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Temporally asymmetric laser pulse for magnetic-field generation in plasmas

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ABSTRACT

Of particular interest in this article, the case study of an asymmetric laser pulse interaction with a plasma for magnetic field enhancement has been investigated. The strong ponderomotive force due to the short leading edge of the propagating laser pulse drives a large nonlinear current, producing a stronger quasistatic magnetic field. An analytical expression for the magnetic field is derived and the strength of the magnetic field is estimated for the current laser-plasma parameters. The theoretical results are validated through the particle-in-cell (PIC) simulations and are in very close agreement with the simulation based estimations. This kind of magnetic field can be useful in the plasma based accelerators as well as in the laser-fusion based experiments.

1. Introduction

During the last few decades, we have witnessed the generation of magnetic field in different areas of physics, such as in cosmic environments (e.g. supernova remnants, gamma-ray bursts), and in laser produced plasmas. Thus, the magnetic fields are found to be important in every scale hierarchy of various plasma systems. The origin of magnetic fields in cosmic and laser produced plasmas has been dealt with great interest in theoretical as well as experimental research [1–3]. The explosive ionization of a solid target with an intense ultra-short laser pulse can generate the largest magnetic fields available terrestrially ($\approx$100 MG). The large magnetic fields are of great significance in laser fusion experiments [4,5], as they can affect the energy flow from the light absorption zone to the ablation region. It is also possible that the strength of these fields can become comparable to those that may exist in many astronomical bodies. Hence, creating models of such astronomical systems in the laboratory may open up new avenues of research in astrophysics. Magnetic field generation mechanisms during laser–solid target interactions have been described by various authors [6–8].

A variety of mechanisms capable of producing large and small-scale magnetic-fields in plasmas have been proposed by now [9–12]. One of the mechanisms is non-collinear density and temperature gradients in a plasma $\nabla n \times \nabla T \neq 0$ [13]. In case of an expanding plasma, the electron pressure gives rise to charge separation; thereby an electric field is produced, which in turn accelerates the ions. In expanding plasma, the density gradient is towards the laser electric field direction at the point of interaction (target normal) and the temperature gradient is in the radial direction. Thus, a dc magnetic field is produced for an optimum angle between the temperature and density gradient, and the generated magnetic field is toroidal. Other mechanism is the ponderomotive force of the laser pulse [14]. The strong axial currents due to the flow of relativistic electrons, axially co-moving with the pulse may also generate a strong magnetic field [15]. Fast electron generation from high-intensity (short-pulse) laser interactions with a solid target may be crucial in this context [16]. High-intensity laser pulses focused on the solid target produce energetic electrons and produce magnetic field as they penetrate to the target [7]. Another mechanism of magnetic field generation in a rarefied uniform plasma is the inverse Faraday effect [17]. Axial magnetic field of tens of kilogauss has been reported experimentally using the Farday rotation diagnostic in low-intensity regime by Horovitz et al. [18]. A huge magnetic field in range of megagauss has been generated by a high-intensity laser pulse by Najmudin et al. [19]. It has also been identified that an inverse Faraday effect is subject to magnetic field generation in inhomogeneous plasmas [20]. The source of azimuthal nonlinear currents and of the axial magnetic field depends on the transverse inhomogeneities of the electron density and laser intensity [21].

Dependence of magnetic field on electron thermal conductivity can create a thermal instability that can also generate dc magnetic fields. Even if the plasma is uniform, a density perturbation across the axial ponderomotive force may grow via electromagnetic oscillation two-stream instability [22] and a magnetic field can be

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produced in this case. Recently, a theory for the self-generated magnetic fields in a collisionless plasma is developed by Liu and Tripathi [23]. Wilks et al. [9] have shown, through numerical simulations, extremely high self-generated magnetic field in an overdense plasma. Sudan et al. [24] have explained analytically the field observed in simulations of Wilks et al. [9]. It is also predicted by numerical simulations that a few hundred megagauss magnetic field can be generated in an overdense plasma [25]. Moreover, intense few-cycle attosecond circularly polarized UV pulses have also been employed to produce intense attosecond-magnetic-field [26]. Spinning attosecond circular electron wave packets are created on subnanometer molecular dimensions, thus generating attosecond magnetic fields of several tens of Teslas.

In general, during the propagation of laser in a plasma, a symmetric laser pulse can become asymmetric because of steepening of the pulse front arising from externally induced nonlinearity (say due to a strong plasma inhomogeneity), backscattering of the laser light, or nonlinear self-modulation and compression of the pulse front. Often any large variation in the refractive index of the plasma can lead to asymmetry of the laser pulse propagating in it [27]. Gordon et al. [28] have proposed an asymmetric self-phase modulation and compression of short laser pulses in plasma channels. Schreiber et al. [29] have characterized experimentally the asymmetrically compression of an intense ultra-short pulses driving a laser wakefield. They have shown that the pulse duration decreases linearly with the density of the plasma. Self-generated magnetic field in a plasma due to a temporally-asymmetric laser pulse having a sharp rise time and a slow fall time scale has not been well studied. In general, the magnetic field is produced due to the inhomogeneity of both the electron density and the intensity of the laser beam. If there is no such inhomogeneity, the latter will contribute nothing. Thus, the implications of a strong magnetic field can be expected by an asymmetric laser pulse. In this work, therefore, we propose to investigate the interaction effects of a temporally asymmetric laser pulse on the yield of self-generated magnetic field from laser-plasma. Often the asymmetry of the laser pulse can be due to a strong plasma inhomogeneity. We employ an asymmetric laser pulse to enhance the magnetic field strength in a plasma. A strong ponderomotive force due to the short leading front of the propagating laser pulse drives out the local electrons, imparting on them a stronger drift velocity. Thus, a large current density will be rotational that produces a quasistatic magnetic field. In this paper, we extend the earlier works on ponderomotive generation of magnetic field in a specialized case, where an asymmetric pulse is introduced for laser-plasma interactions. This paper is organized as follows. In Sec. 2, a model of the proposed work has been described. The results are presented in sec. 3 and 4. Finally, the summary of the results is discussed in the last section.

2. Theoretical model

Consider the propagation of an asymmetric laser pulse in a plasma with electric field assumed to be

$$\mathbf{E} = \hat{z} A \exp\left[\frac{\tau_0^2}{2\tau^2} - \frac{t-t_g}{\tau}\right] erfc\left[\frac{1}{\sqrt{2}}\left(\frac{\tau_0}{\tau} - \frac{t-t_g}{\tau_0}\right)\right] \times \exp\left[-i(\omega t - \mathbf{k}x)\right] \quad \text{and} \tag{1}$$

$$\mathbf{B} = \frac{c}{\omega}\mathbf{k} \times \mathbf{E}, \tag{2}$$

where τ_0 is the laser pulse duration of a Gaussian pulse, τ is the time constant of the precursor exponential, t_g is the retention time of the precursor Gaussian, $k = (\omega/c)[1 - (\omega_p^2/\omega^2)]^{1/2}$, ω is the laser frequency, $\omega_p = [4\pi n_0(x)e^2/m]^{1/2}$ is the plasma electron frequency, $n_0(x)$ is the electron plasma density, c is the velocity of light in vacuum, e and m are the charge and mass of an electron, respectively. Here, we have employed a density gradient, $n_0(x) = n_0^0(1 + x/d_l)$, where d_l is the density gradient length and n_0^0 is the initial electron density.

An asymmetric short laser pulse propagates along the direction of density gradient ($\nabla n_0 \parallel \hat{x}$) in a plasma (where the intensity of the laser has a variation along $\hat{z}$). Response of electrons to the electromagnetic field is governed by the equation of motion

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\frac{e}{m}(\mathbf{E} + \boldsymbol{v} \times \mathbf{B}). \tag{3}$$

Expanding the dependent variables into an equilibrium part and a perturbation part to obtain the oscillatory electron velocity at fundamental frequency as $\boldsymbol{v} = e\mathbf{E}/mi\omega$. The laser exerts a stronger ponderomotive force on the plasma electrons due to the short leading front of the laser pulse, i.e. $\mathbf{F}_p = -(e^2/4m\omega^2)\nabla E^2$. The ponderomotive force produces a drift velocity component at twice of the fundamental frequency in direction of propagation (or in x-direction) which can be calculated by using the equation of motion. We again use the linear expansion to obtain the electron velocity component at twice of fundamental frequency

$$\boldsymbol{v}_d = -\frac{e^2 E^2 \mathbf{k}}{4m^2\omega^3}. \tag{4}$$

Here, the ponderomotive force at fundamental frequency is nonparallel to the density gradient. Thus, the fast oscillations (at fundamental frequency) parallel to z-direction are neglected as they do not contribute as usual in magnetic field generation. The ponderomotive force at second fold of fundamental frequency contributes in accelerating of electrons in axial direction. Thus, in a result, a nonlinear rotational current associated with this electron velocity component can be generated. This nonlinear current can be given by $\mathbf{J}_a = -n_0(x)e\boldsymbol{v}_d$ or

$$\mathbf{J}_a = -n_0(x)e\boldsymbol{v}_d = \frac{n_0(x)e^3E^2\mathbf{k}}{4m^2\omega^3}. \tag{5}$$

This nonlinear current driven by the ponderomotive force produces electric and magnetic fields $\mathbf{E}_a$ and $\mathbf{B}_a$, respectively. The relevant Maxwell's equations are

$$\nabla \times \mathbf{E}_a = -\frac{1}{c}\frac{\partial \mathbf{B}_a}{\partial t}, \tag{6}$$

$$\nabla \times \mathbf{B}_a = \frac{4\pi}{c}\mathbf{J}_a - \frac{1}{c}\frac{\partial \mathbf{E}_a}{\partial t}, \tag{7}$$

Eqs. (6) and (7) are combined as

$$\nabla^2\mathbf{B}_a + \frac{4\omega^2}{c^2}\mathbf{B}_a = \frac{4\pi}{c}\nabla \times \left[\frac{n_0(x)e^3E^2\mathbf{k}}{4m^2\omega^3}\right], \tag{8}$$

which can also be written as

$$\nabla^2\mathbf{B}_a + k'^2\mathbf{B}_a = \frac{4\pi}{c}\frac{n_0^0}{d_l}\frac{e^3E^2k}{4m^2\omega^3}\hat{z}, \tag{9}$$

where $k'^2 = 4\omega^2/c^2$. Eq. (9) is a second order differential equation that can be solved using constant coefficient method. The solution of this equation can give us the generated magnetic field ($\mathbf{B}_a$). Assuming the solution of Eq. (9) as $\mathbf{B}_a = Ae^{-2i(\omega t - kx)} + A'e^{-i(2\omega t - k'x)}$. Substituting this solution in Eq. (9) and equating the coefficients of $e^{-2i(\omega t - kx)}$, one can get the values for these coefficients A and A'. Therefore, the self-generated magnetic field $\mathbf{B}_a$ can be obtained as

$$\mathbf{B}_a = \left(\frac{\omega_{p0}^2}{\omega^2}\right)\left(\frac{mc\omega}{e}\right)\left(\frac{c^2ka_0^2}{\omega^2 d_l}\right)\exp\left[\frac{\tau_0^2}{\tau^2} - \frac{2(t-t_g)}{\tau}\right] \times \left[erfc\left[\frac{1}{\sqrt{2}}\left(\frac{\tau_0}{\tau} - \frac{t-t_g}{\tau_0}\right)\right]\right]^2\hat{z}, \tag{10}$$