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Effect of obliqueness of external magnetic field on the characteristics of magnetized plasma wakefield

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Abstract

A direct three-dimensional model to study the wakefield in underdense magnetized plasma is introduced. The model is based on an analytic procedure by Laplace transformation for calculating the magnetized plasma wake equations. Wakefield is excited using a high-intensity ultrashort laser beam. In the presence of external magnetic field perpendicular to the direction of the laser pulse propagation direction, plasma electrons rotate around the magnetic field lines, leading to the generation of an electromagnetic component of the plasma wakes at plasma frequency. This component is polarized perpendicularly to the direct current magnetic field lines and propagates in the forward direction and normal direction with respect to the laser pulse propagation direction, both perpendiculars to the direction of the applied magnetic field. Intensity of the radiation in different plasma densities and different magnetic field strengths has been observed.

Keywords: Wakefield; Pondermotive force; Magnetized plasma; Laplace transformation

Background

Looking forward to inertial confinement fusion, the interaction of laser and plasma has attracted the attention of many researchers. Because of the wide range of plasma density and temperature as well as laser pulse width and intensity, many different noticeable and interesting phenomena have been observed from this part of nonlinear physics [1-5]. Laser pulse makes plasma electrons to oscillate at laser frequency (quiver motion), which leads to the formation of ponderomotive force in plasma. The nature of ponderomotive force is strongly affected by the pulse width and energy of laser pulse, and the occurred phenomena in plasma are strongly governed by the nature of this nonlinear force. Plasma density profile will be modified by this force, and wakefield will be generated. In the interaction of high-intensity ultrashort laser pulses with plasma, the strength of wakefield can exceed to 10^9 V/m. Energy of this wake can be used for different purposes such as particle acceleration or radiation [6-9]. When the laser pulse strength $eA = m_0c^2$ is greater than unity, relativistic effects should be taken into account, and the plasma particles will experience a relativistic nonlinear force [10,11].

Several works have been done to study the behavior of wakefield in the interaction of high-intensity ultrashort laser pulse with plasma [12-15]. However, they have not followed the direct procedure in magnetized plasma.

In this theoretical study, we have calculated the behavior of plasma wake, due to the interaction of high-intensity ultrashort laser pulse with magnetized plasma. In this scheme, the interaction between the laser pulse and the plasma causes the ponderomotive force and generates the wakefield at the frequency of ω_p so tunable with varying the plasma density. The initial motion of plasma electrons makes them rotate around the magnetic field lines and generate the electromagnetic part in the wake. The magnetized wake propagates through the plasma with a nonzero group velocity and couples to vacuum at the plasma/vacuum boundary. The theory of radiation from the wakes excited by laser pulse in the magnetized plasma has been introduced by Yoshii et al. [6]. The characteristics of this radiation have been observed by Yugami et al. [7] in a gas-filled chamber, and the first experiment on using gas-jet plasma to excite

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the radiation is reported by Dorranian et al. [1]. The equations of magnetized plasma wakefield are introduced in [1].

Theory

In this model, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields of wakefield in plasma, respectively. Plasma is assumed to be embedded in an external magnetic field of $\vec{B}= B_{0y}\hat{j} + B_{0z}\hat{k}$. So for the basic equations which include the equation of motion and Maxwell equations, we have

$$m\frac{\partial \vec{V}}{\partial t} = -e\vec{E} - \frac{e}{c}\vec{V} \times \vec{B}_0 - \nabla\phi \tag{1a}$$

$$\frac{\partial \vec{E}}{\partial t} = 4\pi en\vec{V} + c\nabla \times \vec{B} \tag{1b}$$

$$\nabla\times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}. \tag{1c}$$

Here, $\vec{E}$ and $\vec{B}$ are the electric and magnetic components of wakefield, respectively. m_0 and e are the mass and charge of electrons, respectively. $\vec{V}$ is the velocity of electrons, and ϕ is the scalar potential of laser pulse in magnetized plasma. It can be assumed that the fields and electron velocity are functions of only z. Writing Equations 1 to 1c in the vector components form and combining them, we have

$$\frac{\partial^2 E_x}{\partial t^2} - c^2\frac{\partial^2 E_x}{\partial z^2} = -\omega_p^2 E_x - \omega_{cz}\left(\frac{\partial E_y}{\partial t} - c\frac{\partial B_x}{\partial z}\right) + \omega_{cy}\frac{\partial E_z}{\partial t} \tag{2a}$$

$$\frac{\partial^2 E_y}{\partial t^2} - c^2\frac{\partial^2 E_y}{\partial z^2} = -\omega_p^2 E_y + \omega_{cz}\left(\frac{\partial E_x}{\partial t} + c\frac{\partial B_y}{\partial z}\right) \tag{2b}$$

$$\frac{\partial^2 E_z}{\partial t^2} = -\omega_p^2 E_z - \omega_{cy}\left(\frac{\partial E_x}{\partial t} + c\frac{\partial B_y}{\partial z}\right) - \frac{\omega_p^2}{e}\frac{\partial\phi}{\partial z}. \tag{2c}$$

To write Equations 2a to 2c, the two derivatives $\partial/\partial x$ and $\partial/\partial y$ are taken to be zero. $\omega_{cy} = eB_{0y}/mc$, $\omega_{cz} = eB_{0z}/mc$, and $\omega_p^2 = 4\pi e^2 n_0/m$ are cyclotron and plasma frequencies, respectively. At this point, we introduce the new variable $\xi = t - z/V_0$, where V_0 is the initial phase velocity of the wakefield. In terms of new variables $\partial/\partial t \to \partial/\partial\xi$ and $\partial/\partial \to -1/V_0\ \partial/\partial\xi$, so we have

$$\frac{\partial^2 E_x}{\partial\xi^2} - \frac{1}{\beta^2}\frac{\partial^2 E_x}{\partial\xi^2} + \omega_p^2 E_x = -\omega_{cz}\left(\frac{\partial E_y}{\partial\xi} + \frac{1}{\beta}\frac{\partial B_x}{\partial\xi}\right) + \omega_{cy}\frac{\partial E_z}{\partial\xi} \tag{3a}$$

$$\frac{\partial^2 E_y}{\partial\xi^2} - \frac{1}{\beta^2}\frac{\partial^2 E_y}{\partial\xi^2} + \omega_p^2 E_y = \omega_{cz}\left(\frac{\partial E_x}{\partial\xi} - \frac{1}{\beta}\frac{\partial B_y}{\partial\xi}\right) \tag{3b}$$

$$\frac{\partial^2 E_z}{\partial\xi^2} + \omega_p^2 E_z = -\omega_{cy}\left(\frac{\partial E_x}{\partial\xi} - \frac{1}{\beta}\frac{\partial B_y}{\partial\xi}\right) + \frac{\omega_p^2}{ec\beta}\frac{\partial\phi}{\partial\xi}, \tag{3c}$$

in which $\beta = V_0/c$. Applying Laplace transformation with respect to ξ, the set of above equations becomes

$$S^2\tilde{E}_x - \frac{1}{\beta^2}S^2\tilde{E}_x + \omega_p^2\tilde{E}_x = \omega_{cy}S\tilde{E}_z - \omega_{cz}\left(S\tilde{E}_y - \frac{1}{\beta^2}S\tilde{E}_y\right) \tag{4a}$$

$$S^2\tilde{E}_y - \frac{1}{\beta^2}S^2\tilde{E}_y + \omega_p^2\tilde{E}_y = \omega_{cz}\left(S\tilde{E}_x - \frac{1}{\beta^2}S\tilde{E}_x\right) \tag{4b}$$

$$S^2\tilde{E}_z + \omega_p^2\tilde{E}_z = -\omega_{cy}\left(S\tilde{E}_x - \frac{1}{\beta^2}S\tilde{E}_x\right) + \frac{\omega_p^2}{e\beta c}S\tilde{\phi}, \tag{4c}$$

where tiled refers to Laplace transformation of variables, s is the Laplace variable, and $\tilde{\phi}$ is the Laplace transformation of ϕ. Answers for this set of equations are given as:

$$\tilde{E}_y = \frac{S\omega_{cz}\left(1 - \frac{1}{\beta^2}\right)}{S^2 - \frac{S^2}{\beta^2} + \omega_p^2}\tilde{E}_x \tag{5a}$$

$$\tilde{E}_z = -\frac{S\omega_{cy}\left(1 - \frac{1}{\beta^2}\right)}{\left(S^2 + \omega_p^2\right)}\tilde{E}_x + \frac{\omega_p^2}{e\beta c\left(S^2 + \omega_p^2\right)}S\tilde{\phi}. \tag{5b}$$

Using Equations 5a and 5b in Equation 4a, one can find

$$\tilde{E}_x = \frac{S^2\left(S^2 + \omega_p^2 - \frac{S^2}{\beta^2}\right)\omega_p^2\omega_{cy}}{Ae\beta c}\tilde{\phi}, \tag{6}$$

in which

$$A = S^2\omega_p^4 + \frac{S^2}{\beta^2}\left(\frac{1}{\beta^2} - 1\right)\left(S^4 + S^2\omega_H^2 + \omega_p^2\omega_{cz}^2\right) + S^2\left(1 - \frac{1}{\beta^2}\right)\left(S^4 + 2S^2\omega_p^2 + \omega_p^4 + S^2\omega_H^2 + \omega_p^2\omega_H^2\right) + \omega_p^6,$$

where

$$\omega_c^2 = \omega_{cy}^2 + \omega_{cz}^2$$

$$\omega_H^2 = \omega_p^2 + \omega_c^2,$$

and for other component of wakefield, we have

$$\tilde{E}_y = \frac{S^3\omega_p^2\omega_{cy}\omega_{cz}\left(1 - \frac{1}{\beta^2}\right)}{Ae\beta C}\tilde{\phi} \tag{7a}$$

$$\tilde{E}_z = \frac{AS\omega_p^2 - S^3\omega_p^2\omega_{cy}^2\left(1 - \frac{1}{\beta^2}\right)}{\left(S^2 + \omega_p^2\right)}\frac{\left(S^2 + \omega_p^2 - \frac{S^2}{\beta^2}\right)}{Ae\beta c}\tilde{\phi}. \tag{7b}$$

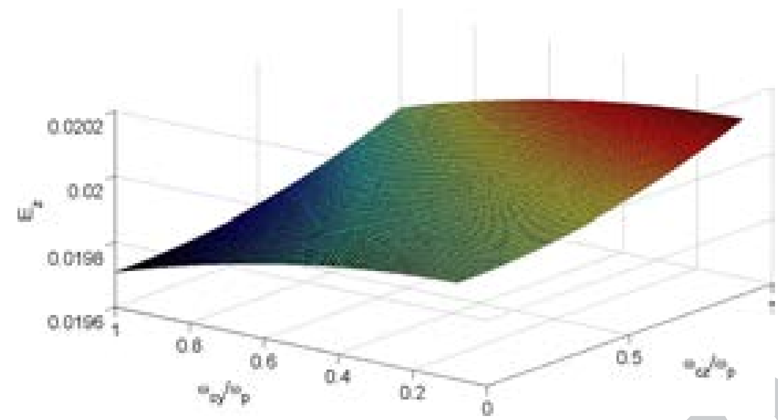

Figure 1 The z component of the wakefield as a function of external magnetic field components.

Magnetic field components can be stated as below:

$$\tilde{B}_{\mathrm{y}} = \frac{\left(S^2 + \omega_{\mathrm{p}}^2 - \frac{S^2}{\beta^2}\right)\omega_{\mathrm{p}}^2\omega_{\mathrm{cy}}S^2}{e\beta^2 cA}\tilde{\phi} \tag{8a}$$

$$\tilde{B}_{\mathrm{x}} = \frac{-S^3\omega_{\mathrm{p}}^2\omega_{\mathrm{cy}}\omega_{\mathrm{cz}}\left(1-\frac{1}{\beta^2}\right)}{2e\beta^2 cA}\tilde{\phi}. \tag{8b}$$

For a laser pulse of the duration τ, electric field E_{L}, and frequency ω_{L}, the ponderomotive potential has the form $\phi = eE_{\mathrm{L}}^2/4m\omega_{\mathrm{L}}^2$. Transforming it to ω space, we have

$$\tilde{\phi}(S) = \int_0^{\xi_0}\frac{eE_{\mathrm{L}}^2}{4m\omega_{\mathrm{L}}^2}\exp(-S\xi)d\xi = \frac{eE_{\mathrm{L}}^2}{4m\omega_{\mathrm{L}}^2}(1-\exp(-S\xi_0)), \tag{9}$$

in which $\xi_0 = \tau_{\mathrm{L}} - z/V_0$. τ_{L} is the laser pulse duration. For $S = i\omega$, it can be written as

$$\tilde{\phi}(i\omega) = \frac{eE_{\mathrm{L}}^2}{4mi\omega\omega_{\mathrm{L}}^2}. \tag{10}$$

After taking into account the contribution of another pole at $S = i\omega$, the final relation for electrical wakefield can be expressed with the relation:

$$E_{\mathrm{x}}(\xi) = \frac{\beta\omega_{\mathrm{p}}^2\omega_{\mathrm{cy}}\alpha\left(\omega_{\mathrm{p}}^2-2\omega^2+2\frac{\omega^2}{\beta^2}\right)}{Q}\left[\sin\left(\omega\frac{\xi_0}{2}\right)\cos\left(\omega\left(\xi-\frac{\xi_0}{2}\right)\right)\right] \tag{11a}$$

$$E_{\mathrm{y}}(\xi) = \frac{-3\beta\omega\omega_{\mathrm{p}}^2\omega_{\mathrm{cy}}\omega_{\mathrm{cz}}\alpha\left(1-\frac{1}{\beta^2}\right)}{2Q}\left[\sin\left(\omega\frac{\xi_0}{2}\right)\sin\left(\omega\left(\xi-\frac{\xi_0}{2}\right)\right)\right] \tag{11b}$$

$$E_{\mathrm{z}}(\xi) = \alpha\omega\lambda\left[\sin\left(\omega\frac{\xi_0}{2}\right)\sin\left(\omega\left(\xi-\frac{\xi_0}{2}\right)\right)\right], \tag{11c}$$

in which

$$Q = \begin{bmatrix}\omega_{\mathrm{p}}^4 + \frac{1}{\beta^2}\left(\frac{1}{\beta^2}-1\right)\left(3\omega^4-2\omega^2\omega_{\mathrm{H}}^2+\omega_{\mathrm{p}}^2\omega_{\mathrm{cz}}^2\right)\\ +\left(1-\frac{1}{\beta^2}\right)\left(3\omega^4-4\omega^2\omega_{\mathrm{p}}^2+\omega_{\mathrm{p}}^4-2\omega^2\omega_{\mathrm{H}}^2+\omega_{\mathrm{p}}^2\omega_{\mathrm{H}}^2\right)\end{bmatrix}e\beta^2 c$$

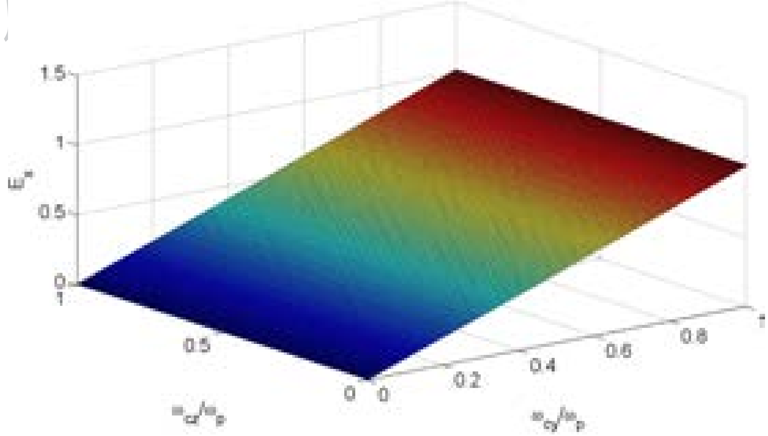

Figure 2 The x component of the wakefield as a function of external magnetic field components.

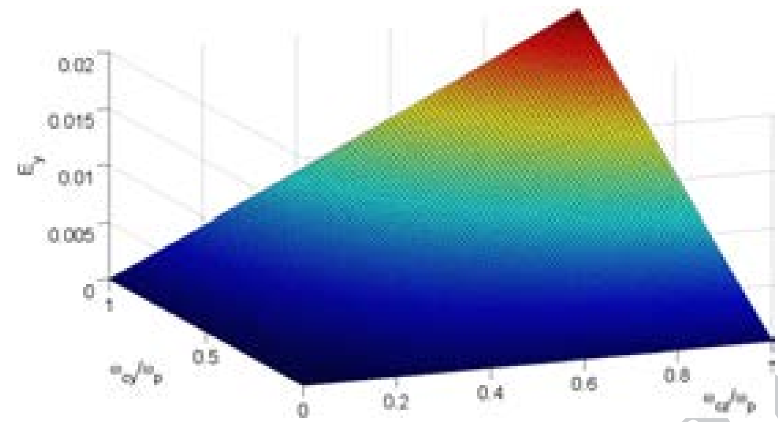

Figure 3 **The y component of the wakefield as a function of external magnetic field components.**

$$\alpha = \frac{eE_{\mathrm{L}}^2}{m\omega\omega_{\mathrm{L}}^2}$$

$$\lambda = \frac{\left(Q - ec\omega_{\mathrm{cy}}^2\left(\beta^2-1\right)\left(\omega_{\mathrm{p}}^2 - 2\omega^2 + 2\frac{\omega^2}{\beta^2}\right)\right)\omega_{\mathrm{p}}^2}{e\beta c\left(\omega_{\mathrm{p}}^2-\omega^2\right)Q}.$$

After calculating the electric fields, velocity and dispersion relation should be calculated. Let us first derive the dispersion relation. Taking $i\omega$ and $-ik$ and substituting for $\partial/\partial t$ and $\partial/\partial z$ into Equations 2a to 2c. Therefore, substituting for magnetic fields from Equation 1c into Equations 2a to 2c and noting $\phi = 0$, we have the dispersion relation as:

$$k = \left[\frac{2\left(\omega^2-\omega_{\mathrm{p}}^2\right)^2 - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}}{2\omega^2\left(\omega^2-\omega_{\mathrm{p}}^2\right) - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}}\right]^{1/2}\frac{\omega}{c}, \qquad (12)$$

in which

$$\Delta = \omega^4\omega_{\mathrm{cy}}^4 + 4\omega^2\omega_{\mathrm{cz}}^2\left(\omega^2-\omega_{\mathrm{p}}^2\right)^2,$$

and for the group velocity, we find

$$v_{\mathrm{g}}^{-1} = \left[\frac{2\left(\omega^2-\omega_{\mathrm{p}}^2\right)^2 - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}}{2\omega^2\left(\omega^2-\omega_{\mathrm{p}}^2\right) - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}}\right]^{1/2}\frac{1}{c} + \frac{I_1}{I_2}\frac{\omega}{2c}, \qquad (13)$$

in which

$$\begin{aligned} I_1 = {} & \pm 4\omega^3\sqrt{\Delta} + 4\omega^5\omega_{\mathrm{cy}}^2 - 8\omega\left(\omega^2-\omega_{\mathrm{p}}^2\right)^3 \\ & + \left(\omega^2-\omega_{\mathrm{p}}^2\right)^2\left[4\omega\omega_{\mathrm{cy}}^2 + 8\omega^3 \pm 2M\right] \\ & + \left(\omega^2-\omega_{\mathrm{p}}^2\right)\left[\mp 2\omega^2 M \mp 4\omega\sqrt{\Delta} - 8\omega^3\omega_{\mathrm{c}}^2\right] \end{aligned}$$

$$I_2 = \sqrt{\left(2\omega^2\left(\omega^2-\omega_{\mathrm{p}}^2\right) - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}\right)^3\left(2\left(\omega^2-\omega_{\mathrm{p}}^2\right)^2 - \omega^2\omega_{\mathrm{cy}}^2 \mp \sqrt{\Delta}\right)}$$

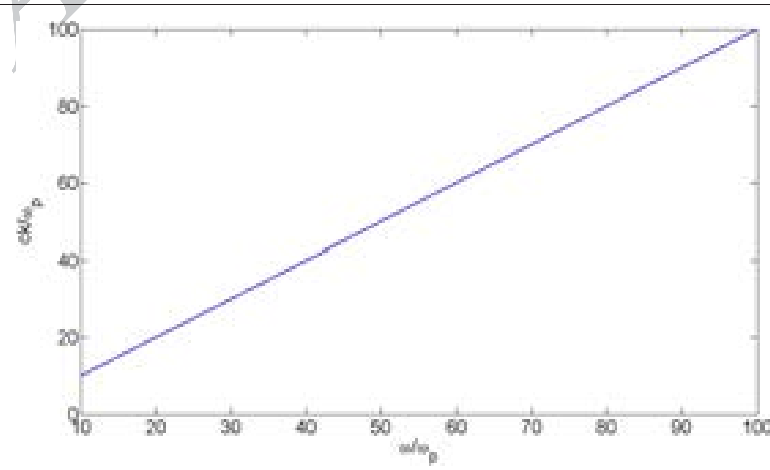

Figure 4 **Dispersion relation of the generated wakefield.**

$$M = \frac{2\left(\omega^3\omega_{cy}^4 + 2\omega\omega_{cz}^2\left(\omega^2 - \omega_p^2\right)^2 + 4\omega^3\omega_{cz}\left(\omega^2 - \omega_p^2\right)\right)}{\sqrt{\Delta}}.$$

Results and discussion

The x, y, and z components of the generated wakefiled are discussed here. In this section, the components of electric field are normalized to E_L, the electric field of the laser pulse. The z component of the wakefield as a function of external magnetic field components is shown in Figure 1. With increasing both components of the external magnetic field, the axial component of plasma wakefield increases. As is clear from the figure, ω_{cz} is more effective on increasing the axial component of wakefield than ω_{cy}.

Radial components of wakefield, i.e., x and y components, are not zero in the presence of external magnetic field. Behaviors of these two components are shown in Figures 2 and 3. An interesting point is that E_x generates in the presence of B_y while for generation of E_y, both B_y and B_z are required. Both radial components of the wakefield increase linearly with increasing the strength of external magnetic field. But the strength of E_x is larger than the strength of E_y. It is also noticeable that E_z and E_y are in phase while E_x generates with $\pi/2$ phase shift in comparison with E_z and E_y. Actually, the laser pulse electric field oscillates in the *x*-direction.

Dispersion relation of the generated wakefield is presented in Figure 4. ω is approximately a linear function of k in the range of consideration without any cutoff or resonance. This is what we have seen in similar works [8,9].

In Figure 5, the group velocity of the plasma wakefield in magnetized plasma is shown. The behavior is expectedly similar to the upper hybrid magnetized plasma modes. The group velocity increases with increasing the wave frequency and finally tends to c.

Conclusion

In this manuscript, the effect of external magnetic field and its direction on the nature of plasma wakefield due to the interaction of high-power ultrashort laser pulse with magnetized plasma are investigated. The first step is the oscillation of plasma electrons in the electric field of laser pulse, leading to the generation of pondermotive force which affects the plasma electric charged particles. Pondermotive force separates negative electrons and positive ions in the direction of laser pulse propagation. Large spatial potential of this separation causes the oscillation of electrons with respect to stationary ions, named as plasma wakefield, i.e., E_z. Wakefield is electrostatic and its large energy dissipates as the thermal energy in plasma medium. Applying the external magnetic field changes the scenario. Magnetic force makes the oscillatory electrons to rotate around the magnetic field lines. This new motion of plasma electrons leads to the generation of new components of plasma wakefield which are electromagnetic, i.e., E_x and E_y. Rotation is on the z-x to z-y planes, depending on the angle between external magnetic field and *z*-axis. They can transmit through plasma to free space and transport a large amount of plasma energy in the radiation form. The frequency of this radiation is close to ω_p, so tunable with plasma frequency, as is shown in Figure 4, and their group velocity is very close to c, as is shown in Figure 5.

Effect of obliqueness of the external magnetic field is clear here. Changing the direction of the external magnetic field from *y*-direction (direction of the magnetic field of laser pulse) to *z*-direction (direction of laser pulse propagation) leads to large enhancement of the axial component of generated wakefield, i.e., E_z, and extinction of radial components of plasma wakes, i.e., E_x and E_y.

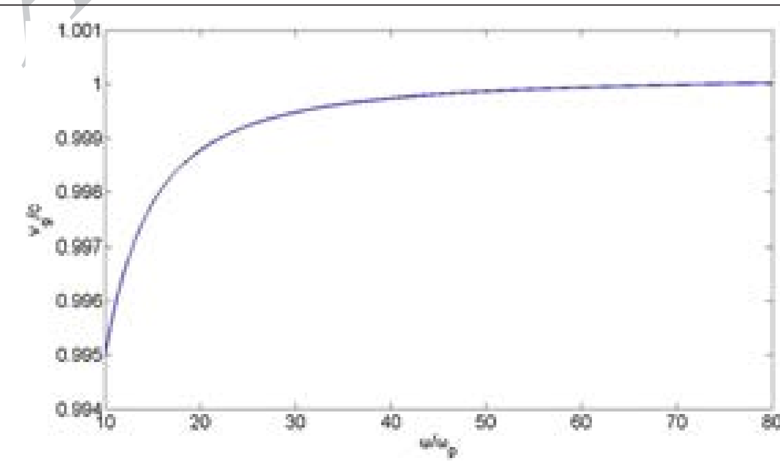

Figure 5 The group velocity of the plasma wakefield in magnetized plasma.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MM and DD both have equal contribution in calculations and analysis the data, as well as writing the manuscript. Both authors read and approved the final manuscript.

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