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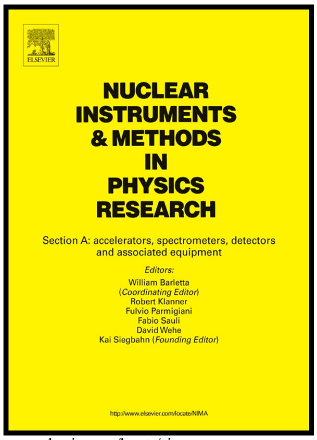

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Dynamics of Electron Bunches at the Laser-Plasma Interaction in the Bubble Regime

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Abstract

The multi-bunches self-injection, observed in laser-plasma accelerators in the bubble regime, affects the energy gain of electrons accelerated by laser wakefield. However, understanding of dynamics of the electron bunches formed at laser-plasma interaction may be challenging. We present here the results of fully relativistic electromagnetic particle-in-cell (PIC) simulation of laser wakefield acceleration driven by a short laser pulse in an underdense plasma. The trapping and acceleration of three witness electron bunches by the bubble-like structures were observed. It has been shown that with time the first two witness bunches turn into drivers and contribute to acceleration of the last witness bunch.

Keywords: laser wakefield acceleration, plasma wakefield acceleration, electron self-injection, electron bunch dynamics, bubble regime, particle-in-cell simulation

1. Introduction

Accelerating gradients in conventional accelerators are currently limited to approximately 100 MV/m [1], due to breakdown that occurs on the walls of the structure at the high electric field. To achieve high energy of the accelerated particles, it is necessary to build large-scale and expensive accelerators. Plasma-based accelerators have the ability to sustain accelerating gradients which are several orders of magnitude greater than those obtained in conventional accelerators [1, 2]. Due to the rapid development of laser technology [1–13] laser-plasma-based accelerators are of great interest now. At present, the intensity of the focused laser pulse exceeds the value of $10^{22}\ W/cm^2$. Over the past decade, successful experiments on laser wakefield acceleration of charged particles in the plasma have confirmed the relevance of this method of acceleration [2–7, 12] Evidently, the extremely large accelerating gradients in the laser plasma accelerators allow to reduce significantly the size and to cut the cost of accelerators, which are widely used in scientific research, material science, industry, medicine and biology. Another important advantage of the laser-plasma-based accelerators is that under certain conditions they can produce ultra-short electron bunches with high energy [3]. The quality of electron bunches produced in laser-plasma accelerators has been improving since first experiments, and the formation of bunches with small energy spread was demonstrated [14–16]. Electron self-injection in the nonlinear bubble wake, generated by an intense laser pulse in underdense plasma, has been studied by numerical simulations (see [8]).

The distance over which the electron bunch can be accelerated in a laser-plasma accelerator is limited by multiple factors, such as laser pulse depletion [1, 7], diffraction etc. In order to prolongate the acceleration length a plasma capillary can be used to guide the pulse [3, 17]. In current paper we explore another method to extend accelerating distance, which is transition from laser-driven to beam-driven scheme during acceleration [18–20]. This may happen after multiple bunches were injected in the accelerating bubble [20], and first injected bunches serve as beam-drivers to accelerate following witness bunches. In [19] via particle-in-cell simulations the self-mode-transition of a laser-driven electron acceleration from laser wakefield to plasma wakefield acceleration has been studied. Self-injected electron bunches play an important role in the interaction of intense laser pulse with the plasma. Multiple bunch trapping in the multiple cavities is the preferred condition for the wakefield scheme suggested in [20]. Radial dynamics of driver-bunches is important. In [22, 23] it has been shown that certain radial dynamics of electron driver-bunches can increase the intensity of the wakefield excitation.

The main aim of this work is to research by means of PIC simulations some aspects of the dynamics of multiple self-injected electron bunches, accelerated in wakefield bubbles, excited by the laser pulse in the plasma. As a result it has been observed that the energy of the last accelerated bunch is in two times larger in comparison with the maximum energy of the 2nd bunch.

2. Parameters of the numerical simulation

Fully relativistic electromagnetic two-dimensional simulation was carried out by the UMKA2D3V code [21]. The geometry of the considered problem, the parameters of the laser pulses and plasma are as follows: computational domain (x, y) has a rectangular shape with the following dimensions: $0 < x < 800\lambda$ and $0 < y < 50\lambda$, where λ is the laser pulse wavelength, $\lambda = 0.8\,\mu m$. The computational time interval is $\tau = 0.05\lambda/c$, where t_0 is the period of the laser pulse, $t_0 = 2\pi/\omega_0$ with ω_0

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