EFFICIENCY ENHANCEMENT INDUCED BY A PRECURSOR ELECTRON BUNCH IN QUASI-PHASE MATCHED DIRECT LASER ACCELERATION*

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Abstract

Direct laser acceleration (DLA) of an electron bunch can be achieved by utilizing the axial field of a well-guided, radially polarized laser pulse in a density-modulated plasma waveguide. However, the ponderomotive force of a TW-class laser pulse excites a plasma wave that can generate a defocusing electrostatic field, which significantly deteriorates the transverse properties of the injected electron witness bunch. [1] To improve the quality of the accelerated witness bunch, an additional leading electron bunch, termed a precursor, is introduced to generate ion-focusing force to effectively confine the trailing witness bunch. We conducted three-dimensional particle-in-cell simulations to investigate the effect of bunch charge, transverse size of the precursor, and the axial separation between the precursor and the witness bunch on the efficacy of DLA. Results indicate that the transverse properties of the witness bunch can be maintained and the overall DLA efficiency can be improved when a favorable ion-focusing force is provided by the precursor. [2]

INTRODUCTION

Using the intense electric field of a radially polarized laser pulse is one of methods to directly accelerate electrons. This scheme has been termed direct laser acceleration (DLA). By guiding a radially polarized laser pulse in a density-modulated plasma waveguide, the acceleration distance is extended and the quasi-phase matching (QPM) condition [3, 4] is provided to improve the overall DLA efficiency. When conducting DLA in a plasma waveguide, however, the background plasma electrons are pushed to concentrate at the center by the ponderomotive force of the donut-shaped distribution of the laser radial field, which results in a radial electrostatic force that can significantly defocus the externally injected electron witness bunch and degrade the transverse bunch quality.

In this study, three-dimensional (3D) particle-in-cell simulations are conducted to simulate the DLA scheme in which an additional precursor electron bunch is injected at an optimal time prior to the arrival of the witness bunch. [2] Consequently, a focusing electrostatic field in the background plasma induced by precursor can be used to mitigate the final transverse expansion of the accelerated electron bunch and extend the effective acceleration distance, which helps to improve the witness bunch properties after DLA.

EFFECTS OF A PRECURSOR BUNCH

The PIC simulations of DLA have been carried out in a 3-D Cartesian coordinate system by using the commercial software package VORPAL. Fig. 1(a) shows the longitudinal field of a 2-TW, radially polarized laser pulse defined to drive DLA. The quadratic plasma density profile defined in low-density waveguide sections is illustrated in Fig. 1(b). To provide the necessary QPM condition, the 4.2-mm long plasma waveguide is composed of alternating waveguide and neutral hydrogen sections, as summarized in Fig. 1(c). A region of uniform, high-density hydrogen gas is ionized by the front foot of laser pulse to produce uniform plasma for the laser and the trailing witness bunch. The 6-fs, 40-MeV witness bunch is defined to have Gaussian shape with a diameter w_b = 3 μm and a total charge of q_b = 5 pC.

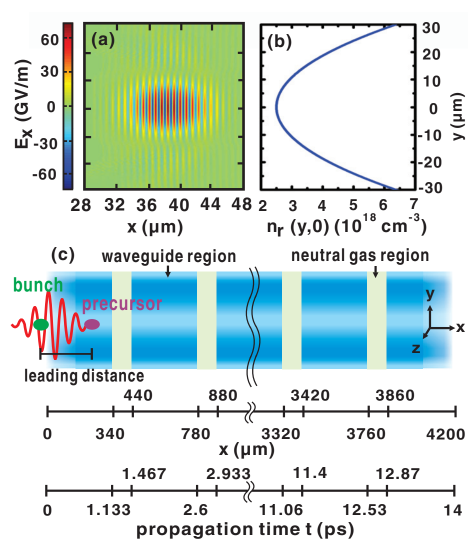

Figure 1: Snapshot of (a) axial E_x electric field of a 20-fs, 2-TW, radially polarized laser pulse with a diameter w_D = 15 μm; (b) transverse plasma density profile $n_r(y, 0)$ of waveguide sections; and (c) illustration of a density-modulated plasma waveguide

To understand the effect of the precursor on DLA, we first assign the precursor with identical parameters to the witness bunch. The precursor is injected in advance of the

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witness bunch by a quarter of the plasma wavelength ($\lambda_p/4 \sim 5.3$ µm). As illustrated in Fig. 2(a), the plasma electrons in front of the witness bunch is depleted by the precursor, from which a well-established ion channel, enclosing nearly all of the witness bunch electrons, is produced in the first low-density region. In contrast, the ion-focusing force on the witness bunch vanishes in a high-density region, as shown in Fig. 2(b). Since the density of background plasma electrons n_{pe} of high-density sections is much larger than the precursor density n_{pre}, the precursor is incapable of exciting a plasma wave under these conditions.

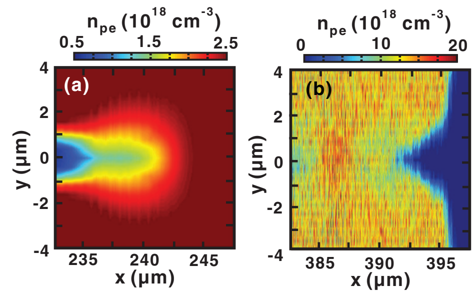

Figure 2: The 2-D density distribution of plasma electrons n_{pe} in (a) the first low-density region and (b) the first high-density region.

The advantage of applying a precursor in DLA is apparent when comparing the final energy spectra in Fig. 3(a). The prominent increase of electron number in the range of 60-110 MeV is attributed to the greatly enhanced ion-focusing effect provided by the precursor. Besides, when the precursor is used, Fig. 3(b) shows that the final emittance of the witness bunch electrons is reduced from $\epsilon_{N,y} \simeq 36\,\pi$ mm mrad to 27 π mm mrad by the definition of default RMS normalized emittance in the y-dimension.

$$\epsilon_{N,y} = \frac{4}{m_e c}\sqrt{\langle y^2\rangle\langle P_y^2\rangle - \langle yP_y\rangle^2}\,\pi \text{ mm mrad}, \qquad (1)$$

utilizing the position y and momentum P_y of particles. To sum up, final collimation of the witness bunch is significantly improved by ion-focusing effect provided by the precursor.

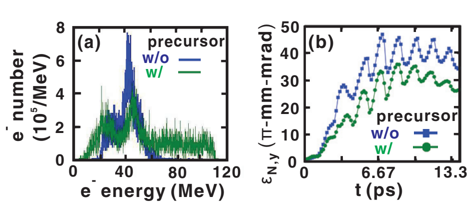

Figure 3: Comparison of (a) final energy spectra and (b) emittance as a function of propagation time t of the witness bunch, which elucidates the effect of the precursor injected with a charge q_{pre} = 5 pC and a diameter w_{pre} = 3 µm.

EFFECT OF THE TRANSVERSE SIZE OF PRECURSOR

With a fixed bunch charge q_{pre} = 5 pC, the transverse size of the precursor is extended from the diameter w_{pre} = 3 µm to 6 µm to reduce erosion of the precursor during propagation. In this way, the initial peak density of the precursor is reduced to a quarter of its value used in the previous simulations. While keeping the same divergence angle, the increased transverse size of the precursor results in the initial $\epsilon_{N,y}$ that is twice its default value. Based on the definition of the minimum β-function which characterizes the beam transverse size variation along the propagation, β^* is twice the value used in previous section.

Figs. 4(a) and 4(b) illustrate the mitigated erosion of the precursor when an larger transverse size is used. Although the initial density of the precursor of w_{pre} = 6 µm is lower, its density can be higher than the one with the initial diameter w_{pre} = 3 µm when t = 7 ps. In addition, the comparison of density distributions of background plasma electrons shown in Figs. 4(c) and 4(d) indicates that the confinement of witness bunch electrons can be improved by the increase of the precursor diameter, such that the ion-focusing effect is eventually enhanced throughout the DLA process.

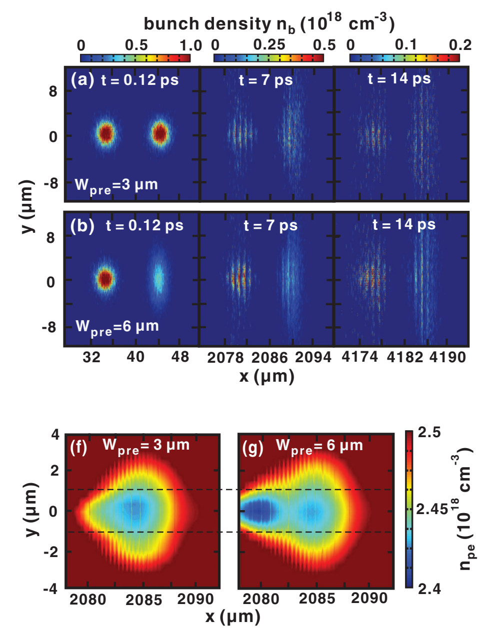

Figure 4: Comparison of the 2-D density variation of two bunches when the precursor charge q_{pre} = 5 pC is injected with a diameter of (a) w_{pre} = 3 µm and (b) w_{pre} = 6 µm and the density distribution of plasma electrons n_{pe} at t = 7 ps for (c) w_{pre} = 3 µm and (d) w_{pre} = 6 µm.

When the precursor diameter is increased, the enhanced ion-focusing effect on the witness bunch can considerably improve the DLA efficiency, This effect is evident from the increased electron number in the energy range of 60–110 MeV, when comparing the energy spectra shown in Figs. 3(a) and 5(a). Moreover, the final emittance $\epsilon_{N,y}$ can be further reduced to 18.8 π mm mrad, as illustrated in Fig. 5(b).

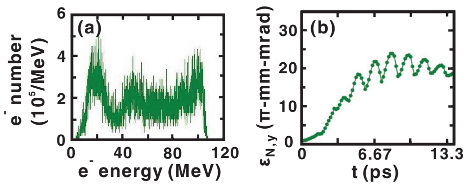

Figure 5: (a) Final energy spectrum of the witness bunch; (b) time evolution of the emittance $\epsilon_{N,y}$ of the witness bunch when the precursor of charge $q_{pre} = 5$ pC and diameter $w_{pre} = 6$ μm is injected.

THE EFFECT OF INTENSE ION-FOCUSING FORCE INDUCED BY THE PRECURSOR

To understand the effect of intense ion-focusing force induced by the precursor (primarily in the low-density regions of the plasma waveguide), the precursor with diameter $w_{pre} = 6$ μm and an increased charge $q_{pre} = 20$ pC is used in the simulation. Compared to the plasma electron densities shown in Fig. 2(a), an expanded diameter of the ion channel created by the 20-pC precursor is shown in Fig. 6(a). Although an enhanced ion-focusing force is provided in the first low-density section, Fig. 6(b) illustrates that the emittance $\epsilon_{N,y}$ of the witness bunch increases abruptly from $t \sim 1.5$ ps when both bunches propagate into the following high-density region. While the ion-focusing effect is ineffective in the high-density region, the repulsive forces between the electrons of the witness bunch induce a rapid expansion of the witness bunch, as shown in Fig. 6(d). As a result, the final energy spectrum of the witness bunch can not be improved, as can be seen in Fig. 6(c).

THE EFFECT OF AXIAL SEPARATION BETWEEN TWO BUNCHES

To understand the effect of axial separation between the precursor and the witness bunch, the precursor with $q_{pre} = 20$ pC and $w_{pre} = 6$ μm is injected with an increased axial separation $\lambda_p/3 \sim 7.07$ μm. When the witness bunch experiences a moderate ion-focusing force with an increased axial separation, the improved confinement of the witness bunch electrons results in its decreased emittance $\epsilon_{N,y}$, as shown in Fig. 7(a). Besides, its emittance $\epsilon_{N,y}$ varies smoothly after entering into the first high-density region of the waveguide. Therefore, the increase of electron number at the high-energy end of the spectrum as shown in Fig. 7(b) is attributed to the improved collimation to the witness bunch and the eliminated retardation force from precursor, when $\lambda_p/3$ is used.

CONCLUSION

Simulation results demonstrate that an electron beam can be directly accelerated by a radially polarized laser pulse in an efficient way. Besides, optical guiding in DLA using a density-modulated plasma waveguide can extend the accelerating distance. By injecting an additional precursor, an extra ion-focusing force is induced to improve the final collimation. As the proper choice and the setup to the precursor are achieved, a favorable ion-focusing effect can be achieved for better collimation of the witness bunch.

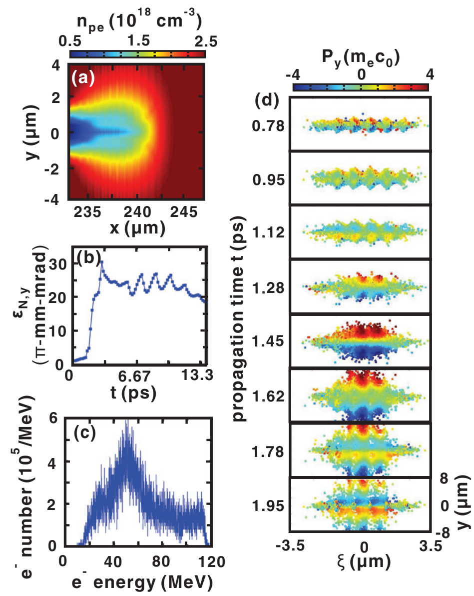

Figure 6: Effect of the precursor injected with a charge $q_{pre} = 20$ pC and a diameter $w_{pre} = 6$ μm: (a) 2-D density distribution of plasma electrons n_{pe}; (b) time dependence of the emittance $\epsilon_{N,y}$ of the witness bunch; (c) final energy spectrum of the witness bunch; and (d) variation of transverse P_y momentum distributions of the witness bunch.

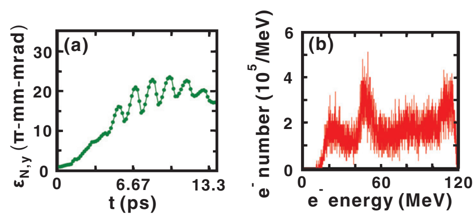

Figure 7: Effect of the precursor with an increased axial separation $\lambda_p/3$: (a) time variation of the emittance $\epsilon_{N,y}$ and (b) final energy spectrum of the witness bunch.

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