Magnetic field in short-pulse high-intensity laser-solid experiments

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High-intensity short laser pulses focused on the surface of a solid target produce large numbers of energetic electrons which in turn produce strong electric and magnetic fields as they penetrate the target. Layers of x-ray-emitting materials buried inside the target are often used to diagnose fast electron transport. We show that the magnetic field grows at the surface of the buried layers, and that this field may in some cases possibly inhibit fast electron penetration. [S1063-651X(98)12708-3]

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Recent developments in laser technology have revolutionized laser-plasma experiments. It is now possible to irradiate solid targets with laser pulses lasting less than 1 psec at intensities exceeding $10^{18}\ \mathrm{W\,cm^{-2}}$. Laser energy is absorbed into a suprathermal population of electrons with energies of 100 keV or more, having collisional mean free paths of the order of 100 μm [1]. In a previous paper [2], we showed that the penetration of fast electrons into the target sets up an electric field, either due to electrostatic charge separation or due to induction, which opposes their penetration and draws an oppositely directed return current in the background thermal plasma. The fast electrons can only penetrate the target to the extent that their current $\mathbf{j}_{\mathrm{fast}}$ can be balanced by a current $\mathbf{j}_{\mathrm{thermal}}$ of thermal electrons. To a good approximation there has to be a detailed local cancellation of the two currents, and the thermal current is driven by an electric field, giving $\mathbf{j}_{\mathrm{fast}} \approx -\mathbf{j}_{\mathrm{thermal}} = -\mathbf{E}/\eta$, where η is the resistivity of the background thermal plasma.

In a second paper [3], we modeled the two-dimensional penetration of fast electrons into a target. The magnetic field at the edge of the circular laser spot focused the fast electrons onto the symmetry axis, causing a degree of beaming into the target. Our estimates showed that the fast electron trajectories are often affected more strongly by the magnetic field than by the electric field, and that the laser intensity at which the magnetic field becomes important is lower than that at which the electric field becomes important.

Fast electron transport is often diagnosed by a layer of high Z material buried a certain distance from the surface of the target. Electrons which penetrate to this layer cause it to emit characteristic x rays. Varying the distance of the layer from the surface gives a means of diagnosing the electron penetration depth. We show here that the presence of the layer may produce a magnetic field which in some cases may possibly be sufficiently strong to limit fast electron penetration, thereby affecting the transport which the layer is intended to diagnose. Our calculations are tentative, semiquantitative, and subject to confirmation by more detailed simulations of specific experiments.

The equations for magnetic field growth [3,4] are

$$\nabla \times \mathbf{B} = \mu_0 (\mathbf{j}_{\mathrm{fast}} + \mathbf{j}_{\mathrm{thermal}}),$$

$$\mathbf{j}_{\mathrm{thermal}} = \frac{\mathbf{E}}{\eta}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{1}$$

where the thermal and fast electron currents no longer cancel exactly but differ by $\nabla \times \mathbf{B}/\mu_0$, which is usually much smaller than both $\mathbf{j}_{\mathrm{fast}}$ and $\mathbf{j}_{\mathrm{thermal}}$. Equations (1) neglect other sources of magnetic field such as the thermoelectric field which may generate field at a material interface [5]. Equations (1) combine to give

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(\frac{\eta}{\mu_0} \nabla \times \mathbf{B} \right) + \nabla \times (\eta \mathbf{j}_{\mathrm{fast}}). \tag{2}$$

This equation identifies a source, $S_B = \nabla \times (\eta \mathbf{j}_{\mathrm{fast}})$, of magnetic field which is resistively diffused through the target by the term $-\nabla \times [(\eta/\mu_0) \nabla \times \mathbf{B}]$. If the plasma resistivity η is uniform, then $S_B = \eta \nabla \times \mathbf{j}_{\mathrm{fast}}$, and the magnetic field grows at points of shear in the fast electron current. Alternatively, the field can grow at points where there is a gradient in the resistivity which is nonaligned with the local fast electron current, in which case $S_B = -\mathbf{j}_{\mathrm{fast}} \times \nabla \eta$. In either case S_B provides a source of magnetic field within the plasma. The magnetic field diffuses about the source with a diffusion coefficient $D = \eta/\mu_0$. By the end of the laser pulse after time τ_{laser} the characteristic diffusion distance is

$$L_{\mathrm{diff}} = \left(\frac{\eta \tau_{\mathrm{laser}}}{\mu_0} \right)^{1/2} = \left(\frac{\eta}{10^{-6}\ \ \Omega^{-1}\ \mathrm{m}^{-1}} \right)^{1/2} \times \left(\frac{\tau_{\mathrm{laser}}}{\mathrm{psec}} \right)^{1/2} 0.9\ \ \mu\mathrm{m}. \tag{3}$$

If the resistivity takes the standard Spitzer value, then

$$L_{\mathrm{diff}} = \left(\frac{Z}{13} \right)^{1/2} \left(\frac{T_{\mathrm{cold}}}{300\ \ \mathrm{eV}} \right)^{-3/4} \left(\frac{\tau_{\mathrm{laser}}}{\mathrm{psec}} \right)^{1/2} \mu\mathrm{m}, \tag{4}$$

where we take $\ln\Lambda = 8.7$ here and throughout the paper. Although L_{diff} could be large for some unionized materials, it is small for conductors or any material which has been heated and ionized. In many cases diffusion can be neglected within the target and the distribution of the magnetic field is determined by the source [3]. The typically low diffusivity also

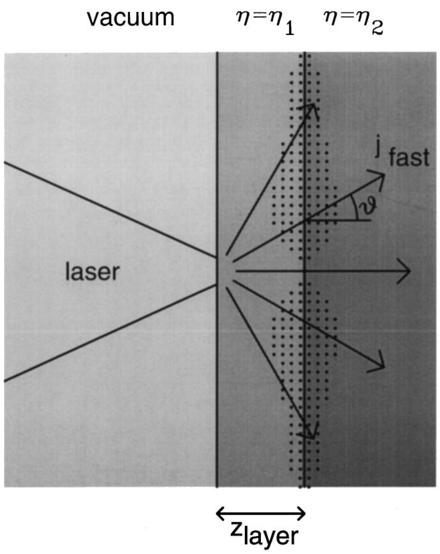

FIG. 1. Schematic diagram of the target consisting of two layers with resistivity η_1 and η_2. The width of the dotted region, which indicates the position where the magnetic field grows, reflects the magnitude of the field rather than its spatial extent.

implies that the magnetic field generated at the target surface, for example by crossed density and temperature gradients $(\nabla n \times \nabla T)$, is unable to penetrate far into the target. It is therefore expected that $\nabla \times (\eta \mathbf{j}_{\text{fast}})$ should be the dominant source of magnetic field within the target.

When targets are constructed of layers of materials with different resistivities, the boundaries between layers can be sites for the growth of magnetic field. The source $\nabla \times (\eta \mathbf{j}_{\text{fast}})$ is necessarily zero in the one-dimensional case of a planar target irradiated by a uniform infinitely large laser spot. However, the laser spot in high intensity experiments is typically 10 μm in radius, and the vector flux of fast electrons has a component perpendicular to the normal to the target surface and therefore perpendicular to $\nabla \eta$, thus leading to magnetic field generation $(S_B \neq 0)$.

We estimate the magnetic field for the case of a target made of two layers of material with resistivities η_1 and η_2, as shown in Fig. 1. For the purposes of estimating the fast electron current, we assume a steady state in which the absorbed laser energy is carried away by the fast electrons. We also assume that the fast electron current is uniform over a hemisphere of solid angle $2\pi r^2$ a distance r (greater than the laser spot radius) from the laser spot. In this case, the absorbed laser power $E_{\text{absorbed}}/\tau_{\text{laser}}$, where E_{absorbed} is the absorbed laser energy in a laser pulse of duration τ_{laser}, can be equated to the rate $(2\pi r^2) j_{\text{fast}} (3T_0/2)$, at which energy is carried from the laser spot by fast electrons with temperature T_0 (in eV). This gives

$$j_{\text{fast}} = \frac{E_{\text{absorbed}}}{3\pi r^2 T_0 \tau_{\text{laser}}}, \tag{5}$$

On the initial assumption that the fast electron current flows unimpeded across the material interface located a distance z_{layer} into the target, we can estimate the source of magnetic field at a distance z from the target surface:

$$S_B = -\mathbf{j}_{\text{fast}} \times \nabla \eta \sim \frac{E_{\text{absorbed}}(\eta_1 - \eta_2)\cos^2\theta \sin\theta}{3\pi z_{\text{layer}}^2 T_0 \tau_{\text{laser}}} \delta(z - z_{\text{layer}}), \tag{6}$$

where $\delta(z - z_{\text{layer}})$ is the delta function, θ is the angle between j_{fast} and the target normal, and the distance from the laser spot is $r = z_{\text{layer}}/\cos\theta$. The source of the magnetic field originates in the jump in the electric field $\Delta E = (\eta_1 - \eta_2) j_{\text{fast}} \sin\theta$ across the interface between the two materials. For the purpose of estimating whether the magnetic field affects the fast electron transport, we neglected the feedback of both the magnetic and the electric field onto the fast electron current, which we assume to be continuous across the interface.

The crucial factor affecting fast electron transport is the integrated magnetic flux $\Phi = \int_{-\infty}^{\infty} B\, dz$ across the interface, where B is in the direction perpendicular to both $\nabla \eta$ and the fast electron current. If the magnetic diffusivity is small, the flux will be concentrated as a large magnetic field close to the interface. If the diffusivity is large, the magnetic field will be smaller but spread over a larger distance in z. In either case Φ is the same, as can be shown by integrating Eq. (2):

$$\Phi = \int_{-\infty}^{\infty} B\, dz \sim \frac{E_{\text{absorbed}}(\eta_1 - \eta_2)\cos^2\theta \sin\theta}{3\pi z_{\text{layer}}^2 T_0}. \tag{7}$$

The magnitude of the magnetic field can be estimated by assuming that (i) $B \sim \int_{-\infty}^{\infty} B\, dz / L_{\text{diff}} \sim \Phi / \sqrt{\eta \tau_{\text{laser}}/\mu_0}$ [from Eq. (3)], (ii) $(\eta_1 - \eta_2) \sim \eta$ for some characteristic resistivity η, and (iii) setting $\cos^2\theta \sin\theta = 0.4$ (its maximum value). In these approximations

$$B \sim \left(\frac{z_{\text{layer}}}{10\ \mu\text{m}}\right)^{-2} \left(\frac{\eta}{10^{-6}\ \Omega^{-1}\ \text{m}^{-1}}\right)^{1/2} \times \left(\frac{\tau_{\text{laser}}}{\text{psec}}\right)^{-1/2} \left(\frac{T_0}{200\ \text{keV}}\right)^{-1} \left(\frac{E_{\text{absorbed}}}{10 J}\right) 240\ \text{MG}. \tag{8}$$

If the resistivity takes the standard Spitzer value, then the difference in resistivity between the two materials will arise from the difference between their ionization states Z_1 and Z_2, giving

$$B \sim \left(\frac{|Z_1 - Z_2|}{10}\right)^{1/2} \left(\frac{T_{\text{cold}}}{300\ \text{eV}}\right)^{-3/4} \times \left(\frac{z_{\text{layer}}}{10\ \mu\text{m}}\right)^{-2} \left(\frac{\tau_{\text{laser}}}{\text{psec}}\right)^{-1/2} \left(\frac{T_0}{200\ \text{keV}}\right)^{-1} \times \left(\frac{E_{\text{absorbed}}}{10\ \text{J}}\right) 220\ \text{MG}. \tag{9}$$

If the magnetic field is large enough, the fast electron Larmor radius is small and the electron transport is magnetized. The fast electrons become magnetized if the gyroradius is smaller than the thickness $\int_{-\infty}^{\infty} B\, dz / B_{\text{char}}$ of the volume occupied by magnetic field, where B_{char} is a characteristic magnetic field at the discontinuity. Hence the parameter determining ''magnetization'' is

$$M = \frac{\int_{-\infty}^{\infty} B \; dz}{r_g B_{\mathrm{char}}} = \frac{\Phi}{\sqrt{m_e T_0 / e}}, \tag{10}$$

where $r_g = \sqrt{(m_e T_0/e)}/B_{\mathrm{char}}$ is the Larmor radius in the field B_{char}. Note that the crucial parameter is the magnetic flux Φ rather than the maximum value of the magnetic field. If $M > 1$, the region occupied by magnetic field is wider than the fast electron gyroradius and the fast electrons are magnetized. Conversely, $M<1$ implies that they are unmagnetized because their gyro-orbit takes them outside the region containing magnetic field. Using Eq. (7), and assuming that the Spitzer resistivity applies,

$$M \sim 20\left(\frac{|Z_1 - Z_2|}{10}\right)\left(\frac{T_{\mathrm{cold}}}{300 \;\; \mathrm{eV}}\right)^{-3/2} \times \left(\frac{z_{\mathrm{layer}}}{10 \;\; \mu\mathrm{m}}\right)^{-2}\left(\frac{T_0}{200 \;\; \mathrm{keV}}\right)^{-3/2}\left(\frac{E_{\mathrm{absorbed}}}{10 \;\; \mathrm{J}}\right). \tag{11}$$

The magnetization M depends strongly on the resistivity, but for our typical parameters it is comfortably above 1, indicating strongly magnetized fast electrons. If this is the case the magnetic field will form an insulating layer at the interface between the two materials. This may be sufficient to inhibit fast electron transport beyond the surface layer, although by symmetry there can be no (azimuthal) magnetic field at the center of the laser spot, at which point fast electrons might leak into the buried layer, and structure in the magnetic field might allow fast electrons to cross the layer by means of cross-field drifts.

Our analysis assumes that the fast electron current is unaffected by the magnetic field, and hence it is invalid once M becomes large, but the analysis is sufficient to determine the conditions in which the magnetic field reaches a value at which it inhibits fast electron transport. Electric fields may reduce the fast electron current, as shown in Ref. [2], but in Ref. [3] we showed that the magnetic field is important at a lower laser intensity than that at which the electric field becomes important. Hence magnetic inhibition may dominate in targets which are strongly two dimensional, because the laser is tightly focused onto a small spot. In one-dimensional configurations where the laser spot is large, the magnetic field will be small and electric field will be the dominant effect inhibiting fast electron transport. In Ref. [2], we listed a number or experiments in which fast electron penetration is strongly reduced below the collisional range. Other very recent experiments such as those by Koch *et al.* [6], Tatarakis *et al.* [7], Saemann and Eidmann [8], and Feurer *et al.* [9] showed similar or related effects. Electric or magnetic fields are candidate explanations for the reduced penetration in these experiments, but a more detailed analysis is needed [7] in each case before firm conclusions can be drawn.

We have considered the change of resistivity across a material boundary as a source of magnetic field, but a similar change in resistivity, although less abrupt, could occur due to the variation in the temperature of the background thermal plasma between the hot target surface and the colder plasma inside the target. This was observed in the calculations presented in Ref. [3], and gave rise to the growth of magnetic field. There are in fact a variety of different experimental configurations in which gradients in resistivity can be expected to generate a magnetic field with a magnitude comparable to that considered above.

In conclusion, a buried layer of x-ray-emitting material is often used to measure the penetration depth of fast electrons. Our analysis shows that it is possible that the magnetic field at the interface with the buried layer may in some cases limit the fast electron penetration at high laser intensity. Our calculations are approximate, and more work on this topic is needed. We can say that in some experiments the magnetic field will have sufficient magnitude to affect the fast electron transport, but we cannot say how large the effect will be. A nonlinear self-consistent transport calculation with the correct geometry is needed if we are to say whether the magnetic field is sufficient effectively to cut off transport into the buried layer, or whether the transport inhibition is marginal. However, our calculations do show that the possibility of magnetized transport inhibition should be considered when designing and interpreting experiments. The use of buried layers to diagnose fast electron transport may be distorting the effect which the buried layer is intended to diagnose.

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