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Dephasing time of a positron accelerated by a laser pulse*

Du Chun-Guang(杜春光), and Li Shi-Qun(李师群)

Department of Physics, Tsinghua University, Beijing 100084, *China*

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The dephasing time of a positron in the total field associated with a laser pulse in a plasma is studied numerically. It is shown that the dynamics of the positron is quite different from that of an electron due to the electrostatic potential in the body of the pulse. The dephasing time of the positron increases with the pulse length and decreases with the pulse intensity nonlinearly. In the long pulse case ($L \gg \lambda_p$) the dephasing time is proportional to the pulse length. These results provide a scientific basis for experiments to observe the positron acceleration scheme, and may be important to the physics of laser–particle interactions in multi-component plasmas.

Keywords: positron acceleration, dephasing time, laser–plasma interactions
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The dynamics of a test particle in the fields associated with a laser pulse is important for the study of the physics of laser–particle and laser–plasma interactions,[1] especially for the new concept of accelerators.[2−6] For a particle initially in front of the pulse, if the pulse speed is c (c is the light speed in vacuum), the particle will always be overtaken by the pulse eventually. The acceleration effect of the leading edge of the pulse on the particle will be counteracted by the deceleration effect of the back edge of the pulse. However, if the pulse speed is less than c (for example in a plasma), the particle can be accelerated by the leading edge of the pulse to a speed higher than that of the pulse, and it outruns the pulse eventually (not suffering from the deceleration of the back edge of the pulse).[7] Our recent research shows that in the long-pulse case ($L \gg \lambda_p$), this acceleration scheme is more profitable to the positron acceleration than to the electron acceleration, due to the electrostatic potential generated by the pulse in the plasma, thus greatly decreasing the intensity threshold of the pulse for positron acceleration.[8] In this paper, we numerically study the dephasing time of an accelerated positron to determine the propagation time and plasma length required for observing this direct acceleration scheme for positrons, where the pulse is assumed to be of any length. The dephasing time is the interaction time between the particle and the pulse whose intensity is above the repelling threshold (or the time interval during which the particle is accelerated until it outruns the pulse).

The basic dynamics of the interaction of a particle of charge q and mass m with an electromagnetic field is described by the momentum equation

$$d_t \boldsymbol{p} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right), \tag{1}$$

and the energy equation

$$d_t(\gamma m c^2) = q\boldsymbol{E} \cdot \boldsymbol{v}, \tag{2}$$

where $\boldsymbol{v}$ is the velocity of the particle, and γ is the Lorentz factor associated with this velocity, which is defined by $\gamma^{-2} = 1 - \boldsymbol{v}^2/c^2$. The fields associated with the laser–particle interaction can be described by the normalized vector and scalar potentials, i.e. $\boldsymbol{a} = q\boldsymbol{A}/m_e c^2$, and $\phi = e\Phi/m_e c^2$, respectively. The Coulomb gauge $\nabla \cdot \boldsymbol{a} = 0$ is used and, for convenience in the following analyses, the time t and momentum $\boldsymbol{p}$ are normalized as $t \to ct$ and $\boldsymbol{p} \to \boldsymbol{p}/m_q c$, respectively.

We suppose that the pulse is of plane-wave radiation, and a positron is initially in front of the pulse and not moving transversely, so that its motion is governed by the equations

$$d_t p_z = -\frac{1}{2\gamma}\partial_z a^2 - \partial_z \phi, \tag{3}$$

$$d_t \gamma = \frac{1}{2\gamma}\partial_t a^2 + \frac{p_z}{\gamma}\partial_z \phi, \tag{4}$$

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$$\boldsymbol{p}_\perp = -\boldsymbol{a}. \tag{5}$$

The pulse is assumed to be circularly polarized and propagates without significant distortion, i.e.

$$\boldsymbol{a} = \frac{1}{\sqrt{2}} a(\xi)(\cos(k\eta)\boldsymbol{e}_x + \sin(k\eta)\boldsymbol{e}_y), \tag{6}$$

where $\xi = z - \beta_g t$, $\eta = z - \beta_\phi t$, and β_g and β_ϕ are group and phase velocities associated with the pulse divided by c, respectively.

Neglecting the modification of the pulse fields due to the test particle, the scalar potential ϕ can be written as a function of $\boldsymbol{a}$ under the quasi-static approximation[9]

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

where the boundary condition ($\phi = 0$ when $\xi = 0$) is assumed. Our numerical analysis shows that this scalar potential ϕ is always positive in the whole body of the pulse, and the negative ϕ can only appear behind the pulse.

We study the time evolution of the longitudinal momentum p_z by solving Eqs.(3), (6) and (7) numerically. As in Refs.[7] and [10], we assume that the distortion of the pulse shape is very slow and can be neglected during the time of the laser–particle interaction. To illustrate the particle motion, we consider the simple profile as in Ref.[10],

$$a(\xi) = a_0 \sin(\pi \xi \beta_g/(2L)). \tag{8}$$

It is shown that for a low intensity pulse, the pulse will overtake the particle. Thus eventually the particle oscillates longitudinally in the wake field behind the body of the pulse. If the pulse intensity is above the repelling intensity, however, the longitudinal momentum of the particle will continuously increase with time and eventually the particle will outrun the pulse.

In general, the dynamics of a positron is very different from that of an electron due to the electrostatic field in the body of the pulse. In the following numerical analysis we define γ_0 as the Lorentz factor associated with the initial velocity of the test particle, and γ_p as that associated with the group velocity of the pulse, i.e. $\gamma_0^{-2} = 1 - \boldsymbol{v}_0{}^2/c^2$. $\gamma_p^{-2} = 1 - \boldsymbol{v}_g{}^2/c^2$. Figure 1 shows the difference between the time dependence of an electron and that of a positron, where the pulse intensity is large enough to accelerate a positron, but not to accelerate an electron. It is shown that the trajectory of a positron could be completely different from that of an electron in the body of a laser pulse propagating in a plasma.

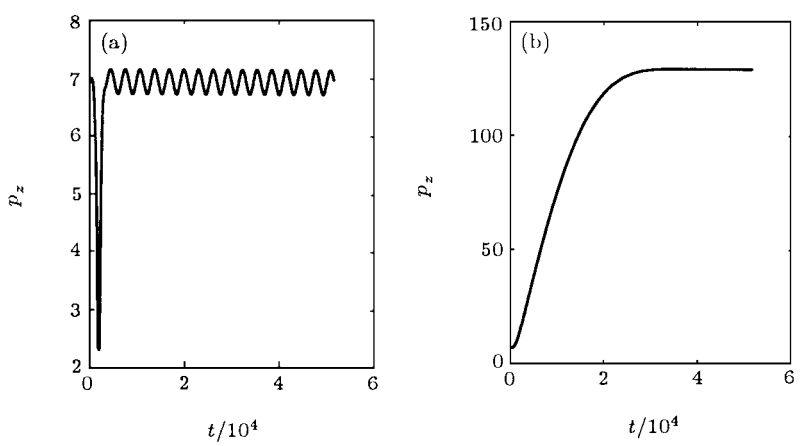


Fig.1. The difference between the time dependence of an electron (a) and that of a positron (b), where $k_p L = 10$, $\gamma_0 = 7$, $\gamma_p = 30$, and $a_0^2 = 1$. The time t is expressed in units of optic cycle.

We assume that, initially, $\xi = 0$ and the particle is slower than the pulse. Then ξ will become negative and decrease to a minimum value, then increase, at time t_d, $\xi = 0$ again, and the particle just runs out of the pulse (outruns the pulse). The particle speed increases monotonically during the time interval from 0 to t_d. Here t_d is the dephasing time. At a certain γ_p, for a shorter dephasing time, a shorter acceleration distance is needed.

Figure 2 shows the dependence of the dephas-

ing time of an accelerated positron on the normalized pulse length k_pL. It is obvious that this dephasing time nonlinearly increases with k_pL, but not like that in Ref.[10] (where it is proportional to k_pL). This dephasing time is proportional to k_pL only in the long-pulse limit $k_pL >> 1$.

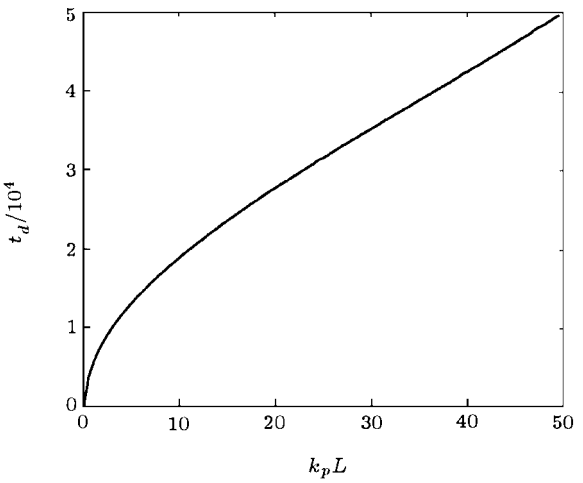


Fig.2. The dependence of the dephasing time of an accelerated positron on the normalized pulse length k_pL, where $a_0^2 = 10$. The other parameters are the same as in Fig.1.

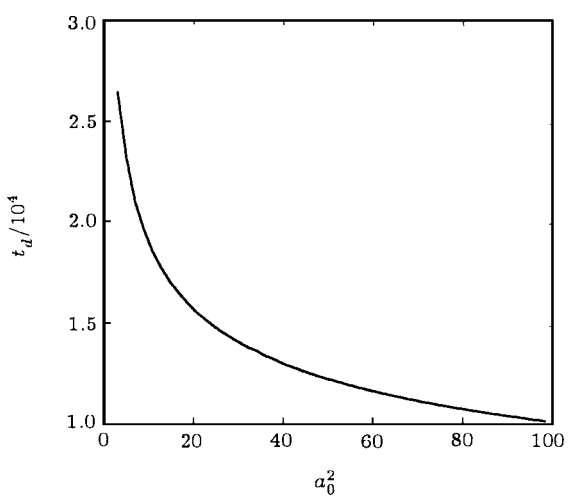


Fig.3. The dependence of this dephasing time on pulse intensity a_0^2. The parameters are the same as in Fig.1.

Although a positron can be accelerated to a high energy by a low-intensity pulse,[8] it is still necessary to use a pulse of higher intensity to decrease the dephasing time. Figure 3 shows the dependence of this dephasing time on the pulse intensity a_0^2. It is shown that this dephasing time decreases when a_0^2 increases. Thus one can improve the acceleration rate by increasing the pulse intensity.

In addition, the dependence of the dephasing time on the initial energy of the particle γ_0 is illustrated in Fig.4. It is shown that, in the case of small γ_0, the dephasing time decreases when γ_0 increases. In the case of large γ_0, however, the dephasing time increases with γ_0.

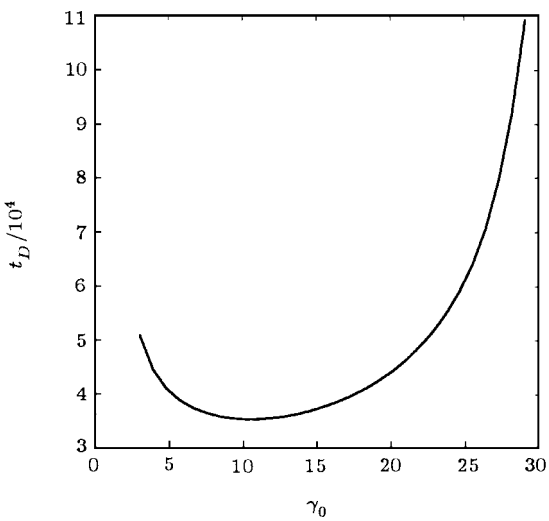


Fig.4. The dependence of the dephasing time of an accelerated positron on the Lorentz factor associated with the initial speed of the particle γ_0. The parameters are the same as in Fig.1.

In conclusion, the trajectory and dephasing time of a positron associated by a laser pulse of any length in an electron–ion plasma have been studied. It is shown that the positron can be accelerated to a high energy even when the pulse intensity is low. The dephasing time nonlinearly increases with k_pL. This dephasing time is proportional to k_pL only in the long-pulse limit $k_pL \gg 1$. This dephasing time decreases when the pulse intensity a_0^2 increases. These results may be important to the laser–particle acceleration concept and the physics of laser–particle interactions in positron and multi-component plasmas.[11]

References

[1] Kruer W L 1988 *The Physics of Laser Plasma Interactions* (New York: Addison-Wesley)

[2] Sprangle P, Esarey E and Krall J 1996 *Phys. Plasmas* **3** 2183

Wurtele J S (ed) 1993 *Advanced Accelerator Concepts, American Institute of Physics Conf. Proc.* No 279 (New York: American Institute of Physics)

[3] Du C G and Xu Z Z 1999 *Acta Phys. Sin.* **48** 78 (in Chinese)

[4] Zeng G H and Xu Z Z 1997 *Acta Phys. Sin.* **46** 2384 (in Chinese)

[5] Lai G J and Ji P Y 2000 *Acta Phys. Sin.* **49** 2399 (in Chinese)

[6] Ji P Y 2001 *Chin. Phys.* **10** 314

[7] McKinstrie C J and Startsev E A 1996 *Phys. Rev.* E **54** R1070

[8] Du C G and Xu Z Z 2000 *Phys. Plasmas* **7** 1582

[9] Sprangle P, Esarey E and Ting A 1990 *Phys. Rev. Lett.* **64** 2011

[10] Mckinstrie C J and Startsev E A 1997 *Phys. Rev.* E **56** 2130

[11] Greaves R G and Surko C M 1995 *Phys. Rev. lett.* **75** 3846

Surko C M, Leventhal M and Passner A 1989 *Phys. Rev. Lett.* **62** 901

Zank G P and Greaves R G 1995 *Phys. Rev* E **51** 6079

Berezhiani V I, Skarka V and Mahajan S 1993 *Phys. Rev.* E **48** R3252

Berezhiani V I, El-Ashry M Y and Mofiz V A 1994 *Phys. Rev.* E **50** 448