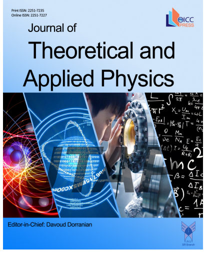

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Evolution of electromagnetic soliton during laser-plasma interaction in an electron-positron-ion plasma having constant density gradient

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Original Research

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Abstract:

Laser propagation in an electron-positron-ion (EPI) plasma medium having a constant density gradient is studied for the soliton evolution in the presence of a parallelly applied strong magnetic field. In a nonlinear regime, laser-plasma interaction forms an electron density hill that moves backward due to the density gradient. This hill localizes laser energy by the mechanism of resonance absorption ($\omega_l = \omega_{pe}$) and remains stable for a longer period, qualifying for the evolution of electromagnetic soliton. The position of the soliton from where it starts moving backward depends on the slope of the linear density variation. If the slope increases, then the position of the soliton is closer to the plasma boundary ($x = 0$). Another interesting property of the soliton is that its height decreases, and width increases as the temperature of plasma species rises. We simulate this phenomenon of electromagnetic soliton evolution in 1-D and 2-D by using Particle-In-Cell (PIC) simulation using the EPOCH-4.17.10.

Keywords: Particle-In-Cell; Electron-Positron-Ion plasma; Resonance absorption; Electromagnetic soliton; Constant density gradient; Plasma species temperature

1. Introduction

In electron-positron plasma, the nonlinear propagation of electromagnetic (EM) waves is an attractive topic [1, 2]. In the early universe and near the polar caps of pulsars electron-positron (EP) plasma is found [3]. This plasma along with ions, i.e. electron-positron-ion (EPI) plasma, predominates in astrophysical plasmas, and its wave propagation is distinct from that of EP plasmas. The intense laser-plasma interaction can be a process of pair production resulting in a 3-component EPI plasma [4]. These EPI plasmas have been seen in laboratories, where positrons are used as probes to study transport in the tokamaks [5–7]. The early universe and its evolution have been investigated with the help of EPI plasmas [8–10]. Several theoretical investigations started due to EPI plasma. In cold EPI plasma, the study of weakly nonlinear electromagnetic waves has been done [11]. During analytical investigation of the propagation of EM radiation in unmagnetized EPI plasma it was found that EPI plasma may be localized with the generation of an electrostatic (ES) potential [12].

The high-power lasers absorbed by the plasma, are an important topic nowadays because it has given many applications such as plasma heating [13], plasma-based charge particle acceleration [14, 15], and fast and shock ignition in inertial confinement fusion [16, 17]. The nonlinear laser-plasma interaction is an interesting topic and it rises to phenomena such as self-focusing [18], wakefield generation [19], harmonic generation [20], and EM soliton generation [21, 22]. In underdense plasma, the nonlinear laser pulse energy absorption through the process occurs, and this process supports converting the pulse energy into a plasma wakefield damped in plasma [23]. Few research has been published on the study of the nonlinear propagation of laser through EP plasma or EPI plasma. Relativistic electromagnetic (EM) soliton can be generated by the interaction of laser with the ultra-dense plasma [24] or underdense plasma [25]. The EM soliton is also generated in 1-D, 2-D, and 3-D

PIC simulations [26, 27]. The relativistic electromagnetic (EM) soliton moves with an acceleration speed proportional to the density gradient in an inhomogeneous plasma [28]. If high-frequency EM radiation interacts with EPI plasma, then a 3-D EM soliton excites where the soliton frequency is larger than the Langmuir frequency [29]. The analytical investigations of relativistic EM soliton have also been developed and exactly relativistically lasers were considered and there are all the ingredients to describe 1-D circularly polarized soliton [30]. In the overdense plasma, an EM wave, especially the laser has been found to penetrate with the application of a strong applied magnetic field [31]; the components of field propagated inside the plasma. While considered the relativistic effects, EM solitons have been obtained with relativistic amplitudes [32]. Not only this, experiments based on Laser-plasma interaction have been used for Solar Burst Studies [33] where relativistic effects are important. Relativistic solitons have also been investigated experimentally [34–36]. Recently, many researchers have observed ion-acoustic solitons in EPI plasma [37, 38], and also an EM envelope soliton [39, 40].

In this article, we carried out 1-D and 2-D PIC simulations for the electromagnetic solitons created by an intense laser pulse propagating in an electron-positron-ion plasma. The laser pulse and electron density are found to change with magnetic field strength. In the case of purely electron-positron plasma, soliton-like structures are not easily excited, but we have observed such structures in EPI plasma. We have considered four parts to deeply understand this process. Case 1 discusses the EM soliton generation, while case 2 shows the soliton propagation via a plasma density gradient. In the third case, we observed that the position of the soliton, where it is generated, depends on the slope (angle) of the linear density variation. The fourth case describes the behaviour of the EM soliton under the impact of temperature of plasma species.

2. Simulation setup

In an external magnetic field, we have used EPOCH-4.17.10 for carrying out 1-D and 2-D particle-in-cell (PIC) simulations to study a laser-plasma interaction considering an EPI plasma. Today, a few hundred Tesla of magnetic fields is easily achievable, and it is expected that a kilo-Tesla fields will be produced soon in laboratory. Using a recently constructed mega-gauss generating apparatus, a peak field of 1.2 kT was obtained using the electromagnetic flux-compression (EMFC) approach [41]. After reading several scientific publications on the subject, we can understand that the soliton can be generated in the vicinity of kilo-Tesla magnetic fields while considering the overdense plasma. For this purpose, several research tests have used the laser intensity of 10^{23} Wm^{-2} [23]. In one-dimensional simulation box length $L_x = 80$ μm has been chosen, and the plasma medium starts at $x = 0$. Similarly, in a 2-D simulation square box with dimension $L_x = 80$ μm and $L_y = 80$ μm has been taken. The right side of the simulation box is open, and the laser is incident on plasma from the left side of the box. The laser propagates along the x-direction, and the applied external magnetic field (B_0) is also along the same direction, i.e. in the direction of laser propagation. The electric field of the interacted EM field is directed along the y direction, and a magnetic field is along the z direction. The laser is plane polarized because of the electric field along the y direction. We consider a short-pulse laser of wavelength $\lambda_l = 4.6$ μm ($\omega_l = 4.09 \times 10^{14}$ rad/s). The laser profile is Gaussian with the intensity of $I = 1 \times 10^{24}$ Wm^{-2}. The plasma density in the region $x = 0$ to $x = 45$ μm is linearly varying and corresponding electron plasma frequency is equal to 0.61×10^{14} rad/s at $x = 1$ μm. In the first case, the applied external magnetic field is $B_0 = 1$ kT, and all the species' temperatures are taken as 300 eV. The mass of the ion is 1836×12 times the mass of an electron and the mass of positron is equal to the electron mass. The temperature range is taken as $T = 200$ eV to 400 eV which is appropriate to investigate how temperature affects the soliton structure. The range of angle is from $\theta = 45$ degrees to $\theta = 75$ degrees, which is appropriate to investigate the impact of linear density variation (gradient) on the soliton position. We have used the same plasma parameters for 1-D and 2-D simulations. For the 2-D simulation, we take a square box in the x-, y-directions. The number of steps is taken as $n_x = 2000$ and $n_y = 2000$, and all parameters are the same as 1-D. The duration of the laser pulse is taken as 10 femtoseconds, and the y-direction of the simulation box is periodic.

3. Results and discussion

Initially we considered only EP plasma and observed through the simulations that the Gaussian laser enters inside the plasma, but nonlinear wave that can qualify as solitary wave/soliton is not observed. However, in the case of EPI plasma a soliton-like structure can occur. The nonlinear force is found to pull the electrons and positrons away from each other, but the carbon ions being heavier don't move much. The plasma (electrons) hill development occurs when these three species, i.e. ions, positrons, and electrons, separate out from their mean positions. This localises a lot of laser energy inside a plasma hill due to resonance absorption at $x = 44$ μm, creating a standing soliton. The plasma density is lower in the soliton's backward direction, so it moves in this direction.

For a longer period from $t = 0.3$ ps to $t = 0.5$ ps, Figure 1 depicts the electron density hill or the soliton profile. The corresponding transverse electric field components E_y and E_z localized at the position of the density hill are shown in Figure 2. The corresponding transverse magnetic field components B_y and B_z are shown in Figure 3, showing their peak position at the position of the density hill and its localization. These results prove the generation of EM soliton, because the electron density hill retain its shape for longer time and all the electric and magnetic field components are localized at the peak position of the density hill.

In order to confirm the results of 1-D simulation, we have also carried out 2-D simulations and portrayed the density variation (hill), transverse electric field components and transverse magnetic field components in Figure 4. Here the position of the density hill and the peaks (dips) of the field components appear at the same place as in the 1-D

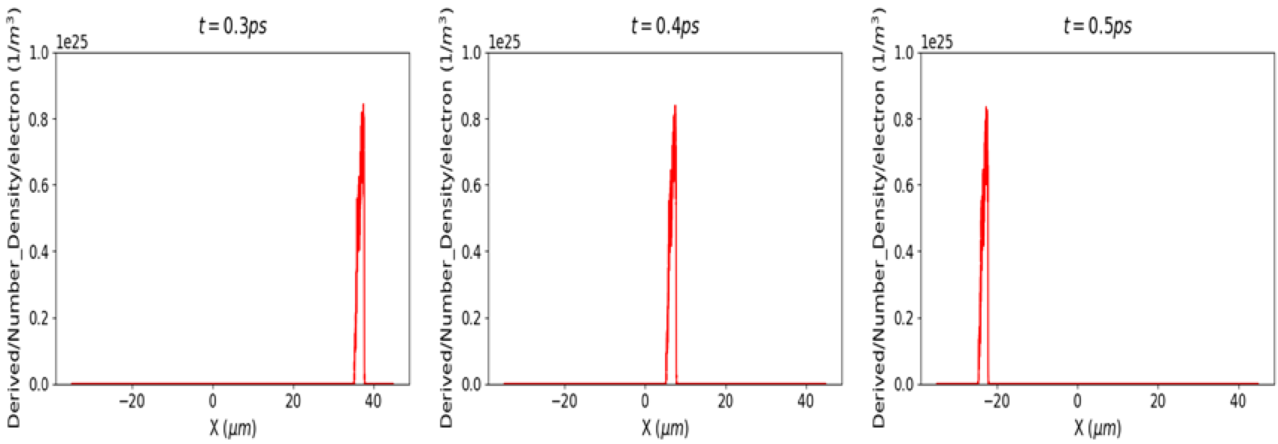

Figure 1. Electron density snapshots with different times. Here, temperature T = 300 eV, wavelength of the laser $\lambda_l = 4.6$ μm, laser intensity $I = 1 \times 10^{24}$ Wm^{-2}, inclination angle of density variation $\theta = 45$, and external magnetic field $B_0 = 1$ kT.

case, confirming the elliptically polarized electromagnetic soliton. Since the background plasma density is inhomogeneous and the density rises in the forward direction, the soliton starts moving in the backward direction due to the density gradient. It appears that the pressure difference leads this backward movement of the soliton.

In order to understand the mechanism of soliton generation, we have run the simulations by changing the slope of density variation (linear), i.e. by changing the angle or the scale length of the density gradient. This angle is chosen as 45 degrees (Figure 5 a), 60 degrees (Figure 5 b) and 75 degrees (Figure 5 c). The appearance of density hill corresponding to these angles or slopes is shown in Figure 5. For the lowest angle of 45 degrees (Figure 5 a), the position where the density hill develops and soliton evolves, is 44 μm. This position keeps on moving in the backward direction with the larger angle or the larger slope of the density variation. For example, the position reads as $x = 16.5$ μm (Figure 5 b) and $x = 2$ μm (Figure 5 c) for 60 degrees and 75 degrees angle, respectively. The point of observation is that the plasma density at all these positions amounts to the critical density (corresponding plasma frequency ω_{pe}).

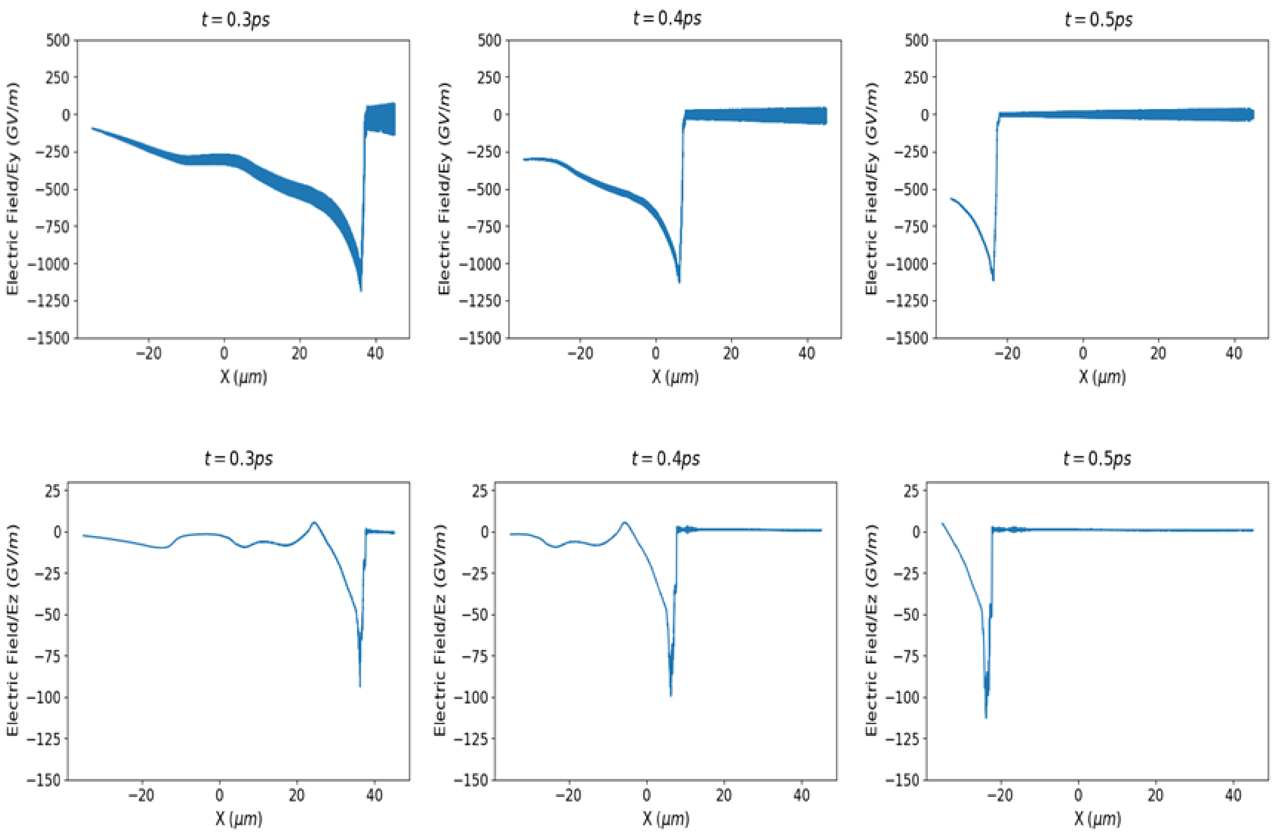

Figure 2. The components of electric field for the same parameters as used in Figure 1.

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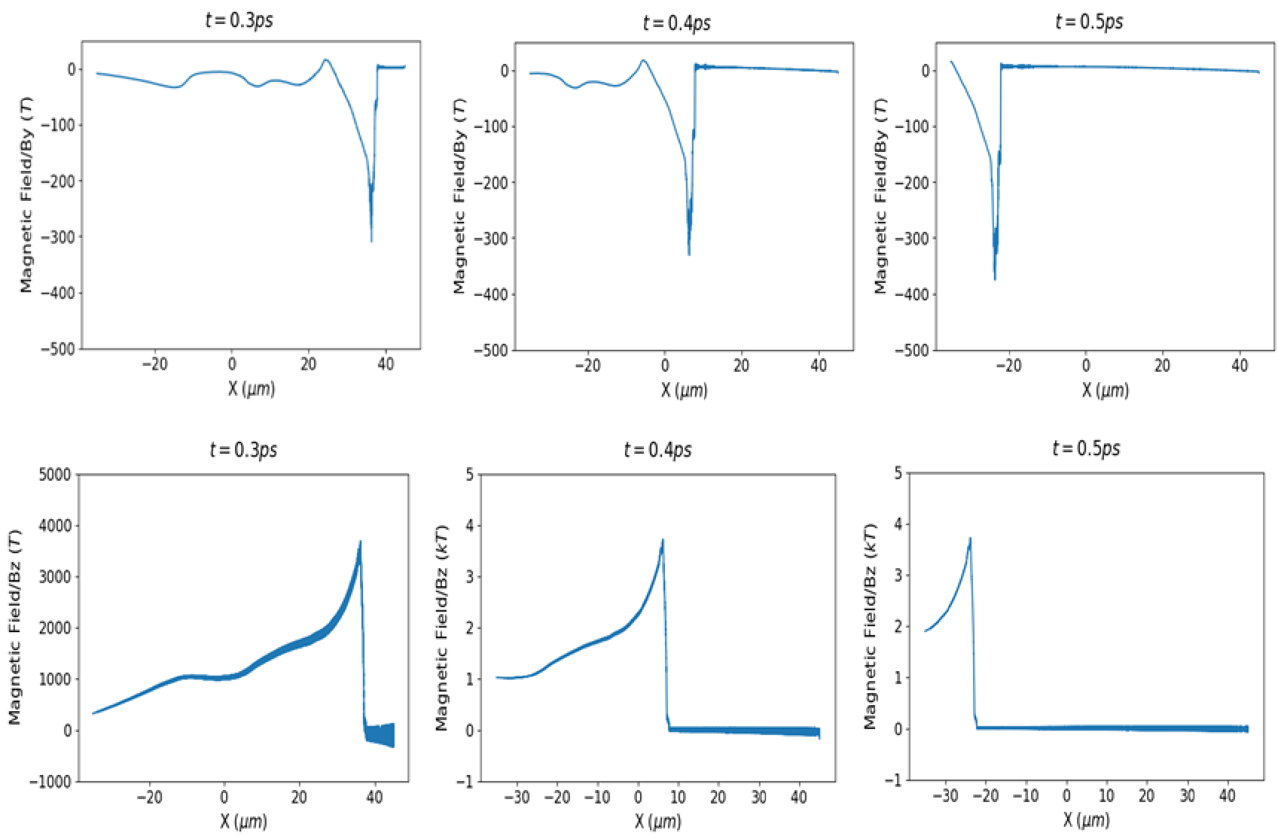

Figure 3. The components of magnetic field for the same parameters as used in Figure 1.

This is also seen that most of the energy of the laser (frequency ω_l) is absorbed at these positions only, satisfying the condition $\omega_l = \omega_{pe}$. Hence, this is understood that the soliton generates due to the resonance absorption of the laser energy. On the other hand, less energy of the laser is wasted within the plasma medium when we increase the slope of the density gradient, increasing the soliton's height (compare Figures 5 a, 5 b and 5 c). Because the critical point is closer to the plasma boundary ($x = 0$) when the slope angle increases, the soliton's location is found to be closer to the starting point/border of the plasma.
Finally, we uncover the role of temperature of plasma species on the soliton generation and its propagation characteristics. Choosing the temperature as 200 eV, 300 eV and 400 eV, we have plotted the soliton structure in Figure 6. Here this is seen that the soliton's amplitude decreases, and its width increases, when the temperature is raised. Interesting observation is that but its location remains static. Other researchers have also found the similar behaviour of the solitons with respect to the temperature of the plasma species [42]. The reason behind this is the thermal motion of the plasma species because of which the density hill broadens as the electrons now need larger region to settle down during the laser-plasma interaction.
Based on the results of above figures, we can say that a large amplitude soliton excitation is possible in a magnetized overdense warm plasma consisting of electrons, positrons, and a trace number of heavy ions. We argue that even a trace number of heavy ions is required for the formation of solitons; a pure electron-positron plasma cannot sustain this disruption. In a pure electron-positron plasma, a radiation pulse of any intensity will always be stretched out [43, 44]. The presence of trace amounts of heavy ions prevents the pulses from spreading out, and solitons arise as a result of the modulational interactions of these pulses. In passing, we suggest that such soliton potentials propagating with $v_g \approx c$ might readily produce resonant particle acceleration [45].
We can make a comparative study with the findings of Berezhiani and Mahajan [6], who analytically solved the problem of cold plasma for the excitation of EM soliton. The parameters of plasma used in their work are different. In our case, these parameters are 4.6 μm and 10^{24} Watts/m^2, respectively. They took the unmagnetized plasma while we have taken magnetized plasma. The size of the simulation box for the soliton wave, in our case, is also different from their value ($L_x = 80$ μm). We make another comparative study with the work of Dorranian et al. [40], who first took a circularly polarized laser and used theoretical nonlinear Schrodinger equation (NSE) to deduce that a bright and dark solitons are formed. Moreover, they focused on the nonthermal electron effect on the dynamics of EM relativistic solitons. In our case, we have observed elliptically polarized EM solitons which are sensitive to the thermal motion of the plasma species, and probably these are bright solitons in view of the density hill structure. In other works, the nonlinear circular polarized laser was found to propagate in magnetized plasma with superthermal ions and mixed nonthermal high-energy tail electrons distributions and q-nonextensive velocity distributions were observed [46, 47].

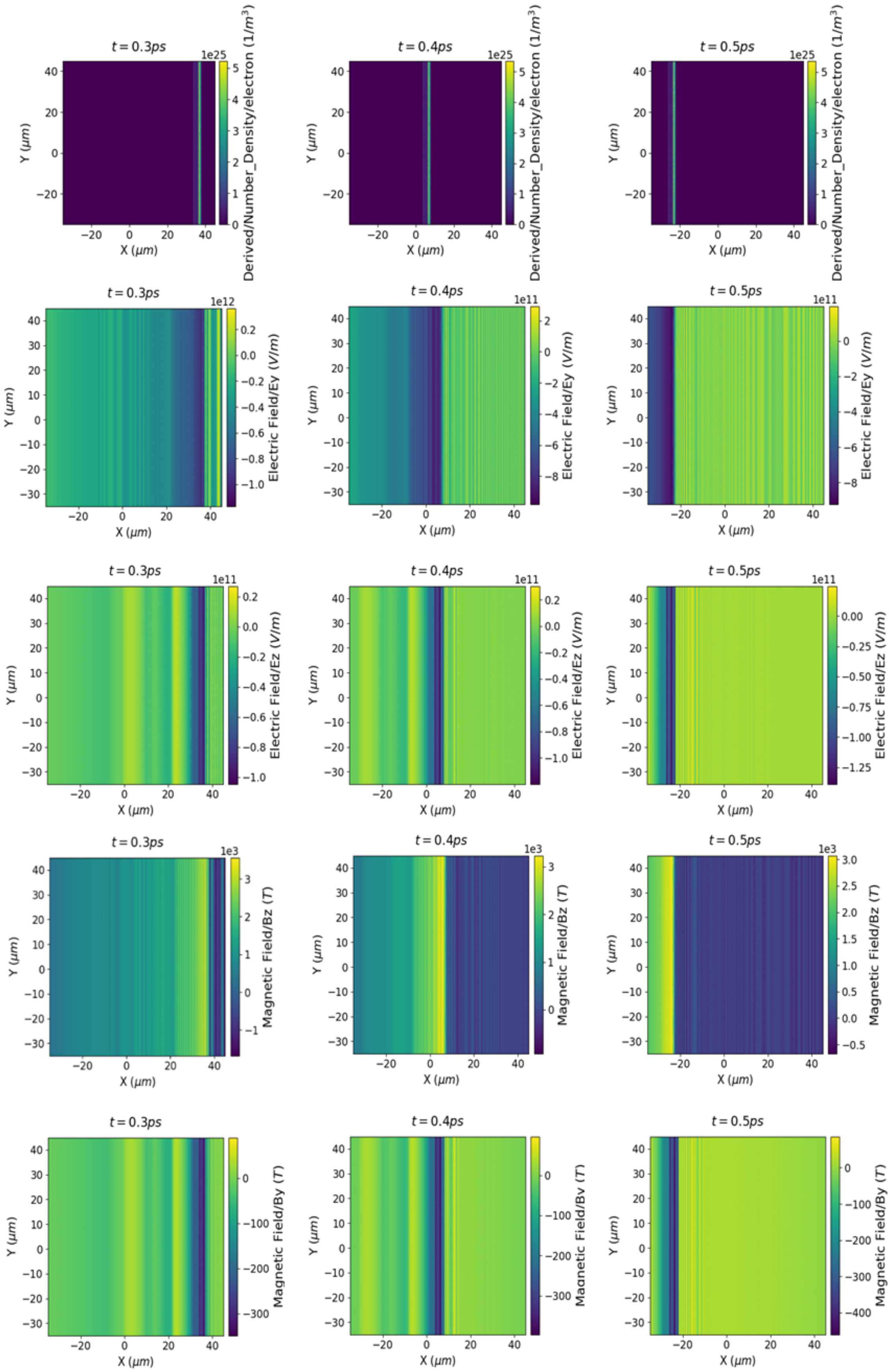

Figure 4. Snapshots of electron density, electric field, and magnetic field at different times (2-D) for the same parameters as in Figures 1 - 3.

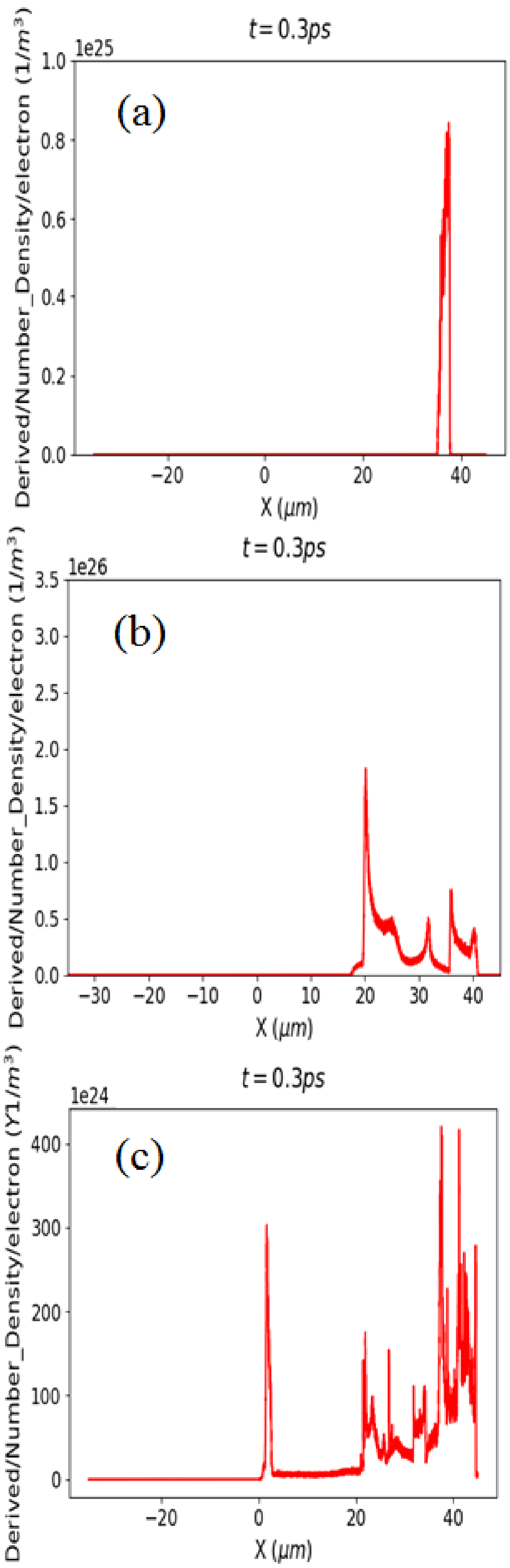

Figure 5. The position of soliton with inclined angle (a) $\theta = 45$ degrees, (b) $\theta = 60$ degrees, and (c) $\theta = 75$ degrees.

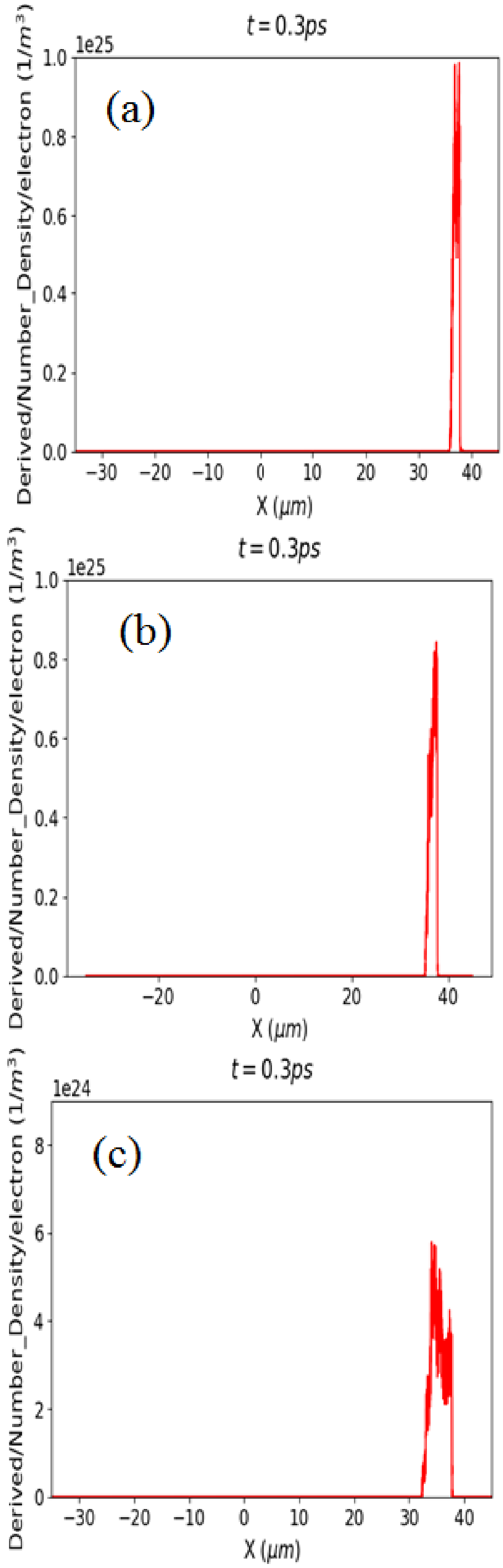

Figure 6. Temperature effect on soliton position (a) T = 200 eV (b) T = 300 eV and (c) T = 400 eV.

However, in the present work, we simulated the EM soliton by taking thermal electrons, positrons and heavy ions and the also the initial laser is plane polarized. But in the presence of external strong magnetic field, the penetration of the laser is possible in overdense plasma and also the elliptically EM solitons can be excited when the resonance condition is met [48].

4. Conclusion

The present 1-D and 2-D PIC simulation results on an electromagnetic soliton generated by an intense laser pulse in an EPI inhomogeneous plasma show that the laser energy evolves as the soliton via resonance absorption phenomenon, while a part of the energy is passed through the plasma. The soliton structure remains stable for a longer time, but it then starts dispersing in the plasma having a constant density gradient. The position of soliton evolution and its movement in backward direction depend on the scale length of the density gradient. For stronger density gradient in the plasma, the position of the soliton appears closer to the plasma boundary where laser and plasma interact. The plasma species temperature shows a significant impact on the soliton structure, and the soliton becomes wider and shorter in the presence of higher temperature. Such a structure may find application in charged particle acceleration, particle trapping and communication.

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Authors Contributions
Mathematical formulation, PIC simulation by EPOCH, Investigation, Writing-review & editing was done by Gaurav Kumar. Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing–review & editing, Supervision, and Funding acquisition was done by Hitendra K. Malik.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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