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Two-color ionization injection using a plasma beatwave accelerator[☆]

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Abstract

Two-color laser ionization injection is a method to generate ultra-low emittance (sub-100 nm transverse normalized emittance) beams in a laser-driven plasma accelerator. A plasma beatwave accelerator is proposed to drive the plasma wave for ionization injection, where the beating of the lasers effectively produces a train of long-wavelength pulses. The plasma beatwave accelerator excites a large amplitude plasma wave with low peak laser electric fields, leaving atomically-bound electrons with low ionization potential. A short-wavelength, low-amplitude ionization injection laser pulse (with a small ponderomotive force and large peak electric field) is used to ionize the remaining bound electrons at a wake phase suitable for trapping, generating an ultra-low emittance electron beam that is accelerated in the plasma wave. Using a plasma beatwave accelerator for wakefield excitation, compared to short-pulse wakefield excitation, allows for a lower amplitude injection laser pulse and, hence, a lower emittance beam may be generated.

Keywords: laser-plasma accelerator, plasma beatwave accelerator, high-brightness electron beams

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1. Introduction

Plasma-based accelerators [1] can produce large accelerating gradients, several orders of magnitude larger than conventional technology, enabling compact sources of high-energy beams. Rapid experimental progress has occurred in the field of laser-driven plasma accelerators, and electron beams accelerated to $\gtrsim 4$ GeV energies have been demonstrated using an intense laser driving a plasma wave in cm-scale plasmas [2].

The generation of electron beams in laser-plasma accelerators relies on trapping of electrons from the background plasma into the laser-driven plasma waves (wakefields). Various methods of injection have been demonstrated, including self-trapping in highly-nonlinear plasma waves [3–6], single-pulse ionization injection [7–9], and density gradient injection [10–12]. In the regime where background plasma electrons are self-trapped, experiments show that beams with $\lesssim 1$ μm normalized transverse emittance can be produced [13, 14].

Single-pulse ionization injection is an attractive injection method because it allows trapping at lower plasma densities, and, hence, can produce higher energy beams [15]. Single-pulse ionization injection uses a high-intensity laser ($a > 2$, where $a = eA/m_e c^2$ is the normalized vector potential of the laser, c is the speed of light, and e and m_e are the electron charge and mass, respectively) to ionize and drive a sufficiently large wake in a high-Z gas (e.g., Nitrogen). The inner-shell electrons are ionized near the peak of the laser, at a location in the wake potential that is favorable for trapping [9]. Although this method enables trapping at lower plasma densities, beams produced by single-pulse ionization injection typically have poor beam quality since the wakefield drive laser is continually injecting electrons as it propagates into fresh plasma, resulting in large beam energy spreads, and, since the trapped electrons are ionized near the peak of the high-intensity laser, they will experience a transverse ponderomotive kick that will contribute to increased emittance as

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well as retain a residual transverse momentum from the quiver motion in the ionizing laser $p_\perp \simeq a(t_i)m_e c$, where t_i is the ionization time. A comparison of the emittance of electron beams generated by ionization injection versus density gradient injection was reported in Ref. [16], showing ionization injection produced larger emittance beams.

To reduce the electron beam emittance it has been proposed to use a low-intensity laser to ionize electrons at a trapped phase in a plasma wakefield that is independently excited by a particle beam [17] or an intense laser [18, 19]. The laser-based method, referred to as two-color ionization injection [18–20] relies on laser pulses of different colors: a long wavelength laser pulse, with large ponderomotive force and small peak electric field, excites a plasma wake without fully ionizing a high-Z gas; a short-wavelength injection laser pulse, with small ponderomotive force and large peak electric field, co-propagating and delayed with respect to the wake drive laser, ionizes a fraction of the remaining bound electrons at a trapping phase of the wake, generating an electron beam.

In this work we propose to drive the plasma wakefield for two-color ionization injection using a plasma beatwave accelerator (PBWA). This method enables one to use a lower intensity ionization injection pulse, producing smaller emittance electron beams. Section 2 describes the advantages of using a PBWA. Section 3 describes wakefield excitation in the PBWA. An example of PBWA-driven two-color ionization is given in Sec. 4. A summary is given in Sec. 5.

2. Optimizing two-color ionization injection

In two-color ionization injection the distribution of ionized electrons resulting from laser tunneling ionization will determine the trapped charge and beam emittance. If the normalized vector potential of the ionizing laser has the form $\boldsymbol{a}_i = e\boldsymbol{A}_i/m_e c^2 = a_i \exp[ik_i(z-ct)]\exp(-r^2/w_i^2)\hat{\boldsymbol{x}}$, where w_i is the laser spot size, and $\lambda_i = 2\pi/k_i$ is the laser wavelength, then the root mean square (rms) radius of the transverse distribution of ionized electrons is [19]

$$\sigma_x = \sigma_y \simeq (w_i/\sqrt{2})\Delta, \tag{1}$$

with

$$\Delta = \left(\frac{3\pi r_e a_i}{\alpha^4 \lambda_i}\right)^{1/2}\left(\frac{U_H}{U_I}\right)^{3/4}, \tag{2}$$

where $r_e = e^2/m_e c^2$ is the classical electron radius, α is the fine structure constant, and U_i is the potential of the state of the gas used for ionization injection, normalized to $U_H \simeq 13.6$ eV. The parameter Δ^2 is proportional to the laser field amplitude $E_i \propto a_i/\lambda_i$, and $\Delta^2 \ll 1$ is satisfied at the ionization threshold. (Here we assume the Keldysh parameter $\gamma_K = \left[2U_i/(m_e c^2 a_i^2)\right]^{1/2}$ satisfies $\gamma_K < 1$, such that tunneling ionization is the dominant ionization mechanism.) The rms of the transverse momentum distribution of the ionized electrons in the plane of laser polarization is approximately [19]

$$\sigma_{p_x} \simeq a_i \Delta. \tag{3}$$

For a small ionization injection laser amplitude $a_i^2 \ll 1$, the momentum gain from the ponderomotive force of the ionizing laser may be neglected.

By reducing the amplitude of the ionization pulse, the emittance of the trapped bunch may be reduced. However, the ionization laser electric field ($E_i \propto a_i/\lambda_i$) must be sufficiently high to ionize an atomically-bound electron remaining after the passage of the wakefield-driving laser. This requires

$$a_i/\lambda_i > a_0/\lambda_0, \tag{4}$$

where $a_0 = eA_0/m_e c^2$ and λ_0 are the normalized laser vector potential amplitude and wavelength, respectively, of the (long-wavelength) laser driving the wakefield. Using a larger wavelength ratio of drive laser to ionization laser ($\lambda_0/\lambda_i \gg 1$) enables use of a lower amplitude ionization injection laser ($a_i \ll a_0$). For example, using a short-pulse 10 μm CO_2 laser to drive the wake and a frequency-doubled (0.4 μm) Ti:Al_2O_3

laser for ionization injection (i.e., $\lambda_0/\lambda_i \simeq 25$) has been considered for two-color ionization injection to produce ultra-low emittance beams [21]. However, short-pulse CO$_2$ laser technology is still in development [22].

The wakefield excited by the drive laser, with amplitude a_0, must be sufficiently large to enable trapping of an electron ionized at the proper phase of the wakefield. Behind the drive laser pulse, and assuming $a_i^2 \ll 1$, the trapping condition may be expressed as [1] $1-\gamma_p^{-1} \leq \phi(\psi_i) - \phi(\psi_t)$, where $\psi_i = k_p\xi_i$ is the phase position in the plasma wakefield of the ionized electron (initially at rest) and $\psi_t = k_p\xi_t$ is the wake phase position of the trapped particle with velocity equal to the phase velocity of the plasma wave. Here $\gamma_p \gg 1$ is the Lorentz factor of the plasma wave phase velocity, $\xi = z - ct$ is the co-moving variable, $\omega_p = k_p c$ is the electron plasma frequency, and $\phi = e\Phi/m_e c^2$ is the normalized potential of the wakefield. The optimal ionization phase ψ_i for trapping is at the peak of the wake potential, $\phi(\psi_i) = \phi_{\max}$ and $E_z(\psi_i) = 0$. In the 3D quasi-linear regime, where the peak of the accelerating field satisfies $E_z \lesssim E_0 = m_e c\omega_p/e$, there exists a phase region that is both focusing and accelerating for the electrons. To remain in this accelerating and focusing phase region requires $\phi(\psi_t) \geq 0$, assuming the wake is quasi-linear. Hence the trapping condition becomes $1-\gamma_p^{-1} \leq \phi_{\max}$. In the limit $\gamma_p \gg 1$, the peak field near the axis is related to the potential by [1] $\phi_{\max} = (E_z/E_0)^2/2 + ([1+(E_z/E_0)^2/2]^2 - 1)^{1/2}$, and the approximate wakefield amplitude required for trapping in a focusing wake phase is

$$E_z/E_0 > 1/\sqrt{2}. \tag{5}$$

The wakefield amplitude excited by a resonant, linearly-polarized, Gaussian laser pulse is [1] $E_z/E_0 \simeq (\pi/8\mathrm{e})^{1/2} a_{0,l}^2 (1 + a_{0,l}^2/2)^{-1/2}$, such that the required drive laser amplitude for trapping is $a_{0,l} > 1.7$.

The amplitude of the drive laser required to excite a wake such that $E_z/E_0 > 1/\sqrt{2}$ may be reduced by using circular polarization. To drive an equal amplitude wakefield with a circular-polarized pulse requires $a_{0,\mathrm{c}} = a_{0,l}/\sqrt{2}$, and for a resonant, circularly-polarized, Gaussian laser, the required drive laser amplitude for trapping is $a_{0,\mathrm{c}} > 1.2$; hence, a lower injection pulse amplitude could be used, satisfying Eq. (4). Using a circular-polarized laser is equivalent to using two linearly-polarized pulses to drive the wake. Multiple drive laser pulses may also be considered for wakefield excitation, and a train of resonantly-spaced (i.e., at the plasma wavelength) laser pulses may be used, with reduced single-pulse amplitude [23]. In the linear regime, a train of resonantly-spaced laser pulses with individual amplitudes $a_{0,\mathrm{t}} < 1$ will drive a wakefield amplitude $E_z/E_0 \simeq (\pi/8\mathrm{e})^{1/2} a_{0,\mathrm{t}}^2 N_\mathrm{t}$, where N_t is the number of lasers in the pulse train. The amplitude of an individual pulse in the resonant pulse train to excite the required wakefield is $a_{0,\mathrm{t}} = a_{0,l}/\sqrt{N_t}$. By using a pulse train, the ionization laser amplitude may be reduced compared to a single pulse,

$$a_i > a_{0,t}\frac{\lambda_i}{\lambda_0} = \frac{a_{0,l}}{\sqrt{N_t}}\frac{\lambda_i}{\lambda_0}. \tag{6}$$

Note that increasing the wavelength ratio is typically more effective in reducing the ionization laser amplitude compared to increasing the number of pulses in a train. For example if one considers a $\lambda_i = 0.4$ μm (frequency-doubled Ti:Al$_2$O$_3$ laser) ionization injection pulse, one would need a train of $N_t > 100$ drive pulses with $\lambda_0 = 0.8$ μm to achieve an equivalent performance as using a $\lambda_0 = 10$ μm CO$_2$ laser. (Also note that with $N_t \gtrsim (M_i/Z_i^2 m_e)^{1/2}$, where M_i is the mass of the ion and Z_i is the ion charge state, one expects ion motion to strongly perturb the laser-driven wakefield excited by the pulse train [24]). However, using drive and ionization lasers originating from the same laser system has the advantage of intrinsic synchronization [23].

As Eq. (6) indicates, improved performance (minimizing a_i) can be achieved by using both a larger wavelength ratio $\lambda_0 \gg \lambda_i$ and a train of pulses $N_t > 1$ to excite the required wakefield amplitude ($E_z/E_0 > 0.7$). This may be achieved by beating two long-wavelength laser pulse to effectively generate a train of resonant pulses in the plasma beatwave accelerator (PBWA) configuration.

3. PBWA wakefield excitation

The plasma beatwave accelerator (PBWA) [1, 25] operates by temporally co-propagating two long laser pulses of frequencies ω_{01} and ω_{02}, such that the laser frequencies are tuned to satisfy the resonance condition

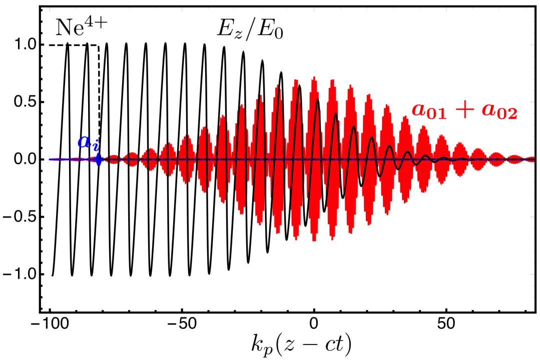

Figure 1: Example of PBWA-driven two-color ionization injection: normalized vector potentials of the beating CO_2 lasers (red curve), the normalized vector potential of the ionization pulse (blue curve), the excited wakefield E_z/E_0 (black curve), and the fraction of atoms ionized to Ne^{4+} (dashed black curve). The PBWA uses two lines of a CO_2 laser: 10.6 μm and 9.6 μm wavelengths. Each CO_2 laser is linear-polarized, with a Gaussian profile, 3.5 ps (FWHM) duration, 140 μm spot size ($Z_R \simeq 6$ mm), 2 J of energy ($a_{01} = 0.34$ and $a_{02} = 0.38$), propagates in Ne gas, ionizing the gas to Ne^{3+}, producing a plasma electron density of $n_0 = 1.3\times10^{17}$ cm^{-3} and a wake. A frequency-doubled (0.4 μm wavelength) Ti:Al$_2$O$_3$ laser with $a_i = 0.057$ (linear polarization), 60 fs duration (FWHM), delayed with respect to the CO_2 pulses, ionizes to Ne^{4+} ($U_i = 97.11$ eV) and generates a trapped electron beam.

$\omega_{01} - \omega_{02} \approx \omega_p$. When this condition is satisfied the ponderomotive force of the envelope of the beating lasers resonantly drives a large amplitude plasma wave. The laser beat wave acts as a series of laser pulses and generates a plasma wave of maximum amplitude $E_z/E_0 \simeq a_{01}a_{02}k_pL/4$, where $a_{01} < 1$ and $a_{02} < 1$ are the amplitudes of the two lasers and L is the length of the overlapping pulses. If the pulse length contains $N = L/\lambda_p$ beat periods, then $E_z/E_0 \simeq \pi N a_{01}a_{02}/2$. For large N, the amplitude of the plasma wave will saturate due to the nonlinear plasma wavelength growth as the wakefield amplitude increases. The plasma wave can be driven to larger amplitudes by using a laser beat period that is slightly longer than ω_p^{-1} [26]. Autoresonant phase locking of the plasma wave to a slowly chirped beat frequency may also be considered to drive the plasma wave amplitude beyond the detuning limit while reducing the sensitivity to laser and plasma parameters [27].

Figure 1 shows an example of plasma wave driven by the beating of two lines (9.6 μm and 10.6 μm) of a CO_2 laser in a plasma of density $n_0 = 1.3 \times 10^{17}$ cm^{-3}. The plasma wake (black curve) shown in Fig. 1, $E_z/E_0 = -\partial_\xi \phi$, was derived using the nonlinear quasi-static Maxwell-fluid equation for the wake potential [1]

$$k_p^{-2}\frac{\partial^2\phi}{\partial\xi^2} = \frac{1+a^2}{2(1+\phi)^2} - \frac{1}{2}, \tag{7}$$

where $a = [a_{01}\cos(\omega_{01}\xi/c+\varphi_1)+a_{02}\cos(\omega_{02}\xi/c+\varphi_2)]\exp(-\xi^2/2L^2)$, with $\varphi_{1,2}$ arbitrary laser phases. Note that, in this example, $(\omega_{01}-\omega_{02})/\omega_p \approx 0.91$ to account for lengthening of the plasma wavelength when the wake grows to $E_z/E_0 \sim 1$. The two lasers are both 3.5 ps (FWHM) Gaussian pulses with 2 J of energy such that $a_{01} = 0.34$ and $a_{02} = 0.38$. Here the number of beat periods is $N \approx 20$. The PBWA excites a plasma wave with amplitude $E_z/E_0 \simeq 0.9$. We consider propagation of the PBWA pulses in a Ne gas jet with gas density of $n_g = 4.3 \times 10^{16}$ cm^{-3}, such that the two pulses ionize the gas to Ne^{3+}, producing an electron plasma density of $n_0 = 1.3 \times 10^{17}$ cm^{-3}. Note that these laser parameters are achievable at present CO_2 laser facilities [28, 29].

4. PBWA-driven two-color ionization injection

By using a PBWA to excite a large amplitude plasma wave, a low intensity ionization pulse may be employed for ionization injection resulting in an ultra-low emittance beam. For equal energy beat lasers pulses ($a_{01}k_{01} = a_{02}k_{02}$), the condition Eq. (6) becomes $a_i > 2a_{01}k_{01}\lambda_i/(2\pi\sqrt{N})$. For example, using the

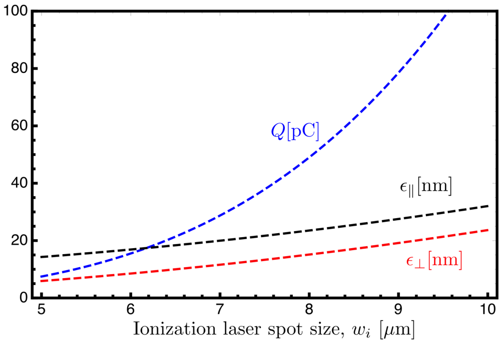

Figure 2: Normalized transverse emittance [parallel, Eq. (8) (dashed black curve), and orthogonal, Eq. (9) (dashed red curve), to the ionization laser polarization] and the charge Eq. (10) (dashed blue curve) versus ionization laser spot size (all other parameters are the same as Fig. 1).

PBWA parameters shown in Fig. 1, a frequency-doubled ($\lambda_i = 0.4$ μm) Ti:Al_2O_3 laser with amplitude $a_i = 0.057$ propagating at the optimal phase in the wakefield can ionize the gas to Ne^{4+} ($U_i = 97.11$ eV), generating a trapped electron beam.

For a small ionization injection laser amplitude $a_i^2 \ll 1$, propagating in a uniform plasma, the final normalized transverse emittances are [19, 21],

$$\epsilon_{\|} = k_\beta w_i^2 \left[1 + 2a_i^2/(k_\beta w_i)^2\right] \Delta^2/4, \tag{8}$$

and

$$\epsilon_{\perp} = k_\beta w_i^2 \Delta^2/4, \tag{9}$$

where $\epsilon_{\|}$ ($\epsilon_{\perp}$) is the transverse normalized emittance parallel (orthogonal) to the plane of ionization laser polarization, and k_β is the betatron wavenumber in the wakefield. The trapped charge contained in the beam can be estimated assuming ionization over a Rayleigh length,

$$Q \sim e n_g Z_{Ri} \pi w_i^2 \Delta^2, \tag{10}$$

where $Z_{Ri} = \pi w_i^2/\lambda_i$ is the Rayleigh range of the ionization laser. Figure 2 shows the charge Eq. (10) and transverse emittances Eqs. (8) and (9) versus ionization laser spot size w_i. Beams with transverse emittances of order 10 nm can be generated using PBWA-driven two-color ionization injection. Figure 2 also demonstrates the trade-off between charge ($Q \propto w_i^4$, with interaction length limited by diffraction) and transverse emittance ($\epsilon \propto w_i^2$).

The expected energy spread will be determined by the ratio of the distance over which injection occurs, approximately $\sim Z_{Ri}$, to the total length over which the beam is accelerated, approximately the dephasing length $L_d \sim k_0^2/k_p^3$. Hence $\Delta\gamma/\gamma \sim k_p^3 Z_{Ri}/k_0^2$, neglecting beam loading effects. For $w_i = 5$ μm and the parameters of Fig. 1, $\Delta\gamma/\gamma \sim 0.1$.

5. Summary

In this work we have proposed the use of a PBWA to drive a wakefield for two-color ionization injection. By beating two long-wavelength lasers (e.g., CO_2) to effectively create a train of resonant, long-wavelength pules for wakefield excitation, this method can reduce the laser electric field amplitude required to excite a large amplitude wakefield, thereby reducing the ionization pulse intensity required to ionize and trap electrons in the plasma wave. Hence smaller emittance beams can be generated. If the ionization injection laser amplitude is sufficiently low such that $a_i \ll k_p w_i$ then the transverse emittance of the trapped beam will be dominated by the transverse momentum gained from the wake potential [cf. Eqs. (8) and (9)]. An example was presented using laser parameters that are available with existing laser technology [28, 29] showing the potential to generate ultra-low emittance electron beams, on the order of tens of nm, using two-color ionization injection in a PBWA-driven wakefield.

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