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Control of laser light by a plasma immersed in a tunable strong magnetic field

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Abstract: The interaction between laser light and an underdense plasma immersed in a spatio-temporally tunable magnetic field is studied analytically and numerically. The transversely nonuniform magnetic field can serve as a magnetic channel, which can act on laser propagation in a similar way to the density channel. The envelope equation for laser intensity evolution is derived, which contains the effects of magnetic channel and relativistic self-focusing. Due to the magnetic field applied, the critical laser power for relativistic self-focusing can be significantly reduced. Theory and particle-in-cell simulations show that a weakly relativistic laser pulse can propagate with a nearly constant peak intensity along the magnetic channel for a distance much longer than its Rayleigh length. By setting the magnetic field tunable in both space and time, the simulation further shows that the magnetized plasma can then act as a lens of varying focal length to control the movement of laser focal spot, decoupling the laser group velocity from the light speed c in vacuum.

1. Introduction

Compared to the low breakdown threshold (limited to 10^{12} W cm^{-2}) of optical crystal devices, a plasma can tolerate much higher laser intensities ($\sim 10^{17}$ W cm^{-2} or more) and hence is routinely used as an amplification medium in the Raman [1–4] or Brillouin [5–8] amplification regime to amplify seed laser pulses or as a plasma mirror [9] to increase the contrast of intense laser pulses. Furthermore, plasma may be used for cross beam energy transfer [10], polarization control of light waves [11–14], information storage and retrieval [15], generation of relativistic single-cycle tunable infrared pulse [16], optical modulator [17], and apertures [18, 19].

In particular, the optical properties of a plasma can be modified by an applied magnetic field which modifies the motion of the constituent electrons and ions. Therefore, intense laser interaction with magnetized plasmas is attracting significant attention and many novel phenomena have been discovered. For example, a circularly polarized (CP) laser pulse can penetrate into an overdense plasma along a strong longitudinal magnetic field ($\mathbf{B} \parallel \mathbf{k}$) without resonance or cutoff [20–22] and the transmission process can be controlled by a strong pulsed magnetic field [23], where $\mathbf{B}$ and $\mathbf{k}$ are the external magnetic field and laser wave vector, respectively. A magnetized plasma can also enhance the self-focusing and self-compression of CP pulses [24] or realize a spherical compression [25] at lower densities. An initial linearly polarized (LP) laser pulse may even split into a right-handed and a left-handed CP pulses during its propagation in a strongly magnetized plasma [13]. In particular, the magnetized plasma can act as a novel

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high-power waveplate, which can convert a LP laser pulse with 5 petawatt (PW) peak power into a 10 PW CP pulse [14]. Moreover, a transverse magnetic field ($\mathbf{B} \perp \mathbf{k}$) can significantly mitigate the stimulated Raman scattering [26].

Here we study the interaction between CP laser light and an underdense plasma with a longitudinal magnetic field. The analytical expression of critical power for relativistic self-focusing in a magnetized plasma is derived, which indicates that the magnetic field lowers the threshold power [24]. A magnetic field with nonuniform transverse distribution can pave a magnetic channel in a uniform plasma, in which the ultrashort laser pulse can propagate with a nearly constant intensity for a distance many times longer than the Rayleigh length. It is further shown that a plasma slab immersed in a spatio-temporally tunable magnetic field can act as a lens of varying focal length to realize the dynamic focusing of laser beams in vacuum.

2. Theoretical analysis

We first consider the propagation of right-handed CP laser light in a uniform underdense plasma subjected to an external longitudinal magnetic field $\mathbf{B}_{\text{ext}}$. The laser light is assumed to propagate along the z-axis. The laser vector potential in the plasma is governed by [27]

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})\mathbf{A} = \frac{4\pi n_0 e}{mc}\frac{\mathbf{p}}{\gamma}, \tag{1}$$

where m and $-e$ are the respective mass and charge of electron, $\mathbf{A}$ is the laser vector potential, n_0 is the plasma density, c is the speed of light in vacuum, $\mathbf{p}$ is the electron momentum, $\gamma = \sqrt{1 + |\mathbf{p}|^2/m^2c^2}$ is the electron Lorentz factor. It is worth pointing out that the electron density perturbation is neglected and only the relativistic nonlinearity and external magnetic field are taken into account in the above analytical model. The equation of electron motion in a magnetized plasma is [28]

$$\frac{\partial(\mathbf{p} - e\mathbf{A}/c)}{\partial t} = \frac{\partial(e\phi - mc^2\gamma)}{\partial z}\hat{e}_z - e\mathbf{B}_{\text{ext}} \times \frac{\mathbf{v}}{c} + \mathbf{v} \times (\frac{\partial}{\partial z}\hat{e}_z) \times (\mathbf{p} - e\mathbf{A}/c)], \tag{2}$$

where ϕ is the laser scalar potential, $\mathbf{v} = \mathbf{p}/m\gamma$ is the fluid velocity. The laser pulse is assumed to be long enough ($L \gg 2\pi/\omega_{p0}$) so that the plasma wakefield excitation and longitudinal ponderomotive force is very small. Therefore $\mathbf{v} \simeq \mathbf{v}_\perp$ and $\mathbf{p} \simeq \mathbf{p}_\perp$. For a CP laser light propagating along the z direction: $\mathbf{A}(r, z, t) = \frac{1}{2}A(r, z, t)(\hat{e}_x + i\hat{e}_y)\exp[i(kz - \omega t)] + c.c$, where $c.c$ is the complex conjugate, and $\hat{e}_x$ and $\hat{e}_y$ are the unit vectors in x and y axes, respectively. Under these assumptions, together with the first order approximation, it is easily derived from Eq. (2) that

$$\mathbf{p} = \frac{e\mathbf{A}}{c}\frac{\gamma\omega}{\gamma\omega - \omega_c}, \tag{3}$$

where $\omega_c = eB_{\text{ext}}/mc$. Correspondingly, the wave equation Eq. (1) in a magnetized plasma can be rewritten as

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})\mathbf{A} = \frac{\omega_{p0}^2}{c^2}\frac{\omega}{\omega\gamma - \omega_c}\mathbf{A}. \tag{4}$$

For a non-relativistic plane wave ($\gamma = 1$ and $\nabla^2 = \partial^2/\partial z^2$), the dispersion relation for right-handed CP light wave in a magnetized plasma is recovered as $c^2k^2/\omega^2 = 1 - \omega_{p0}^2/\omega^2(1 - \omega_c/\omega)$, where ω_{p0} is the plasma oscillation frequency. The normalized laser vector potential is $\tilde{\mathbf{A}} = e\mathbf{A}/mc^2 = \frac{1}{2}a(r, z, t)(\hat{e}_x + i\hat{e}_y)\exp[i(kz - \omega t)] + c.c$, where a is given in dimensionless form. Furthermore, we introduce the dimensionless variables $\tau = \omega t$, $\tilde{r} = \omega r/c$ and $\tilde{z} = \omega(z - v_g t)/c$, where $v_g = c^2k/\omega$ is the laser group velocity. For a weakly relativistic CP laser in a magnetized plasma ($a_0 \ll 1$), the electron Lorentz factor is $\gamma \simeq 1 + a^2/4(1 - \tilde{B})$, where $\tilde{B} = \omega_c/\omega$. For the sake of simplification, the tildes will be omitted in the following analysis. In terms of the slowly varying envelope and paraxial approximations, Eq. (4) takes the form

$$i\frac{\partial a}{\partial \tau} = \left[-\frac{1}{2}\nabla_\perp^2 - \frac{n_0}{n_c}\frac{1}{8(1-B)^4}a^2\right]a, \tag{5}$$

where $n_c = m\omega^2/4\pi e^2$ is the critical plasma density.

Applying the variational principle approach, we can write the Lagrangian corresponding to Eq. (5) as

$$L = -\frac{i}{2}(a^*\frac{\partial a}{\partial \tau} - a\frac{\partial a^*}{\partial \tau}) + \frac{1}{2}\nabla_\perp a \cdot \nabla_\perp a^* - \frac{n_0}{n_c}\frac{1}{16(1-B)^4}|a|^4. \tag{6}$$

From Eqs. (5) and (6), two conservative quantities can be obtained, which are the power P for the incident laser and the Hamiltonian H for the system:

$$P = \int |a|^2 d^2r, \tag{7}$$

$$H = \int \left(\frac{1}{2}\nabla_\perp a \cdot \nabla_\perp a^* - \frac{n_0}{n_c}\frac{1}{16(1-B)^4}|a|^4\right) d^2r. \tag{8}$$

Using the methodology adopted in [27], then the critical laser power for relativistic self-focusing in a magnetized plasma can be obtained as

$$P_c = 17.4\left(\frac{\omega}{\omega_{p0}}\right)^2\left(1-\frac{\omega_c}{\omega}\right)^4 \textbf{GW}. \tag{9}$$

It implies that the external magnetic field can lower the critical power significantly as $\omega_c \to \omega$.

Considering a magnetic field with a nonuniform transverse distribution $B = B(r)$, then the index of refraction including magnetic field effects is given by

$$\eta(r) \simeq 1 - \frac{\omega_{p0}^2}{2\omega^2}\frac{1}{\gamma(r) - B(r)} \tag{10}$$

It suggests that even for a nonrelativistic laser intensity ($\gamma = 1$), the focusing of laser light may still occur if $\partial B/\partial r > 0$, which can be termed as "magnetic focusing". Thus, a transversely nonuniform magnetic field can provide a channel to guide laser light in a uniform plasma, which is similar to the light guiding in a preformed plasma density channel [29, 30]. For simplification of analysis, the magnetic field is assumed to have a linear transverse profile as $B(r) = B_0 r$, then the laser envelope equation takes the form

$$i\frac{\partial a}{\partial \tau} = \left\{-\frac{1}{2}\nabla_\perp^2 - \frac{n_0}{2n_c}[1 - \frac{1}{\gamma - B(r)}]\right\}a. \tag{11}$$

Further, if this nonuniform magnetic field is time-varying, i.e. $B = B(r, t)$, then the magnetized plasma can act as a lens of varying focal length, which can manipulate the movement of focused laser peak in vacuum.

3. Simulation results and discussions

To verify this magnetic focusing, we have performed two-dimensional PIC simulations using the code Osiris [31]. In the simulations, a right-handed CP laser pulse with a wavelength $\lambda = 1$ μm is incident along the z axis into a magnetized plasma. A fully ionized hydrogen plasma is used with uniform density $n_0 = 0.3n_c$ and the electron and ion temperatures $T_e = T_i = 0$. The simulation mesh sizes are $dz = 1/40$ and $dy = 1/30$ μm, respectively, with 4 particles in each cell.

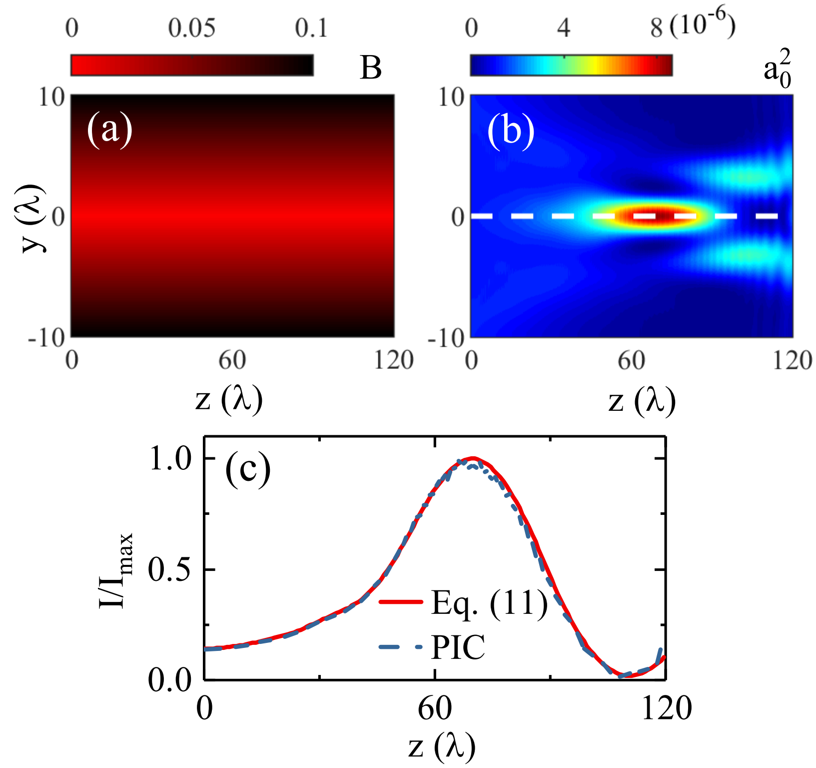

Fig. 1. (a) The spatial strength distribution of an external longitudinal magnetic field that is along the z axis, and the magnetic field strength is normalized to $m\omega c/e \simeq 1.07 \times 10^4$ T. (b) An incident plane wave is experiencing a magnetic focusing in a plasma with a nonuniform magnetic field as shown in (a). (c) The laser intensity distribution along the laser propagation axis, namely the lineout in (b), which is obtained from the PIC simulation or numerical solution of Eq. (11). In the simulation, the laser pulse initially has a weak enough intensity ($a_0 = 0.001$).

First, the laser light is set to be weak enough to ignore the relativistic self-focusing ($\gamma \equiv 1$), and it is only needed to consider the magnetic focusing. Figure 1 displays an example for the magnetic focusing of a weak enough laser light with an amplitude $a_0 = 0.001$ ($I_0 \simeq 10^{12}$ W/cm^2). An uniform laser intensity profile (plane wave) is used for the convenience in comparing with the theoretical result by Eq. (11). The simulation box is 120×20 μm in the z $\times$ y directions, respectively. The external magnetic field is along the z axis and its strength has a linear profile in the y direction, i.e. $\vec{B} = B_0|y|\vec{e}_z$, where $B_0 = 0.01, -10 \leq y \leq 10$ as shown in Fig. 1(a). One can see from Fig. 1(b) that a laser intensity peak appears on the z axis whose location, $z \simeq 63\lambda$, can be considered as the focus of this magnetic channel. The on-axis laser intensity distribution is presented in Fig. 1(c), which shows that the laser intensity is enhanced about 6-fold at the focus. For comparison, the on-axis laser intensity estimated from the numerical solution of Eq. (11) is also plotted in Fig. 1(c). It clearly indicates that a very good agreement is obtained between the PIC simulation and theoretical model. It is worth pointing out that the laser light focusing will happen again after the defocusing, and such focusing and defocusing will appear periodically if the magnetic channel is long enough.

In the above simulation, a uniform laser intensity profile is used for the convenience in comparing with the theoretical model. In most realistic cases, the laser typically has a nonuniform

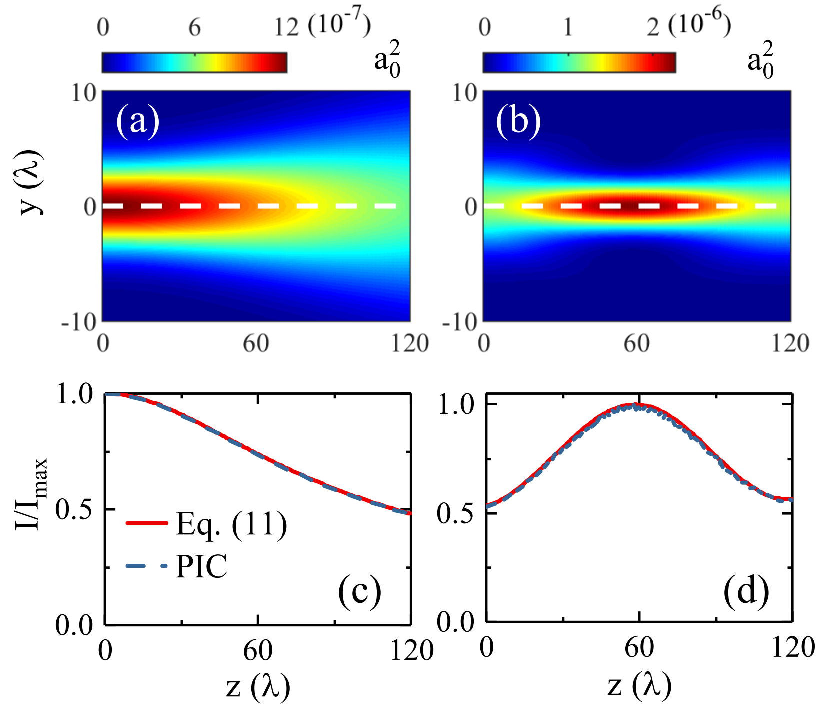

Fig. 2. The spatial distribution of electronic field energy density for a laser beam with a transverse Gaussian profile during its interaction with a plasma without (a) or with (b) a longitudinal magnetic field. (c) and (d) are the lineout distribution corresponding to the white dashed lines in (a) and (b), respectively, where the PIC simulation results are in good agreement with the predictions by Eq. (11). Except the laser transverse mode, other parameters are the same as those in Fig. 1.

intensity profile like a Gaussian profile $\exp(-r^2/w_0^2)$. To confirm the usability of the theoretical model, we have also performed simulations in which the laser intensity has a flattop longitudinal profile but a Gaussian transverse profile. The initial laser focal spot is set at $z = 0$ with a waist $w_0 = 5\lambda$ and the other parameters remain the same as those in Fig. 1. After propagating away from the focal spot, the laser intensity reduces quickly if there is no magnetic field, as shown in Fig. 2(a). Figure 2(c) shows that Eq. (11) can still describe the propagation of a Gaussian laser beam precisely. When the laser propagates in the magnetized plasma, its intensity distribution as shown in Fig. 2(b) is distinctly different from that in Fig. 2(a). Figure 2(d) clearly shows that the focal spot moves to the position $z \simeq 60\lambda$. Meanwhile, the good agreement between the PIC simulation result and the numerical solution of Eq. (11) indicates that our theoretical model for the magnetic focusing is applicable to more realistic scenarios.

With increasing laser intensity, the relativistic self-focusing becomes stronger gradually, mitigating the transverse divergence of the laser. However, such a laser beam also means a stronger ponderomotive force than that in Fig. 2, which strongly perturbs the electron density of the plasma. If only the laser amplitude changes from $a_0 = 0.001$ to $a_0 = 0.05$, and other parameters remain the same as those in Fig. 2, the simulation results show that the electron density perturbations will become perceptible at 175 fs (145 fs) after the laser beam enters the unmagnetized (magnetized) plasma. That is to say, the influence of the ponderomotive force on the plasma density takes some response time to emerge. Therefore, it is still possible to guide a weakly relativistic ultrashort laser pulse in a magnetized plasma over a distance far beyond the

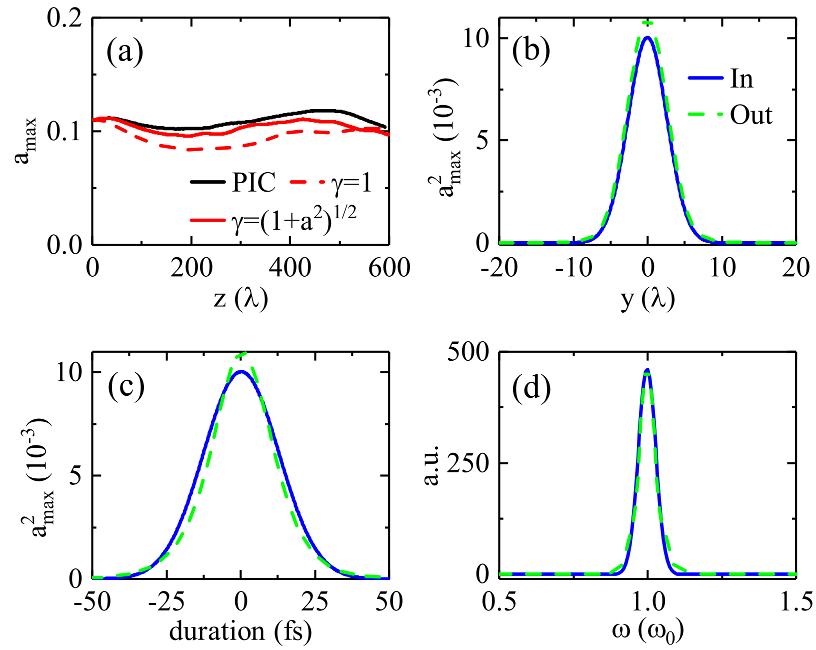

Fig. 3. The guidance of weakly relativistic laser pulses by magnetic focusing in plasma. (a) The maximum of the laser vector magnitude a_{max} as a function of the plasma length. The black line represents the 2D PIC simulation results. Red lines represent the theoretical predictions with (solid) or without (dashed) accounting for relativistic laser intensity effects. (b)-(d) The spot size, duration, and spectrum of the output laser pulse after it passes through a magnetized plasma 8 times longer than Rayleigh length, where the according parameters for input laser are also drawn for comparison.

Rayleigh length.

In order to test the guidance of weakly relativistic short laser pulses by the magnetic focusing in plasmas, we have performed 2D PIC simulation with a moving window in the z direction. We have assumed a Gaussian laser pulse with $a_0 = 0.1$, a waist $w_0 = 5$ μm, and a duration of 30 fs (full width at half maximum). The plasma is uniform with $n_0 = 0.3n_c$, and the external magnetic field $B(y) = B_0|y|$ is along the z-axis, where $B_0 = 1/400, -10 \leq y \leq 10$.

The PIC simulation results in Fig. 3(a) show that the laser amplitude a is approximately constant during it propagates in the magnetized plasma, far beyond the Rayleigh length ($Z_R \simeq 78.5\lambda$). It is worth mentioning that since the value of a_{max} is diagnosed in the plasma, so the initial value of a_{max} is not equal to $a_0 = 0.1$ in vacuum. The formula describing the relation between a_{max} and a_0 is $a_{max} = 2a_0(1 + \sqrt{\eta})^{-1}$, and in this simulation case $a_{max} \simeq 0.109$. Since a weakly relativistic laser pulse can induce a relativistic mass increases of electrons and effectively change the plasma refractive index, the relativistic effect cannot be neglected. Figure 3(a) confirms that the theoretical result including the relativistic effect ($\gamma = (1 + a^2)^{1/2}$) is more consistent with the PIC simulation result than the result ignoring the relativistic effect ($\gamma = 1$). Figures 3(b) - 3(d) compare the spot size, duration, and spectrum of the input and output laser pulses, the magnetized plasma has a thickness of 8 times the Rayleigh length. The transverse spot size of the output laser is almost identical to that of the input laser, which is very important in laser guiding. Although the output duration reduces a little, the Fourier analysis of the output pulse indicates the variation in spectrum can be neglected. Therefore, it is feasible to use the magnetic focusing to guide the weakly relativistic laser pulses over long distances in plasmas.

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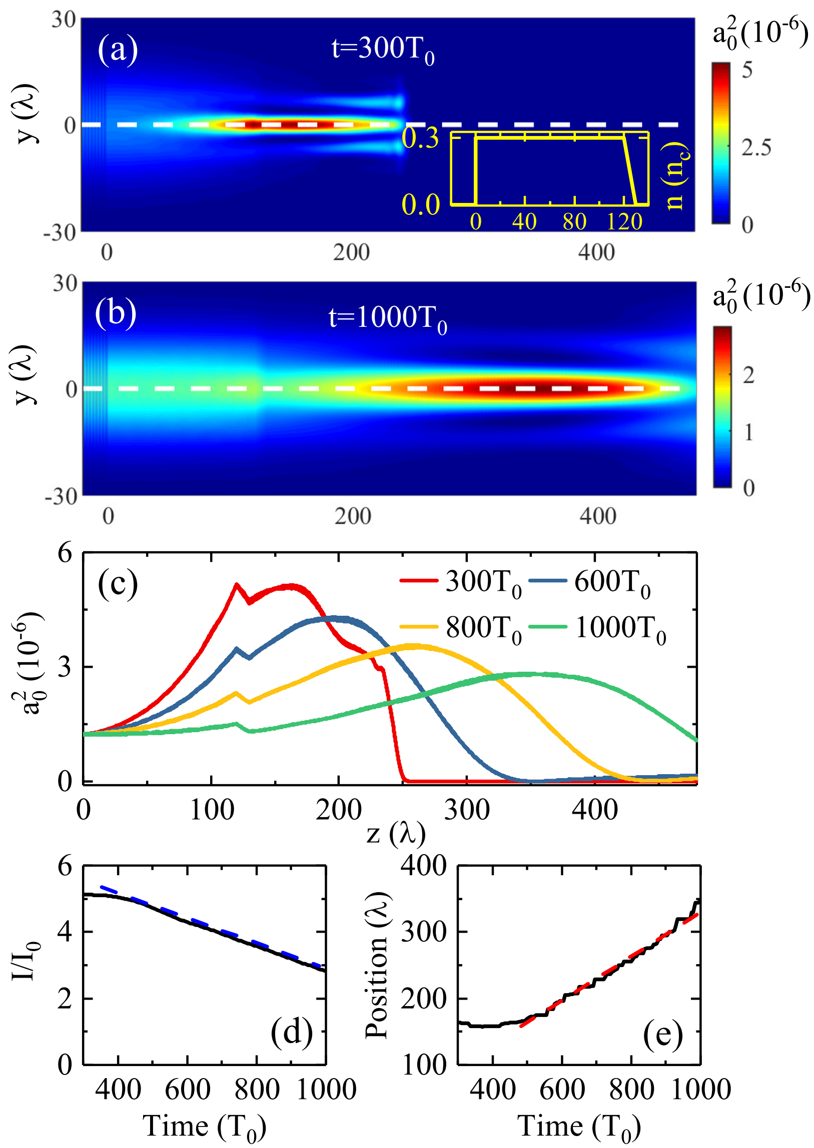

Fig. 4. Control of the position of peak intensity of the laser light in vacuum. (a) A nonuniform magnetic field in transverse space is exploited to make the peak intensity in a defined position. (b) A spatiotemporal magnetic field is exploited to move the peak intensity position. (c) The lineout of laser intensity on the z axis at given times. (d) and (e) shows the peak intensity of the laser light and its position as a function of the time, where the bule and red dashed lines show their linear relation to time, respectively.

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In the above analysis and simulations, the effect of magnetic field always dominates the laser focusing since weakly relativistic laser intensities ($a_0 \leq 0.1$) are employed. For the cases $a_0 \to 1$, the laser focusing can also be achieved by the combination of the magnetic focusing and the relativistic self-focusing. However, Eq. (10) suggests that the relativistic self-focusing will be much more important than the magnetic focusing in the cases $a_0 \to 1$ and $B \ll 1$.

If the nonuniform magnetic field is time-varying, then the focusing capability of the magnetized plasma will vary with time. Consequently, the dynamic focusing of an input laser pulse can be achieved. A 2D PIC simulation is performed to show that the plasma under a time-varying nonuniform magnetic field can act as a lens of dynamic focal length to control the movement of the laser intensity peak in vacuum. The simulation box is $500 \times 60\ \lambda$ in the $z \times y$ directions, respectively. The magnetic field has the following spatio-temporal expression

$$B = \begin{cases} |y|/300, & 0 \leq t \leq 300 \\ (1000 - t)|y|/(300 * 700), & 300 \leq t \leq 1000 \end{cases} \tag{12}$$

where $-30 \leq y \leq 30$. In order to mitigate the effect of reflected light from the right plasma-vacuum interface, a linear density ramp is exploited, the inset in Fig. 4(a) shows the longitudinal density profile. The other parameters employ the same values as those in Fig. 2. When $t \leq 300T_0$, the nonuniform magnetic field is constant in time, so it can steadily focus the laser pulse at the position of $z = 160\lambda$, as shown in Fig. 4(a). The magnetic field varies with time for $t > 300T_0$, resulting in the move of the position of laser intensity peak. Figure 4(b) shows the intensity peak is at the position of $z \simeq 350\lambda$ at the time of $t = 1000T_0$. The on-axis laser intensity profiles at several different times are compared in Fig. 4(c), which clearly shows the movement of the position of laser intensity peak in vacuum. Figures 4(d) and 4(e) indicate both the peak intensity and its position are linearly proportional to time and the forward velocity of laser intensity peak in vacuum is about $0.33c$. It can be found from Figs. 4(d) and 4(e) that the peak intensity and its position are still nearly constant between $300T_0 \leq t \leq 450T_0$ although the magnetic field has already started to change. This can be explained as follows: it takes a response time for this spatio-temporal magnetic field to affect the laser focus, and this response time is about $t = L/v_g \simeq 143T_0$, where L is the thickness of the plasma slab and v_g is the laser group velocity in the plasma. The phenomenon found here is similar to the flying focusing technique [32, 33], which can control the propagation velocity of the peak intensity and has many applications [34–36] in laser-matter interactions.

4. Conclusion

In conclusion, we propose a method to guide a short laser pulse propagating through a uniform plasma, and to control the movement of laser focal spot in vacuum. The short pulse guiding is realized by the application of a nonuniform magnetic field in the transverse space, and the control of the movement of laser focal spot is achieved by using a spatio-temporal tunable magnetic field that is nonuniform in the transverse space and varies with time. This provides a new degree of freedom for manipulating the propagation of intense laser pulses in plasmas. In particular, a spatio-temporal tunable magnetic field make it possible to decouple the velocity of laser intensity peak in vacuum from the speed of light c, which is of great benefit for light-matter interactions. For example, the intense slow ($v \leq c$) pulses could facilitate laser-driven acceleration of ions [37].

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