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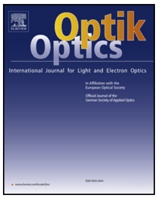

Original research article

Magnetic field generation by amplitude modulated laser pulse in a rippled plasma

Sweta Baliyan[a], M. Rafat[a], Anuraj Panwar[b,*], Vivek Sajal[b], C.M. Ryu[c]

[a] *Department of Applied Sciences and Humanities, Jamia Millia Islamia, New Delhi, India*
[b] *Department of Physics and Material Science and Engineering, Jaypee Institute of Information Technology Noida, UP, India*
[c] *Gwangju Institute of Science and Technology, Gwangju, South Korea*

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ABSTRACT

The mechanism of a self-generated magnetic field by an amplitude modulated laser beam propagation through a rippled plasma is analyzed. The amplitude modulated laser beam exerts a ponderomotive force on plasma electrons, giving them oscillatory velocities at the modulation frequency. The oscillatory velocity couples with the electron density ripple and drives a nonlinear current. This nonlinear current generates a magnetic field. The magnetic field amplitude shows the resonant enhancement at the laser modulation frequency close to the electron plasma frequency, proportional to the ripple density and the laser intensity. In the relativistic case, it also scales directly with the electron plasma frequency and inversely proportional to the square of laser spot size and can approach the order of several hundred-kilogauss.

1. Introduction

Mechanism for the generation of the magnetic field is a fascinating, forefront area of research for both the laboratory [1–3] and astrophysical plasmas [4]. Several mechanisms of magnetic field generation in laser plasma have been proposed [5], for instance non-parallel electron density and temperature gradients $\nabla n \times \nabla T \neq 0$, collision frequency dependent ponderomotive force [6,7], resonance absorption [8–10], thermal instability and strong axial current due to the flow of relativistic electrons [11,12]. In laser-solid interaction experiments an expanding bubble of plasma has perpendicular temperature and density gradients. Such inhomogeneous plasma produces magnetic fields via the Biermann effect [13]. Pukhov et al. [14] observed a strong flow of relativistic electrons along the pulse in 3D PIC simulations of interaction of short pulse laser with a plasma. These high energetic electrons are the source of quasistatic magnetic field up to hundred megagauss. Sudan [15] examined the ponderomotive force driven by spatial and temporal variations of laser pulse. Ponderomotive force played an important role in the generation of large magnetic fields. Berezhiani et al. [16] and Kim et al. [17], showed that due to the interaction of an intense laser beam with a plasma, the plasma becomes inhomogeneous and generates a low frequency current. This current, due to the inverse Faraday effect, produces a quasistatic magnetic field in an underdense plasma. Mora and Pellat [7] showed that the collisional absorption of the laser induced a nonlinear anisotropy in the electron pressure tensor, which is also acts as a source of self-generated magnetic fields. Lei et al. [18] developed a model of a self-generated magnetic field by non-relativistic laser in an initially uniform underdense plasma in the collision dominated limit. They observed that the axial magnetic field is generated only by a circularly polarized laser, whereas the azimuthal magnetic field can be produced by both linearly and circularly polarized laser. Mamta et al. [19] presented the PIC simulations of magnetic field enhancement by an asymmetric laser pulse interaction with a plasma. Tripathi and Liu [20] presented a model of magnetic field

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[*] Corresponding author.
E-mail address: anurajrajput@gmail.com (A. Panwar).

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generation by an amplitude modulated laser filament in a plasma. The laser exerts a time dependent ponderomotive force on electrons. The ponderomove force imparts an oscillatory velocity to electrons and induced nonlinear current density in the presence of plasma inhomogeneity. The non-linear current produces a quasistatic magnetic field. Annou et al. [21] showed resonance enhancement in the self generated magnetic field near the plasma resonance and stated that the magnetic field scales directly proportional with the laser intensity as well as with the plasma frequency, but is inversely with the laser spot size. A. Kumar [22] developed a relativistic theory for the self generated magnetic fields in a collisionless plasma. Pathak and Tripathi [23], showed that Raman shifted backward second harmonic generation is a strong signature of the existence of a transverse static magnetic field in a laser produced plasmas.

Generation of magnetic fields in a rippled plasma is also very important because the presence of such fields can considerably influence the laser beam propagation, radiation generation and nonlinear plasma instabilities. In this paper we have developed a theoretical model for the magnetic field generation by an amplitude modulated laser beam propagating through a density rippled plasma. The physics of the process is as follows: the amplitude modulated laser beam (linearly polarized in the x-direction) whereas the density ripple is in the z-direction as,

$$n_e = n_0^0 + n_e^q \quad \text{and} \quad n_e^q \sim n_q e^{\mathrm{iqz}} \tag{1}$$

where, n_0^0 is the equilibrium plasma density. The laser beam exerts a ponderomotive force on plasma electrons, giving them a drift velocity at the modulation frequency. The oscillatory velocity couples with the electron density ripple and drives a nonlinear current. This nonlinear current generates a large amplitude magnetic field. In Section 2, we have developed an analysis for a linear polarized beam and Section 3 we extended the magnetic field generation analysis for the relativistic Gaussian laser beam. In Section 4, the conclusion is given.

2. Analysis for linear polarized laser beam

Consider the propagation of a modulated and transversely filamented laser beam through a rippled plasma,

$$\overrightarrow{E_l} = \hat{x}A_{l0}\left(1 + \mu\cos\Omega\left(t - \frac{z}{\mathrm{v}_g}\right)\right)\cos\frac{q_l}{2}\mathrm{y}e^{-i(\omega_l t - k_l z)} \tag{2}$$

where, $k_l = \omega_l/c(1 - \omega_{\mathrm{pe}}^2/\omega_l^2)^{1/2}$ and $\mathrm{v}_{gl} = k_l c^2/\omega_l$ is the group velocity of the laser beam, μ is the index of modulation and Ω is the modulation frequency and c is the speed of light. The laser beam imparts the oscillatory velocity to the electrons,

$$\vec{\mathrm{v}}_l = \frac{e\overrightarrow{E_l}}{m_e i\omega_l} \tag{3}$$

where, m_e and e are the electronic mass and charge, respectively. The laser beam exerts a ponderomotive force, $\overrightarrow{F_{\mathrm{pl}}} = e\vec{\nabla}\Phi_{\mathrm{pl}}$ on electrons. The ponderomotive potential in terms of oscillatory velocity becomes as,

$$\Phi_{\mathrm{pl}} = -\frac{m_e}{4e}(\vec{\mathrm{v}}_l\cdot\vec{\mathrm{v}}_l^{\,*}) \tag{4}$$

Using Eqs. (2) and (3) into Eq. (4), we can get the following expression of the ponderomotive potential as,

$$\Phi_{\mathrm{pl}} = \Phi_q + \Phi_p + \Phi_{p+} + \Phi_{p-} \tag{5}$$

where,

$$\Phi_q = \phi_{p0}\frac{\exp(-\mathrm{iq}_l y)}{2} \tag{6}$$

$$\Phi_p = \phi_{p0}\mu\exp\left\{-i\Omega\left(t - \frac{z}{\mathrm{v}_g}\right)\right\} \tag{7}$$

$$\Phi_{p+} = \phi_{p0}\frac{\mu}{2}\exp\left(-i\left\{\Omega\left(t - \frac{z}{\mathrm{v}_g}\right) - q_l y\right\}\right) \tag{8}$$

$$\Phi_{p-} = \phi_{p0}\frac{\mu}{2}\exp\left(-i\left\{\Omega\left(t - \frac{z}{\mathrm{v}_g}\right) + q_l y\right\}\right) \tag{9}$$

and

$$\phi_{p0} = -\frac{\mathrm{e}A_{l0}^2}{4m_e\omega_l^2} \tag{10}$$

Here, we have neglected the constant term because it does not induce the nonlinear current density. The ponderomotive force imparts an oscillatory velocity to electrons at the laser modulation frequency (Ω),