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Studies of LWFA-driven PWFA Hybrid Acceleration

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Introduction

The plasma-based acceleration (PBA) has acceleration gradients exceeding those in conventional acceleration by several orders of magnitude[1]. The beam-driven plasma wakefield acceleration (PWFA) offers acceleration gradients of 1-100 GeV/m. Compared to the laser-driven plasma wakefield acceleration (LWFA), it achieves higher single-stage energy gain. However, the availability of PWFA driven by linear accelerators is limited, posing a constraint on the widespread implementation of this technology. LWFA is more feasible due to the better accessibility of lasers and is capable of generating femtosecond-scale GeV electron bunches with peak currents exceeding 10 kA which can serve as ideal electron bunches for PWFA.

To investigate the LWFA-driven PWFA hybrid acceleration process we proposed, we use the Fourier-Bessel Particle-in-Cell (FBPIC) algorithm in particle simulations. In the LWFA stage, we utilize two ultra-intense lasers (both normalized vector potentials $a_0 > 3$) to trigger two ionization injections of electron bunches in mixed gaseous targets. These two electron bunches are subsequently used for the PWFA stage to sustain the acceleration process. This scenario is illustrated in Fig. 1.

Through our simulation studies, we observe the entire acceleration process and consider the feasibility of this LWFA-driven PWFA hybrid acceleration process.

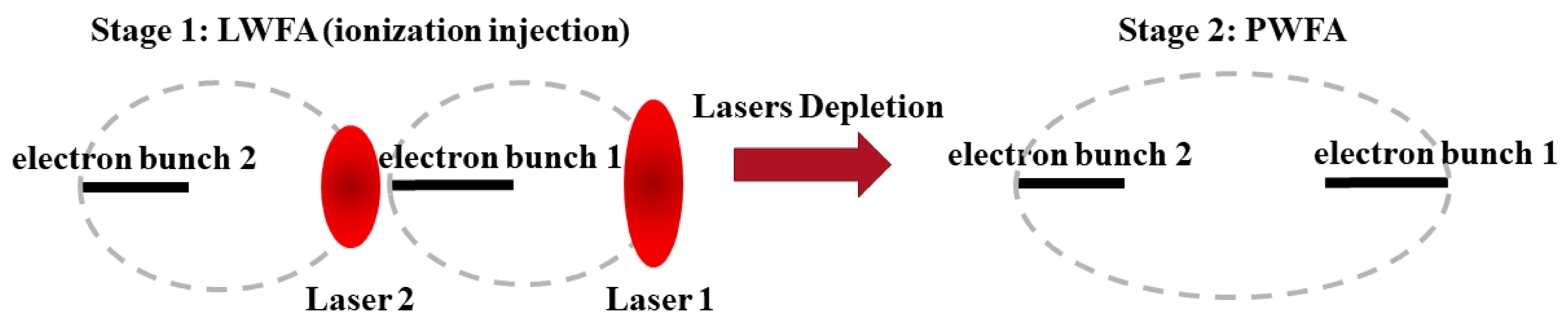

FIG. 1. Illustration on LWFA-driven PWFA hybrid acceleration.

Simulation Setup

1. Ionization injection

Ionization-induced injection in mixed gaseous targets has been considered as an effective scheme to gain high charge electron bunches. This mechanism is based on two processes: pre-ionization and ionization.

Pre-ionization means at least one gas element in the mixed gaseous targets should have a relatively low ionization threshold and can be pre-ionized and acted as background plasma, and ionization means this gas element should have inner shells with higher ionization thresholds such that the laser with sufficiently high intensity can release these inner shell electrons which will be trapped and accelerated in the wake[2].

2. Simulation parameters

In our hybrid acceleration scheme, we use carbon dioxide (CO_2) gas as the gaseous target, for C^{4+} and O^{6+} have large differences in ionization energy, as shown in Fig. 2(a) and Fig. 2(b).

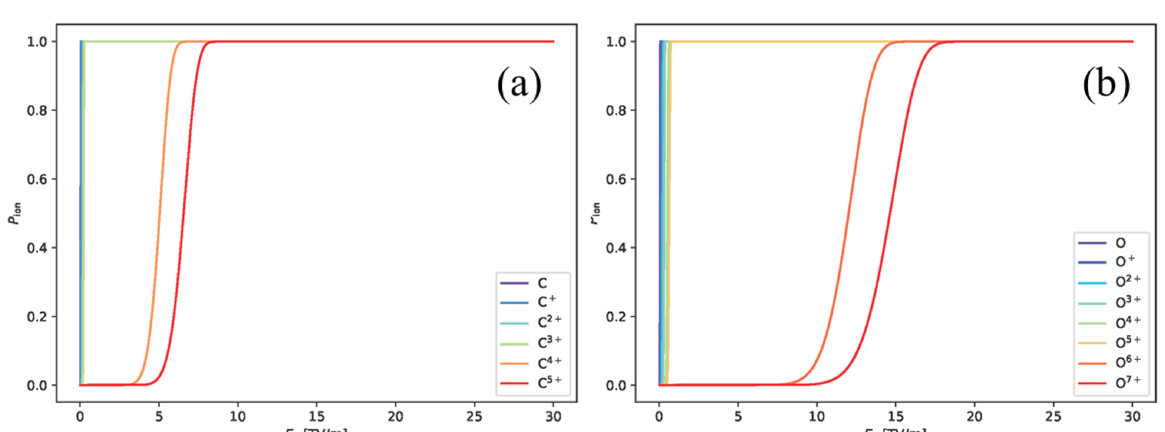

FIG. 2. Ionization energies of carbon atom and oxygen atom.

Under the assumption that the gaseous target has been fully pre-ionized by the laser pluses, we choose laser 1 to ionize the C^{4+} but not to ionize O^{6+} with electric-field intensity above 8 TV/m and below 19 TV/m, while laser 2 to ionize O^{6+} with electric-field intensity above 19 TV/m. Detailed laser parameters are shown in Table. 1.

TABLE 1. Laser parameters

	λ_0	a_0	w_0	τ_{FWHM}
Laser 1	0.8 μm	3.5	11 μm	20 fs
Laser 2	0.4 μm	4.0	4 μm	10 fs

Results and Conclusion

We choose the carbon dioxide gas density $n_{CO_2} = 1 \times 10^{17}\mathrm{cm}^{-3}$ such that the density of C^{4+} is $n_{C^{4+}} = 1 \times 10^{17}\mathrm{cm}^{-3}$, the density of O^{6+} is $n_{O^{6+}} = 2 \times 10^{17}\mathrm{cm}^{-3}$, the pre-ionized background plasma density is $n_e = 1.6 \times 10^{18}\mathrm{cm}^{-3}$. From our simulation studies, we have observed two different acceleration stages:

1. LWFA stage

The two lasers can trigger ionization injections of two electron bunches in LWFA stage.

The injection of the first electron bunch is shown in Fig. 3. Fig. 3(a) is the snapshot in the y-z slice, Fig. 3(b) is the z-direction momentum distribution. Detailed bunch parameters are shown in Table. 2.

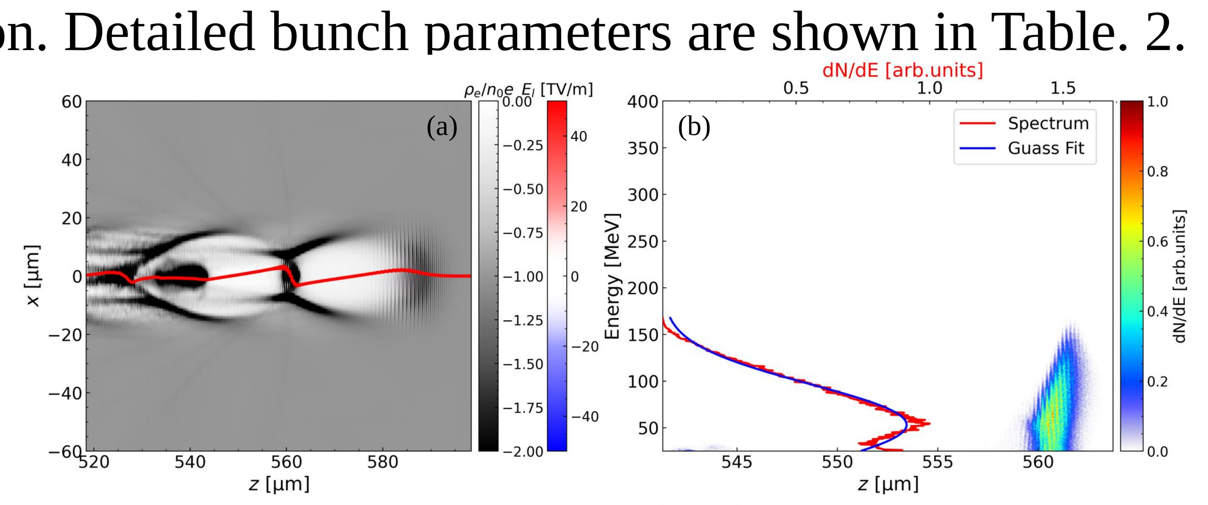

FIG. 3. The injection process of the first electron bunch.

TABLE 2. First electron bunch parameters

Charge (>25 MeV)	center energy	energy spread	emittance (x-direction)	emittance (y-direction)
280.05 pC	53.23 MeV	102.22 MeV	8.54 mm mrad	1.54 mm mrad

The injection of the second electron bunch is shown in Fig. 4. Fig. 4(a) is the snapshot in the y-z slice, Fig. 4(b) is the z-direction momentum distribution. Detailed bunch parameters are shown in Table. 3

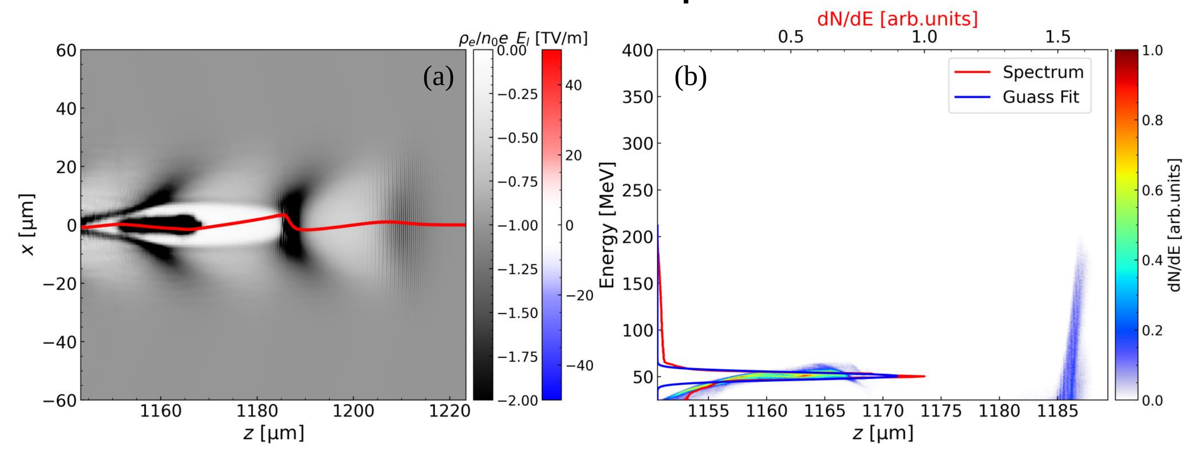

FIG. 4. The injection process of the second electron bunch.

TABLE 3. Second electron bunch parameters

charge (>25 MeV)	center energy	relative energy spread	emittance (x-direction)	emittance (y-direction)
550.60 pC	50.72 MeV	18.08 %	11.04 mm mrad	3.78 mm mrad

2. PWFA stage

The two electron bunches from LWFA stage are used in PWFA stage to sustain acceleration process. This process is shown in Fig. 5. Fig. 5(a) is the snapshot in the y-z slice, Fig. 5(b) is the z-direction momentum distribution. Detailed bunch parameters are shown in Table. 4.

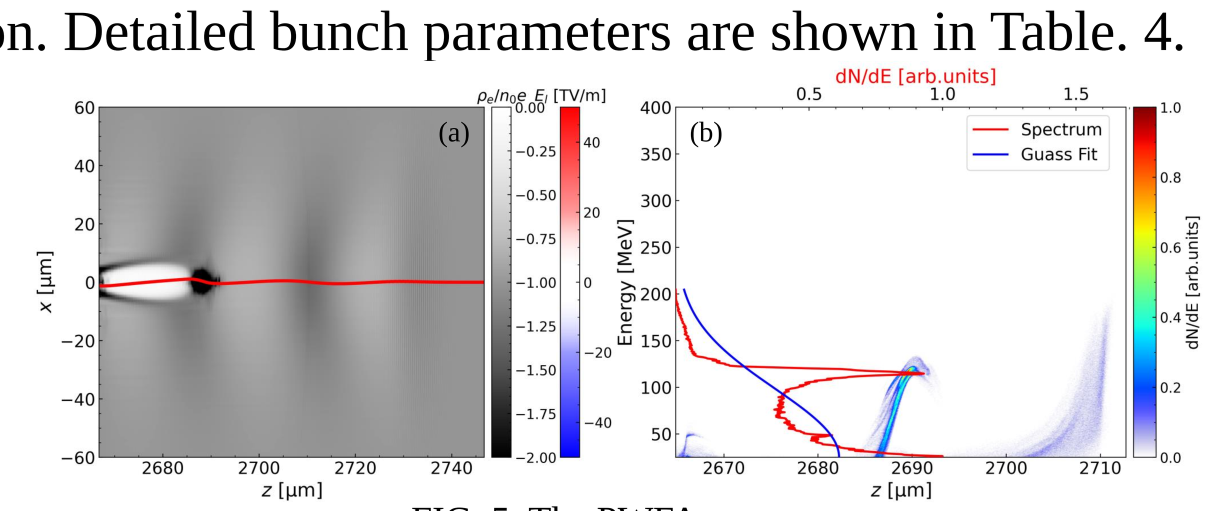

FIG. 5. The PWFA process.

TABLE 4. PWFA electron bunch parameters

charge (105 – 125 MeV)	center energy	relative energy spread	emittance (x-direction)	emittance (y-direction)
48.96 pC	114.03 MeV	13.42 %	35.4 mm mrad	9.29 mm mrad

Future Directions

We have already proved the feasibility of this LWFA-driven PWFA hybrid acceleration process.

In our future work, we will further investigate this hybrid acceleration process. We will optimize simulation parameters, such as gas distribution, gas density, laser intensity, the frequencies and spatial distribution of two lasers, etc., to improve the bunch's quality.

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