Self-Guidance and Self-Focusing of Rippled Electromagnetic Radiation Pulse in High Density Magnetoactive Plasma

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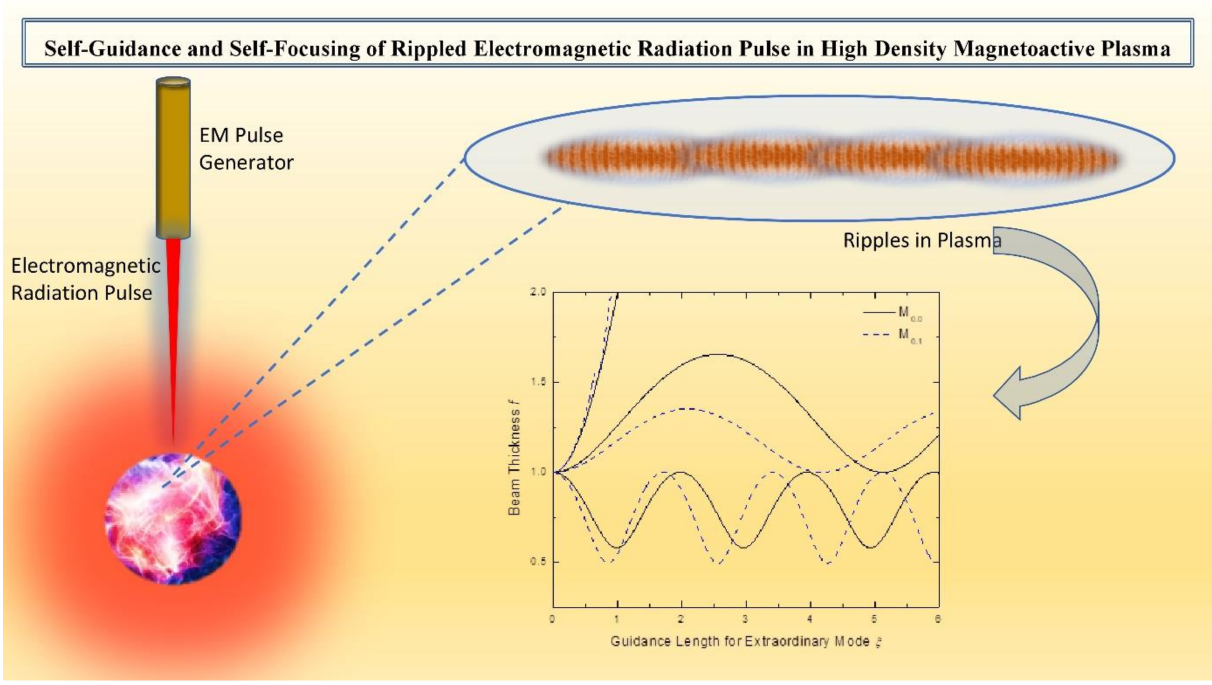
Date Received: 02-01-2023 Date Accepted: 04-05-2023

Graphical Abstract



Abstract

Inside the plasma, when an intense rippled electromagnetic radiation pulse experiences self-focusing, one need to taking account of radial expansion in view of charge displacement due to ponderomotive force on electron and variation in the mass of oscillating electron under the influence of relativistic effect due to electromagnetic field. The extraordinary-mode (E-mode) propagation in a magnetoactive plasma, with stationary magnetic field, which is analogous to the wavering magnetic field of the electromagnetic radiation pulse, is the key feature for the self-guided propagation of rippling electromagnetic radiation pulse in magnetoactive plasma. If the condition for ultra-fast volume ionization is achieved, the radiation pulse itself can generate such a stationary magnetic field. It is demonstrated that external magnetic field affects the channels, causing them to bend. These effects cast new light on the phenomena of self-focusing of rippled electromagnetic radiation pulse. They raise the possibility of combining energy from several channels into one. It is found that the magnetic field strongly influences the plasma dynamic behavior and overall propagation of rippled electromagnetic radiation pulse.

Keywords: *Self-focusing, Self-guidance, Magnetized-plasma, Beam-propagation, Nonlinearity.*

1. Introduction

With the recent growth in the electromagnetic radiation engineering and technology, facilitated it to produce ultra-short electromagnetic radiation pulses having high power intensity band of above 10^{20} W/cm^2, changes the situation to fully novel rules for the collaboration of electromagnetic radiation pulse with plasmas. The innovative results which were never reached before are now achievable with the development of muti-functioning femto- and terra watt electromagnetic radiation pulse interaction with plasma. Therefore, the phenomena of electromagnetic radiation pulse interaction with plasma are appealing highly consideration of researchers now a days. Current studies with a highly ultra-short electromagnetic radiation pulse and plasma having concentration of interaction density is greater than 0.1 times of the critical density concentration have exposed an example of charge particle acceleration and the particles are continuously escalated by electromagnetic radiation pulse (Fuchs et al. 1998; Tabak et al. 1994; Mason et al. 1998). Due to interaction of electromagnetic radiation pulse with charge particle leading to betatron resonance, hence plasma produces both the axial and azimuthal components of magnetic fields.

Irradiance of solid target increases the high density charged particles which cannot be thermally expanded due to the very short duration of the electromagnetic pulse. The electromagnetic pulse cannot then intensely penetrate the plasma and interrelates only with sharply edged plasma surface. For classically dense plasma there is an increase in effective mass of charge particle and decrease in plasma frequency due to influence of high intensity of electromagnetic pulse. Sign of this conversion from surface to volume electromagnetic pulse plasma interaction is the existing challenge. The condition appears changed when electromagnetic wave propagates in matter. The matter shows highly nonlinear behavior at high electromagnetic field strengths. The generated magnetization is no longer similar to that of internal filed strength. Thus, the nonlinearity occurred due to the coupling of electromagnetic wave with plasma causes a number of procedural and very interesting phenomena. The variety of inhomogeneous nonlinear extremely sharp electromagnetic radiation pulse interactions that appear in plasma, with the appearance of magnetic lines of forces having quasistatic in nature is certainly to be one of the utmost significant and interesting, mainly for the occurrence of these fields might be significant impact on the inclusive plasma dynamics.

Propagation of intense laser beams (Varshney et al. 2016; Javan et al. 2014; Sen et al. 2014), self-focusing (Asgharnejad et al. 2021; Karanpreet Virk et al. 2021; Patil et al. 2013) and cross focusing (Gupta et al. 2016; Varshney et al. 2013) of electromagnetic modes with in the magnetoactive plasmas been explored in the past for different types of nonlinearities. The phenomena of self-trapping and self-focusing of electromagnetic laser radiation in magnetoactive plasma has been explored when collisional nonlinearity leads on the extended period range and when ponderomotive nonlinearity leads on shorter period range (Sinha et al. 1980). In the existence of Earth's magnetic lines of forces, electromagnetic radiation self-focusing on ionosphere and filamentation in plasmas has also been studied (Sodha et al. 2007, 2008). The nature of plasma medium is generally inhomogeneous, when electromagnetic beam interacts with it, hence this is a matter of significant attention. In this article, we describe self-guidance and self-focusing of rippled electromagnetic radiation pulse in high density magnetoactive plasma. This magnetic field may be applied externally or generated itself during electromagnetic radiation pulse interaction with plasma. Due to the influence of this self-produced or external magnetic lines of forces the relativistic oscillation of charged particles revealed key outcome on mechanics of guidance of electromagnetic radiation pulse.

In high density magnetoactive plasma analytical formulation for rippled electromagnetic beam propagation is presented in section 2. The wave equation for propagation length of electromagnetic beam has been solved under WKB and paraxial theory. For an extensive choice of critical parameters namely cyclotron-to-beam frequency ratio ω_c/ω and plasma-to-beam frequency ω_p^2/ω^2 numerical results and discussion are made in section 3. With the current relevance of present work conclusions are made in section 4.

2. Rippled Electromagnetic Beam Propagation

The operative dielectric tensor for the rippled electromagnetic beam in plasma due to influence of magnetic field and variation in the mass of charged particle expressed by (Sodha et al. 1974)

$$\varepsilon_{\pm} = \varepsilon_{o\pm} + i\varepsilon_{2\pm} \tag{1}$$

and $$\varepsilon_{zz} = \varepsilon_{ozz} + \varepsilon_2 \tag{2}$$

where, $$\varepsilon_{o\pm} = 1 - \frac{\omega_p^2}{\omega^2(1 \mp \omega_c/\omega)};$$

in the above Equation (2) the term $\varepsilon_{ozz} = \left(1 - \omega_p^2/\omega^2\right)$ is the linear term and ($\varepsilon_{2\pm}$, ε_2) are the nonlinear terms. In the presence of electromagnetic filed due to the oscillation of charged particle, the maximum kinetic energy with relativistic magnitude is given by

$$E_{\text{kin}} = \left[mc^2\left(1+\frac{e^2E^2}{m^2\omega^2c^2}\right)^{1/2} - mc^2\right] \tag{3}$$

Where E represents the real maximum electric strength of the electromagnetic beam, ω is the frequency of electromagnetic beam, and speed of light is c in absence of any medium. Hence, when magnetic lines of forces is produced along propagation axis of electromagnetic radiation pulse, the operative dielectric function can be rewritten as

$$\varepsilon'_{\pm} = \varepsilon'_{o\pm} - r^2\varepsilon'_{2\pm}(f) \tag{4}$$

The general rippled electromagnetic beam equation for the plasma is written as,

$$\left(\frac{\omega^2\varepsilon.\boldsymbol{E}}{c^2}\right) - \nabla(\nabla.\boldsymbol{E}) + \nabla^2\boldsymbol{E} = 0 \tag{5}$$

The two different modes of propagation for rippled electromagnetic beam in a magnetized plasma are represented by following equation (Sen et al. 2014)

$$\frac{\omega^2}{c^2}\varepsilon'_{+}\boldsymbol{A}_1 + \frac{\partial^2\boldsymbol{A}_1}{\partial z^2} + \left(\frac{1}{2}+\frac{\varepsilon_{o+}}{2\varepsilon_{ozz}}\right)\left(\frac{1}{r}\frac{\partial\boldsymbol{A}_1}{\partial r}+\frac{\partial^2\boldsymbol{A}_1}{\partial r^2}\right) + \left(-1+\frac{\varepsilon_{o-}}{\varepsilon_{ozz}}\right)\left(\frac{1}{r}\frac{\partial\boldsymbol{A}_2}{\partial r}+\frac{\partial^2\boldsymbol{A}_2}{\partial r^2}\right) + \left(i+\frac{i\varepsilon_{o-}}{\varepsilon_{ozz}}\right)\frac{\partial^2\boldsymbol{A}_2}{\partial x\partial y} = 0 \tag{6}$$

$$\frac{\omega^2}{c^2}\varepsilon'_{-}\boldsymbol{A}_1 + \frac{\partial^2\boldsymbol{A}_2}{\partial z^2} + \left(\frac{1}{2}+\frac{\varepsilon_{o-}}{2\varepsilon_{ozz}}\right)\left(\frac{1}{r}\frac{\partial\boldsymbol{A}_2}{\partial r}+\frac{\partial^2\boldsymbol{A}_2}{\partial r^2}\right) + \left(-1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\left(\frac{1}{r}\frac{\partial\boldsymbol{A}_1}{\partial r}+\frac{\partial^2\boldsymbol{A}_1}{\partial r^2}\right) + \left(-i-\frac{i\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\partial^2\boldsymbol{A}_1}{\partial x\partial y} = 0 \tag{7}$$

Here, in the Equation (6) and (7) $\mathbf{A_1}$ and $\mathbf{A_2}$ shows amplitude for two different modes viz ordinary and extraordinary modes of rippled electromagnetic beam which are loosely coupled with each other. Also, as the change in the value of filed in the direction perpendicular to z axis is very slow, therefore we will consider only one mode (extraordinary mode) at one time and its behavior of propagation is studied inside the plasma. Let us consider magnitude of extra ordinary mode equal to zero hence equation for the magnitude of ordinary mode can be written as

$$\frac{\partial^2\boldsymbol{A}_1}{\partial z^2} + \frac{1}{2}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right)\boldsymbol{A}_1 + \frac{\omega^2}{c^2}\varepsilon'_{+}\boldsymbol{A}_1 = 0 \tag{8}$$

In the same manner if we consider magnitude of ordinary mode equal to zero similar equation for the magnitude of extra ordinary mode can be derived. To find the general solution for derived equations WKB approximation is used and Equation (8) expressed as

$$\boldsymbol{A}_1(r,z) = A(r,z)\,exp\{\,i(\omega t - \frac{\omega}{c}\int[\varepsilon'_{o+}]^{1/2}\,dz\}\left[\frac{\varepsilon'_{+}(0)}{\varepsilon'_{+}(f)}\right]^{1/2} \tag{9}$$

Where $\quad k_{+}(f) = \frac{\omega}{c}[\varepsilon_{o+}(f)]^{1/2}$

The propagation length of electromagnetic beam is given by z and here *f* is the function of propagation length which is known as beam thickness parameter. By using above analysis, we get the differential equation for beam thickness parameter and propagation length (Sen et al. 2014)

$$\frac{d^2f}{dz^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\varepsilon'_{2+}(f)f}{\varepsilon'_{o+}}=\frac{c^2}{4\omega^2\varepsilon'_{o+}r_o^4f^3}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)^2 \quad (10)$$

For the normalization of above equation, we use $\xi = zc/\omega r_o^2$

$$\frac{d^2f}{d\xi^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\varepsilon'_{2+}(f)f}{\varepsilon'_{o+}}=\frac{1}{4\varepsilon'_{o+}f^3}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)^2 \quad (11)$$

Equation (11) governs change in rate of beam-thickness with guidance-length of electromagnetic radiation pulse.

3. Results and Discussion

The numerical investigation of self-guidance and focusing of rippled electromagnetic radiation pulse in high density magnetoactive plasma are presented here. Aimed at the better understanding of equations obtained, numerical computations are done by using PTC Mathcad for the standard values and parameters of electromagnetic beam interaction with plasma. Change in rate of beam-thickness with guidance-length for extra ordinary mode of rippled electromagnetic radiation pulse for high concentration magnetoactive plasma is depicted in Figures (1-3) by using OriginLab.

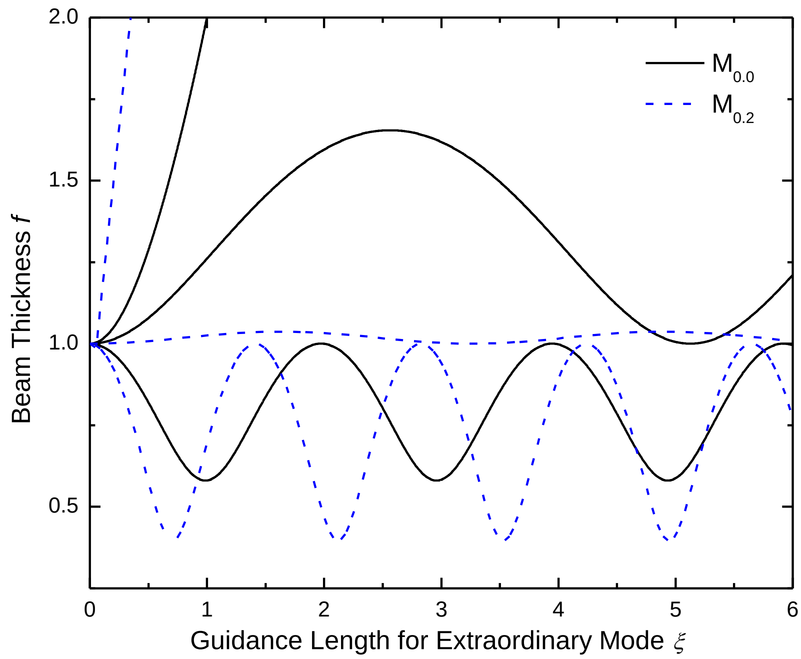


Figure 1: Change in rate of beam-thickness with guidance-length for extraordinary mode of rippled electromagnetic radiation pulse, corresponding to initial points $(r_o\omega/c) = 0.5, 2.0, 5.0$ and $(e^2E_0^2/m^2\omega^2c^2) = 10, 20, 30$ respectively; At $\omega_p^2/\omega^2 = 1.8$ and $\omega_c/\omega = 0.0$ $(M_{0.0}), 0.20(M_{0.2})$.

The three different categories of curves obtained here in absence of magnetic field and in presence of magnetic field are specifically for divergence, guidance, and focusing of rippled electromagnetic radiation pulse inside the plasma. From graphical investigation of equations, in Figure 1 it is projected that on growing magnitude of magnetic lines of forces, divergence of electromagnetic radiation pulse tends to self-guided mode. The wavelength period decreases in focusing area and focus spot shifted near to each other, thus guidance length of rippled electromagnetic radiation pulse increases. For one another set of parameters as mentioned in Figure 2, if magnitude of magnetic lines of forces decreases, the self-guided mode of electromagnetic pulse tends to divergence but still it is less diverging as compared to divergence in absence of magnetic field.

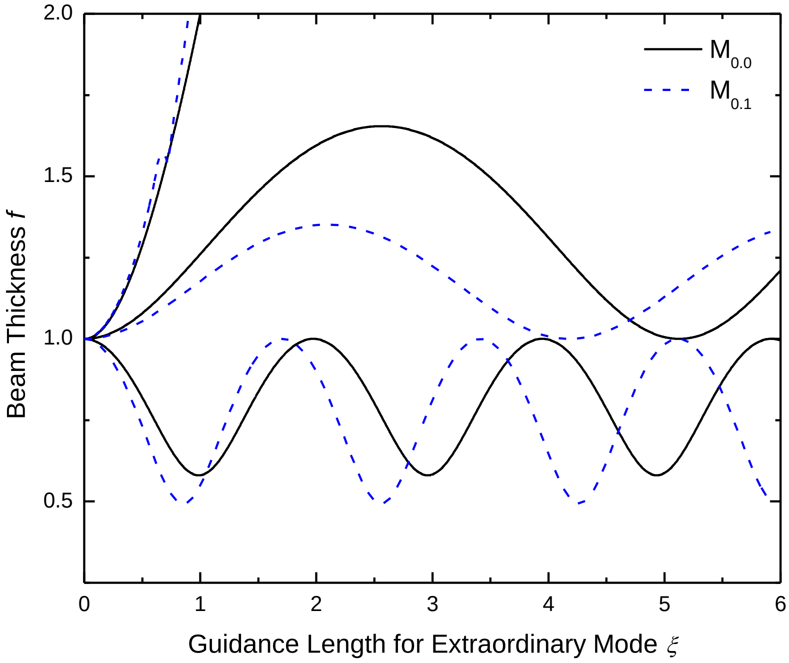


Figure 2: Change in rate of beam-thickness with guidance-length for extraordinary mode of rippled electromagnetic radiation pulse, corresponding to initial points $(r_o\omega/c) = 0.5, 2.0, 5.0$ and $(e^2E_0^2/m^2\omega^2c^2) = 10, 20, 30$ respectively; At $\omega_p^2/\omega^2 = 1.8$ and $\omega_c/\omega = 0.0$ $(M_{0.0}), 0.10(M_{0.1})$.

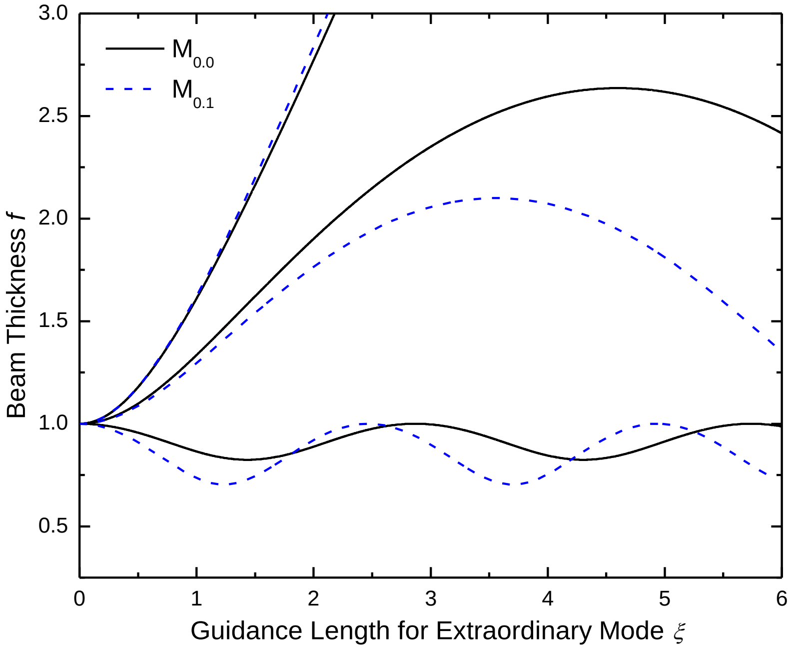


Figure 3: Change in rate of beam-thickness with guidance-length for extraordinary mode of rippled electromagnetic radiation pulse, corresponding to initial points $(r_0\omega/c) = 0.5, 2.0, 5.0$ and $(e^2E_0^2/m^2\omega^2c^2) = 10, 20, 30$ respectively; At $\omega_p^2/\omega^2 = 0.5$ and $\omega_c/\omega = 0.0$ $(M_{0.0})$, $0.10(M_{0.1})$.

Figure 3 shows the divergence, oscillatory divergence, and focusing of rippled electromagnetic radiation pulse for lesser value of plasma-to-beam frequency ω_p^2/ω^2. As can be seen in figure 3 for reduced value of plasma-to-beam frequency divergence is more while there is enhancement in defocusing of the electromagnetic pulse. Thus, it's a clear indication that in high density magnetoactive plasma, with grow in the magnitude of magnetic lines of forces, improvement in guiding and the focusing of rippled electromagnetic radiation pulses is improved. Further for higher values of plasma-to-beam frequency, it enhances the ability of rippled electromagnetic radiation pulses to guide and concentrate in plasma. This investigation is of direct significance to the explanations on rippled electromagnetic radiation pulse guiding in high concentration magnetoactive plasma.

4. Conclusion

In conclusion, this work focuses on studying the characteristics of a self-guided and self-focusing rippled electromagnetic pulse within a high density magnetoactive plasma. By utilizing propagation equations, WKB theory, and paraxial theory, the researchers have developed an analytical model that greatly aids in comprehending propagation dynamics of rippled electromagnetic pulse for a wide range of normalized parameters applicable to magnetoactive plasma. This work contributes to the comprehension of the mechanisms involved in controlling and manipulating electromagnetic radiation pulses in plasma with a high concentration of charged particles and a strong magnetic field. The theoretical framework and findings contribute to our understanding of plasma physics and offer practical implications for optimizing laser-plasma interactions in numerous applications.

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