an outgoing stream of fast electrons by Landau damping. In an infinite plane plasma (as is usually considered in modeling resonance absorption), the outgoing component of electron motion does not produce any magnetic field since the outward current is exactly canceled by a return current which provides charge neutrality. In finite geometry, however, the return current may follow a different path, producing a current loop and a finite magnetic field. Therefore, the mechanism we are proposing depends explicitly on finite-geometry effects to introduce an addtional contribution to the magnetic field generation.

Let $\vec{J}_0$ be the current density associated with the outgoing stream of fast electrons. (This unidirectional stream has actually been directly observed in gas-target laser-interaction experiments.[7]) If we ignore the displacement current, Ampere's law may be written

$$\nabla\times\vec{B}=(4\pi/c)(\vec{J}_0+\vec{J}_{\rm ret}), \tag{1}$$

where $\vec{J}_{\rm ret}$ is the return current of cold electrons. $\vec{J}_{\rm ret}$ is driven by the small self-consistent electric field which guarantees charge neutrality:

$$\vec{J}_{\rm ret}=\sigma[\vec{E}+(\vec{v}/c)\times\vec{B}], \tag{2}$$

where σ is the electrical conductivity and $\vec{v}$ is the velocity of plasma convection. If we substitute Eqs. (1) and (2) into Faraday's law, the result is the usual formula for magnetic field diffusion, with one additional term:

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times(\vec{v}\times\vec{B})+\frac{c^2}{4\pi\sigma}\nabla^2\vec{B}+\frac{c}{\sigma}(\nabla\times\vec{J}_0). \tag{3}$$

The magnetic field diffuses out from the region of fast-electron current at a rate which depends on the plasma conductivity.

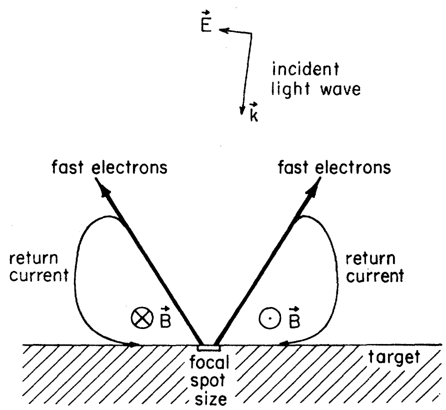

FIG. 1. The incoming light wave is linearly polarized in the plane of the page. The resonantly accelerated electrons and the return currents also tend to be localized in the plane of the page. This results in the magnetic field geometry of Ref. 1.

Initially, the return current exactly cancels the fast-electron stream. With time, the return current diffuses away from the outgoing stream and returns via a different path, causing a net current loop and a magnetic field. Realistically, the current may also return via nearby support structures and metallic surfaces,[8] making an important contribution to the magnetic field in that way.

The fast-electron current $\vec{J}_0$ carries away the energy from resonance absorption. The outgoing current density may therefore be estimated from

$$J_0 = AIe/kT_{\text{fast}}, \quad (4)$$

where A is the absorption fraction, I is the laser intensity per unit area of target surface, kT_{fast} is the typical fast-electron energy produced by resonance absorption, and e is the electron charge. The current density in the focal spot may be substantial, approaching 10^{10} A/cm^2 in the focal spot of a 10^{14}-W/cm^2 laser beam. For conditions typical of a laser-produced plasma, the magnetic field buildup will be limited by the rather high electrical conductivity σ.

The geometry associated with this magnetic field generation mechanism can be visualized in Fig. 1. The outgoing stream of resonantly accelerated electrons has been directly observed in gaseous-target laser-interaction experiments.[7] In resonance absorption, electrons are accelerated nearly parallel to the plasma density-gradient vector. Because of surface roughness, cavitation, rippling, etc., this vector will point in a wide range of directions. Because of the well-known angular dependence of resonance absorption, the electron acceleration is maximum in the plane of polarization of the laser beam. The return currents will also tend to flow predominantly within this plane, producing the field geometry shown in Fig. 1. This geometry has the symmetry observed by Sakagami *et al.*[1]

Some similar issues have been addressed by Raven and Rumsby.[9] They observe a superposition of resonance-absorption–produced fields and a thermoelectrically generated $\nabla n \times \nabla T$ field. Far from the focal spot, neither contribution, nor their superposition, can produce the field geometry observed by Sakagami *et al.*[1]

In conclusion, a consideration of the role played by finite geometry in resonance absorption leads to a new mechanism for magnetic field generation. The return currents which accompany resonant electron acceleration are responsible for the magnetic fields observed in Ref. 1.

[1]Y. Sakagami, H. Kawakami, S. Nagao, and C. Yamanaka, Phys. Rev. Lett. 42, 839 (1979).

[2]J. P. Friedberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, Phys. Rev. Lett. 28, 795 (1972).

[3]J. J. Thomson, C. E. Max, and K. Estabrook, Phys. Rev. Lett. 35, 663 (1975).

[4]B. Bezzerides, D. F. Dubois, and D. W. Forslund, Phys. Rev. A 16, 1678 (1977).

[5]W. F. DiVergilio, A. Y. Wong, H. C. Kim, and Y. C. Lee, Phys. Rev. Lett. 38, 541 (1977).

[6]W. L. Kruer and K. Estabrook, Phys. Fluids 20, 1688 (1977).

[7]P. Kolodner and E. Yablonovitch, Phys. Rev. Lett. 37, 1754 (1976).

[8]R. F. Benjamin, G. H. McCall, and A. W. Ehler, Phys. Rev. Lett. 42, 890 (1979).

[9]A. Raven and P. T. Rumsby, Phys. Lett. 60A, 42 (1977).