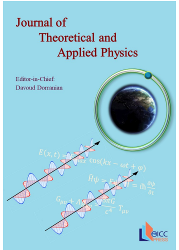

Volume 17, Issue 2, 172324 (1-7)

Journal of Theoretical and Applied Physics (JTAP)

https://dx.doi.org/10.57647/j.jtap.2023.1702.24

Excitation of R- and L-waves by laser propagation through over-dense magnetized plasma and their verification

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Received 04 November 2022; Accepted 09 January 2023; Published online 13 January 2023

Abstract:
Laser-plasma interaction is a fascinating subject in view of its various applications in wave generation, particle acceleration, radiation generation, etc. The laser beam gets reflected at the vacuum-plasma interface if the plasma density is equal or larger than the critical density. However, in the presence of strong magnetic field in the order of kilo Tesla, the beam can travel some distance through over-dense plasma. Here $\mathbf{E}\times\mathbf{B}$ heating and pondermotive force play role for the laser beams to propagate through the over-dense plasma. In the present article, taking the external magnetic field along the propagation direction of the laser beam we have observed the R- and L- waves to be excited. The applied magnetic field is chosen in such way that the laser frequency ω_l falls between the electron cyclotron frequency ω_{ce} and ion cyclotron frequency ω_{ci}. Under this situation, it generates only an R-wave. If the laser frequency is considered to be less than the ion cyclotron frequency ($\omega_{\text{laser}} < \omega_{ci}$) then an L-wave is additionally generated. In both the cases, an electrostatic disturbance is also formed with different but significant electric field amplitudes. We simulate these R- and L-waves in 1-D by using Particle-in-Cell (PIC) simulation using the EPOCH-4.17.10. Specifically, the electric and magnetic fields are studied that are associated with these waves, and the waves are verified based on the dispersion relation and the polarization studies.

Keywords: Over-dense plasma; Particle-In-Cell; R-wave; L-wave; Electron cyclotron frequency; Ion cyclotron frequency

1. Introduction

In the case of plasma density equal or larger than the critical density, the laser is found to reflect at the vacuum plasma interface [1, 2] and is unable to interact with the plasma or has a poor interaction with the unmagnetized plasmas [3–6]. However, a stronger magnetic field of magnitudes in the order of kilo Tesla can help laser to penetrate through the over-dense plasma, providing an effective interaction. The magnetic fields of this order have now been achieved in some advanced laboratory experiments [6]. It turns out that there is a good likeliness for technological improvement to catch up in future to have the regime of magnetized electrons and ions available in laser-plasma interaction experiments [7, 8]. It is important to understand the laser-plasma interaction under the effect of a strong magnetic field because it will find more useful applications in future. For investigating such situation and explaining the physics of laser-plasma interaction, Particle-In-Cell (PIC) simulations have been developed with sophistication [8, 9]. This has been largely observed that some part of energy of the incident EM wave is transferred to an electron plasma wave, i.e. a phenomenon called resonance absorption. The energy of the laser has been found to be absorbed in the plasma in many schemes [10, 11] including Brunel heating scheme, $\mathbf{J}\times\mathbf{B}$ resonance absorption, etc. [12–16]. If the laser intensity is in the nonrelativistic regime, then the role of $\mathbf{J}\times\mathbf{B}$ electron heating is taken to be negligible. The electromagnetic wave can be absorbed resonantly by linear mode conversion into a plasma wave when it is obliquely incident on an inhomogeneous plasma [17–19]. It has found importance for microwave laboratory experiments and laser target experiments [20]. Presently, many researchers interest has been directed toward the application of the right circular wave (R-wave) to the plasma because this wave can realize localized electron heating [21]. Another applica-

Table 1. Laser and plasma parameters in a 1D simulation.

Parameters	Over dense plasma ($B_0 = 14.2$ kT)Whistler (R-wave)	Over dense plasma ($B_0 = 99.4$ (14.2×7) kT)R-L wave
	Plasma Parameters	
Density (n_0)	9×10^{26} per m^3	9×10^{26} per m^3
Frequency(ω_{pe})	17.5×10^{14} rad/s	17.5×10^{14} rad/s
$(\omega_{pi})(m_i/m_e = 30)$	3.2×10^{14} rad/s	3.2×10^{14}rad/s
	Laser Parameters	
Intensity (I)	3×10^{19} Watt/m^2	3×10^{19} Watt/m^2
Frequency (ω)	1.89×10^{14} rad/s	1.89×10^{14} rad/s
Wavelength (λ)	10 microns	10 microns

tion of an R-wave is the formation of confining potentials in mirror devices and suppression of large disruptions in tokamaks [22, 23].

In the present paper, we employ a one-dimensional PIC simulation for electromagnetic wave propagation through the over-dense plasma. In particular, we consider an intense laser pulse and a strong magnetic field of few tens of kilo Tesla magnitude. With an appropriate strength of the magnetic field, we can excite either R-wave or both the R- and L-waves simultaneously in the plasma. We develop fast Fourier transformation (both in time and space) for verifying the excitation of these waves and determining their propagation characteristics.

2. Simulation setup

At $x = 0$, the plasma medium is taken to exist. The laser is incident on the plasma from the left side, and the right side of the simulation box is assumed to be open. The laser is considered to propagate along the x-direction and the external magnetic field (B_0) is also taken in the same direction. The electric field of the laser is directed along the y-direction and its magnetic field is along the z-direction. We have used 1-D Particle-In-Cell (PIC) simulation to study the interaction of this laser with such a plasma. The 1-D simulation box with dimension $L_x = 2000$ μm has been chosen. The grid size is $\Delta x = 0.04$ μm. We consider a carbon dioxide short-pulse laser having wavelength $\lambda = 10$ μm (frequency $\omega_{\text{laser}} = 1.89 \times 10^{14}$ rad/s). The laser profile is taken to be Gaussian with peak intensity of $I = 3 \times 10^{19}$ Wm^{-2}. The number density of the plasma is taken as $n_0 =$

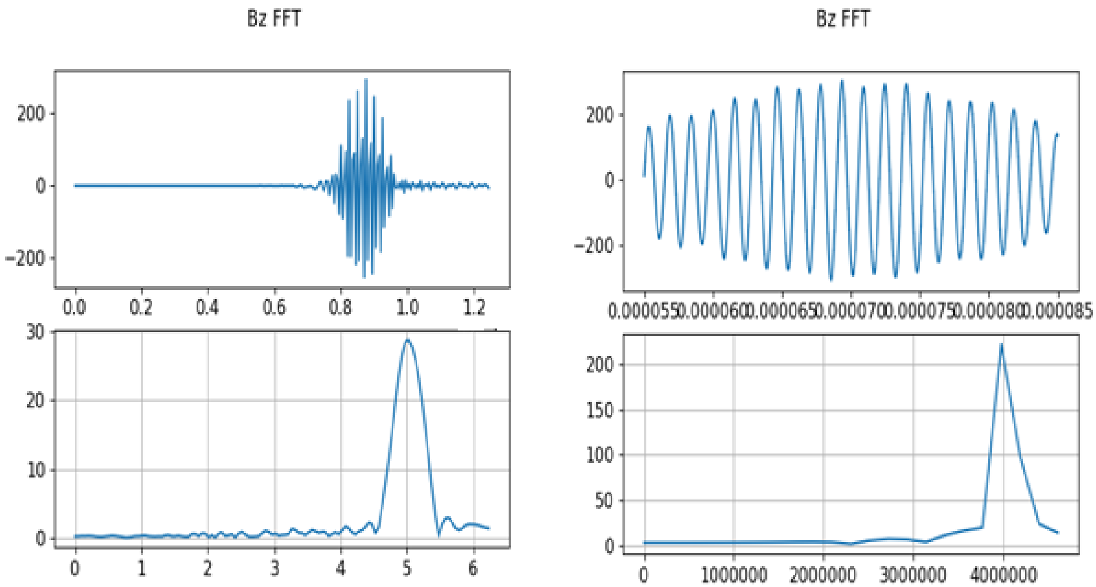

Figure 1. Propagation of electric field E_y and magnetic field B_z corresponding to R-wave.

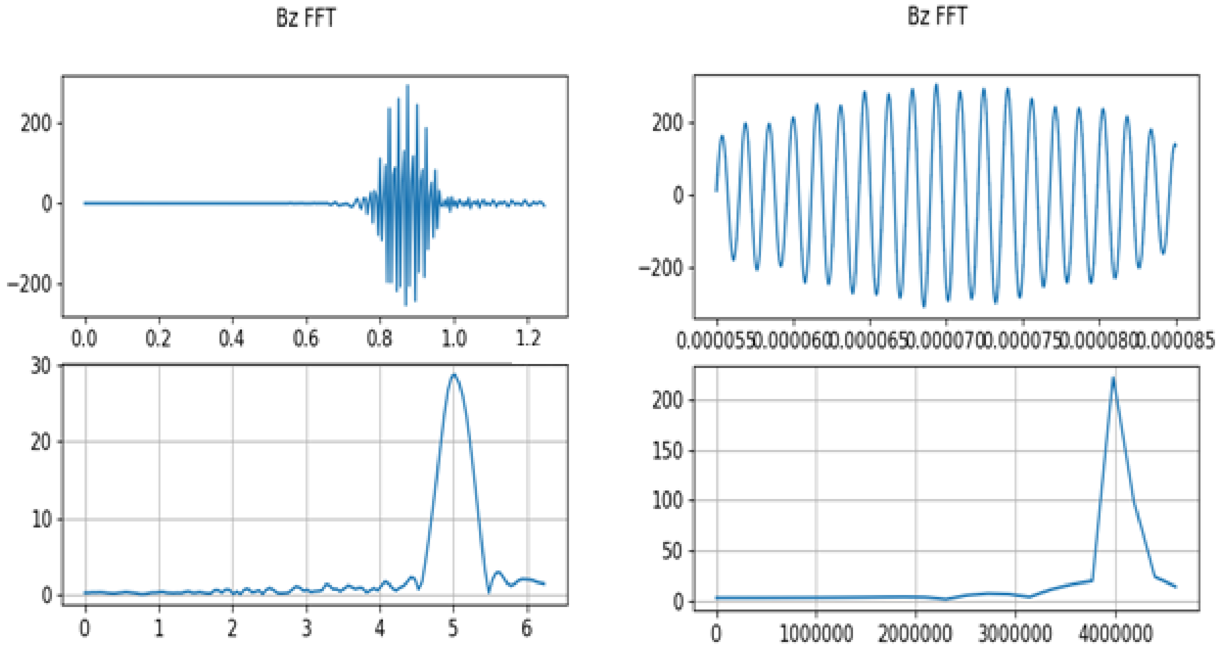

Figure 2. Fast Fourier Transformation (FFT) of the magnetic field in time (left portion) and space (right portion).

9×10^{26} m^{-3}, corresponding to which the plasma frequency is 17.5×10^{14} rad/s. The complete simulation parameters are given in Table 1. To reduce the computational time, we use the simulations at a reduced mass of ions, which is taken to be 30 times heavier than the electrons ($m_i/m_e = 30$). For Whistler wave (R-wave), the electron cyclotron frequency $\omega_{ce} = 24.96 \times 10^{14}$ rad/s and ion cyclotron frequency $\omega_{ci} = 0.83 \times 10^{14}$ rad/s. For both the R and L waves (together) the electron cyclotron frequency $\omega_{ce} = 174.72 \times 10^{14}$ rad/s and ion cyclotron frequency is $\omega_{ci} = 5.83 \times 10^{14}$ rad/s.

3. Results and discussion

We have considered two cases in our simulation. In the first case, the laser frequency is taken between the electron cyclotron frequency and ion cyclotron frequency ($\omega_{ci} < \omega_{\text{laser}} < \omega_{ce}$) by fixing $B_0 = 14.2$ kT (R-wave case) and for the second case the laser frequency is less than the ion cyclotron frequency ($\omega_{\text{laser}} < \omega_{ci}$) by fixing $B_0 = 99.4$ kT (R- and L-waves). In the first case, the laser does propagate through the plasma and generates R-wave. The corresponding electric field (E_y) and magnetic field (B_z) are shown in Figure 1, where the mode (fields) is (are) clearly seen moving through the plasma. We have also obtained the fast Fourier transformation (FFT) of the magnetic field B_z and

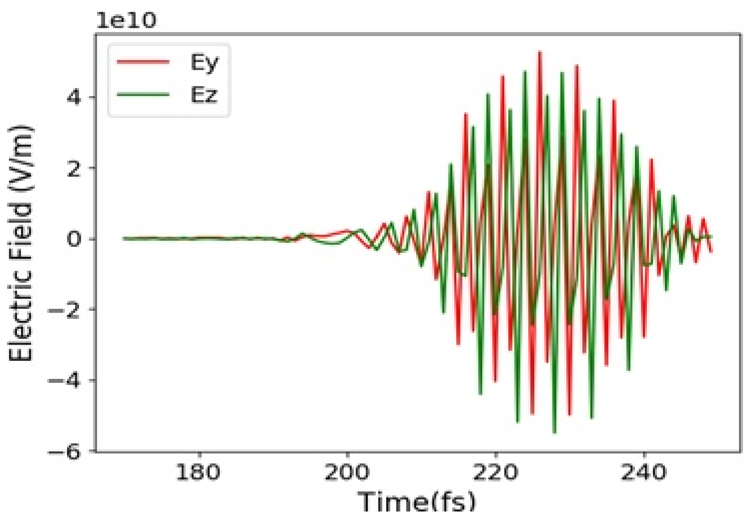

Figure 3. Checking the polarization of R-wave through the fields E_z and E_y.

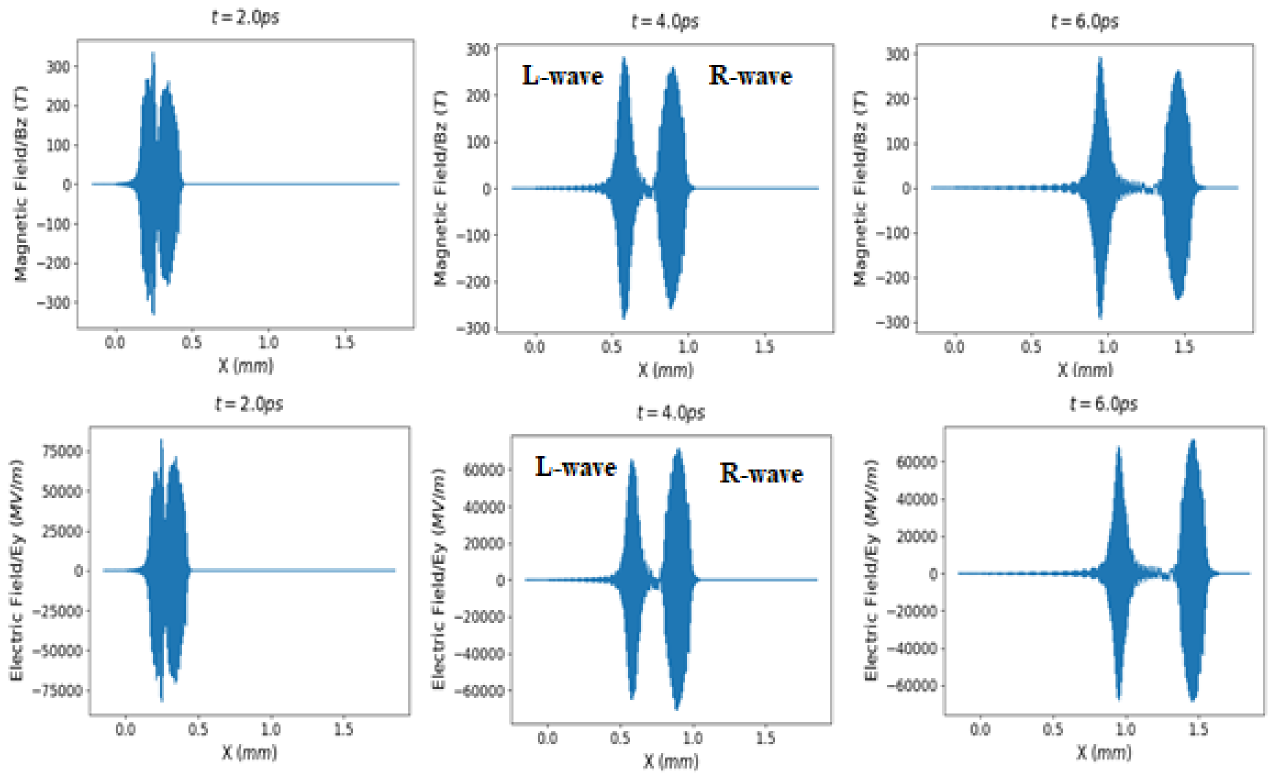

Figure 4. Propagation of electric field E_y and magnetic field B_z Corresponding to R- and L-waves.

have shown it in Figure 2. Here, the peak value of FFT (time) of the magnetic field in left portion of Figure 2 gives rise to the frequency of R-wave and the peak value of FFT (space) in right portion of Figure 2 gives the wave vector (k) of the R-wave. We consider the values of ω, k, ω_{ci}, ω_{ce} and

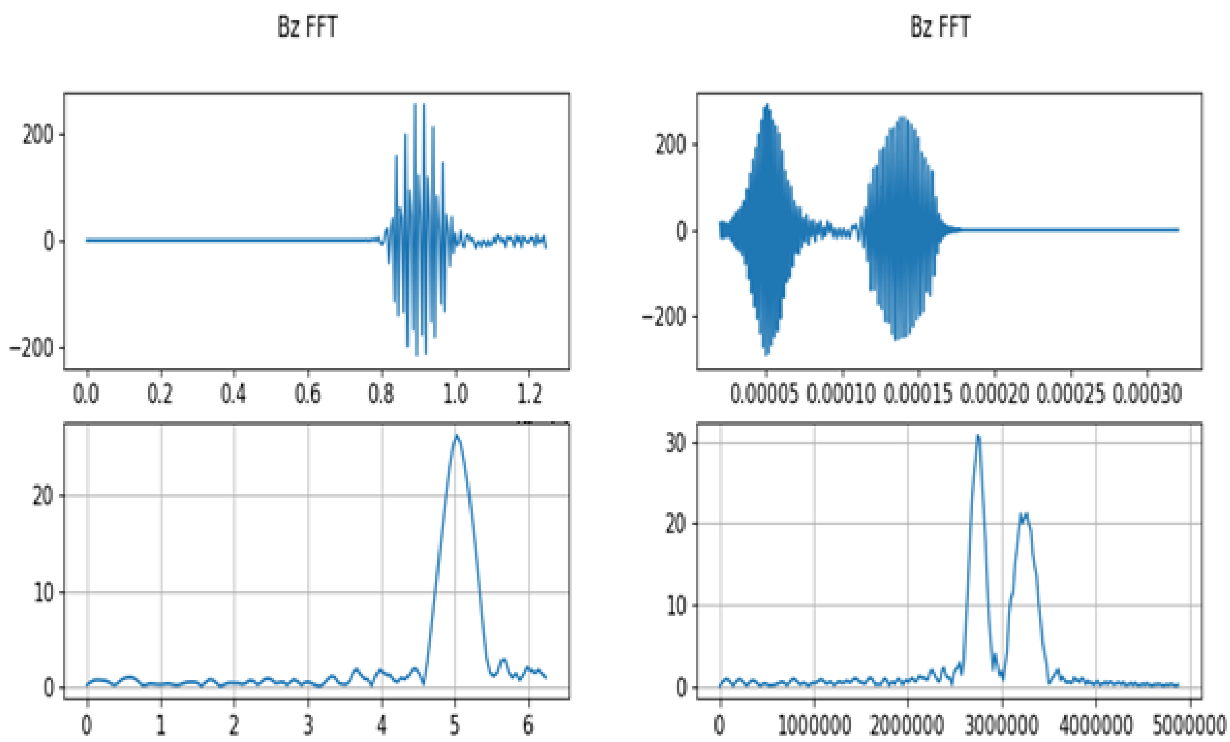

Figure 5. Fast Fourier Transformation (FFT) of the magnetic field in time (left portion) and space (right portion).

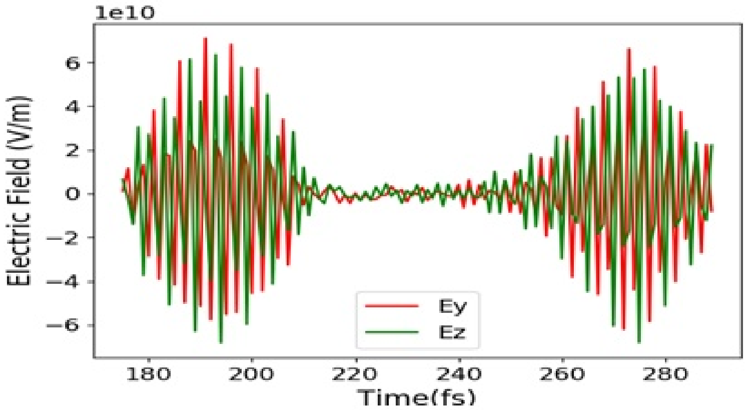

Figure 6. Checking the polarization of R- and L-waves through the fields E_z and E_y.

ω_{pe} and put them in the following dispersion equation [24]

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{Pe}^2}{(\omega - \omega_{ce})(\omega + \omega_{ci})} \tag{1}$$

for the verification of excitation of the R-wave. For the given set of values, this equation is satisfied and hence, the excitation of the R-wave is confirmed. In addition to this, in Figure 3 we check the polarization and observe that the field component E_z is ahead of E_y, further confirming the excitation of the wave.

In the second case, the laser propagation through the plasma is considered for $B_0 = 99.4$ kT, that generates both the R- and L-waves. The propagation of their fields is shown in Figure 4, where a larger gap is seen between the electric field as well of the magnetic field of the R- and L-waves due to their different velocities. Fast Fourier transformation (FFT) of the magnetic field of these waves is shown in Figure 5. Here the peak values of FFT (time) in left portion of Figure 5 gives rise to the frequencies of the L- and R-waves and the peak value of FFT (space) in right portion of Figure 5 gives the wave vector (k) of these waves. Considering the values of ω, k, ω_{ci}, ω_{ce} and ω_{pe} so obtained are put in the following equation

$$\text{L-mode}: \quad \frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{Pe}^2}{(\omega + \omega_{ce})(\omega - \omega_{ci})} \tag{2}$$

For the given set of values, equation (1) is satisfied, that proves the excitation of the R-wave, and the verification of equation (2) for the said values proves the excitation of the L-wave. This can be seen that the phase velocity of the R-wave is larger than L-wave. This is verified through the second case (both RL-wave case), where the L-wave is found to be behind the R-wave. Here this is noticed that after some time the separation of the R-wave and L-wave is increased, confirming the faster movement of the R-wave at 0.67 c compared to the L-wave propagating at 0.51 c.

The two dispersion parts correspond to left (L)-handed and right (R)-handed circularly polarized plane waves. The electric field vector of the L-wave rotates anticlockwise in time as viewed along the direction of the applied external magnetic field and clockwise in time for the R wave [1]. This can be understood as follows. An applied magnetic

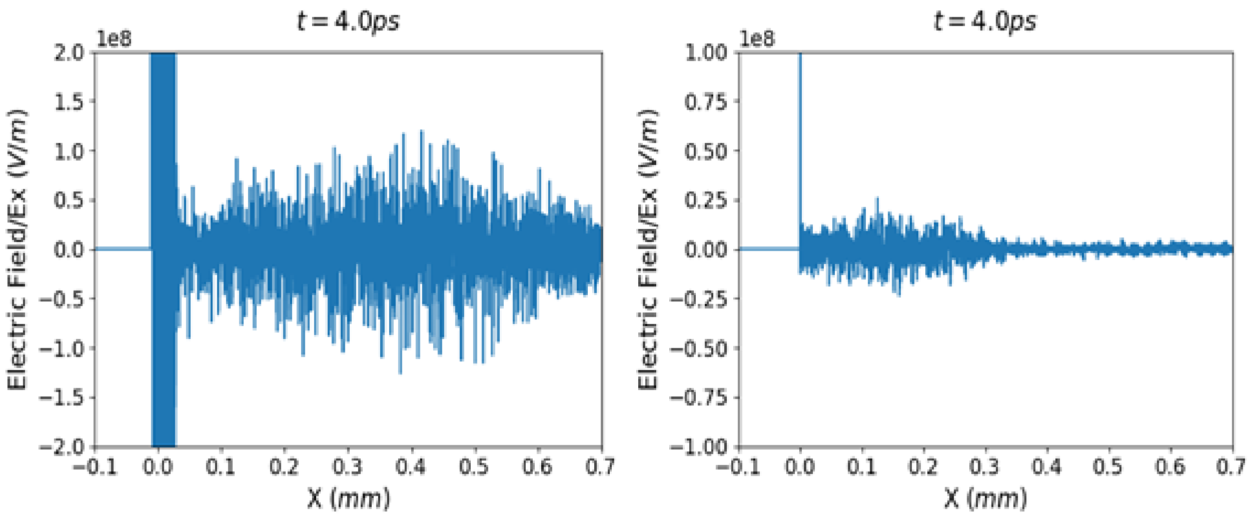

Figure 7. Snapshot of E_x at $t = 4$ ps for R-wave case (left portion) and for RL-wave case (right portion).

field in the x-direction is along the direction of propagation of the laser. The linearly plane-polarized incident wave may be decomposed into two right and left circularly polarized waves. Hence, we can write

$$E(\text{incident}) = E(y-\text{direction}) = E_R(\text{incident}) + E_L(\text{incident}) \quad (3)$$

In the complete region, the R- and L-wave components are completely decoupled and can be treated separately. For R-wave, the field component E_z is ahead of E_y due to the phase difference in both the electric field components. Similarly for L-wave, the component E_y is ahead of E_z. In Figure 6, we check the polarization and observe that the field component E_z is ahead of E_y in the case of R-wave and the component E_y is ahead of E_z in the case of L-wave.

We can make a comparative study with the findings of Goswami et al. [25] who also simulated the situation of over-dense plasma for the excitation of R- and L-waves. The parameters used in their work are different. For example, they considered a carbon dioxide short-pulse laser having wavelength $\lambda = 9.42\ \mu$m and intensity $I = 3.5 \times 10^{19}$ Wm^{-2}, whereas in our case these parameters are 10 μm and 3×10^{19} Wm^{-2}, respectively. They had taken the ion mass as 25 times of the electron mass, while we have considered this as 30 times. The size of the simulation box for RL wave in our case is also 2 times of their value. The applied magnetic field in our case is also larger, which has led to additional result of electrostatic excitation in the plasma (Figure 7) along with the R- and L-waves, i.e. when the applied magnetic field is such that the laser frequency ω_{laser} is less than the ion cyclotron frequency $\omega_{ci}(\omega_{\text{laser}} < \omega_{ci})$. Clearly, they had missed this important observation that higher magnetic field helps exciting the electrostatic disturbances with significant amplitude in both the cases including the R-wave excitation, i.e. when the laser frequency ω_{laser} falls between the electron cyclotron frequency ω_{ce} and ion cyclotron frequency ω_{ci}. In our case, we observed electric field $E_x = 2 \times 10^8$ V/m when only the R-wave is excited and $E_x = 0.25 \times 10^8$ V/m for the case of RL-waves. Not only this, the R- and L-waves are excited with larger electric field component E_y and magnetic field component B_z in the presence of higher magnetic field. The time FFT peak value (5.1×10^{14} for R-wave and RL-waves) is larger, indicating that the frequency of generated wave is larger. Based on our results we can say that more laser energy converts into EM wave and electrostatic excitation due to the higher external magnetic field, and the reflected part of the laser energy also decreases.

Finally, this is worth mentioning that not only the L-wave gets absorbed but also the R-wave. Experimentally it has been demonstrated that the R-wave or the L-wave can both be selectively launched into a steady-state dc-discharge plasma with a helical antenna [25]. But we simulated these waves (R- and L- waves) with the help of PIC simulation. In the future, many applications of RL-waves are expected to evolve, and one of these is particle acceleration where the charged particle (electron) is trapped inside the wave field, moves together with the wave and finally accelerates due to the energy exchange mechanism. This is also mentioned that the above results were obtained based on the Gaussian profile of the lasers. However, we can extend the present investigation with other profiles of the lasers that have proved to be effective in other optical phenomena also [26–28].

4. Conclusion

A strong magnetic field can cause the laser to propagate even in an over-dense plasma. Considering appropriate values of the magnetic field, we proved that the excitation of either R-wave or both the R- and L-waves simultaneously is possible and hence, their multiple applications can be sought. Along with this, there exist electrostatic disturbances in the plasma carrying a significant amount of energy. The fast Fourier transformation of the magnetic field led to the determination of the frequency and wave numbers of these waves. Another confirmation of these waves was done based on the polarization of the electric fields. Both the waves were found to propagate at different velocities and hence, created a difference in the instantaneous position of the electric fields.

Acknowledgement

Author GK acknowledges the University Grants Commission (UGC), Government of India, for financial support and High Performance Computing (HPC) Facility of the IIT Delhi for allowing to run the simulations.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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