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SIMULATIONS ON LASER WAKEFIELD GENERATION IN A PARABOLIC MAGNETIC-PLASMA CHANNEL

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Abstract

To utilize of the laser-plasma channel for laser wakefield acceleration, we have studied the non-paraxial theory of nonlinear propagation of ultra-intense relativistic Gaussian laser pulse in a preformed spatially tapered magneto-plasma channel having a parabolic density profile. A three-dimensional envelope equation for the laser field is derived, which includes the non-paraxial and applied magnetic field effects. An analytical expression for the wakefield is derived and analyzed the results with the help of particle-in-cell (PIC) simulations. It is shown that wakefield structures and the phase of axial component of the wakefield depend on applied external magnetic field. This aspect of theoretical observation can be used in the production of highly collimated mono-energetic x-rays.

INTRODUCTION

A plasma has an important ability to generate energetic electrons from interaction with a high-intensity laser. When the ponderomotive force associated with the laser field (if the duration of the laser pulse is comparable or shorter to the plasma wave period) can excite a plasma wave (wakefield) that propagates with a velocity close to the speed of light [1]. If electrons with sufficient energy matching the accelerating electric fields are injected into the wakefield, they can be trapped by the wakefield and accelerated to high energy. This scheme is known the laser wakefield acceleration (LWFA), which may play a crucial role in developing future advanced accelerators. Recently, a major work has been carried out for achieving good quality and sellf-injected electron beam from the LWFA scheme [2-4].

It is well know that the optical guiding is necessary for the propagation of an intense laser pulse over a distance of many Reyleigh lengths. In earlier studies, it has been shown that a preformed plasma channel with a radially symmetric density profile can produce higher electron energies by the optical guiding effects, which exceeds the limit by the diffraction [5]. Excitation of the accelerating wakes in an arbitrary plasma channel by a short intense laser pulse was first considered by Shvets et al. [6] with the emphasis on the hollow channels with a sharp plasma-vacuum interface. Numerical simulations of short pulses in an untapered channel have demonstrated with stable propagation over many tens of Rayleigh lengths. One of the interesting One of the interesting features of wake excitation in plasma channels with sharp density gradients is the excitation of a damped quasi-mode. This quasi-mode, whose frequency is very close to the frequency of surface mode in a hollow channel, resonates with the plasma at the resonant point. A very strong electric field develops at the resonant point, eventually leading to wave breaking and plasma heating.

In this article, we explain the excitation of wakefield acceleration in an inhomogeneous plasma channel in presence of an external longitudinal magnetic field using the quasimatched conditions as the matched conditions are no more applicable for relativistic laser pulse due to the transverse and longitudinal oscillations of the laser spot about its focal point. In addition, we analyzed the effect of an external magnetic field in the wakefield structure and accelerating length in the proposed scheme of laser-plasma interaction [7]. The external magnetic field effect on channel radius and the laser spot size was studied. Further, we discuss the effect of external magnetic field on the phase of axial component of the wakefield.

SIMULATION RESULTS

We present relativistic 2D PIC simulations of the propagation of a laser pulse in a parabolic plasma channel for different strength of the magnetic field. We use a laser pulse with an intensity of $1.3\times10^{19}\ W/cm^2$ (normalized vector potential of $a_0 = 3$), central wavelength $\lambda = 1\mu m$, focused to a spot size of $r_0 = 50\mu m$. The pulse has a Gaussian transverse and temporal profile with $33\ fs$ pulse duration. The laser pulse propagate along the z-direction through a preformed plasma channel with the transverse plasma density $n_r \approx n_0 + \Delta n r^2 / r_0^2$, where the plasma density $n_0 \approx 10^{19}\ cm^{-3}$. The simulation box with dimensions of $400\times 200\mu m^2$ moves at the speed of light, which is resolved with 8000×400 cells. Five particles per cell are used for simulations. The magnetic field is varied from one Tesla to 1000 T. Such a high magnetic field cannot be generated in the laboratory easily, but a quasistatic laser generated magnetic field with that kind of magnitude is possible in some. Figure 1 shows the spatio-temporal evolution profile of the laser pulse in the given plasma system.

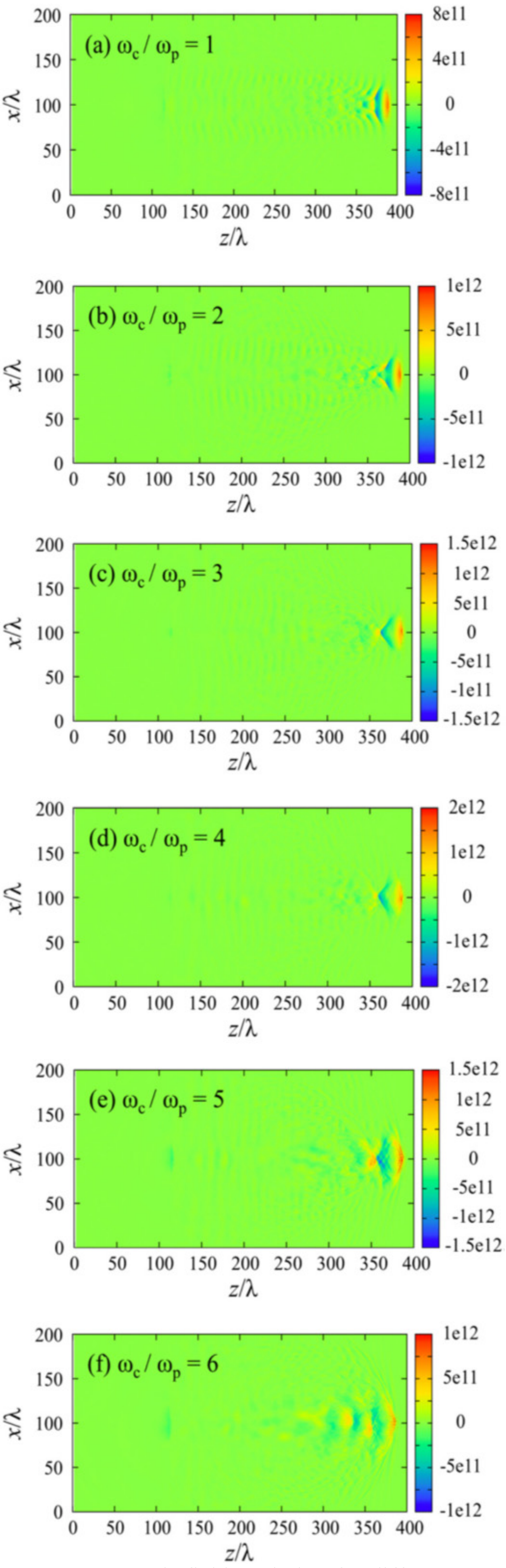

Figure 1: Laser wakefield evolution for different strength of the magnetic field in a plasma channel.

The results of the 2D PIC simulations are shown in Fig. 2, which represent the laser wakefield evolution for different strengths of the magnetic field in the parabolic channel. The simulation result suggests that the response of plasma channel is different for different strengths of magnetic fields. Generally speaking, the energy gain increases as ω_c/ω_p increases, where $\omega_c = eB/mc$ is the electron cyclotron frequency and $\omega_p = (4\pi n_0 e^2/m)^{1/2}$ is plasma electron frequency. However, the pattern of growth rate of the energy gain for different magnetic field ratio is not uniform.

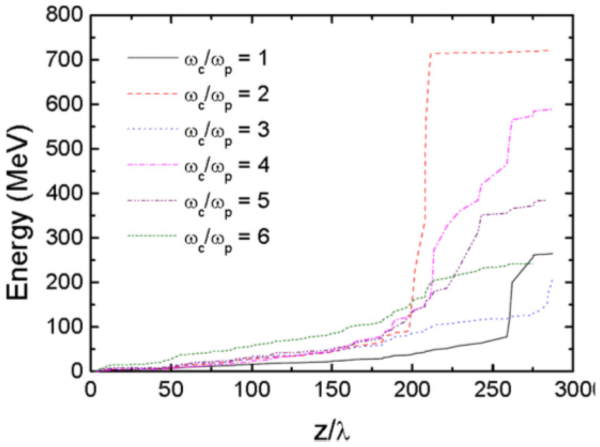

Figure 2: Electron energy for different magnetic fields.

It is shown that the energy gain is maximum for a particular strength of the magnetic field, which could be a state of autoresonance. For other strength of the magnetic field, some may corresponding to a state for which the acceleration mechanism ceases due to phase shift between the plasma wave and the accelerated bunch. The wakefield gets longitudinal part, in addition, to transverse part in the presence of the external magnetic field. . It is observed that the wake is transversely homogeneous inside the channel and has maximum amplitude at $k_p z \approx 28$ (Fig. 3). It shows that the shape of transverse profile of the channel does not depend on the applied external magnetic field and it remains stable for increasing the external magnetic field.

It is, therefore, concluded that the wakefield developed at the resonant location z, where the local plasma frequencies can match the frequencies of plasma modes, eventually leading to the wave breaking and plasma heating. The longitudinal wakefield spectrum as a function of the magnetic field ratio ω_c/ω_p can be observed from these results. It is observed that the wakefield has a maximum amplitude at the resonant state. For increasing strength of the magnetic field, the resonant location does not change, but the wakefield amplitude grows with the strength of external magnetic field. This eventually enhances the field amplitude, which could ultimately lead to the wave breaking.

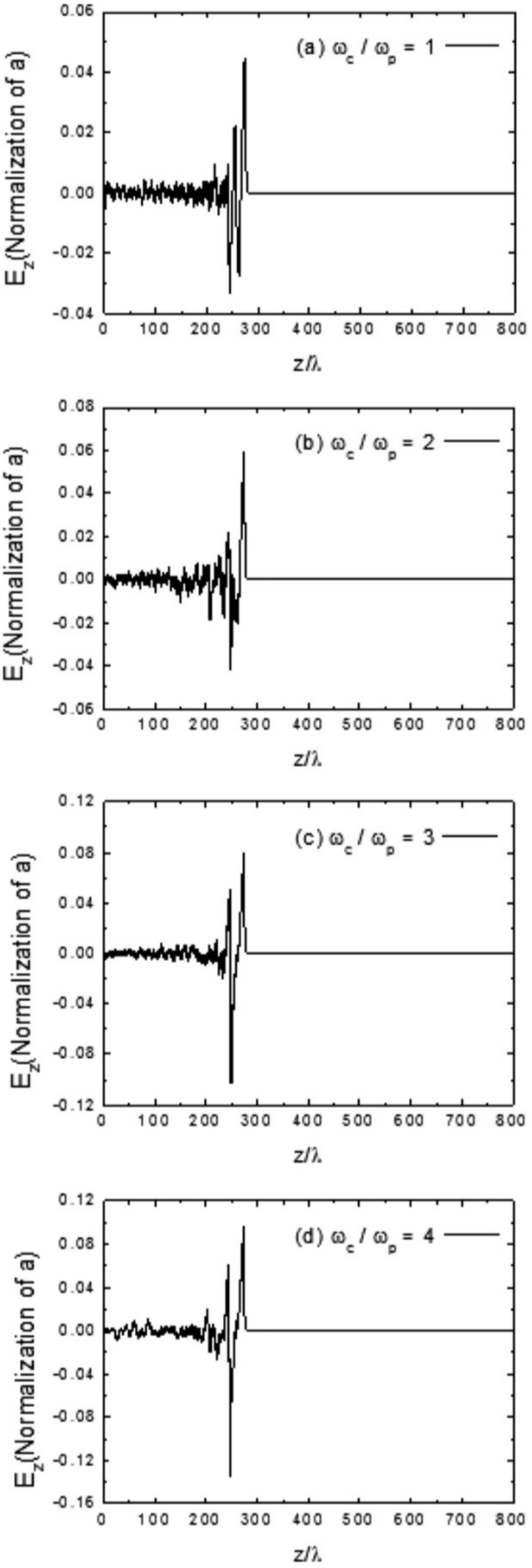

Figure 3: Longitudinal wakefield for different magnetic fields ratios.

CONCLUSIONS

We studied the excitation of a laser wakefield in an inhomogeneous plasma channel by a relativistic intense, short, and circularly polarized laser pulse in the presence of the external longitudinal static magnetic field. The presence of an external magnetic field leads to excitation of the damped quasi-modes, and this, in turn, makes the plasma density perturbation nonlocal. Time evolution of the electromagnetic field inside the channel is completely determined by the external magnetic field. The amplitude of the surface mode is driven by the longitudinal rather than the transverse gradient of the ponderomotive potential and its value depends on the applied external magnetic field.

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