EPJ Web of Conferences **59**, 17003 (2013)
DOI: 10.1051/epjconf/20135917003

Double ionization effect in electron accelerations by high-intensity laser pulse interaction with a neutral gas

Devki Nandan Gupta[a]

Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India

Abstract. We study the effect of laser-induced double-ionization of a helium gas (with inhomogeneous density profile) on vacuum electron acceleration. For enough laser intensity, helium gas can be found doubly ionized and it strengthens the divergence of the pulse. The double ionization of helium gas can defocus the laser pulse significantly, and electrons are accelerated by the front of the laser pulse in vacuum and then decelerated by the defocused trail part of the laser pulse. It is observed that the electrons experience a very low laser-intensity at the trailing part of the laser pulse. Hence, there is not much electron deceleration at the trailing part of the pulse. We found that the inhomogeneity of the neutral gas reduced the rate of tunnel ionization causing less defocusing of the laser pulse and thus the electron energy gain is reduced.

1. INTRODUCTION

Interest in laser-matter interactions has increased over the past few years due to the availability of ultrahigh power lasers [1]. Among them, the laser particle accelerations in vacuum and plasma have become very important. However, there are still some fundamental limitations in vacuum electron accelerations; one is that the electric field distribution is extremely complex in the focal plane of a linearly polarized, focused Gaussian beam, as the transverse field components tend to deflect particles and increase the beam emittance. The other is that, the interaction length is limited, such that the oscillatory electromagnetic field does not cancel out any net acceleration [2].

The single and double ionization of an atom in a strong field has been a primary problem in atomic physics for many years [3]. Typically, an electron is promoted into the continuum via tunnel ionization, which displaces an electron from the core using very little kinetic energy. From this description of the interaction dynamics, it is clear that the ponderomotive energy, sometimes referred to as quiver energy, is an important quantity in strong-field physics [4]. The laser-induced optical field ionization of a gas produces a radial density profile with a peak on the axis that causes the laser pulse to diverge; indeed, if the laser intensity is high enough, the neutral gas can be doubly ionized, which further enhances the pulse divergence [5].

In this article, we propose the introduction of a localized neutral gas at the trailing part of the laser pulse as a means of reducing electron deceleration in vacuum. Double ionization of the neutral gas can significantly defocus the laser pulse, and the electron accelerates by being pushed in front of the laser pulse in vacuum and gains energy, though it then decelerates due to its interaction with the trailing part of the laser pulse. The reduction in electron deceleration (via defocusing of the laser induced by the double ionization of the neutral gas) allows the electron continuously to accelerate. We subsequently formulate the problem in which the equations of laser defocusing have been obtained, where the inhomogeneous profile of the gas is considered.

[a]e-mail: dngupta@physics.du.ac.in

2. FORMULATIONS

We consider the propagation of a laser through vacuum, followed by an inhomogeneous neutral gas along the z-direction. The laser electric field at the entrance of the neutral gas can be assumed as

$$\vec{E} = \hat{x} E_0 \cos(\omega t - \omega z_1/c)\exp\{-[t-(z_1-z_0)/\upsilon_g]^2/\tau_L^2\}, \tag{1}$$

where $E_0 = E_{00}\exp(-r^2/2r_0^2)$ for $t > 0$, z_0 is the initial position of the pulse peak, z_1 is the position of the pulse peak for interaction, τ_L is its duration, r_0 is the laser spot size, and ω is the laser frequency. We then define the quantity $\omega_{pm} = (4\pi n_m e^2/m)^{1/2}$, where $-e$ and m are the charge and mass of an electron. Here, the ω_{pm}^2 profile is

$$\begin{aligned}
\omega_{pm}^2(z) &= \frac{z}{L_n}\left(\frac{\omega_{pm0}^2}{\omega^2}\right) \quad \text{for} \quad 0 < \frac{z}{R_d} < \frac{L_n}{R_d},\\
&= \frac{\omega_{pm0}^2}{\omega^2} \quad \text{for} \quad \frac{L_n}{R_d} < \frac{z}{R_d} < N\frac{L_n}{R_d},\\
&= \frac{\omega_{pm0}^2}{\omega^2}\left[1-\left(\frac{z}{L_n}-N\right)\right] \quad \text{for} \quad N\frac{L_n}{R_d} < \frac{z}{R_d} < (N+1)\frac{L_n}{R_d},\\
&= 0 \quad \text{for} \quad z < 0 \quad \text{and} \quad z > (N+1)L_n,
\end{aligned} \tag{2}$$

where ω_{pm0} is a constant depending on the neutral density of the gas, L_n is the density scale length, $R_d = \omega r_0^2/c$ is the diffraction length, c is the velocity of light, and N is an integer. For higher laser intensities, the second ionization may occur that gives rise to a higher plasma density ($n_0 = n_1 + 2n_2$, where n_1 and n_2 are the densities of singly and doubly ionized ions, respectively). This evolving plasma density varies due to the steps of gas ionization, such that $\partial\omega_{p1}^2/\partial t = \Gamma_1(\omega_{pm}^2 - \omega_{p1}^2 - \omega_{p2}^2) - \Gamma_2\omega_{p1}^2$ and $\partial\omega_{p2}^2/\partial t = \Gamma_2\omega_{p1}^2$, where, $\Gamma_j = (I_{0j}/\hbar)(\pi|E|/2E_{Aj})^{1/2}\exp(-E_{Aj}/|E|)$ is the rate of single and double ionization, $\omega_{pj}^2 = 4\pi n_j e^2/m$ (where $j = 1,\ 2$ for single and double ionization, respectively), $E_{Aj} = (4/3)(2/m)I_{0j}^{3/2}/e\hbar$ is the characteristic atomic field, I_{0j} is the ionization potential for single and double ionization, $|E|$ is the amplitude of the electric field, and $h = 2\pi\hbar$ is the Plank's constant. Inside the ionized gas ($z > 0$), the laser field can be assumed as

$$\vec{E} = \hat{x} A \cos(\omega t - \omega z/c)\exp\{-[t-(z-z_0)/\upsilon_g]^2/\tau_L^2\}, \tag{3}$$

where $\upsilon_g = c(1-\omega_{p0}^2/\omega^2)^{1/2}$ is the group velocity of the laser pulse and $\omega_{p0}^2 = \omega_p(t,z,r=0)$. Following the procedure used by Gupta et al. [5], we obtain the equations governing the laser frequency and beam width parameter as

$$\frac{\partial\omega_{p10}^2}{\partial t'} = \exp(-\alpha)\Omega^2/\alpha^2 - 1.22\exp(3.29\alpha)\omega_{p10}^2/\alpha^{1/2} - \exp(1-\alpha)\omega_{p10}^2\alpha, \tag{4}$$

$$\begin{aligned}
\frac{\partial\omega_{p12}^2}{\partial t'} = &-\exp(-\alpha)(1+2\alpha)\Omega^2/4f^{5/2}\alpha^{1/2} - 1.22\exp(3.29\alpha)\omega_{p12}^2/\alpha^{1/2}\\
&+ 1.22\exp(3.29\alpha)(1+6.58\alpha)\omega_{p10}^2/4f^{5/2}\alpha^{1/2} - \exp(\alpha)\Omega_2^2/\alpha^{1/2},
\end{aligned} \tag{5}$$

$$\frac{\partial\omega_{p20}^2}{\partial t'} = -1.22\exp(3.29\alpha)\omega_{p10}^2/\alpha - \exp(1-\alpha)\omega_{p20}^2\alpha, \tag{6}$$

$$\frac{\partial\omega_{p22}^2}{\partial t'} = -1.22\exp(3.29\alpha)(1+6.58\alpha)\omega_{p10}^2/4f^{5/2}\alpha^{1/2} + 1.22\exp(3.29\alpha)\omega_{p12}^2/\alpha^{1/2}, \tag{7}$$

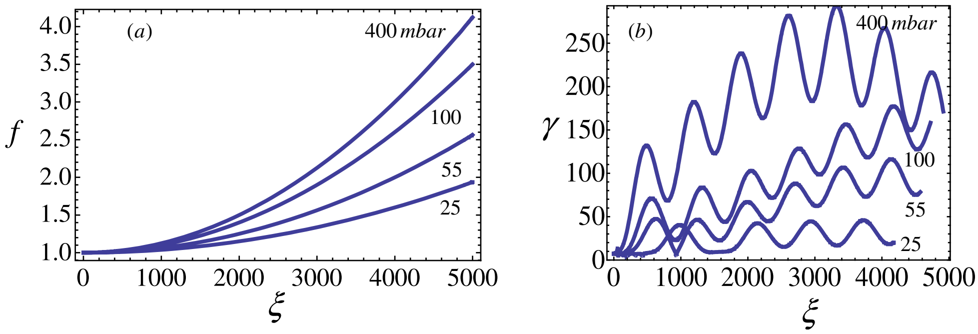

Figure 1. (a) Beam-width parameter and (b) electron energy with normalized propagation distance for different gas pressures of 25, 55, 100, and 400 mbar at room temperature.

$$\frac{\partial f}{\partial z'} = \frac{1}{r_0^2 f^3} - \frac{\Omega_3^2 f}{r_0^2 \omega_0^2} - \frac{\Omega_4^2 kc}{\omega_0^3}\left(\frac{\partial^2 f}{\partial t' \partial z'} + \frac{\partial^2 f}{\partial t'^2}\frac{\Omega_4^2 kc}{\omega_0^3}\right), \tag{8}$$

where a new set of variables $t' = t - z/c$, $z' = z$ have been defined, $\alpha = E_1 f/A_{00}$, $\Omega_1^2 = \omega_{pm}^2(z) - \omega_{p10}^2 - \omega_{p20}^2$, $\Omega_2^2 = \omega_{p12}^2 + \omega_{p22}^2$, $\Omega_3^2 = \omega_{p12}^2 + 2\omega_{p22}^2$, and $\Omega_4^2 = \omega_{p10}^2 + \omega_{p22}^2$. The equations governing the electron momentum and energy can then be written as

$$\frac{d\vec{p}}{dt'} = -e\left(\vec{E} + \frac{1}{c}\vec{\upsilon} \times \vec{B}\right), \tag{9}$$

$$\frac{d\gamma}{dt'} = -\frac{e}{mc^2}\vec{E}.\vec{\upsilon}, \tag{10}$$

where $\gamma^2 = 1 + (p_x^2 + p_z^2)/m^2c^2$. In solving the above equations, we normalize the frequency by $1/\omega$, the time by ω, the distance by ω/c, and the momentum by $1/mc$. We solve Eqs. (4)–(10) numerically to obtain the electron energy. The initial and boundary conditions, corresponding to the initial wave front, include: $\vec{r} = 0$, $p_x = 0$, $\omega_{p0} = 0$, $\omega_{p2} = 0$, $\partial f/\partial t' = 0$, and $f = 1$ at $t = 0$.

3. NUMERICAL RESULTS

We choose the following parameters: $a_0 = eA_{00}/m\omega c = 3.5$, $\tau_L = 100$, $z_1 = -20$, $r_0 = 80$, $I_0 = 24\,eV$, $E_A/E_0 = 3$, $\lambda = 1\mu m$, $\omega_{pm0}/\omega = 0.0187$, 0.0275, 0.037, 0.0742 corresponding to the gas pressures of 25, 55, 100, and 400 mbar, respectively, at room temperature, $L_n/R_d = 2$, $\gamma_0 = 3$, and $N = 2$. An intense laser, propagating through a neutral gas of an axially inhomogeneous density, produces plasma via tunnel ionization. The plasma has both radial as well as axial inhomogeneity; the former causes defocusing of the laser as the refractive index is minimum on the axis. On the other hand, if the laser intensity is sufficiently high, double-stage photo-ionization can be possible, which may produce even higher plasma density on the axis of the laser propagation. As a result, the laser strongly defocuses and may have much less intensity at the trailing part of the pulse. An electron injected for acceleration in this region will gain energy continuously.

Figure 1 shows the beam-width parameter f and the electron energy γ as a function of z for different initial neutral gas densities. The initial equilibrium densities of the neutral gas atoms are $\omega_{pm0}/\omega = 0.0187$, 0.0275, 0.037, 0.0742. The plasma produced by the tailing portion of the laser, caused stronger defocusing (due to double ionization), and the electron gained net energy. These figures show the effect of initial neutral gas density on electron energy gain and on defocusing of the laser pulse, in which a higher equilibrium gas density results in higher defocusing [Fig. 2(a)] and electron gains more energy [Fig. 2(b)]. Hence, the electron energy gain is seen to depend on the initial equilibrium density of neutral gas atoms, i.e. if the laser pulse is properly defocused, an electron can retain more energy.

4. CONCLUSIONS

We have studied the interaction of a high-intensity laser with an inhomogeneous neutral gas at different pressure and then discuss the application of this interaction for electron acceleration in vacuum. Via this mechanism, an electron in vacuum can be accelerated to higher energy by using a high-intensity laser propagating in a neutral gas of inhomogeneous density profile, where the neutral gas was used to reduce the electron deceleration based on its interaction with the trailing part of the laser. The higher density plasma on the laser axis is produced due to the double-step photo ionization of the neutral gas, which strongly defocuses the laser. However, inhomogeneity in the gas density reduces the defocusing of the laser pulse due to a corresponding decrement in the diffraction divergence of the laser in a tunnel-ionized plasma. The inhomogeneity of the gas reduces the rate of tunnel ionization and causes less defocusing of the laser pulse and thus the electron gains less energy compared to the homogeneous gas, which is the practical situation in helium gas-jet experiments.

References

[1] M.D. Perry and G. Mourou, Science **264**, 917 (1994)
[2] D. Umstadter, Phys. Plasmas **8**, 1774 (2001)
[3] K.Y. Kim, I. Alexeev, and H.M. Milchberg, Opt. Express **10**, 1563 (2002)
[4] L.V. Keldysh, Sov. Phys. JETP **20**, 1307 (1965)
[5] D.N. Gupta, H.J. Jang, and H. Suk, Appl. Phys. Lett. **94**, 021502 (2009)