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Plasma wakefield acceleration in self-ionized gas or plasmas

S. Deng,[1] C. D. Barnes,[3] C. E. Clayton,[2] C. O'Connell,[3] F. J. Decker,[3] O. Erdem,[1] R. A. Fonseca,[2] C. Huang,[2]
M. J. Hogan,[3] R. Iverson,[3] D. K. Johnson,[2] C. Joshi,[2] T. Katsouleas,[1] P. Krejcik,[3] W. Lu,[2] K. A. Marsh,[2] W. B. Mori,[2]
P. Muggli,[1] and F. Tsung[2]
[1]*University of Southern California, Los Angeles, California 90089, USA*
[2]*University of California, Los Angeles, California 90095, USA*
[3]*Stanford Linear Accelerator Center, Stanford, California 94309, USA*

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Tunnel ionizing neutral gas with the self-field of a charged particle beam is explored as a possible way of creating plasma sources for a plasma wakefield accelerator [Bruhwiler *et al.*, Phys. Plasmas (to be published)]. The optimal gas density for maximizing the plasma wakefield without preionized plasma is studied using the PIC simulation code OSIRIS [R. Hemker *et al.*, in *Proceeding of the Fifth IEEE Particle Accelerator Conference* (IEEE, 1999), pp. 3672–3674]. To obtain wakefields comparable to the optimal preionized case, the gas density needs to be seven times higher than the plasma density in a typical preionized case. A physical explanation is given.

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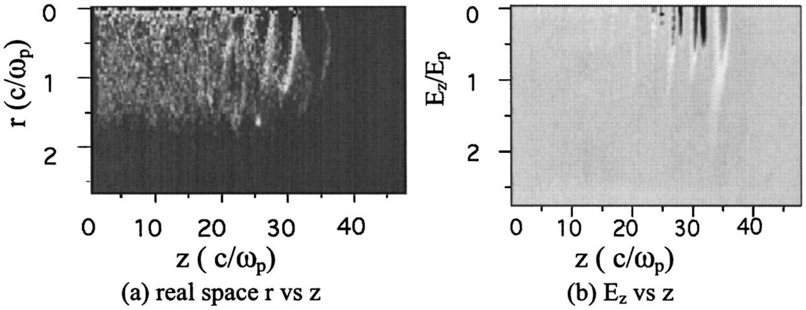
Recently, there has been great interest in the plasma wakefield accelerator (PWFA) as a possible energy doubler (or afterburner) for a linear collider [1]. In the afterburner as well as in an upcoming experiment at SLAC (E164) [2], a high-density short bunch is used to drive nonlinear (blowout regime [3]) plasma wakes and multi-GeV peak accelerating gradients. One critical issue for both experiments is the need for long homogeneous plasma sources of high density—up to 10 meters of 2×10^{16} cm^{-3} plasma for the afterburner. For UV single-photon ionized metal vapors, laser ionization typically can ionize gases up to a density-length product of order 10^{15} cm^{-3} meters per 100 mJ of laser energy.

Recently, Bruwhiler *et al.* [4] proposed the possibility of creating plasma sources by tunnel ionizing neutral gas with the self-field of the driving beam. There have also been some previous experiments that showed evidence of ionization by short pulse beams in gases, although the mechanism for those was impact ionization [5,6]. In this paper, we revisit this topic, and extend the work of Bruwhiler *et al.* by studying the optimal gas density for maximizing the plasma wakefield. The ionization and wake generation are modeled with the PIC code OSIRIS [7]. We find that for parameters typical of the above experiments, the wakefield is much smaller than in the preionized case when the gas density is equal to the optimal plasma density [8]. Increasing the gas density by a factor of about seven yields wakefields comparable to the optimal preionized case. A physical explanation for this behavior is given.

The physical problem and nominal parameters modeled in this paper are the following: A 50 GeV beam consisting of 2×10^{10} electron particles has a Gaussian distribution with rms radius $\sigma_r=20$ μm and length $\sigma_z=63$ μm. The beam is incident upon neutral (un-ionized) gas. Initially the gas (here we use Li gas) density is set to be $n_0=1.4\times10^{16}$ cm^{-3}, which approximately maximizes the wakefield amplitude in a preformed plasma (according to the linear theory, the optimal density corresponds to $\omega_p\sigma_z/c=2^{1/2}$ [8]). As described in Ref. [4], the self-fields of the drive beam are so strong that they can ionize the neutral gas and create plasma when the beam passes through the neutral gas. But the wakefields created are much smaller than in the preionized case because the electrons are not created quickly enough through ionization to respond resonantly to the drive beam. One way to solve this problem is to use a higher-density drive beam. Here we consider another solution—increasing the gas density. Two-dimensional (2D) PIC simulations are done with the OSIRIS code, which includes an ionization package. The ADK tunnel ionization model [9] is used in the code.



(a) real space r vs z
(b) E_z vs z

FIG. 1. (a) Real space r vs z of ionized electrons. (b) 2D contour of E_z field. [Axes in both (a) and (b) are in units of c/ω_p. Here $c/\omega_p=44.8$ μm.]

The simulation parameters are the following:

d_t	$t_{\max}$	System size		Grid number		Beam center position	
$0.037/\omega_{p0}$	$52.2/\omega_{p0}$	$z=48c/\omega_{p0}$	$r=8c/\omega_{p0}$	$z=400$	$r=200$	$z=35c/\omega_{p0}$	$r=0c/\omega_{p0}$

Here $\omega_{p0}=6.69\times10^{12}$, corresponding to a plasma density $n_0=1.4\times10^{16}\ \mathrm{cm}^{-3}$. The same n_0 and ω_{p0} will be used throughout this paper.

We did six runs separately with gas density $n_{\mathrm{gas}}=1n_0$, $3n_0$, $6n_0$, $7n_0$, $8n_0$, $10n_0$, as well as six runs with a preformed (fully ionized) plasma. Sample simulation results are shown in Figs. 1–4.

Figure 1 shows the real space of ionized electrons and 2D contours of the accelerating wake electrical field $E1$ for $n_{\mathrm{gas}}=3n_0$.

Figure 2 shows the amplitude of the wakefield versus gas or plasma density. The wakefield is scaled with the cold nonrelativistic wavebreaking field $E_p=mc\omega_p/e=11.4$ GV/m at a plasma density of $1n_0$. The amplitude of the wakefield is quite small at $n_{\mathrm{gas}}=n_0$. The amplitude increases with the gas density, and peaks around $n_{\mathrm{gas}}=7n_0$, while in the preionized case, the wake peaks around $3n_0$. So the optimal density for maximizing the wakefields is higher for the self-ionization case than for the preionized case. (As expected even in the preionized case, the optimal density is larger than the linear theory optimal density n_0 because the nonlinear wake drives the plasma electrons relativistically, increasing their mass and decreasing the plasma frequency. The density must be higher to compensate for this frequency decrease.)

This behavior can be understood as follows. As the beam enters the neutral gas, the head of the beam cannot ionize the gas until its electric fields reach a threshold value. The rapidly ionized plasma ‘‘sees’’ an effectively shortened beam, because it does not see the head of the beam (i.e., it does not experience any electric forces from the head of the beam; for relativistic beams the transverse electric field at any axial position depends only on the beam density at that position). In Fig. 4, the start position of the wake shows this effect clearly—the start position of the wake is delayed in the self-ionized case until a threshold value is reached. The effectively shorter beam then needs a higher gas density to match the plasma period (wavelength) to the effective pulse length. For threshold ionization near the peak of the beam density, the beam is effectively shortened by half its length. We may then expect the matched plasma density to be larger by a factor of 4 (to shorten the wavelength by two). Transverse effects may favor further increasing the gas density. The reason for this is this decreases the transverse area of the plasma that needs to be ionized to support the wake (proportional to the plasma blowout radius squared and inversely proportional to plasma density). These qualitative arguments are consistent with the simulations in which the optimal gas density was seven times the linear theory and 2.5 times the preionized optimum density.

The wavelength in a wakefield accelerator is important to know both for optimizing the wakefield and for optimally loading a second beam of particles to be accelerated. Figure 3 shows the change of wake wavelength with density. The wavelength is normalized to $\lambda_p=2\pi c/\omega_p$, where $\omega_p=(4\pi ne^2/m)^{1/2}$ and $n=n_{\mathrm{gas}}$ or n_{plasma} for the self-ionized and preionized cases, respectively. For $n_{\mathrm{gas}}=1n_0$ to $4n_0$, the wakefield is not strong enough to fully ionize the neutral gas, so the plasma density is in fact smaller than the gas density, which leads to a longer wavelength. As the gas density increases, both the plasma density and the wakefields increase. The wakefields in turn cause more ionization. After the gas

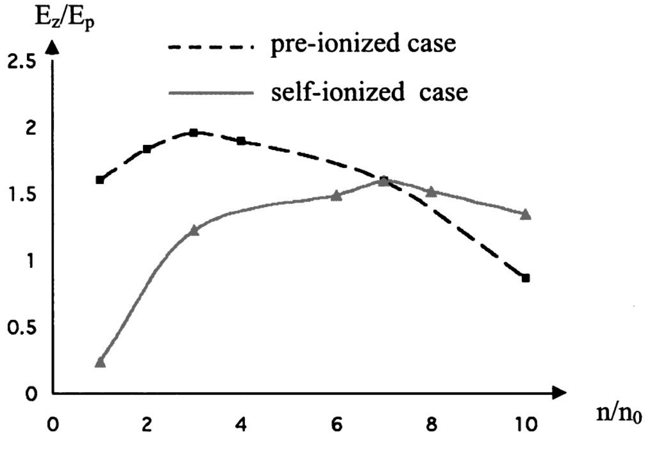


FIG. 2. Scaled amplitude of the longitudinal electric field E_z/E_p vs gas or plasma density, $E_p=11.4$ GV/m.

FIG. 3. Scaled wavelength vs gas or plasma density, $\lambda_p=2\pi c/\omega_p$, where $\omega_p=(4\pi ne^2/m)^{1/2}$ and $n=n_{\mathrm{gas}}$ or n_{plasma}.

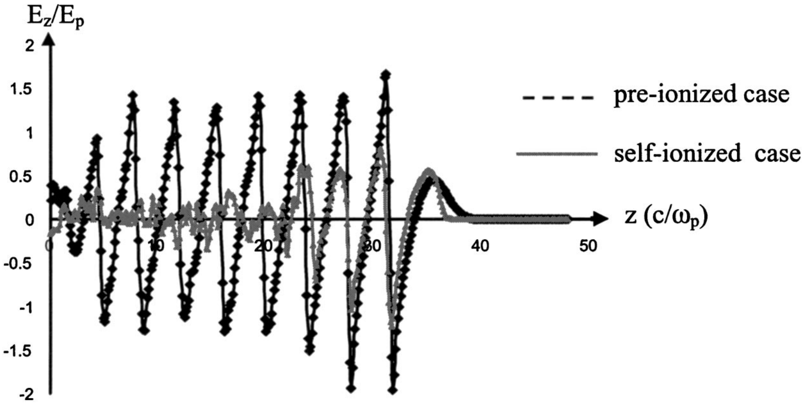


FIG. 4. Comparison of the longitudinal electric field of the preionized case and the self-ionized case. (The z axis is in units of c/ω_p. Here $c/\omega_p = 44.8\ \mu$m.)

density increases to some point (around $4n_0$), the change of the wavelength with density for the self-ionization case parallels that of the preionized case: λ increases due to nonlinear effects and peaks at a density corresponding to the peak wake amplitude (around $n_{gas} = 7n_0$ for the self-ionized case and $n_{plasma} = 3n_0$ for the preionized case).

The above results support the thesis that self-ionization can be used as a way to create plasma sources for plasma wakefield accelerators. The beam wakefield can be made comparable to the preionized plasma case if the gas density is increased appropriately.

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