Axial Magnetic Fields in Laser-Produced Plasmas

J. Briand, V. Adrian, M. El. Tamer, A. Gomes, Y. Quemener, J. P. Dinguirard, and J. C. Kieffer
Centre de Physique Atomique, Université Paul Sabatier, Toulouse, France, and GRECO Interaction Laser-Matière, Ecole Polytechnique, Palaiseau, France
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Important axial magnetic fields can grow up through the dynamo effect in laser-matter interactions. The growth rate of these fields is calculated for an isothermal plasma. Faraday rotation on the backscattered emission shows that axial fields in the megagauss range are present in a laser-produced plasma.

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Because of their impact on pellet design in inertial-confinement fusion, self-generated magnetic fields[1] have been the motivation for many experimental and theoretical studies. Toroidal fields in the megagauss range have been inferred from Faraday-rotation diagnostics of laser-produced plasmas.[2-4] It has recently been shown that thermal transport inhibition, lateral transport, and fast plasma blowoff could be related to the properties of these large-scale self-generated magnetic fields.[5-7] From a theoretical point of view, a large variety of mechanisms can produce spontaneous magnetic fields in a laser-produced plasma.[8] Large-scale toroidal magnetic fields can arise from a $\nabla n_e \times \nabla T_e$ mechanism,[1] from hot electron ejection from the focal spot,[9] or from an anisotropic electron pressure.[10] Furthermore, small-scale magnetic fields can be produced by filamentation,[11] resonance absorption,[12] and thermal[13] and Weibel instabilities.[14] It has recently been suggested[15,16] that an axial magnetic field can grow up from these small-scale magnetic fields through the dynamo effect. In this Letter, we recall first how such an effect can produce axial magnetic fields in laser-produced plasmas. Then, we present an analytical evaluation of the growth rate for these fields in the simple case of a self-similar expansion. Furthermore, we present an experiment which indicates that an axial magnetic field of 0.6 MG exists in a plasma produced by the interaction of an intense 0.53-μm laser beam with a plane target.

The classical magnetohydrodynamic formalism[17] gives

$$\frac{d}{dt}\left(\frac{\mathbf{j}}{n_e}\right)=\frac{e^2}{m_e}\left[\mathbf{E}+\mathbf{V}\times\mathbf{B}-\frac{1}{n_e e}(\mathbf{j}\times\mathbf{B})+\frac{1}{n_e e}\nabla p_e-\frac{1}{n_e}\mathbf{R}\right], \quad (1)$$

where $\mathbf{V}$ is the hydrodynamic velocity and $\mathbf{j}$ is the current in the plasma. $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields and m_e, n_e, and e are respectively the electron mass, density, and charge. p_e is the pressure tensor and the last term in Eq. (1) is the momentum gained through collisions (including the thermoelectronic, resistive, and cross-field terms). The terms on the right-hand side of Eq. (1) are the various electric fields which can generate a current $\mathbf{j}$ and then a magnetic field $\mathbf{B}$ (through the relation $\nabla\times\mathbf{B}=\mu_0\mathbf{j}$). The $\nabla p_e/n_e$ term is the classical source of toroidal magnetic fields in the laser-produced plasmas. The $\mathbf{j}\times\mathbf{B}$ term is the Hall effect which is a second-order term and which can be neglected during the initial increase of the magnetic field. The $\mathbf{V}\times\mathbf{B}$ term is the electromotive induction force (the Faraday effect). Usually, in classical magnetohydrodynamics, this term leads to a tying of the **B**-field lines to the flow lines. However, it can also generate axial and/or toroidal magnetic fields through the *dynamo effect.* Indeed, for an isothermal plasma, Eq. (1) gives to the first order $\partial\mathbf{B}/\partial t=\nabla\times(\mathbf{V}\times\mathbf{B})+\eta\nabla^2\mathbf{B}$; η is the magnetic diffusion coefficient related to the magnetic Reynolds number R_m through the relation $R_m=VL/\eta$, where L is the characteristic gradient scale length. If a turbulence on the velocities grows, it can be easily shown (see, for instance Moffatt[18]) that for $R_m >> 1$ a magnetic instability can spread out, giving rise to a feedback process between two orthogonal fields which grow as $\exp(t/t_c)$, where $t_c=L/V$. From wavelength scaling of plasma parameters,[8] the magnetic Reynolds number is

$$R_m=20(I\lambda^2)^{5/3}(2Z/A)^{1/6}\tau/Z,$$

where I is the absorbed irradiance in units of 10^{14} watts per square centimeter, λ is the wavelength in micrometers, Z is the charge, A is the atomic number, and τ is the pulse length in picoseconds. One sees that the condition $R_m >> 1$ is very easily fullfilled in laser-created plasmas. Furthermore, one sees that the characteristic time t_c is very short, some tens of picoseconds. This indicates that the dynamo effect will develop in laser-produced plasmas as soon as these conditions are met. If for instance there is a toroidal magnetic field in the plasma, as produced by the $\nabla n\times\nabla T$ effect, then a poloidal field can develop, giving rise to an axial component and consequently to a helicoidal field. Furthermore, the poloidal field will enhance the toroidal field and for low toroidal fields such a mechanism can act as a new source of field in the plasma. However, the magnetic instability will be limited by the Laplace force which will slacken the plasma motion, and by the Hall term which will produce a rotation of the current lines around **B**. Various other effects such as hot spots, suprathermal electrons, filamentation, and ripples can be origins of the development of a dynamo effect through the production of local fields.

We have done an analytic evaluation of the **B**-field growth rate in the case of a self-similar plasma expansion. For simplicity we consider an isothermal corona, thus neglecting the toroidal fields arising from the $\nabla n_e \times \nabla T_e$ mechanism. Then the density ρ, the velocity **V**, and the field **B** obey the three following relations:

$$\partial\rho/\partial t + \nabla \cdot (\rho \mathbf{V}) = 0, \quad (2)$$

$$(\partial/\partial t + \mathbf{V}\cdot\nabla)\mathbf{V} = -\nabla p/\rho, \quad (3)$$

$$(\partial/\partial t + \mathbf{V}\cdot\nabla)\mathbf{B} = (\mathbf{B}\cdot\nabla)\mathbf{V} - \mathbf{B}(\nabla\cdot\mathbf{V}), \quad (4)$$

where saturation and damping terms have been neglected. We will suppose that the field **B** is independent of θ. Then, doing an expansion of the axial and radial velocity and of the axial (B_z) and radial (B_r) fields around the z axis [assuming $V_r = ru(z)$, $V_z = a(z) + b(z)r^2$, $B_r = r\alpha(z)$, $B_z = \gamma(z) + \beta(z)r^2$, and $r << z$], we obtain to the first order

$$B_r(r,z) = B_m \frac{c_s t r}{z^2}\left(1 + \frac{c_s t}{z}\right)\exp\left(-2\frac{z}{c_s t}\right), \quad (5)$$

$$B_z(r,z) = B_m \frac{c_s^2 t^2}{z^2}\exp\left(-2\frac{z}{c_s t}\right), \quad (6)$$

where c_s is the ion acoustic velocity, and $B_m = c_s(\mu_0\rho_c)^{1/2}$ is the magnetic field arising from the normalization of B in Eq. (4). For instance, $B_m = 2.5$ MG in an Al plasma. The curves in Fig. 1 show the variation of B_r/B_m [Fig. 1(a)] and B_z/B_m [Fig. 1(b)] with time for several values of z and r. These curves are limited to the horizontal asymptote $B/B_m = 1$, which is the value of saturation of the fields (B_m being the field for which the magnetic pressure is equal to the kinetic pressure). Taking into account the Laplace force will smooth the curves near the asymptote. It is clear that an axial magnetic field can increase very quickly to large values through the dynamo effect.

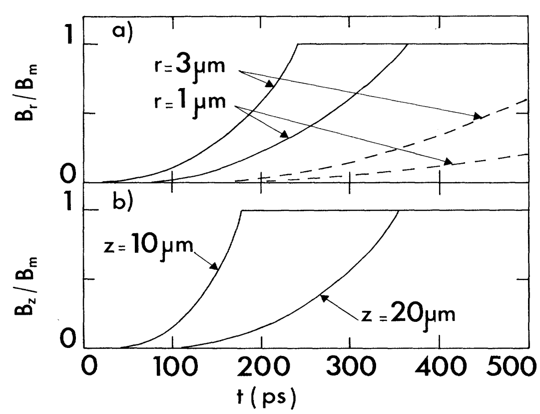

FIG. 1. Variation of the (a) radial and the (b) axial magnetic fields normalized to the maximum value B_m which is the field that gives a magnetic pressure equal to the kinetic pressure. In (a) the solid curves correspond to $z = 10$ μm and the dashed curves to $z = 20$ μm ($c_s = 10^7$ cm/s).

We have performed an experiment which shows that an axial field of 0.6 MG is present in a laser-produced plasma, by analysis of the polarization of the backscattered radiation. Indeed, in the presence of an axial magnetic field in the corona the laser wave, which is initially polarized, will be slightly depolarized and will also undergo a Faraday effect, giving rise to a rotation $\Delta\alpha$ of the polarization of the incident beam. The rotation can be roughly estimated with the usual relation $\Delta\alpha \simeq BL$, where α is in degrees, B is in megagauss, and L, is a characteristic gradient scale length, is in microns. Then, for instance, for $L = 5$ μm one has $\Delta\alpha = 5°$ per megagauss. We use one beam of the GRECO laser system[19] of Ecole Polytechnique in Palaiseau, frequency doubled by a potassium-dihydrogen-phosphate crystal ($\lambda = 0532$ μm) and linearly polarized (P polarization). The beam is focused normally onto a plane infinite Al target to a 50-μm-diam spot by a $f/1$ lens. The experiments have been done at an energy level of 5 J with a 100-ps (full width at half maximum) pulse, producing an irradiance of 10^{15} W/cm.^{2} A part of the incident radiation is sent onto the slit of a streak camera by means of a prismatic slide; this slit is parallel to the direction of the laser polarization. With use of backscattered radiation, the

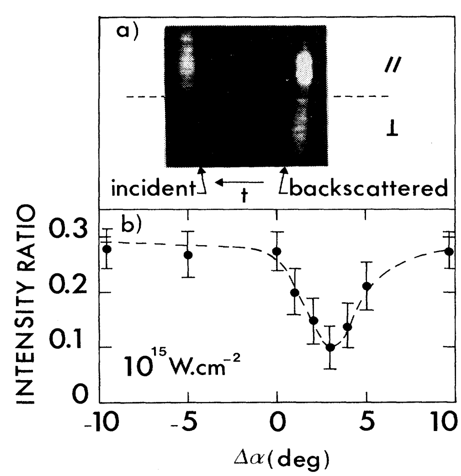

FIG. 2. (a) Experimental result obtained in one shot and showing the incident and backscattered light after passage through the polarization analyzer. Above the dashed line the polarization is parallel to the laser polarization; below it it is perpendicular. (b) Variation of the relative intensity of backscattered emission passing through the polarizer P_1 with the Faraday rotation angle $\Delta\alpha$.

plasma is imaged onto the slit of the same camera, such that the system provides a spatial resolution of about 10 μm. By use of an optical delay line on the direct beam, the two images (laser and backscattered light) are obtained in one shot on the same photograph. The camera slit is such that only an analysis of the thin plasma slice parallel to the initial laser polarization is possible, over its whole length.

Attenuators and a 0.532-μm interference filter were located just in front of the camera slit which was divided into two equal parts. The first part allows the passage of radiation carrying a polarization parallel to that of the laser (P polarization); the other end corresponds to orthogonal polarization, which allows therefore an analysis of an eventual polarization change. Experimental results in Fig. 2(a) show that the laser beam is observed only at one end of the slit while an important part of the backscattered light passes through the orthogonal polarizer (P_1). This polarizer is then turned around its initial position (perpendicular to the laser polarization), with the other polarizer unchanged. The intensity transmitted by P_1 normalized to the intensity of the incident radiation transmitted by the parallel polarizer is given in Fig. 2(b) for various angles of rotation of P_1. We observe a minimum for $\Delta\alpha = 3°$. Neither the classical depolarization processes (by definition of depolarization) nor the other local sources of axial fields can explain the present experimental data. This experiment shows clearly that the backscattered light undergoes a Faraday-rotation effect produced by an axial magnetic field of 0.6 MG as estimated from the previous simple relation.

Depolarization is observed in the Fig. 2(b) and this prevents our obtaining complete extinction. Usually these depolarization effects are related to the density-gradient steepening, the suprathermal electrons, and the resulting modifications of the electron velocity distribution. In our experimental conditions, these effects are not very important (for instance, the hot electron temperature is 5 keV at our irradiance[20]). In P polarization, without axial field, resonant absorption does not produce depolarization and affects only the wave amplitude. Stimulated Brillouin scattering could depolarize. However, in our experimental conditions we are far below the theoretical threshold.[8] All of these effects can depolarize but cannot explain the observed data. The results cannot be explained by an azimuthal asymmetry because of the good laser-beam homogeneity and the good quality of the focusing optics. Furthermore, all the local processes, such as hot spots which could generate axial fields and whose effect could be amplified by the large-aperture optics ($f/1$), would produce only a local Faraday effect. This would be translated on the photograph in Fig. 2(a), which is spatially and time resolved, by a spatial-intensity modulation corresponding to local Faraday rotations. This is not what is observed. The same arguments remain valid for other local effects such as filamentation. Furthermore, we are also far below the filamentation thresholds[8] and therefore the consequences of filamentation do not have to be considered. Nevertheless local effects, when generated, can act as sources of a nonlocal dynamo effect.

A rippled critical surface could generate nonazimuthal magnetic fields. It has recently been shown[21] with structured targets that magnetic fields could develop in the plane of the structures through the dynamo effect. Then the presence of ripples at the critical surface could induce through the dynamo effect radial magnetic fields and consequently axial fields as previously discussed at the beginning of this Letter.

In summary, it seems possible to affirm that an axial magnetic field develops in laser-produced plasmas through the dynamo effect. The growth rate is sufficiently large to produce fields in the megagauss range which can be detected by Faraday rotation on the backscattered emission. These fields, which have been detected in the present experiment at the wavelength of 0.532 μm and in plane geometry could be present in spherical geometry and at shorter wavelengths and could strongly affect thermal transport. Furthermore, it must be noted that the dynamo effect will enhance toroidal fields, which can exist and increase even if the $\nabla n_e \times \nabla T_e$ source disappears.

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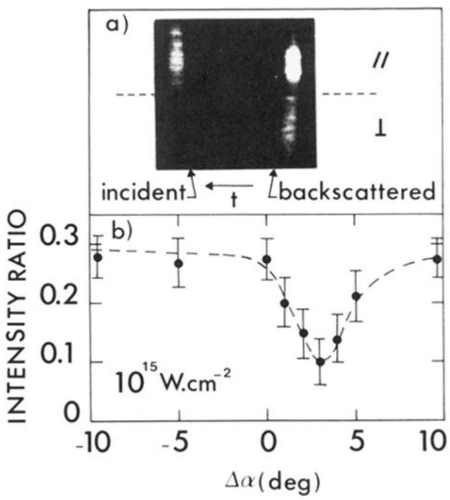

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