MODELING OF QUASI-PHASE MATCHING FOR LASER ELECTRON ACCELERATION*

M.-W. Lin, I. Jovanovic†, Department of Mechanical and Nuclear Engineering,
The Pennsylvania State University, U.S.A.

Abstract

Sensing of shielded fissile materials at long range is critically dependent on the development of compact particle accelerators. Direct laser acceleration (DLA) of electrons has the potential to meet this requirement. In DLA, the axial component of the electric field of a focused radially polarized laser pulse accelerates particles. The acceleration gradient could be estimated as 77 MeV/mm for 800 nm laser with power of 0.5 TW and 8.5 μm guided mode radius. The implementation of long guided propagation of laser pulses and the phase matching between electrons and laser pulses may limit the DLA in reality. A preformed corrugated plasma waveguide could be applied to extend the laser beam propagation distance and for quasi-phase matching between laser and electron pulses for net acceleration. We perform numerical calculations to estimate the phase matching conditions for a radially polarized laser pulse propagating in a corrugated plasma waveguide. Further, the electric field distribution of a radially polarized laser pulse propagating in this waveguide is also analyzed via particle-in-cell simulations, and will be used to guide future experiments.

INTRODUCTION

Radiation signatures of fissile materials, such as highly penetrating neutrons and γ-rays, are most promising for their detection at long range. However, the available spontaneous radiation signatures are usually rare and emitted in the full sold angle, making the passive remote detection very difficult in practice. These challenges motivate the development of active interrogation systems. To generate γ-rays for active detection, it is necessary to use particle accelerators to produce electron beams with up to GeV energies, and then convert the energy into γ-rays by bremsstrahlung or inverse Compton scattering. Meeting the typical specifications for described applications is demanding with small size, low weight and low cost.

Laser-driven acceleration schemes that utilize ultrafast (fs) laser pulses have a potential to realize electron accelerator with significantly reduced dimensions. For example, the acceleration gradient in laser wake field acceleration (LWFA) [1, 2] is typically in the order of GV/cm, almost 4 orders of magnitude greater than in conventional linear accelerators. The generation of monoenergetic GeV electron beams in 3 mm accelerating length has been demonstrated in the prior work [2], indicating the potential of LWFA to significantly reduce the linear dimensions of accelerators. However, since the excitation of a plasma wave by laser pulse is a highly nonlinear process, LWFA typically requires tens of TW laser peak power for efficient acceleration. Those pulses are currently produced by laser systems employing a complex and expensive series of low repetition rate fs laser amplifiers, which limits the performance and attractiveness of the technique for some applications. Therefore, the motivation exists to investigate alternative methods for laser electron accelerators operating with 1-2 order lower peak powers than LWFA.

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 laser laser power [4, 5], and is estimated as 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 from phase-matched pulses below TW peak power, available from compact, high repetition rate laser systems.

Two significant challenges of DLA may limit its implementation. They include the realization of guided propagation of ultraintense pulses over extended distances and the phase matching between the propagating electrons and laser pulses. Optical guiding in DLA using a preformed plasma waveguide [4] has a potential to extend the accelerating distance over several Rayleigh ranges. Furthermore, similar to the ubiquitous quasi-phase matching (QPM) in nonlinear optics, corrugated waveguide techniques [5, 6] with axially periodic plasma density modulation could be used to quasi-phase match the laser and electron pulses. A net acceleration can be produced by breaking the symmetry between acceleration and deceleration phases. As the number of QPM periods increases, it is possible for electrons to acquire energy above 100 MeV even for modest laser peak powers below 1 TW.

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. The electric field distribution of the radially polarized laser pulse propagating in the waveguide is also analyzed in order to guide the design of future DLA experiments.

* Work supported by the Defense Threat Reduction Agency.

† ijovanovic@psu.edu

QUASI-PHASE MATCHING OF DLA IN A CORRUGATED PLASMA WAVEGUIDE

Guiding a radially polarized laser pulse in a plasma waveguide with a quadratic increase of electron density along radial direction for DLA was proposed by Serfim [4]. In this prior work, 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:

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

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. In Eq. (1), it is obvious that the phase velocity (V_{ph}) of a laser pulse in the plasma waveguide is determined by the plasma density and the guided mode radius (in paraxial approximation, the r_0 is the radial position at which the axicon-shaped longitudinal electric field E_x decreases to zero). V_{ph} increases with plasma density and decreases with the mode radius. Since the electron beam can never move 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 $Ne_{high} = 1.25\times10^{19}$ 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. On the other hand, 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

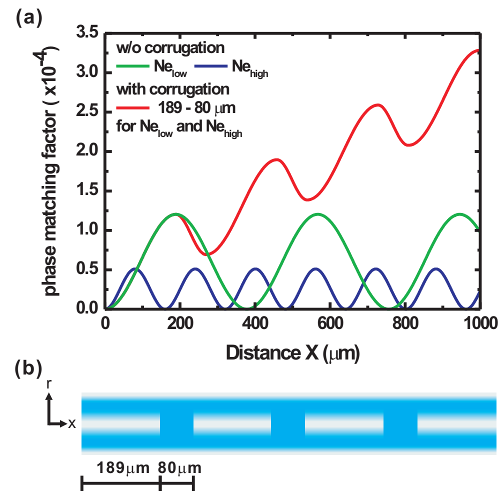

Figure 1: (a) Dependence of phase matching factor f on propagation distance for uncorrugated waveguides with $Ne_{high} = 1.25 \times 10^{19}$ cm^{-3} and $Ne_{low} = 2.25 \times 10^{18}$ cm^{-3} and corrugated waveguide with periodic Ne_{low} and Ne_{high} modulation (b) Plots for the structure of the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

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 $Ne_{low} = 2.5\times10^{18}$ cm^{-3} and r_0 = 8.5 µm while the high-density region is 82 µm long with $Ne_{high} = 1.25 \times 10^{19}$ 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

Particle-in-cell (PIC) simulation is an important tool for laser plasma simulation providing precise calculation for EM fields by solving Amperes and Faradays laws [7]. We carried out 3D simulations in order to understand the evolution of EM fields of the laser pulse as it propagates in a preformed plasma waveguide. Those results are crucial for determining parameters of the corrugated waveguide with good guiding properties in DLA setup.

The simulation was performed in a moving frame co-propagating 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 the nominal density $Ne_0 = 1.25 \times 10^{19}$ cm^{-3}. On this normalized scale, the plasma density increases quadrati-

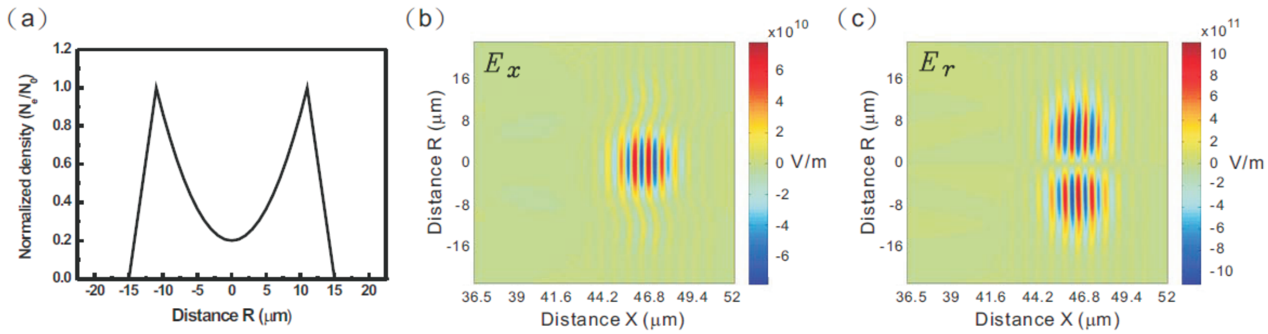

Figure 2: (a) Electron density profile normalized to $Ne_0 = 1.25 \times 10^{19}$ cm^{-3} for the plasma waveguide in the PIC simulations. Snapshots for the (b) longitudinal electric field E_x and (c) radial electric field E_r shown at the focal position.

cally from 0.2 at 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 Ne_0. 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. Figures 2(b) and 2(c) are snapshots for longitudinal E_x and radial E_r fields shown at the focal position. As it can be seen in Fig. 3, the peak value of E_x varies as pulse propagates in the waveguides 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 simultaneously 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

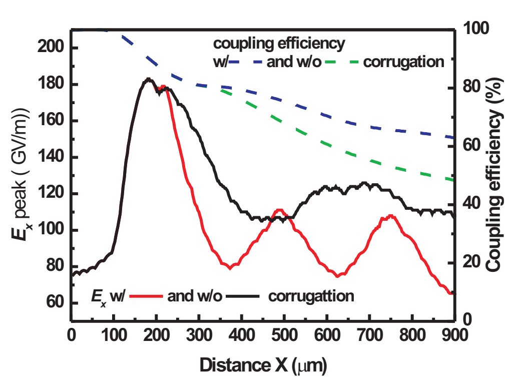

Figure 3: Dependence of the longitudinal electric field E_x peak value and laser pulse energy coupled efficiency in the plasma channel on the propagation distance in cases with and without corrugation.

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 62.5% at the output coupling efficiency (defined here as the pulse energy in the volume of plasma channel). 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 48% for the corrugated waveguide. The reduction of mode radius maintains the magnitude of E_x at the end of the waveguide close to its value at the focal position. This is an important property for the long-range DLA in plasma waveguides

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 showed that the radially polarized laser pulse can be guided in a corrugated waveguide with experimentally achievable requirements. The coupled efficiency of laser pulse energy exceeds 40% in a 900-μm plasma waveguide, regardless of corrugation. 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 ≃1mm.

REFERENCES

[1] E. Esarey et al., Rev. Mod. Phys. **81**, 1229 (2009).
[2] W.P. Leemans et al., Nature Physics **2**, 696 (2006).
[3] W. D. Kimura et al., Phys. Rev. Lett. **74**, 546 (1995).
[4] P. Serafim, IEEE Trans. Plasma Sci. **28**, 1155 (2000).
[5] A.G. York et al., Phys. Rev. Lett. **100**, 195001 (2008).
[6] C.-C. Kuo et al., Phys. Rev. Lett. **98**, 033901 (2007).
[7] C. Nieter and J. R. Cary, J. Comput. Phys. **196**, 448 (2004).
[8] Y. I. Salamin, New J. Phys. **8**, 133 (2006).