PIC SIMULATION OF ELECTRON ACCELERATION IN A WAKE FIELD GENERATED BY A HIGH-POWER LASER PULSE IN PLASMA

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Acceleration in a plasma wake field is simulated with 2D axially symmetric hybrid PIC code. The dependence of the parameters of the accelerated electrons on the laser pulse duration (at a given pulse energy) is studied and the range of pulse duration values for efficient electron acceleration is found.

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1. INTRODUCTION

When focused, petawatt laser pulses reach intensities up to I=10^{21} W/cm^2 and an electric field is E=10^{14} V/m [1]. An appealing application for these laser fields is the high-gradient acceleration of charged particles. Indeed, would it be possible to use the petawatt laser field efficiently, a TeV accelerator may have length of a few centimeters only. T. Tajima and J. Dawson [2] have proposed to convert the transverse laser field into the longitudinal one of a plasma wave. The terawatt laser pulses exert Gigabar pressures on plasma electrons, separating them from ions and generating electric wake fields in the order of TV/m. It appears that the most attractive for wake field acceleration are laser pulses shorter than the plasma wavelength.

Recently, impressive progress in the generation of short quasi-monoenergetic bunch of ultra relativistic electrons in laser plasma has been achieved [3]. One of the models [4,5], describing generation of quasi-monoenergetic bunch of ultra relativistic electrons, assumes that the generation is caused by transition to strongly nonlinear regime of laser-plasma interaction. The fast plasma wave breaking occurs at this regime. As a result, a periodic plasma wave mutates to the solitary ionic cavity – “bubble” which is free from plasma electrons and moving behind the laser pulse. The background plasma electrons can be trapped in the bubble. The external electron bunch and the trapped electrons can be accelerated up to very high energy.

Recent dramatic progress in laser pulse compression makes generation of ultrashort ultrahigh intensity laser pulses possible [6]. Therefore, it is important to study the effect of the laser pulse duration on the acceleration rate. The laser pulse energy is assumed to be unchanged.

2. ACCELERATION THEORY

The one-dimensional electron dynamics in electromagnetic fields is governed by Hamiltonian

$$H = \sqrt{1 + (P_x + A_x)^2} - \varphi , \qquad (1)$$

where P_x is the canonical electron momentum, A_x is the vector potential, φ is the scalar potential. We use dimensionless units, normalizing the time to $1/\omega_p$, the velocity to the speed of light c, the lengths to c/ω_p, the electromagnetic fields to $mc\omega_p/|e|$, the electron density n to the background density n_0, $\omega_p = \left(4\pi e^2 n_0 / m\right)^{1/2}$ is the plasma frequency, e and m are the electron charge and electron mass, respectively.

We consider the electron acceleration in the electromagnetic field of plasma wake generated by the laser pulse. The electromagnetic potentials are the function of $\xi = x - v_0 t$, where v_0 is the group velocity of the laser pulse. If potentials are the function of ξ then Hamiltonian (1) is not invariant of motion. We can change variables in the Hamiltonian from x and P_x to ξ and $P_\xi = P_x$ by a canonical transformation with generating function

$$S\left(P_\xi , x, t\right) = \left(x - v_0 t\right) P_\xi . \qquad (2)$$

The Hamiltonian in the new variables takes the form transformation

$$H = \sqrt{1 + \left[P_x + A_x(\xi)\right]^2} - \varphi(\xi) - v_0 P_x . \qquad (3)$$

Hamiltonian (3) does not depend on time and it is invariant of motion. It can be rewritten in the form

$$H = \gamma - \Phi(\xi) - v_0 p_x = const , \qquad (4)$$

where $\gamma = \sqrt{1 + p_x^2}$ is the relativistic gamma-factor, $\Phi(\xi) = \varphi - v_0 A_x \approx \varphi - A_x$ is the wake potential, $p_x = P_x + A_x$ is the kinetic momentum. The gauge

$$\varphi = -A_x \qquad (5)$$

is used.

The change in the electron energy in the ultrarelativistic limit $\gamma >> 1$, when the electron passes the distance corresponding the change in the wake potential $\Delta\Phi$, is

$$\Delta\gamma \approx 2\gamma_0^2 \Delta\Phi , \qquad (6)$$

where $\gamma_0 = \left(1 - v_0^2\right)^{-1/2}$ is the gamma-factor of the laser pulse. It is seen from Eq. (5) that the electron energy gain is proportional to the change in the wake potential and to the square of the gamma-factor of the laser pulse.

3. SIMULATION RESULTS

We simulate the bubble generation by two-dimensional relativistic particle-in-sell hybrid code in cylindrical geometry. The quasistatic approximation (the plasma wake is assumed to be slowly changed in the laser pulse frame) is used to accelerate computation. It

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follows from fully three-dimensional particle-in-cell simulations [7] that the laser pulse change is not significantly and the number of the trapped electrons is very small when the electrons stay in accelerating phase. In present simulation the dynamics of the laser pulse and the effect of the trapped electrons on the bubble are neglected.

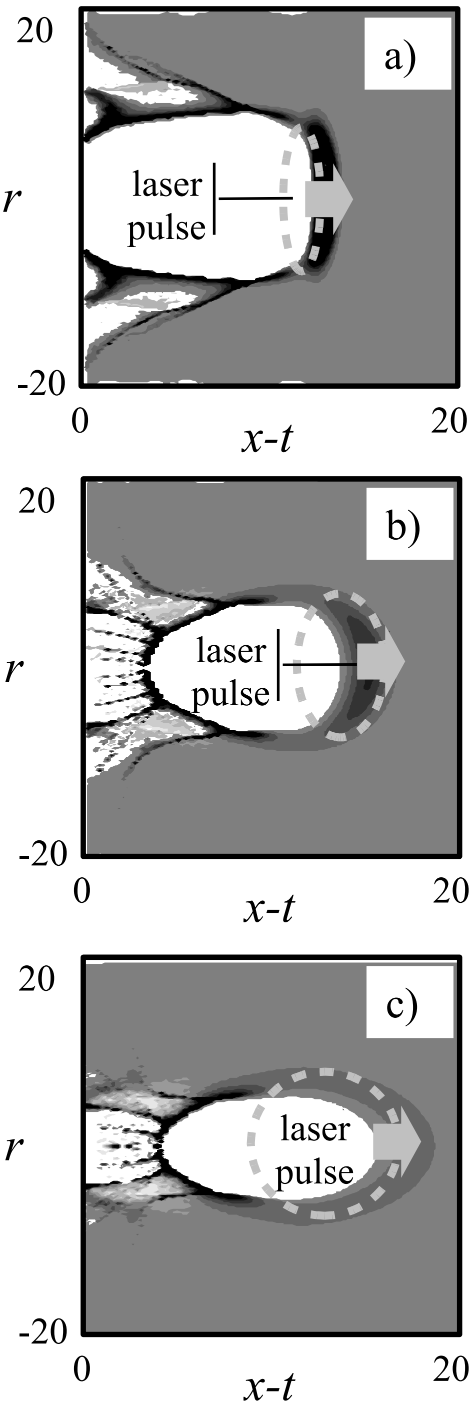

Fig.1. Density plot of bubble generation by the laser pulse with $L_l = 1$, $a_0 = 14.1$ *(a);* $L_l = 2$, $a_0 = 10$ *(b);* $L_l = 5$, $a_0 = 6.3$ *(c). It is assumed* $L_l a_0^2 = const$

The incident laser pulse is circularly polarized, has the Gaussian envelope $a = a_0 \exp\left(-r^2/r_l^2 - \xi^2/L_l^2\right)$, and the wavelength $\lambda = 0.82$ μm. The parameter of the laser pulse $r_l = 5$. The pulse propagates in plasma with the density $n_0 = 10^{19}$ cm^{-3}. This laser pulse generates the bubble. It is assumed $L_l a_0^2 = const$.

The density plot of bubble generated by the laser pulse is shown in Fig.1, where $L_l = 1$, $a_0 = 14.1$ (Fig.1,a); $L_l = 2$, $a_0 = 10$ (Fig.1,b); $L_l = 5$, $a_0 = 6.3$ (Fig.1,c). It is seen from Fig.1 that the shortest laser pulse generates the largest bubble. The simulation results is similar to that [4,5] obtained by fully three dimensional relativistic particle in cell code [8].

The wake potential peaks at the axis $r = 0$ ($\Phi = 0$ is assumed at infinity) [5]. Therefore, the maximal change in Φ is achieved if the electron moves along the axis $r = 0$. The wake potential of the bubbles at the axis $r = 0$ shown in Fig.1 is presented in Fig.2.

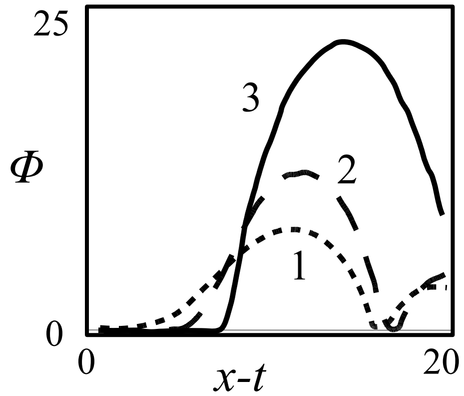

Fig.2. Φ *as function of* ξ *at the axis* $r = 0$ *for the laser pulse with* $L_l = 5$, $a_0 = 6.3$ *(line 1);* $L_l = 2$, $a_0 = 10$ *(line 2);* $L_l = 1$, $a_0 = 14.1$ *(line 3)*

It is seen from Fig.2 that the largest $\Delta\Phi$ is achieved for shortest laser pulse. Thus, the electron energy gain due to laser wake field acceleration is highest for the shortest laser pulse.

4. CONCLUSIONS

It conclusions we study the effect of the laser pulse duration on the laser wake field acceleration. The electron energy gain due to laser wake field acceleration is highest for the shortest laser pulse.

It can be explained as follows. Inside the bubble the electrons are absent while the ions are uniformly distributed. As a result the electric field is a linear function of ξ while the wake potential is proportional to ξ^2 [5]. The maximum of the accelerating field (in the bubble boundary) as well as the maximum of the wake potential (in the bubble center) are proportional to the bubble size. Therefore, high acceleration rate can be achieved in the large bubble.

The shorter is the laser pulse the larger radius, where the laser intensity is still high, and the bigger is the generated bubble (for given laser pulse energy). So, the wake field acceleration is more efficient with laser pulse as short as possible.

The ponderomotive force concept is used to study laser pulse duration effect. This concept is based on the averaging over laser field periods. Therefore, our results are valid not for very short pulses. The laser pulse should contain many laser periods. More accurate analysis is needed to study the interactions with ultrashort laser pulse with a few laser periods.

Our results are obtained under assumptions that the group velocity of the laser pulse does not depend on the pulse duration. However, further investigations are needed to study the effect of the pulse duration on the group velocity.

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МОДЕЛИРОВАНИЕ МЕТОДОМ ЧАСТИЦ В ЯЧЕЙКАХ УСКОРЕНИЯ ЭЛЕКТРОНОВ В КИЛЬВАТЕРНОЙ ВОЛНЕ, ГЕНЕРИРУЕМОЙ МОЩНЫМ ЛАЗЕРНЫМ ИМПУЛЬСОМ В ПЛАЗМЕ

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В настоящей работе процессы ускорения электронов в кильватерной волне моделируются с помощью двумерного аксиально-симметричного гибридного численного кода, использующего метод частиц в ячейках. На основании проведенных численных расчетов определены зависимости параметров ускоренных электронов от длительности лазерного импульса (при заданной его энергии) и найдены области оптимальных значений длительности импульса, отвечающие наиболее эффективной генерации ускоренных электронов.

МОДЕЛЮВАННЯ МЕТОДОМ ЧАСТОК В ОСЕРЕДКАХ ПРИСКОРЕННЯ ЕЛЕКТРОНІВ У КІЛЬВАТЕРНІЙ ХВИЛІ, ГЕНЕРИРУЕМОЙ ПОТУЖНИМ ЛАЗЕРНИМ ІМПУЛЬСОМ У ПЛАЗМІ

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У дійсній роботі процеси прискорення електронів у кільватерній хвилі моделюються за допомогою двовимірного аксіально-симетричного гібридного чисельного коду, що використає метод часток в осередках. На підставі проведених чисельних розрахунків визначені залежності параметрів прискорених електронів від тривалості лазерного імпульсу (при заданій його енергії) і знайдені області оптимальних значень тривалості імпульсу, що відповідають найбільш ефективної генерації прискорених електронів.