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Steady magnetic field generation due to transient field ionization in ultrashort laser-solid interaction

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Using particle-in-cell simulations we show that a steady, megagauss magnetic field can be generated due to ionization dephasing in the interaction of an ultrashort laser pulse with a dielectric target. The magnetic field amplitude is limited by the screening of the laser-produced plasma and depends upon the ionization threshold of the target material rather than the laser intensity.

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Since the advent of table-top-terawatt lasers, there has been a growing interest towards nonlinear optical effects in the interaction of high intensity, ultrashort laser pulses with matter. In particular, transient ionization effects can be used to tailor a laser pulse in space and time as well as to change its spectrum [1]. Prepulse suppression via ionization-induced shuttering has been observed experimentally [2]. Of particular interest are thin foil dielectric targets (typically, plastic foils of sub-μm thickness) which are transparent to laser light below the ionization threshold, and might be used as ultrafast optical shutters. Some recent theoretical studies on transient ionization effects in thin foils dealt with generation of ionization harmonics [3] and related pulse shortening [4], and with pulse shaping [5].

Recently, transient ionization effects have been also considered in the attempt to explain experimental observation of high transparency of thin foil solid targets to 30 fs, $10^{18}\,\mathrm{W\,cm^{-2}}$ pulses [6]. Experiments with longer pulses and metal targets [7] and simulations of laser interaction with fully ionized plasmas [8] also find significant transmission, but much lower than observed in [6], almost within 30 fs. This comparison suggests that the very short pulse duration and transient ionization effects might play an important part. In this framework the possibility to generate a strong steady magnetic field during transient ionization was hypothesized in [6,9]. An effect of this kind was first studied by Wilks, Dawson, and Mori in [10] (hereafter referred to as the WDM model), where the effects of creating a plasma around a laser pulse, *independently* of the intensity and the phase of the latter, were considered. It was found that for an ionization time much less than a laser cycle, the laser wave was ‘‘converted’’ both into transmitted and reflected EM components with upshifted frequency, and into a steady magnetic field $\mathbf{B}_{st}$, which is parallel to the laser field $\mathbf{B}_L$ and approaches the intensity of B_L if the plasma is very overdense with respect to the original frequency. If this would hold also in the interaction of a very intense pulse with a solid target, B_{st} of several MG could be generated. Teychenné *et al.* [9] suggest that in a very thin dielectric foil (with thickness much less than the laser wavelength), an *ultrafast* (i.e., instantaneous) ionization would take place over the whole target volume since the laser field is nearly uniform over the foil, leading to uniform magnetization of the plasma and overdense propagation of the laser pulse as an extraordinary mode [9]. Clearly the proposed mechanism for generation of MG steady fields is very different from already known models [11], which in addition predict steady magnetic fields in the skin layer only.

In this Rapid Communication we use 1D3V PIC simulations with ionization included to study the generation of the steady magnetic field due to transient field ionization effects in a thin foil ‘‘solid’’ target, i.e., the material is taken to be hydrogen with a density typical of solid materials ($\approx 10^{23}\,\mathrm{cm^{-3}}$). It is found that a steady magnetic field is generated, due to the nonadiabatic nature of the plasma response to the EM wave (which is also responsible for magnetic field generation in the WDM model), also known as ‘‘ionization dephasing’’ [12]. However, it extends only over a distance of some skin depths into the overdense plasma, and its amplitude is much smaller than that of the laser field. This is due to the fact that the rapid creation of an overdense plasma leads to an immediate screening of the EM wave, preventing volume ionization of the target and keeping the value of B_{st} close to B_L at the instant of ionization, i.e., when the laser intensity reaches the ionization threshold, and *not* at pulse or cycle peak.

In the simulations both pulses with a ‘‘$\sin^2$’’ envelope, of the form $\sin^2(\pi t/\Delta t_L)$, and with a ‘‘square’’ envelope of the form $\theta(t)\,\theta(\Delta t_L - t)$, with $\theta(t)$ the step function, were studied. Atomic units (a.u.) [13] will be used throughout the paper. The laser frequency was $\omega_L = 0.05$, less than the hydrogen ionization potential ($\omega_H = 0.5$), corresponding to the regime of adiabatic field ionization (AFI). The ionization rate was taken from recent calculations reported in [14]. The nonzero ejection energy of the field-ionized electrons [15] was taken into account; we assumed that it depends linearly upon the electric field. The laser energy loss due to ionization is included introducing a phenomenological ‘‘polarization’’

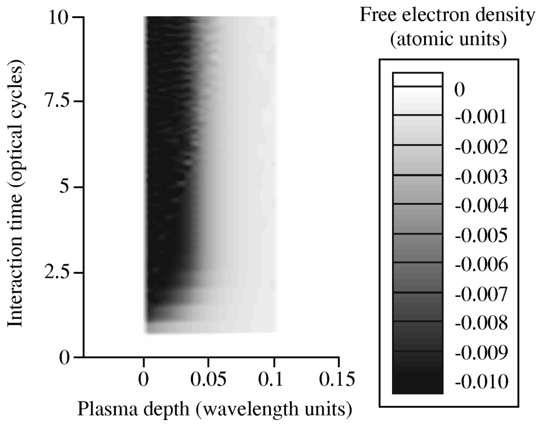


FIG. 1. Spatial and temporal distribution of electron charge density in the target for the case of a ‘‘sin^2’’ pulse. Parameters of the PIC simulation are $E_{Lo}=1.0$, $\omega_L=0.05$, $\omega_p/\omega_L=7$, and $\Delta t_L=10\pi/\omega_L$.

current [16,17]. The effects of ejection energy and laser power depletion due to ionization were also studied by fluid simulations, some of which are reported in [16]; however, they were found not to deeply affect the simulation results.

Figure 1 shows the electron charge density in the foil vs time and space, for a simulation with a ‘‘sin^2’’ laser pulse, peak laser field $E_{Lo}=1.0$ a.u. (corresponding to an intensity of $3.5\times10^{16}\ \mathrm{W\,cm^{-2}}$), pulse duration $\Delta t_L=10\pi/\omega_L=12.5$ fs, density $n_o=0.01$ a.u.$=6.7\times10^{22}\ \mathrm{cm^{-3}}$, plasma frequency $\omega_{po}=\sqrt{4\pi n_o e^2/m_e}\approx7\omega_L$, target thickness $d=0.1\lambda_L$, with $\lambda_L=2\pi c/\omega_L$ the vacuum laser wavelength. The laser impinges from the left. Ionization is almost instantaneous at the left target boundary, i.e., about 80% of electrons are ionized within a single laser cycle. However, we see that about one third of the volume of the target is fully ionized. The depth of the ionized region is about two times the skin depth $d_p=c/\omega_{po}$.

Figure 2 shows the magnetic field, which is found to persist also after the end of the laser pulse. Cases (a) and (b) refer to the cases of a ‘‘sin^2’’ and a ‘‘square’’ pulse, respectively. Other simulation parameters are the same of Fig. 1. The steady field is much less than the laser magnetic field, even in the case (b) of a square pulse, when ionization already occurs at the first laser cycle, causing in particular the sign of B_{st} to change with respect to the ‘‘sin^2’’ case at the same laser intensity. This magnetic field disappears if a fully ionized target is assumed.

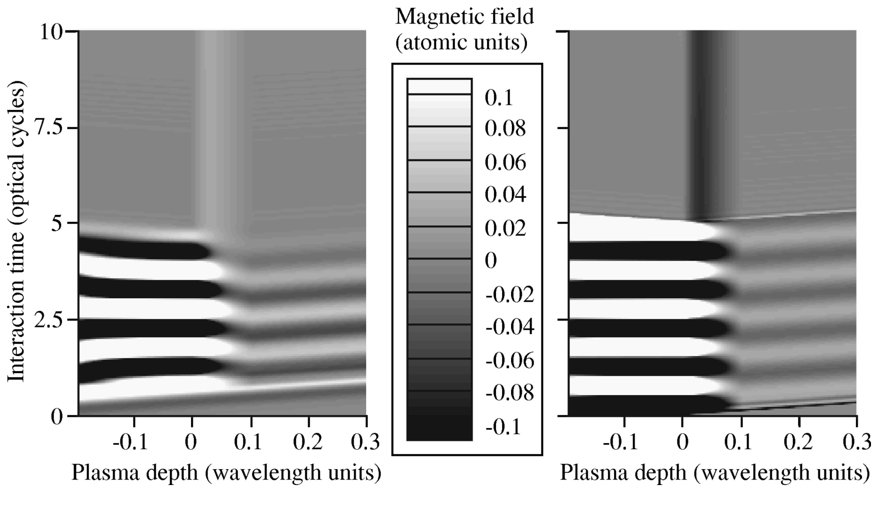
Figure 3 shows the spatial profiles of the magnetic field and free electron density five cycles after the end of the pulse for different field amplitudes ($E_{Lo}=0.1,1,10.0$ a.u.) and also the square profile $E_{Lo}=1$ case. The steady field is always much weaker than the laser field, even for the most intense case and its sign varies according to the phase of the laser cycle, where most of the ionization occurs. Simulations with different slab widths or densities and other pulse lengths have also been performed and similar results have been obtained. Regarding the final density profile, we do not obtain full volume ionization except for the $E_{Lo}=10$ case (corresponding to an intensity of $3.5\times10^{18}\ \mathrm{W\,cm^{-2}}$), which does not yield a noticeably higher magnetic field.

To elucidate the simulation results, and particularly the moderate value of B_{st} with respect to what might be expected from WDM, we discuss how a steady dc current and thus a steady magnetic field are generated in a simple and heuristic way, to show that their origin is the nonadiabatic nature of the response of a bound electron to a very short pulse. Suppose a *single* bound electron to be at rest at $x=0, t=0$. An EM wave with zero rise time (a step envelope) is normally incident on the surface $x=0$ for $t\geqslant0$. To simply model ionization with a nonzero ejection energy, we assume that the electron becomes free instantaneously when the field reaches a threshold value E_T, and has an initial velocity v_I, in the direction opposed to the instantaneous laser field. The solution to the equation of motion of the *single* electron, neglecting the magnetic force, is

$$v_y(t)=v_{qo}(\cos\omega_L t-\cos\omega_L t_I)+v_I, \tag{1}$$

where $v_{qo}=eE_{Lo}/m_e\omega_L$, and we assumed $E_{Lo}\sin\omega_L t_I=E_T$. Thus the ionized electron acquires a steady velocity

$$v_{st}=v_I-v_{qo}\sqrt{1-(E_T/E_{Lo})^2}. \tag{2}$$


(a)

(b)

FIG. 2. Spatial and temporal distribution of magnetic field in the target: the two cases of a ‘‘sin^2’’ (a) and a ‘‘square’’ (b) laser pulse are shown. Parameters are the same as in Fig. 1.

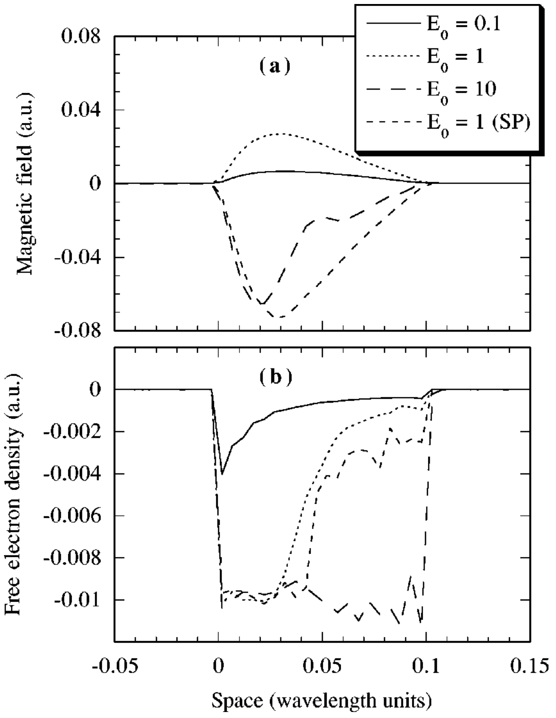


FIG. 3. Spatial distribution of magnetic field (top) and electron charge density (bottom) five cycles after the end of the pulse, for ''$\sin^2$'' pulses with $E_{Lo}=0.1$, 1.0, 10.0, and a ''square'' pulse (SP), with $E_{Lo}=1.0$. Other parameters are as in Figs. 1 and 2.

The larger v_I and the lower E_T/E_{Lo}, the larger v_{st} becomes. It might seem at this point that shaped pulses with very steep rising edges and large densities of instantaneously ionized electrons may lead to ultrastrong dc currents and steady magnetic fields even exceeding the laser field. To show why this is not the case, we first notice that multiplying Eq. (2) by the electron density, and neglecting (for large E_{Lo}) E_T and v_I, we get a dc current $j_{st,n_e\ll n_c}=j_o \equiv(\omega_{po}^2/4\pi\omega_L)E_{Lo}$; if E_{Lo} is proportional to $\sin(k_Lx)$ as in the WDM model, we get a static field $B_{st}\approx(\omega_{po}^2/\omega_L^2)B_{Lo}$, which is the WDM result in a well *underdense* plasma. When the plasma is *overdense* and the *collective* response of the electrons has to be taken into account, the oscillating term in Eq. (1) leads to instantaneous generation of a reflected EM wave that lowers the field of the ''source'' (in the WDM terminology) wave; thus, in the WDM model, the static current is reduced and the magnetic field in a very overdense plasma saturates to the value of B_{Lo}.

The situation is further different when ionization is generated by the ''source'' wave itself. Here, ultrafast ionization leads to instantaneous screening of the EM, wave which will be strongly reflected when n_e becomes larger than the critical density, forcing v_{qo} in Eq. (2) to remain close to its value at $t=t_I$, i.e., $v_{qo}\approx v_q(t_I)=eE_T/m_e\omega_L$.

For hydrogen we may take for E_T the ''critical'' value at which the Coulomb barrier for the bound electron is suppressed by the electric field, i.e., $E_T\approx0.15$ a.u. [15]. The ejection velocity is $v_I\approx0.7$ a.u. [15]. For the parameter of the simulations of Fig. 1, $v_q(t_I)\approx3$ a.u.; therefore, $v_{st}\approx8\times10^8\,\mathrm{cm\,s^{-1}}$. Assuming $n_e\approx10^{23}\,\mathrm{cm^{-3}}$ for the density of instantaneously ionized electrons, the steady current is $j_{st}\approx5\times10^{22}$ CGS units. The spatial scale length of the ionized region is $d_p\approx2.5\times10^{-6}$ cm and thus from Ampere's law we found the order of magnitude of $B_{st}\approx j_{st}d_p\approx2$ MG. In our simulations with a square envelope pulse, $B_{st}\approx0.8$ MG is found. In general, we expect in simulations the steady field to be lower than predicted by our rough model because the dc current is limited by effects of nonzero pulse rise time, finite ionization rate, and ejection velocity statistics; moreover, looking at the ionization rate [15], we see that even at moderate fields (in the tunneling regime) ionization is so fast that $E_T\approx0.15$ a.u. is likely to be an overestimate for the threshold field.

Equation (1) also shows why, even if ionization is nearly instantaneous $[n_e\approx n_o\theta(t-t_I)]$, and the target is a ''thin'' foil, i.e., its thickness is $d\ll\lambda_L$, there is *not* full volume ionization of the target. Since the oscillating current is the same as in a fully ionized plasma of density n_o, the incident wave is allowed to penetrate only over a length $\sim d_{po}=c/\omega_{po}$. The field-ionized region will extend over a region with a depth where the screened electric field is above the ionization threshold; the depth L_I of the ionized region may thus be estimated posing $E(x=0)\exp(-L_I/d_{po})\approx E_T$; for $x>L_I$, the laser field is damped below the ionization threshold. Roughly assuming the surface field to be close to the vacuum field, for $E(x=0)\approx1$, and $E_T\approx0.15$ [18] we find $L_I\approx1.9d_{po}$; for $E(x=0)\approx10$ we find $L_I\approx4.2d_{po}$, close to the target thickness; thus there is a reasonable agreement with the simulations results, considering the roughness of the model.

The first fundamental difference with the physical situation of the WDM model lies in the ''matching'' conditions before and after plasma creation. In the WDM case the instantaneous ionization and the assumption of a plasma with a large extent containing the whole length of the source laser pulse impose the matching of the wavevectors and *not* of the frequencies before and after plasma creation, allowing frequency upshift of the EM wave. In the present case, continuity of the electric field at the plasma-vacuum boundary and, in the limit of instantaneous ionization, across the ionization front, imposes the matching of the frequencies and *not* of the wave vectors [19]. The EM wave in the field ionization-produced plasma always obeys the dispersion relation $\omega_L=\sqrt{\omega_{po}^2+k^2c^2}$, with k becoming imaginary when $\omega_{po}>\omega_L$. The second fundamental difference with WDM is that in that case the creation of the plasma *independently* of the phase of the ''source'' laser pulse leads to the maximum degree of ionization dephasing and nonadiabaticity, since the initial shift between field and velocity varies in space between 0 and 2π. In such a situation the maximum steady velocity equals the quiver velocity. This is not allowed in our situation where the ionization threshold imposes a phase constraint. As a consequence of those fundamental differences the WDM results (in particular the predicted value of the steady magnetic field) cannot be extrapolated to the case of the interaction of a ''single'' laser pulse with a nonionized solid target.

We finally discuss to what extent our numerical results might depend upon the approximations of our physical model. Clearly, in real experiments, transparent dielectric targets are not made of hydrogen only. However, ionization of outer shell electrons, which ionization potentials close to the hydrogen value, should occur at similar field values and is already enough, at solid densities, to create a very overdense plasma. Inner electrons will be ionized by AFI or by collisional ionization at higher intensities and later times. Since they will become free with different phases, they are not expected to contribute collectively to the total dc current. Nonsequential ionization might be beneficial in increasing the number of electrons ionized instantaneously, but is not expected to change dramatically the dc current.

Further limitations might come in principle from the one-dimensional nature of the PIC simulations. Two-dimensional effects are important, for example, for magnetic field generation by thermal or ponderomotive force effects [11]. However, the ionization dephasing mechanism which accounts for the dc current generation does not depend upon the interaction geometry. We may further notice that the mechanism is expected to be more efficient for extremely ultrashort pulses; when focused onto the target, the pulse length will be typically shorter than the spot diameter; thus, spatial boundary effects would be probably negligible. The most important effect neglected in our simulations could be electron-ion collisions, whose importance in a similar context is discussed in [4]; clearly, they are likely to quench rather than increase the ionization-generated steady fields.

In conclusion, we have shown that fast field ionization effects lead to generation of a steady magnetic field of intensity ≈ 1 MG in the skin layer of a solid-density hydrogen target. Simulation results are satisfactorily explained by a simple model of nonadiabatic plasma response. Our results show that the suggestion made in [9] that this effect may lead to enhanced laser propagation is incorrect because of both the too low magnetic field intensity and the absence of volume ionization of the target. As a consequence this effect does not lead to high transparency of thin foil targets as observed in [6], which remains unexplained so far.

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[13] To convert into practical units, the atomic unit values of electric and magnetic field, frequency, and density are $E_{\mathrm{a.u.}}=5.1\times10^{9}\,\mathrm{V\,cm^{-1}}$; $B_{\mathrm{a.u.}}=17.1\times10^{6}\,\mathrm{G}$; $\omega_{\mathrm{a.u.}}=4.1\times10^{16}\,\mathrm{sec^{-1}}$; $(n_e)_{\mathrm{a.u.}}=6.7\times10^{24}\,\mathrm{cm^{-3}}$. The laser intensity corresponding to $E_{\mathrm{a.u.}}$ is $3.5\times10^{16}\,\mathrm{W\,cm^{-2}}$.

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[18] These approximate unequalities overestimate both the surface and the threshold field. The surface field, however, should be increased with respect to the steady state value during the transient phase because of absorption increase by ionization dephasing [12].

[19] Mathematically, the boundary conditions of the WDM model are those of an initial-value problem, while the present case corresponds rather to a boundary-value problem.