MODELING AND EXPERIMENTAL UPDATE ON DIRECT LASER ACCELERATION*

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Abstract

Moderate-energy, high-repetition-rate electron beams are needed in a variety of applications such as those in security and medicine, while requiring that the acceleration be realized in a compact and relatively inexpensive package. Laser wakefield acceleration is an attractive technology which meets most of those requirements, but it requires the use of relatively high peak power lasers which do not scale readily to high repetition rates. We are developing the theoretical and experimental basis for advancing the science and technology of direct laser acceleration (DLA) of charged particles using the axial component of the electric field of a radially polarized intense laser pulse. DLA is an acceleration method which exhibits no threshold and is thus compatible with the use of lower peak power, but much higher repetition rate lasers. We are currently numerically investigating the conditions for quasi-phase-matched DLA of electrons in plasma waveguides and experimentally implementing the quasi-phase-matched waveguide structure in laser-produced plasmas.

INTRODUCTION

Laser-driven acceleration schemes could lead to significantly smaller accelerator systems, which is exemplified bylaser wake field acceleration (LWFA) [1, 2]. In LWFA, the acceleration gradient is on the order of GV/cm, which is almost 4 orders of magnitude greater than in conventional linear accelerators. Generation of monoenergetic GeV electron beams in 3 mm accelerating length has been demonstrated in the prior LWFA work [2], and there is current work to increase the acceleration gradient to 10 GeV. LWFA is a nonlinear process which requires 10's of TW peak power from the laser for effective acceleration wake field to be generated. Those pulses are currently produced by complex and relatively low repetition rate laser systems, which limits the performance and attractiveness of the technique for some applications. Investigation of alternative methods for laser electron accelerators is needed, which would allow operation with considerably lower peak powers available from novel fiber lasers. For example, modern fiber lasers are essentially unlimited in repetition rate, while being severely constrained in peak power due to the relatively small fiber core area.

Direct laser acceleration (DLA) of electrons, such as inverse Cherenkov acceleration [3, 4, 5], has the potential to meet the requirements for future compact accelerator-driven systems. In DLA, electrons are accelerated by the axial component of the electric field of a focused, radially polarized laser pulse. The acceleration gradient scales as the square root of the laser peak power [4, 5], and is estimated to be 77 MeV/mm for 800 nm laser wavelength with peak power of 0.5 TW and 8.5 μm mode radius. Therefore, field gradients on the order of hundreds of MeV/cm are expected even below TW peak power from the drive laser.

Two significant challenges associated with DLA exist and have to be addressed. They are (1) realization of guided propagation of ultraintense pulses over extended distances and (2) phase matching between the propagating electrons and laser pulses. Optical guiding in DLA using a preformed plasma waveguide [4] can extend the accelerating distance. Corrugated waveguide techniques [5, 6] with axially periodic plasma density modulation could be used to quasi-phase match (QPM) the laser and electron pulses. A net acceleration can be produced by breaking the symmetry between acceleration and deceleration phases.

In this work, we investigate the QPM conditions for DLA of electrons in plasma waveguides. First, numerical calculations are presented to estimate the phase matching conditions for a radially polarized laser pulse propagating in a density-modulated plasma waveguide, including the plasma and waveguide dispersion [4]. Next, the particle-in-cell (PIC) simulation [7] focuses on the propagation of radially polarized femtosecond pulses in plasma waveguides. In simulations, the quasi-phase matched acceleration for electron test particles launched at proper time intervals relative to the laser pulse is also verified, which will be used to guide future experiments.

QUASI-PHASE MATCHING OF DLA IN A CORRUGATED PLASMA WAVEGUIDE

Guiding of a radially polarized laser pulse in a plasma waveguide for DLA has been pr previously studied. In [4], the dispersion relationship for a radially polarized laser pulse was derived in the paraxial approximation. The refractive index n of the laser pulse can be expressed as:

$$n^2 = 1 - \frac{{\omega_p}^2}{{\omega_0}^2} - \frac{8c^2}{{\omega_0}^2{r_0}^2}, \tag{1}$$

where ω_p is the plasma frequency, ω_0 is the laser frequency, c is the speed of light and r_0 is the guided mode radius. The phase velocity of a laser pulse in the plasma waveguide is affected by the plasma density and the guided mode radius. In paraxial approximation, the r_0 is the radial position at

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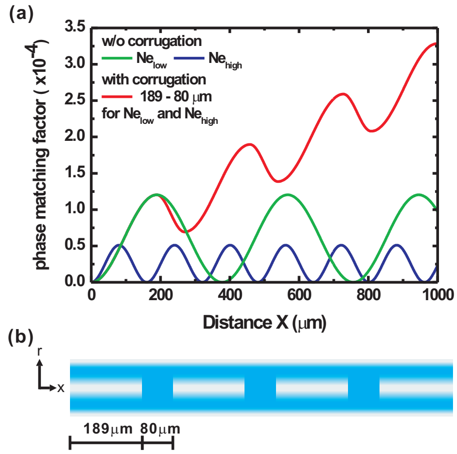

Figure 1: (a) Dependence of phase matching factor f on propagation distance for uncorrugated waveguides with $N_{e,high} = 1.25 \times 10^{19}$ cm^{-3} and $N_{e,low} = 2.25 \times 10^{18}$ cm^{-3} and corrugated waveguide with periodic $N_{e,low}$ and $N_{e,high}$ modulation. (b) Plots for the structure of the corrugated waveguide for QPM calculation and PIC simulation.

which the axicon-shaped longitudinal electric field E_x decreases to zero. The phase velocity increases with plasma density and decreases with the mode radius. Since the electrons can never travel faster than c, this results in the phase mismatch effect between the laser pulse and the electrons.

The energy gain of an electron accelerated by the electromagnetic (EM) wave can be approximated with:

$$\Delta U \cong -q_e \int dz E \sin\left[i \int_0^z (k_L - \frac{\omega_0}{v_e})\, dz' \right], \qquad (2)$$

where q_e is electron charge, E is the amplitude of the electromagnetic wave, k_L is the wave vector of laser pulse and v_e is the speed of electrons with propagating distance $z = v_e t$. By defining ω_0/v_e as the wave vector k_e of the electrons, the phase matching effect between laser pulse and electrons can be quantified as the phase matching factor f:

$$f = -\int dz \sin\left[i \int_0^z (k_L - k_e)\, dz' \right]. \qquad (3)$$

The electrons fall out of phase by π after propagating for a coherence length $L_{coh} = \pi/|k_L - k_e|$. In case that there is a 15 MeV electron beam (with v_e = 0.9995c) initially injected synchronously with the laser pulse of r_0 = 8.5 μm in the waveguide, the L_{coh} is only 82 μm as the plasma density is $N_{e,high} = 1.25 \times 10^{19}$ cm^{-3} in the waveguide center. For this case, the corresponding factor f plotted as the blue line in Fig. 1(a) only shows an oscillation of small energy gain along the propagation distance. If there is a density-modulated plasma waveguide in which the electron beam is accelerated in the longer low-density region, and then losing a fraction of its energy in the short dephasing region with a high density, there could be a net energy gain at the end of a modulation period. Fig. 1(b) shows the structure of the corrugated plasma waveguide which could be applied for the QPM in DLA. To further accelerate the 15 MeV electron beam, the length of low-density regions matches coherence length of 189 μm for $N_{e,low} = 2.5 \times 10^{18}$ cm^{-3} and $r_0 = 8.5$ μm while the high-density region is 82 μm long with $N_{e,high} = 1.25 \times 10^{19}$ cm^{-3}. The calculated f, shown as the red line in Fig. 1(a), indicates an accumulation of accelerating net gain over several periods for DLA in this corrugated waveguide. The gain is about 32% of the gain that would occur in a perfectly phase matched case ($f = 1 \times 10^{-3}$ for perfect phase matching over 1 mm acceleration distance) for the QPM between electron beam and laser pulse.

PIC SIMULATION

A 3D particle-in-cell (PIC) simulation [7] was developed to study the evolution of the EM field of the laser pulse as it propagates in a preformed plasma waveguide. The simulation was performed in a moving frame copropagating with the laser pulse. The size of the simulation box is 15.55 μm in the longitudinal direction (x in Fig. 1(b)) and 46.4 μm×46.4 μm in the transverse directions. The computational grid was formed by 311×58×58 cells with four particles per cell. The uncorrugated plasma waveguide is defined as a leaky channel with the electron density cross section shown in Fig. 2(a). While normalized to

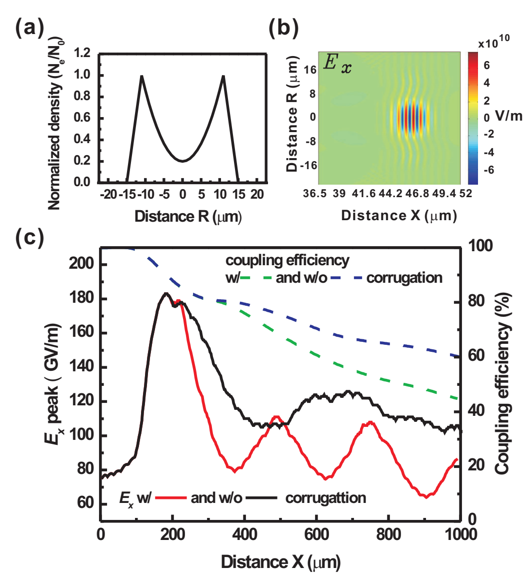

Figure 2: (a) Electron density profile normalized to $N_{e0} = 1.25 \times 10^{19}$ cm^{-3} for the plasma waveguide in the PIC simulations. (b) Snapshots for the longitudinal electric field E_x at the focal position. (c) Dependence of the longitudinal electric field E_x peak value and laser pulse energy coupled efficiency in the plasma channel on the propagation distance in cases with and without corrugation.

the nominal density $N_{e0} = 1.25 \times 10^{19}$ cm^{-3}, the plasma density increases quadratically from 0.2 at the center to 1 at 11 μm, and then drops linearly to 0 at 15 μm. In addition, there are density ramps of 50 μm at both sides of the waveguide. For corrugated plasma waveguide like that shown in Fig.1 (b), the high-density regions are defined as a uniformly distributed plasma region with electron density of N_{e0}. The laser pulse launched in the simulation is formulated according to the paraxial approximation (in vacuum) [8].

For a 5-mJ radially polarized pulse at 800 nm with the pulse duration of 10 fs (FWHM of Gaussian temporal shape), the maximum field strength of the longitudinal electric field E_x is 77 GV/m. The focus is at a position 5 μm ahead of the end of the front density ramp with r_0 = 8.5 μm. Figure 2(b) is the snapshot of the longitudinal E_x field shown at the focal position. As seen in Fig. 2 (c), the peak value of E_x varies as the pulse propagates in the waveguides, both with and without corrugation. Since the pulse energy decreases monotonously along the propagation distance, the variation of E_x peak value is mainly caused by the simultaneous variation of mode radius r_0. For the case of uncorrugated waveguide, r_0 reduces to 5.6 μm at X = 180 μm, increasing the peak of electric field E_x to 183 GV/m. The reduction of pulse mode radius to 6-7 μm in the subsequent regions also helps sustain a high electric field E_x during the propagation. The pulse energy is reduced to 60% at the output. With the corrugated waveguide, the guiding effect is still maintained, although the high-density regions are inherently unfavorable for guiding. The output coupling efficiency decreases to 44.8% for the corrugated waveguide. The reduction of mode radius maintains the

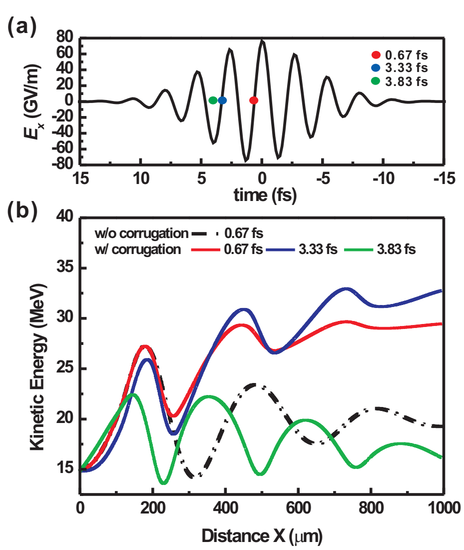

Figure 3: (a) Relative delays between the laser pulse and the electron test particles launched in the simulation. (b) Dependence of the electron test particle kinetic energy on the propagation distance for particles launched from the origin at different delays relative to the laser pulse.

magnitude of E_x at the end of the waveguide, close to its value at the focal position.

To verify that the quasi-phase matched DLA can take place, electron test particles are launched from the origin at different delays with respect to the peak of the laser pulse envelope, as shown in Fig. 3(a). All particles initially have a kinetic energy of 15 MeV and propagate in the same direction as the laser pulse. For the case with an uncorrugated waveguide, the result in Fig. 3(b) indicates that the kinetic energy of the electron oscillates asymetrically because of the variation of field amplitude the electron experiences while passing the laser pulse from the center to the front edge in its propagation. This asymmetric acceleration-deceleration process by a Gaussian laser pulse finally transfers a net energy to the electron, unlike the result in Fig. 2(c) with a flat-top pulse. For the case of corrugated waveguide, results in Fig. 3(c) show that there could be several delays for electrons that meet the acceleration condition. A properly selected delay results in a higher net energy. With the laser pulse and waveguide described previously, the case in Fig. 3(c) indicates the electron particle can be accelerated up to 32.8 MeV in 1 mm of acceleration distance, but this is less efficient than the case expected from a flat-top pulse shown in Fig. 2(c).

CONCLUSION

The parameters that make the QPM condition for DLA realizable with a corrugated waveguide were investigated. The suitable plasma structure can be found with periods of hundreds of μm for plasma density modulations that could be realized by plasma machining techniques [5, 6]. The PIC simulation results show that the radially polarized laser pulse can be guided in a corrugated waveguide with experimentally achievable requirements. Moreover, the variation of guided mode radius helps sustain the longitudinal electric field strength in the propagation, with a long accelerating length of up to $\simeq$1mm. In simulations, electron test particles launched at proper time intervals relative to the laser pulse, as well as proper phase difference between the electrons and the electric field, can be accelerated with the analytically estimated QPM condition in a corrugated plasma waveguide.

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