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Global optimization of the electron acceleration by a Gaussian beam

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For vacuum electron acceleration by a Gaussian beam, the energy gain of the electron is sensitively influenced by the initial parameters of the electron and the laser beam. It is necessary to find a group of optimized initial parameters to achieve the highest energy gain. The relationships between the initial parameters and the energy gains are investigated comprehensively by the global optimization method, and the global maximum as well as the local maxima is obtained. Via employing the global optimization of the initial parameters, more efficient electron acceleration has been achieved.

Introduction

Advances in the technology of intense laser fields [1–3] continue to motivate the research of vacuum laser acceleration in recent years [4–21]. Acceleration configurations employing the tightly focused Gaussian beam have received considerable attentions in the past decade [5–21]. A lot of works have been done to investigate the relationships between the energy gain and the initial parameters [5–7,21], and energy gains in Gev have also been obtained with PW laser and/or with assistance of magnetized plasma [22–24]. Among these works, the relationship between the energy gain and one of the initial parameters has been investigated comprehensively, meanwhile, the other parameters are fixed. To obtain the highest acceleration energy, it is necessary to optimize the choice of all initial parameters in electron acceleration simulation.

In this paper, we obtain the multiple local maxima and the global maximum of the energy gains for the electron acceleration by global optimization method (GOM). The local maxima with high-energy gains are gathered in the plane of the scaled injection energy γ_0 and the aimed distance s to the focus and are defined as a high-energy gain zone (HEGZ). The electron energy $\Xi_0 = \gamma_0 mc^2$, where m is the electron mass, and c is the light speed in vacuum. With a matched carrier-envelope-phase ψ_0, only the electrons with certain γ_0 and s values in the HEGZ can be trapped and accelerated to higher energies. Two groups of energy gain curves have been given. One group is the energy gain curves versus the initial parameters (γ_0, s and ψ_0), and the other group is the maximum energy gain curves with the global optimization of the initial parameters. By the global optimization, we can obtain high-energy gains within a wide range of the initial parameters. At last, the relationships between the energy gains and four initial parameters (γ_0, s, ψ_0 and θ_i) are studied. We can obtain high-energy gains in a range of the injection angle θ_i.

Global optimization method

The Gaussian laser beam polarizes along the x direction and propagates along the z axis. For simplicity, the terms of fifth order in the diffraction angle ε are included in the description of the associated fields, and the electromagnetic fields have been clearly expressed by Salamin et al. [6]. Electron dynamics in vacuum driven by a laser beam are governed by the relativistic equations of motion $d\boldsymbol{p}/dt = -e(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B})$, and $d\Xi/dt = -ec\boldsymbol{\beta} \cdot \boldsymbol{E}$, where the momentum $\boldsymbol{p} = \gamma mc\boldsymbol{\beta}$, the energy $\Xi = \gamma mc^2$, the Lorentz factor $\gamma = (1 - \boldsymbol{\beta}^2)^{-1/2}$, e is the electron charge, and $\boldsymbol{\beta}$ is the velocity scaled by the speed of the light in vacuum c. The peak field intensity I_0 is given in terms of the dimensionless parameter $q = eE_0/mc\omega$, where $I_0\lambda^2 \approx 1.375 \times 10^{18} q^2 (\mathrm{W/cm^2})(\mu\mathrm{m})^2$, λ is the laser wavelength, and ω is the laser frequency. The electron is injected at an injection angle θ_i from a point $(x_0,\ 0,\ z_0)$ towards another point on the beam axis a distance s away from the focus. The GOM is a high-efficiency method aiming to search the multiple

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local maxima and the global maximum of the objective function, which can include one or several input parameters [25].

The energy gain can be calculated by numerically solving the relativistic equations of motion. We take the relativistic equations of motion as the objective function. Without any loss of generality, the maximal laser intensity I_0 will be kept constant. A larger laser waist radius w_0 requires a higher laser power prior to focusing since I_0 is kept constant, therefore, it is of little practical significance and is fixed in advance [6]. The input parameters, including γ_0, s, ψ_0 and θ_i, are important to the energy gain.

Results and discussions

First of all, we study the energy gain with the optimization of three input parameters, γ_0, s and ψ_0. The injection angle θ_i is kept constant.

In Fig. 1(a), the local maxima of energy gains indicated by the points are shown under the three-dimensional coordinates system of γ_0, s and ψ_0. The global maximum of the energy gain is 181 MeV when γ_0, s and ψ_0 are 11.90, $-0.34z_r$, with the Rayleigh length $z_r = \pi w_0^2/\lambda$, and 278.64°, respectively. A HEGZ is shown within the black dashed line in Fig. 1(b). Energy gains of the majority of the points in this zone are higher than 140 MeV. With a matched ψ_0, only electrons with parameters of γ_0 and s in the HEGZ can be trapped and accelerated to high energies.

The HEGZ distributes on both sides of $s = 0$ axis and becomes wider in the $-x$ direction as γ_0 increases. For $\gamma_0 < 6$, because of the low injection energy, the electron injected towards the beam will be reflected and cannot be accelerated to high energy. As γ_0 increases, the electron will be trapped and accelerated to a relatively high energy. In Fig. 1(c) we give the trajectories of the points in the lower bound of the HEGZ. For an electron with larger s in the $-z$ direction, before gaining high energy, it passes through a longer way in the region with strong field near the focus. So, for an electron with larger s in the $-z$ direction, with a matched constant phase, lager injection energy is needed to decrease the phase delay between the electron and the phase of the Gaussian beam.

Figures 2(a)–(c) give the curves of the energy gain with γ_0, s and ψ_0, respectively. The other two parameters are fixed when we obtain the curve of the energy gain versus one of the three parameters. The curves alter if the values of the fixed parameters are changed. For comparison, in Figs. 2(d)–(f) we give the results of the local maximum of the energy gains achieved via the GOM with γ_0, s and ψ_0, respectively. Profiles of the points give the curves with the maximum values of the energy gains if the fixed parameters are changed.

In Figs. 2(a) and (d) we chose a pair of points, A and A', with $\gamma_0 = 7$. There is nearly no energy gain for the point A, and there is an energy gain as high as 133.33 MeV for the point A'. The differences between A and A' are that the point A' possesses matched initial parameters $s = 0.45z_r$ and $\psi_0 = 33.0°$. Similarly, in Fig. 2(b) and Fig. 2(e) we chose a pair of points, B and B', with $s = -0.7z_r$. There is nearly no energy gain for the point B, and there is an energy gain as high as 177.48 MeV for B'. The differences between B and B' are that the point B' possesses matched initial parameters $\gamma_0 = 12.22$ and $\psi_0 = 276.94°$. In Figs. 2(c) and (f), the point C' possessing matched initial parameters $\gamma_0 = 11.80$ and $s = -0.49z_r$ has an energy gain as high as 180.40 MeV. For the region of $\gamma_0 > 7.42$ in Fig. 2(d) and the region of $-1.75z_r < s < 0.8z_r$ in Fig. 2(e), the maximal energy gains are above 150 MeV. In Fig. 2(f), for the whole circle of ψ_0, we can obtain the maximum energy gains higher than 180 MeV. So, with global optimization of the initial parameters, we can obtain higher energy gains, and the results we obtain could be more instructive to the experiments. In principle, the global optimization of the initial parameters is an optimum scheme, and it might be employed to optimize other schemes or setups of electron acceleration as well. The concept of the high-energy gains zone(HEGZ) might also apply for other electron-acceleration theoretical and experimental setups.

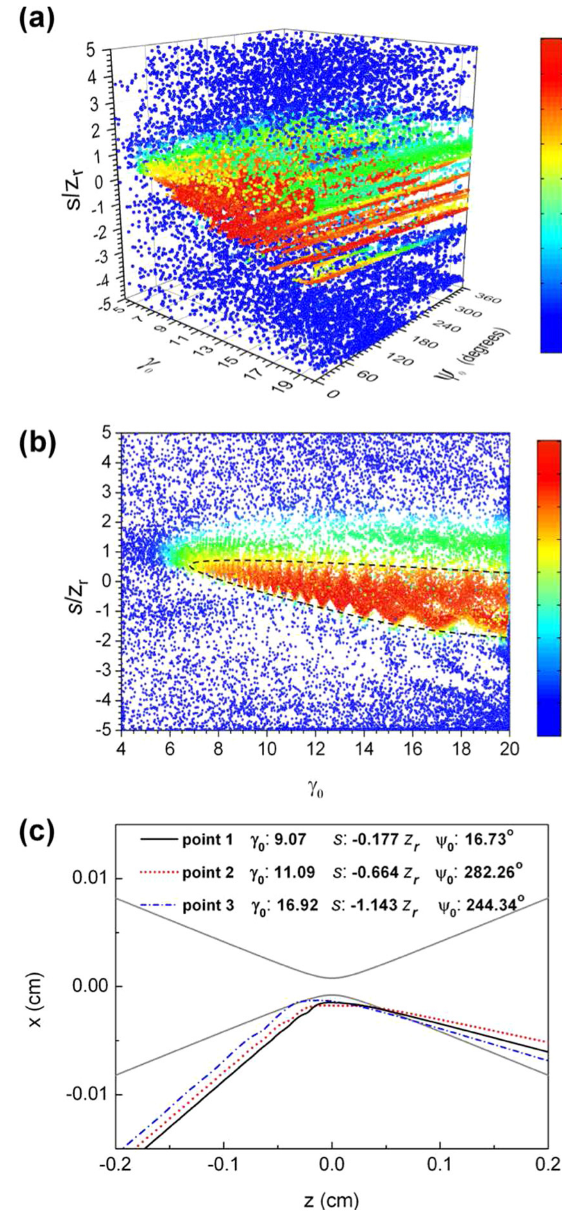

Fig. 1. (a) The scatter plot of the energy gain via the GOM. (b) is the side elevation of (a). Each point in (a) and (b) indicates a local maximum of the electron energy gain. The number of the points is 30,000. The bounds of γ_0, s and ψ_0 are $(4-20)$, $(-5z_r - 5z_r)$ and $(0\text{–}360)°$, respectively. The colors of the points indicate the values of the energy gains of the electrons. (c) Trajectories of the points in the lower bound of the HEGZ. Parameters used here are $q = 15$, $w_0 = 7.8\ \mu m$, $\theta_i = 5°$, the electron initial position is $[x_0 = -(s - z_0)\tan\theta_i,\ 0,\ z_0 = -3\ mm]$, the laser wavelength is $\lambda = 1\ \mu m$, and the full interaction time $\omega t = 1 \times 10^5$.

We also investigate the global optimization of four parameters, including γ_0, s, ψ_0 and θ_i, as shown in Fig. 3. The global maximum of the energy gain is 183.03 MeV when γ_0, s, ψ_0 and θ_i are 11.21, $-0.547z_r$, 27.81° and 5.91°, respectively. For the region of $3.6° < \theta_i < 8.1°$ the maximum of the energy gains is above 170 MeV, so, the selection of the injection angle is the crucial factor for the electron acceleration. We have investigated the global