MODELING OF QUASI-PHASE MATCHING IN AN APERIODIC CORRUGATED PLASMA WAVEGUIDE FOR HIGH-EFFICIENCY DIRECT LASER ELECTRON ACCELERATION *

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Abstract

Direct laser acceleration (DLA) of charged particles using the axial electric field of a radially polarized intense laser pulse is promising for realization of compact accelerators required in security and medical applications. The implementation of guided propagation of laser pulses over long distances and the phase matching between electrons and laser pulses may limit the performance of DLA in reality. A 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. To accelerate electrons from a low initial energy (for example, 5 MeV from a photoinjector gun) up to hundreds of MeV, an aperiodic corrugated plasma waveguide with successive increase of on-axis density modulation period is needed. We conducted particle-in-cell simulations to design the appropriate aperiodic plasma structure for DLA. For each section of the corrugated waveguide, the dependence of density modulation period on the initial electron energy and laser pulse intensity is investigated. The simulation results are guiding the design of proof-of-principle experiments for compact, tabletop DLA.

INTRODUCTION

Direct laser acceleration (DLA) of electrons, such as inverse Cherenkov acceleration [1, 2, 3], 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 axial field amplitude scales as the square root of the laser peak power [2, 3], and is estimated to be 77 GV/m 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.

Optical guiding in DLA using a preformed plasma waveguide [2] can extend the accelerating distance. To compensate for the phase mismatch effect in DLA, corrugated waveguide techniques [3, 4] with axially periodic plasma density modulation could be used to quasi-phase match (QPM) the laser and electron pulses. The QPM period depends on the electron velocity, and changes rapidly for electron beams with low initial kinetic energies (≤20 MeV). Therefore, an aperiodic corrugated waveguide structure is required to achieve effective QPM DLA with low initial electron energies.

In this work we studied the optimal plasma structures for DLA in corrugated plasma waveguides with a range of initial electron energies. A test electron particle model has been developed to search for optimal QPM conditions. Next, particle-in-cell (PIC) simulations [5] have been performed and compared with the results obtained from the test particle method.

ELECTRON TEST PARTICLE MODEL FOR DLA IN CORRUGATED PLASMA WAVEGUIDES

Modelling of DLA is based on the dispersion relation for a guided radially polarized laser pulse in a preformed plasma waveguide [2]. Under paraxial approximation, the refractive index of a guided laser pulse is:

$$\eta = \left(1 - {\omega_p}^2/\omega^2 - 8c^2/\omega^2 {w_0}^2\right)^{1/2}, \quad (1)$$

where ω_p is the plasma frequency, ω is the laser frequency, w_0 is the guided mode radius, and c is the speed of light. The phase velocity $v_{ph} = c/\eta$ and group velocity $v_g = c\eta$ characterize the propagation of the guided laser pulse. With plasma $\eta < 1$, the phase velocity $v_{ph} > c$, resulting in the phase mismatch effect between the laser pulse and the electrons. Electrons will fall out of phase by π with respect to the co-propagating laser field after a dephasing length $L_c = \pi/|k_l - k_e|$ determined by the laser wave vector $k_l = 2\pi\eta/\lambda$ and $k_e = \omega/v_e$ as the equivalent wave vector for the electron beam with velocity v_e. Figure 1 shows the dependence of dephasing length L_c on electron kinetic energy for three plasma electron densities n_e with w_0=8.5 µm and λ = 800 nm.

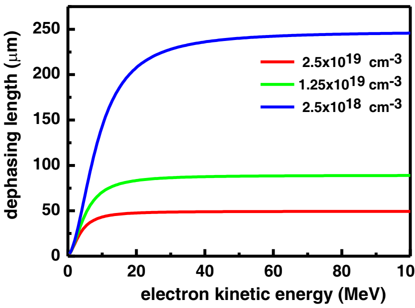

Figure 1: (a) Dependence of dephasing length L_c on electron kinetic energy for n_e=2.5×10^{18} cm^{-3}, 1.25×10^{19} cm^{-3}, and 2.5×10^{19} cm^{-3}.

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The test particle model is developed by solving coupled relativistic equations of motion of a single electron with given initial parameters. The electron trajectory and energy ($\gamma m_e c^2$) are calculated from $d\mathbf{p_e}/dt = q_e\left(\mathbf{E}+\mathbf{v_e}\times\mathbf{B}\right)$ and $m_e c^2 d\gamma/dt = q_e\left(\mathbf{v_e}\cdot\mathbf{E}\right)$ with the Lorentz factor γ, the electron momentum $\mathbf{p_e} = \gamma m_e \mathbf{v_e}$ and electron's charge q_e and rest mass m_e. The electromagnetic field of a co-propagating, guided, radially polarized laser pulse in a corrugated plasma waveguide is considered as the driving field [2]. For a guided radially polarized laser pulse, the electric field $\mathbf{E} = \hat{r}E_r + \hat{z}E_z$, in which the radial field E_r is:

$$\begin{aligned} E_r &= E_0\theta\left(r/w_0\right)\exp[-\left(r/w_0\right)^2] \\ &\times \exp[-2\ln 2\left(z-z_p\right)^2/L_p^2]\cos\left(\phi\right), \end{aligned} \tag{2}$$

and the axial field E_z is:

$$\begin{aligned} E_z &= E_0\theta^2\left(1-r^2/w_0^2\right)\exp[-\left(r/w_0\right)^2] \\ &\times \exp[-2\ln 2\left(z-z_p\right)^2/L_p^2]\sin\left(\phi\right), \end{aligned} \tag{3}$$

for a Gaussian pulse at position z_p, with the phase ϕ, the beam diffraction angle $\theta = \lambda/\pi w_0$, and the pulse length L_p. The characteristic field amplitude E_0 relates to laser peak power P_w as $E_0 = \left(8c\mu_0 P_w/\pi w_0^2\theta^2\right)^{1/2}$. The azimuthal magnetic field is defined as $B_\theta = \left(\eta/c\right)E_r$. The phase of the field is represented by $\phi = \omega\left(t - z\eta/c\right)$. The change of phase and position of the laser pulse can be described by $d\phi/dt$ and $dz_p/dt = v_g(z_p)$. To simulate a corrugated plasma waveguide, the axial plasma electron density is chosen as a function of axial position z by:

$$\begin{aligned} n_{e0}\left(z\right) &= n_{e,L} + \left(n_{e,H} - n_{e,L}\right) \\ &\times H\left(z-\lambda_{L,n}\right)\left[1 - H\left(z-\lambda_{m,n}\right)\right], \end{aligned} \tag{4}$$

where $n_{e,L}$ and $n_{e,H}$ are the plasma electron densities in low- and high-density regions, and $\lambda_{m,n} = \lambda_{L,n} + \lambda_{H,n}$ is the length of nth-modulation period composed of low- and high-density regions of lengths $\lambda_{L,n}$ and $\lambda_{H,n}$, respectively. H is the Heaveside function used to define a sharp axial density change. This axial density distribution function $n_{e0}(z)$ is used to update the axial refraction index $\eta(z)$, on-axis plasma frequency $\omega_{p0}(z)$, and the laser pulse group velocity $v_g(z) = c\ \eta(z)$. Initial parameters include the electron position z_0=0 and r_0=0, radial momentum P_{r0}=0, pulse position z_{p0}=2.4 µm, and field phase ϕ_0=3π. 2 mm plasma waveguides with default plasma electron densities $n_{e,L}$=2.5 × 10^{18} cm^{-3} and $n_{e,H}$=1.25× 10^{19} cm^{-3} are considered. The initial axial momentum P_{x0} and γ_0 factor are assigned according to the desired initial kinetic energy T_0. A 0.5 TW laser pulse with L_p=6 µm (corresponding to a pulse duration of 20 fs) and $E_{z,max} = E_0\theta^2 \simeq$77 GV/m is considered with the dispersion relation determined by w_0=8.5 µm and λ=800 nm.

The same laser wavelength and waveguide diameter are used in all simulations described. Figure 2(a) shows the dependence of electron energy gain ΔT on axial position z for DLA with initial kinetic energies T_0=5-100 MeV with constant density modulation periods in waveguides. The modulation periods are determined by the dephasing length L_c (Fig. 1) for chosen T_0 energies. The results indicate that with constant density modulation one can only achieve QPM DLA for electrons with higher initial kinetic energies (T_0=40 MeV and 100 MeV in this example). In contrast, aperiodic density modulation is required for DLA of electrons with low initial energies (T_0=5 MeV and 15 MeV in this example), as shown in Fig. 2(b). It is particularly important to accurately set the plasma structure period in the first few sections of the waveguide so that the electrons can remain in the acceleration phase. The results reflect the rapid change of dephasing length in the range of $T_0 \lesssim$ 20 MeV. As a result, the modulation period should be increased according to the increased electron energy and then gradually converge to the dephasing length L_c at higher electron energies. We find it sufficiently accurate to approximate each section length $L_{d,n}$ by the average of its initial dephasing length $L_{c,i}$, obtained for the initial electron kinetic energy $T_{0,i}$ of that section, and the final dephasing length $L_{c,f'}$, obtained by the approximated final kinetic energy $T_{0,f'}$ after acceleration by $L_{c,i}$. Thus $L_d = 1/2(L_{c,i} + L_{c,f'})$ provides a good approximation for designing an efficient aperiodic DLA structure.

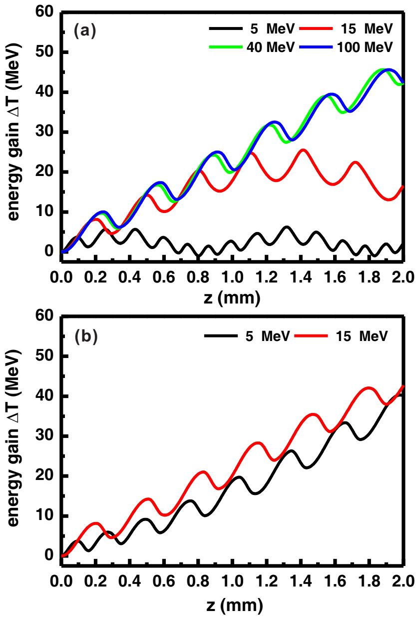

Figure 2: Dependence of electron energy gain ΔT on propagation distance z for electrons with T_0= 5, 15, 40 and 100 MeV in plasma waveguides with (a) constant and (b) aperiodic density modulation (only applied for T_0= 5 and 15 MeV). The other parameters are given in text.

With optimally designed plasma structures, the axial acceleration phase region for QPM DLA can be investigated by injecting test electrons with various initial axial positions z_0 and phases ϕ_0 along the central axis. Figure 3

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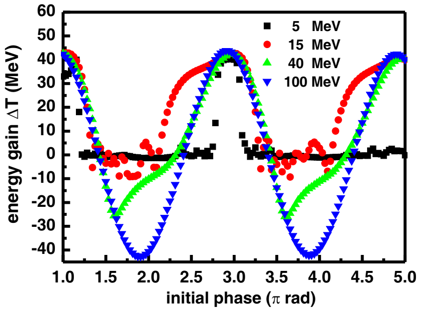

Figure 3: Final electron energy gain ΔT as a function of electron initial phase ϕ_0 for electrons of T_0= 5, 15, 40 and 100 MeV with the same parameters as for Fig.2.

shows the final electron energy gain ΔT as a function of initial phase ϕ_0 for various initial electron kinetic energies T_0. The results indicate that, in general, DLA with higher initial electron energies will exhibit a broader acceleration phase region. In the case of T_0=5 MeV, the acceleration phase region width is about 0.4π around the optimal phase $\phi_0 = 3\pi$ and it increases to π for T_0=100 MeV. Particles with ΔT around 0 in Fig. 3 exhibit rapid energy oscillations throughout the propagation but cannot accumulate energy gain. The acceleration region shifts $\pi/2$ from the initial acceleration region. For example, electrons with initial phase ϕ_0=2.5π–3π decelerate initially, but enter acceleration phases later in the process. The process is reversed when ϕ_0=3.5π–4π.

PIC SIMULATION OF DLA

3D particle-in-cell (PIC) simulations [5] have also been performed. Each simulation is performed in a moving frame co-propagating with the laser pulse. The size of the simulation box is 20.27 µm in the axial direction z and 43.2 µm × 43.2 µm in the transverse direction r. Interlacing waveguide sections and neutral hydrogen gas sections are defined. The waveguide sections have a transverse plasma density profile in which density increases quadratically along r from the central density of n_{e0}=$n_{e,L}$=2.5×10^{18} cm^{-3}. The density profile defines a laser-guided mode radius of w_0=8.5 µm. The neutral hydrogen gas sections have a uniform density distribution with density n_0=$n_{e,H}$=1.25×10^{19} cm^{-3}, and are ionized with the passage of a 20 fs, 0.5 TW, radially polarized laser pulse. In the tests of dephasing length as shown in Fig. 4(a) for DLA in non-corrugated waveguides (only a single waveguide section is defined in space), we find the factor 8 of the waveguide dispersion term in the refractive index η of Eq. (1) should be modified to approximately 5. With this correction, the results from our test particle model agree well with the results from 3D PIC simulations. Figure 4(a) and 4(b) show QPM DLA for T_0=5 MeV, 15 MeV, and 40 MeV in plasma waveguides with proper plasma structure for QPM DLA. The results also show that aperiodic corrugations in plasma waveguides are required for DLA with lower electron initial energies, while a constant density modulation period is applicable for the case of higher electron initial energies.

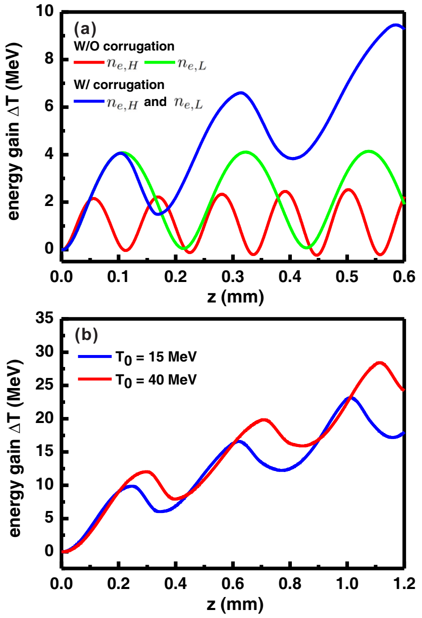

Figure 4: PIC simulation results for the electron energy gain ΔT for (a) electrons with T_0=5 MeV in plasma waveguides without and with corrugation for DLA and (b) electrons with T_0=15 MeV and 40 MeV in plasma waveguides with optimal plasma structure for DLA.

CONCLUSION

Aperiodic modulation of corrugated plasma waveguides are required for DLA with low electron kinetic energies ($\lesssim$20 MeV). For such low injected electron energies, DLA dephasing length changes rapidly with the increased electron energy. Therefore, the plasma structure should be varied accordingly so that electrons can remain in the acceleration phase throughout the propagation distance. In addition, DLA with low initial electron energies will also result in small axial acceleration regions after the QPM process. Our test particle model provide a straightforward method to estimate QPM conditions for DLA, as confirmed by 3D PIC simulations.

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