High Energy Density Physics 11 (2014) 80–88

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Enhanced propagation and focusing of an intense laser beam in high density magnetized plasma

Sonu Sen [a,*], Meenu Asthana Varshney [b], Dinesh Varshney [c]

[a] Department of Engineering Physics, Indore Institute of Science and Technology, Indore 453331, India
[b] Department of Physics, M. B. Khalsa College, Indore 452002, India
[c] School of Physics, Vigyan Bhavan, Devi Ahilya University, Khandwa Road Campus, Indore 452001, India

ARTICLE INFO

Article history:
Received 27 May 2013
Received in revised form
11 January 2014
Accepted 28 March 2014
Available online 8 April 2014

Keywords:
Relativistic effects
Laser–plasma interaction
Magnetized plasma
Beam propagation

ABSTRACT

In the present communication, the steady state propagation of an intense, circularly polarized Gaussian electromagnetic beam in high-density magnetized plasma is studied analytically and numerically. The relativistic oscillation of the mass of the electrons in the field of the pump and longitudinal magnetic field are shown to have a major effect on the dynamics of the propagation of intense electromagnetic wave. The wave equation has been solved under WKB and paraxial approximation by expanding the dielectric tensor for arbitrary large intensity. The propagation of electromagnetic waves in magnetized plasma, in the so-called extraordinary mode has been explicitly considered in the analysis. The variation of beamwidth parameter with distance of propagation has been obtained for chosen values of critical parameters in different regimes. These regimes are steady divergence, oscillatory divergence and self-focusing. Numerical computations are performed for a wide range of dimensionless parameters. It is seen that the laser beamwidth tends to attain a constant value depending upon plasma electron density, axial inhomogeneity and laser irradiance for different strength of magnetic field. Further, enhanced propagation, focusing and penetration of an intense laser beam is evident through plots from slightly underdense to overdense plasma with different types of density profiles.

1. Introduction

The interaction between intense laser radiation and matter is known to produce a wealth of nonlinear effects. Those include fast electron and ion generation indicating that ultra-strong electric fields are produced in the course of the laser–plasma interaction. An equally ubiquitous, although less studied, effect accompanying laser–matter interaction is the generation of ultra-strong magnetic field in the plasma. Magnetic field can have a significant effect on the over all propagation and plasma dynamics [1]. Extremely high (few mega gauss) magnetic field play an essential role in the particle transport, propagation of laser pulses, laser beam self-focusing, penetration of laser radiation into the overdense plasma and the plasma electron and ion acceleration [2].

Recent developments of laser technology have made it possible to generate very intense subpicosecond pulses, and experiments are being carried out to explore new regimes of relativistic laser–plasma interaction. When the plasma is irradiated by such lasers with intensities upto $\sim 10^{20}$ W/cm^2, electrons oscillating in the filed of the waves are strongly relativistic. The physics of interaction of such laser pulses with the plasmas substantially differ from that of the lower intensity cases. One of the most interesting applications envisaged for such laser systems is the Fast-Ignitor Concept [3].

Exploring parts of this scheme with PIC codes, researchers have reported significant light absorption, target surface deformation in mildly overdense plasmas and the forgoing of open channels in underdense plasma. They have predicted the occurrence of intense ($\sim$100 MG) magnetic fields in both regimes [4]. Borghesi et al. [5] through experiments and computations got evidence of a single channel formation in the case of picosecond laser pulse propagating in a preformed fully ionized near critical plasma with a density gradient in the laser direction. The central density is about half of the ambient density with a peak on the axis due to magnetic pinching. Simulation predicts 1–30 MeV electrons and magnetic field rising from few Mega-Gauss to 120 MG in dense region. It is established theoretically and experimentally that magnetic field

* Corresponding author. Tel.: +91 9893434639.
E-mail address: ssen.plasma@gmail.com (S. Sen).

http://dx.doi.org/10.1016/j.hedp.2014.03.003
1574-1818/

spontaneously arises in the laser-produced plasmas and the magnitude of the experimentally observed self-generated magnetic field [6,7] is up to a few hundred Mega-Gauss [8]. This self-generated magnetic field can affect the propagation and focusing of laser beam in plasmas.

Pukhov and Meyer [9] have observed the strong magnetic field generated during laser–plasma interaction that can influence the laser beam propagation. Further, it was reported that an S-polarized wave interacting with a sharp boundary plasma has excited an electromagnetic pulse with relativistic amplitude propagating into the overdense plasma and the transition between an opacity regime and a transparent regime for the propagation of the intense laser pulse into the overdense plasma has been discussed. Laser light may self-focus and propagate in underdense and overdense plasmas via., ponderomotive, thermal and relativistic effects. Nonlinear propagation and self-focusing of laser radiation due to collisional and ponderomotive force in an inhomogeneous plasma has been investigated in the past [10–12]. Earlier, we have studied the relativistic self-focusing of laser beam in an inhomogeneous plasma. It is noticed that with ultra-short laser pulses, nonlinearities associated with relativistic effects can provide a source for the generation of coherent radiation at harmonics of the laser frequency. As the electron quiver motion becomes highly relativistic, the plasma response current develops harmonics. A short pulse is more efficient than a long pulse for harmonic generation [13].

Propagation regimes for an electromagnetic beam in magnetized and unmagnetized homogenous plasma have also been studied in the recent past [14,15]. The media with which the electromagnetic wave interacts are in general inhomogeneous; the effect of inhomogeneities on propagation and focusing is of considerable interest. To illustrate the relativistic interaction regime, we consider a free electron in a plane electromagnetic wave propagating, say, in the z-direction, with electric field in the x-direction and magnetic field in y-direction. In the low intensity regime, one can apply the linear response theory for which the electron oscillates along the direction of the electric field. In the relativistic regime, the magnetic field curves the electron trajectory towards the z-direction.

In the present paper, we describe the steady state propagation of an intense, circularly polarized Gaussian electromagnetic beam in inhomogeneous magnetized plasma. The magnetic field can be self-generated or externally applied during laser–plasma interaction. The relativistic oscillation of the mass of the electron in the field of the pump and longitudinal magnetic field are shown to have a major effect on the dynamics of the propagation of intense electromagnetic wave. Analytical formulation in relativistic high-density magnetized plasma is presented in Section 2. The wave equation has been solved under WKB and paraxial theory by expanding the dielectric tensor for arbitrary large intensity. The propagation of the electromagnetic wave in magnetized plasma, in the so-called extraordinary mode has been explicitly considered in the analysis. In Section 3 numerical results and discussion are made for a wide range of dimensionless parameters, defined through critical parameters namely cyclotron-to-beam frequency ratio $\Omega_c = (\omega_c/\omega)$, plasma-to-beam frequency $\Omega_p = (\omega_p/\omega)$ and beam power (p_0). Conclusions are made in Section 4 with current relevance.

2. Analytical formulation

2.1. Effective dielectric constant

The relativistic equation of motion in presence of external magnetic field or due to Inverse Faraday effect (IFE) is

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m v_e) = -e\left[E_L + \frac{1}{c} v_e \times (B_L + B_o)\right] \tag{1}$$

where, γ is the relativistic Lorentz factor which depends on electric field $\mathbf{E}_L$ of laser beam, $\mathbf{B}_L$ and $\mathbf{B}_o$ denotes magnetic field of laser beam and induced magnetic field or externally applied magnetic field respectively. The laser imparts a quiver velocity to the electrons, $\mathbf{v}_e = (e\mathbf{E}/mi\omega\gamma)$ where, e and m are being the electronic charge and rest mass, respectively, $\gamma = [1 + (e\mathbf{E}/m\omega c)^2]^{1/2}$ is the relativistic gamma factor for circularly polarized wave and c is velocity of light in vacuum. At relativistic intensity the beam exert force on the plasma electrons. The radial dependence on index of refraction is then, $\varepsilon = N^2(r) = (1 - \omega_p^2(r)/\gamma(r)\omega^2)$ where, N is the index of refraction, ω is the light frequency and ω_p is the electron plasma frequency.

In the non-relativistic limit an electromagnetic wave can propagate in a plasma when its displacement current is greater than the plasma current with the condition when $\omega > \omega_p$. At high irradiance, the electromagnetic field is strong enough to make electrons move with velocity close to the velocity of light (relativistically) and the cut off frequency is modified due to relativistic effects and the propagation occurs only when $\omega^2 > (\omega_p^2/\gamma)$. In the case of classical propagation it occurs when critical density is greater than ambient density, i.e., $n_c > n$, where $n_c = (m\varepsilon_0\omega^2/e)$. On the other hand, in the relativistic regime the propagation in an overdense plasma takes place once the amplitude of field strength exceeds a certain threshold value.

Consider the propagation of circularly polarized electromagnetic beam in externally applied static magnetic field $\mathbf{B}_o$ (assume to be along the z-axis) in either of the two counter-rotating circularly polarized modes known as extraordinary or ordinary mode of propagation. The electric vector can be written as

$$E_\pm = E_{o\pm}\exp\{i(\omega t - k_{o\pm}z)\} \tag{2a}$$

where,

$$E_\pm = A_{1,2} = E_x \pm iE_y, \quad k_{o\pm} = \left(\frac{\omega}{c}\right)\varepsilon_{o\pm}^{1/2}$$

is the propagation constant. The Gaussian intensity distribution of these modes at $z = 0$ is given by

$$A_{1,2}A_{1,2}^* = E_{o\pm}^2 \exp\left(\frac{-r^2}{r_o^2}\right) \tag{2b}$$

where 'r' is the radial coordinate of the cylindrical coordinate system and 'r_o' is the initial beam width.

At high intensity huge amount of magnetic fields are generated due to the pulse itself, here we assume to be applied externally. This makes the dielectric tensor direction dependent; consequently, dielectric constant of the plasma shows anisotropic behavior. The components of the dielectric tensor are functions of the electric field. The nonlinearity is due to the dependence of the stationary distribution of electron density in the plasma on the field strength, which arises as a consequence of the relativistic dependence of the electron mass on kinetic energy, and the Lorentz force. To study the propagation regimes, we limit ourselves to weak nonlinearity approximation and assume density is same everywhere initially. Considering the time variation of the fields as $e^{i\omega t}$, we obtain the steady state solution of Eq. (1) due to static magnetic field only (here).

Following Sodha et al. [16] and analysing on the similar lines of Asthana et al. [17] the effective dielectric tensor in magnetized