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TRANSFORMATION RATIO AT PLASMA WAKEFIELD EXCITATION BY LASER PULSE WITH RAMPING OF ITS INTENSITY ACCORDING TO COSINE

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Plasma wakefield excitation by shaped laser pulse, the intensity of which slowly increases up to its maximum in longitudinal direction according to cosine and sharply cuts off at the tail of the pulse, is numerically simulated with the purpose to increase the transformation ratio. The transformation ratio determines the maximum energy, to which electrons can be accelerated, and it is estimated by the ratio of the amplitude of the wake wave after the pulse and the amplitude of the plasma perturbation within the pulse. The length of the shaped laser pulse is selected to be longer than the plasma wavelength. The radius of the pulse is selected to be much smaller than its length. It is shown that for the considered type of laser pulse shaping with these parameters the transformation ratio can be much larger than the limiting value of two, which follows from Wilson theorem developed for particle bunch, and which corresponds to any symmetric particle distribution in a bunch.
KEY WORDS: plasma wakefield excitation, laser pulse, transformation ratio, numerical simulation, asymmetric distribution

КОЕФІЦІЄНТ ТРАНСФОРМАЦІЇ ПРИ ЗБУДЖЕННІ КІЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМІ ПРОФІЛЬОВАНИМ ЛАЗЕРНИМ ІМПУЛЬСОМ ІЗ НАРОСТАЮЧОЮ ЗА КОСИНУСОМ ІНТЕНСИВНІСТЮ

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Проведено 2d3v-числове моделювання збудження кільватерного поля у плазмі профільованим лазерним імпульсом із метою збільшення коефіцієнта трансформації. Інтенсивність лазерного імпульсу повільно наростає за косинусом у поздовжньому напрямку від переднього фронту до максимуму і потім різко обривається на задньому фронті. Коефіцієнт трансформації визначає максимальну енергію, до якої можуть бути прискорені електрони, і оцінюється відношенням амплітуди кільватерної хвилі після імпульсу і амплітуди збурення плазми всередині імпульсу. Довжина профільованого лазерного імпульсу вибрана таким чином, щоб бути більшою за плазмову довжину хвилі. Радіус імпульсу вибран так, щоб бути набагато меншим його довжини. Показано, що з такими параметрами та типом профілювання лазерного імпульсу, що розглядається, коефіцієнт трансформації значно перевищує граничне значення 2, що випливає з теореми Вільсона, яка розвинена для згустку заряджених частинок, і відповідає випадку збудження кільватерної хвилі у плазмі згустком із симетричним розподілом заряджених частинок.
КЛЮЧОВІ СЛОВА: збудження кільватерного поля у плазмі, лазерний імпульс, коефіцієнт трансформації, числове моделювання, асиметричний розподіл

КОЭФФИЦИЕНТ ТРАНСФОРМАЦИИ ПРИ ВОЗБУЖДЕНИИ КИЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМЕ ПРОФИЛИРОВАННЫМ ЛАЗЕРНЫМ ИМПУЛЬСОМ С НАРАСТАЮЩЕЙ ПО КОСИНУСУ ИНТЕНСИВНОСТЬЮ

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Проведено 2d3v-численное моделирование возбуждения кильватерного поля в плазме профилированным лазерным импульсом с целью увеличения коэффициента трансформации. Интенсивность лазерного импульса медленно нарастает по косинусу в продольном направлении от переднего фронта до максимума и затем резко обрывается у заднего фронта. Коэффициент трансформации определяет максимальную энергию, до которой могут быть ускорены электроны, и оценивается отношением амплитуды кильватерной волны после импульса и амплитуды возмущения плазмы внутри импульса. Длина профилированного лазерного импульса выбрана таким образом, чтобы быть больше плазменной длины волны. Радиус импульса выбран намного меньшим его длины. Показано, что для рассматриваемого типа профилирования лазерного импульса с такими параметрами, коэффициент трансформации значительно превышает предельное значение 2, следующее из теоремы Вильсона, развитой для сгустка заряженных частиц, и соответствующей случаю возбуждения кильватерной волны в плазме сгустком с симметричным распределением заряженных частиц.
КЛЮЧЕВЫЕ СЛОВА: возбуждение кильватерного поля в плазме, лазерный импульс, коэффициент трансформации, численное моделирование, асимметричное распределение

For many applications it is important to obtain the beams of high-energy accelerated particles. One of the most effective and promising method for formation of such beams is the acceleration of charged particles in wakefield excited in the plasma by an intense laser pulse[1 – 7]. However, if the laser pulse length does not exceed the length of the plasma wave, the level of plasma perturbations in the laser pulse region and after it (in the wake) are close. The latter leads to the dissipation of the laser pulse on a relatively small spatial interval [8]. In this paper we numerically

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examine the physical mechanism of increase of the product of the longitudinal accelerating electric wakefield and the length of the spatial interval in which this field is excited. This product is proportional to the transformation ratio. The transformation ratio can be estimated by the ratio of the amplitude of wake wave behind the laser pulse to the maximum plasma perturbation within the laser pulse. The transformation ratio is always less than or equals 2 for any symmetric particle bunch distribution [9]. We suppose that it is correct for laser pulse. The transformation ratio can be increased by altering the distribution of the driving bunch [9 – 11], the length of which is longer than the plasma wavelength. In papers [9, 10] mechanisms of increase of the transformation ratio are considered for the case of the plasma wakefield excitation by shaped electron bunch. The question arises about possibility of the transformation ratio increasing at the plasma wakefield excitation by shaped laser pulse. To examine the mechanism of plasma wakefield excitation by shaped laser pulse, the intensity of which slowly rises in longitudinal direction according to cosine and sharply cuts off at the tail of the pulse, we numerically simulate the laser pulse interaction with the plasma on the basis of kinetic model. We present the results of fully relativistic electromagnetic two dimensional particle – in – cell simulation, which was performed by a modified version of the UMKA2D3V code (Institute of Computational Technologies) [12 – 14]. The geometry of the considered problem, the parameters of the laser pulses and plasma are as follows. A computational domain (x, y) has a rectangular shape with the following dimensions: $0 < x < 300\lambda$ and $0 < y < 50\lambda$, λ is the laser pulse wavelength. The number of particles per cell is 8 and the total number of particles is $596{\cdot}10^4$. The simulation of each considered case carried out up to 300 laser periods. The period of the laser pulse $t_0 = 2\pi/\omega_0$, where ω_0 is the laser frequency. The s-polarized laser pulse enters the computation region which is filled with uniform plasma from the left boundary and is incident normally on the plasma. The plasma density $n_0 = 0.01016n_c$, where n_c is the critical plasma density. All considered laser pulses have an asymmetric distribution in which the pulse intensity in the longitudinal direction rises gradually according to cosine from the front of the pulse toward the peak and then falls off sharply. All pulses have a Gaussian profile in the transverse direction. The longitudinal dimensions of the laser pulses are selected to be longer than the plasma wavelength and are equal to 30λ at half maximum. The transverse dimensions of the pulses are selected to be less than the length of the pulse and FWHM (full width at half maximum) = 8λ. The considered laser pulse is fully entered in the plasma at the time $t = 75t_0$. The simulations were performed for normalized amplitudes of the laser vector potential, $b_0 = eE_{x0}/(m_e c\omega_0)$ = 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 21 where e is the electron charge, E_{x0} is the electric field amplitude, m_e is the electron mass, c is the speed of light. Below coordinates x and y, time t, electric field amplitude E_x and electron plasma density n_0 are given in dimensionless form in units of λ, $2\pi/\omega_0$, $m_e c\omega_0/(2\pi e)$, $m_e\omega_0^2/(16\pi^3 e^2)$, correspondingly.

The main aim of this work is the research of the possibility of an increasing the transformation ratio in the Laser Plasma Wakefield Acceleration scheme. For this purpose, a numerical simulation of the wakefield excitation in the plasma by a laser pulse with an asymmetric intensity distribution was carried out.

WAKEFIELD EXCITATION IN PLASMA BY SHAPED LASER PULSE

At first we consider the wakefield excitation by one shaped laser pulse with a low intensity $b_0 = 3$ and $b_0 = 4$. In the case of a laser pulse with an intensity $b_0 = 3$ after 120 laser periods ($t = 120t_0$) from the beginning of the interaction the transformation ratio is equal to 3.8. The transformation ratio reaches a maximum value at the time $t = 160t_0$ and it equals 4.3 (Fig. 1). The transformation ratio equals 5.9 at the time $t = 120t_0$ in the case of wakefield excitation in the plasma by a laser pulse with an intensity $b_0 = 4$ (Fig. 2). The bunch of accelerated electrons is formed after 160 laser periods (Fig.3) and destroyed after 280 laser periods. If an intensity of the laser pulse is $b_0 = 5$ then the transformation

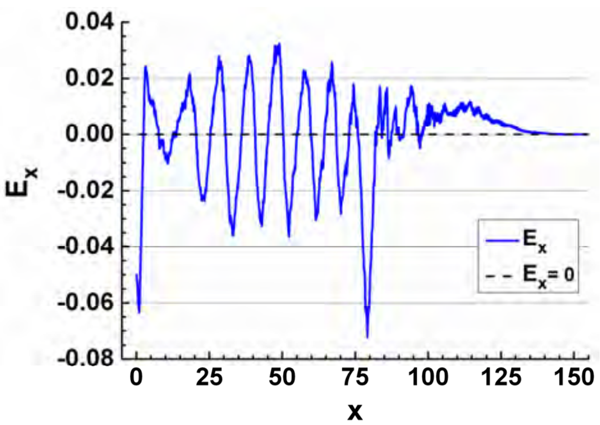

Fig.1. Longitudinal component of the wakefield E_x excited by one laser pulse with intensity $b_0 = 3$ at the time $t = 160t_0$

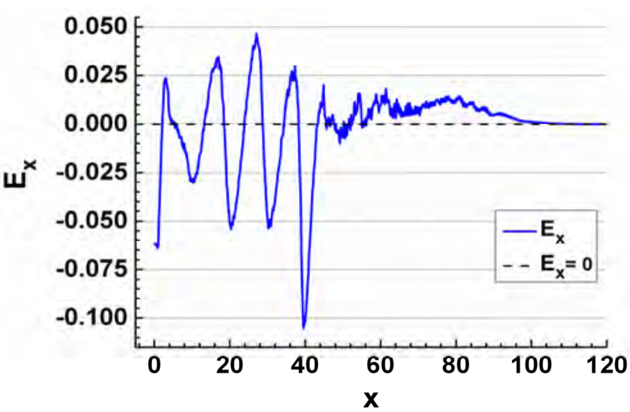

Fig.2. Longitudinal component of the wakefield E_x excited by one laser pulse with intensity $b_0 = 4$ at the time $t = 120t_0$

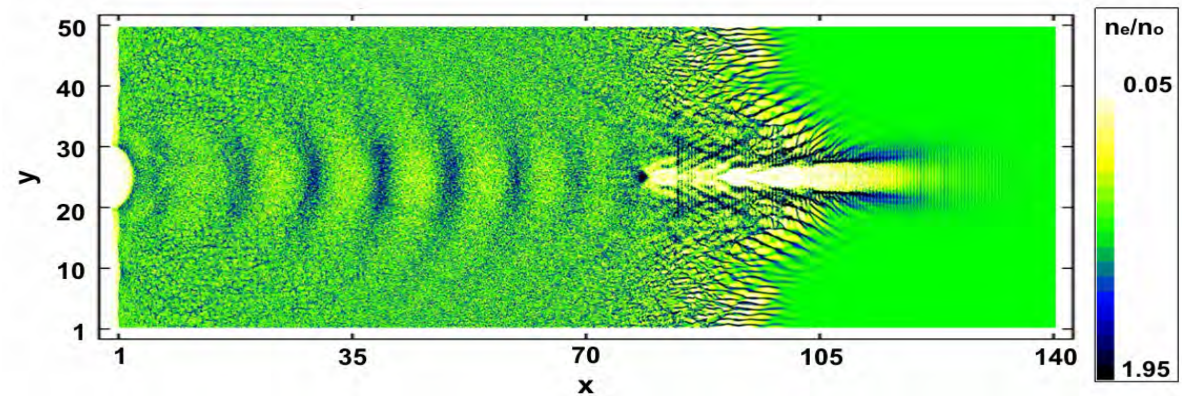

Fig.3. Wake perturbation of plasma electron density, excited by one laser pulse of low intensity $b_0 = 4$ at the time $t = 160t_0$

ratio reaches the value 6.26 at the time $t = 120t_0$ and the accelerated electron bunch, which was formed after 160 laser periods, is not destroyed up to $t = 300t_0$. When the plasma wakefield is excited by a laser pulse with an intensity $b_0 = 6$, the transformation ratio reaches a value 7 after 80 laser periods from the beginning of the interaction and is equal to 5.65 at the time $t = 120t_0$. In the case of wakefield excitation by the laser pulse with an intensity $b_0 = 7$ the transformation ratio is equal to 5.6 at the time $t = 80t_0$ and equals 6.3 after 120 laser periods (Fig.4). Also the formation of explicit bunch of accelerated electrons occurs after 160 laser periods for cases of laser pulses with an intensity $b_0 = 6$ and $b_0 = 7$ (Fig.5), at this time, the transformation ratios are equal to 3.4 and 5.2, respectively. The transformation ratio

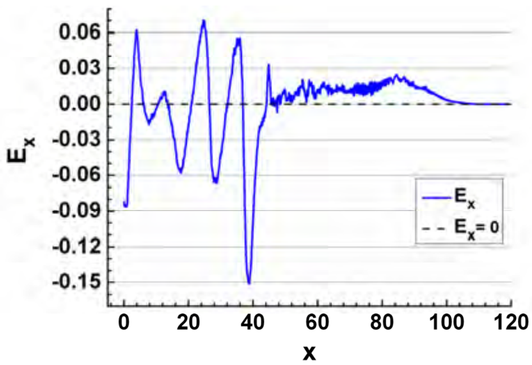

Fig.4. Longitudinal component of the wakefield E_x excited by one laser pulse with intensity $b_0 = 7$ at the time $t = 120t_0$

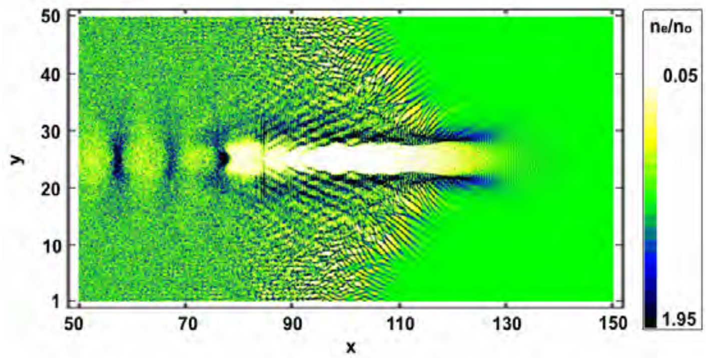

Fig.5. Wake perturbation of plasma electron density, excited by one laser pulse with intensity $b_0 = 7$ at the time $t = 160t_0$

equals 5.8 at the time $t = 80t_0$ and 7.4 at the time $t = 120t_0$ in the case of plasma wakefield excitation by a laser pulse with an intensity $b_0 = 8$. If the intensity of the laser pulse equals $b_0 = 9$ then the transformation ratio is equal to 6.2 after 80 laser periods and is equal to 7.9 after 120 laser periods. The transformation ratio reaches the value 7.6 at plasma wakefield excitation by the laser pulses with intensities $b_0 = 10$ (Fig.6) and $b_0 = 11$ (Fig.7). However, for these cases at the time of formation of the accelerated electron bunch ($t = 160t_0$) transformation ratio equals 4.4 and 5.5, correspondingly.

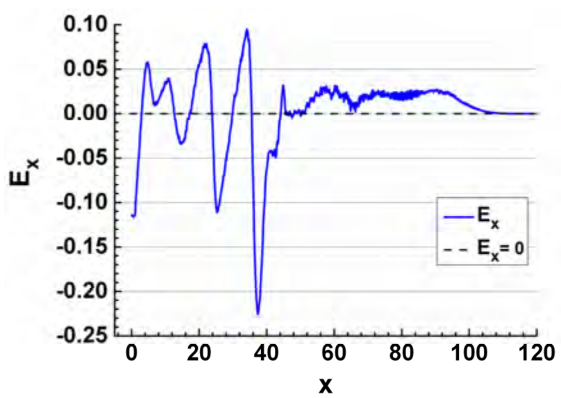

Fig.6. Longitudinal component of the wakefield E_x excited by one laser pulse with intensity $b_0 = 10$ at the time $t = 120t_0$

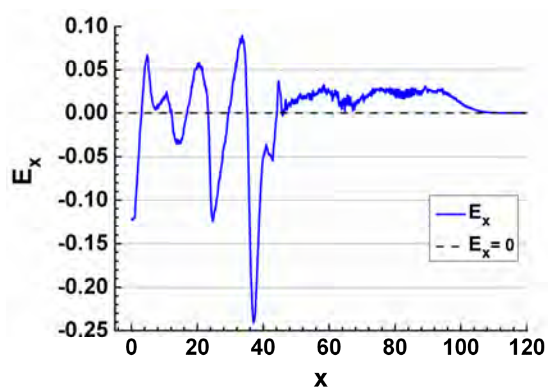

Fig.7. Longitudinal component of the wakefield E_x excited by one laser pulse with intensity $b_0 = 11$ at the time $t = 120t_0$

Now we consider wakefield excitation by a laser pulse of large intensity $b_0 = 12$. The transformation ratio is equal to 6 after 80 laser periods from the beginning of the interaction and reaches the maximum value 9 at the time $t = 120t_0$ (Fig. 8). The accelerated electron bunch is formed after 160 laser periods (Fig. 9), and is not destroyed up to $t = 300t_0$ (Fig. 10).

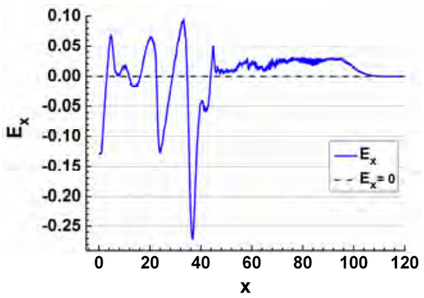

Fig.8. Longitudinal component of the wakefield E_x excited by one laser pulse of large intensity $b_0 = 12$ at the time $t = 120t_0$

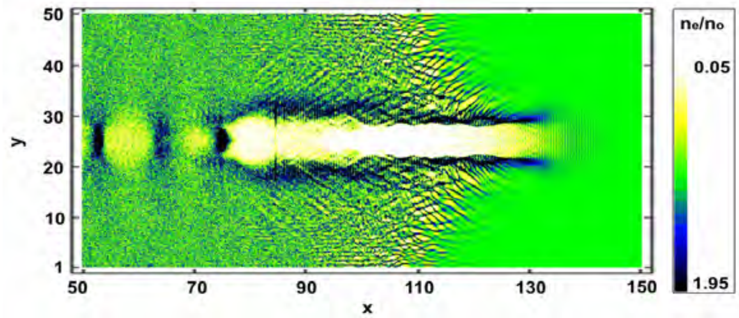

Fig.9. Wake perturbation of plasma electron density, excited by one laser pulse of large intensity $b_0 = 12$ at the time $t = 160t_0$

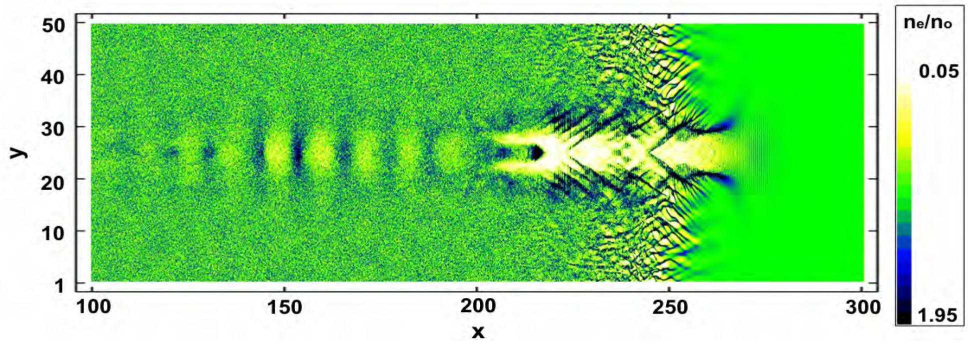

Fig.10. Wake perturbation of plasma electron density, excited by one laser pulse of large intensity $b_0 = 12$ at the time $t = 300t_0$

When the laser pulse of large intensity $b_0 = 21$ excites the wakefield in the plasma, the transformation ratio reaches the value 7.6 at the time $t = 120t_0$ (Fig. 11). In this case the formation of accelerated electron bunch occurs at the time $t = 180t_0$ (Fig. 12), in addition, we observe the formation of a sequence of quasi bunches of electrons (Fig. 13).

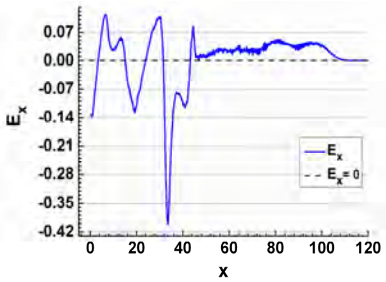

Fig.11. Longitudinal component of the wakefield E_x excited by one laser pulse of large intensity $b_0 = 21$ at the time $t = 120t_0$

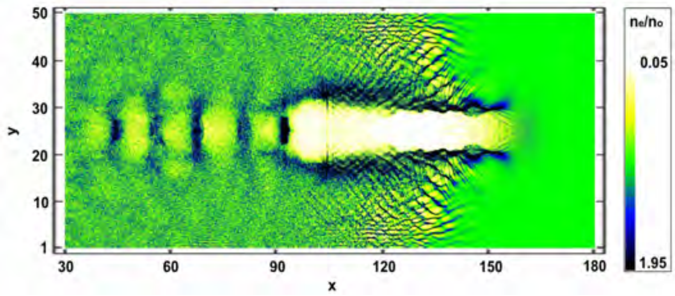

Fig.12. Wake perturbation of plasma electron density, excited by one laser pulse of large intensity $b_0 = 21$ at the time $t = 180t_0$

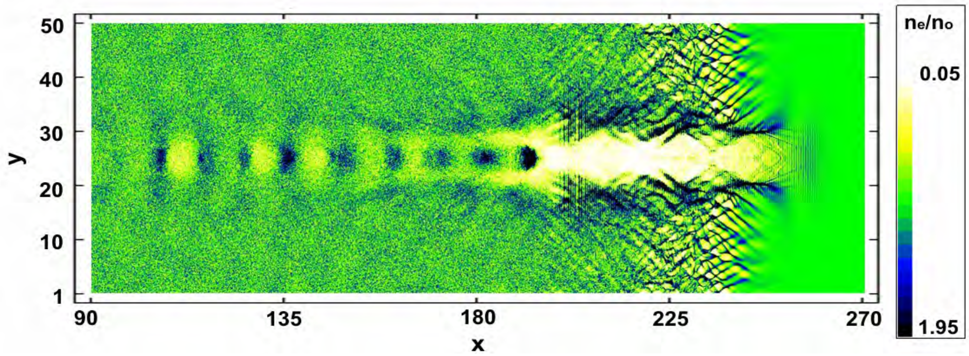

Fig.13. Wake perturbation of plasma electron density, excited by one laser pulse of large intensity $b_0 = 21$ at the time $t = 280t_0$

CONCLUSIONS

It is shown that for an asymmetric laser pulse distribution in which the pulse intensity rises gradually according to cosine from the front of the pulse toward the peak and then falls off sharply behind the peak, the transformation ratio can be much larger than two. The numerical simulation shows that, in order to reach the value of the transformation ratio larger than two, it is necessary that the length of the exciting pulse be greater than the plasma wavelength. In addition, the pulse radius must be much less than the pulse length. Finally, the numerical simulation of the laser plasma wakefield excitation indicates that for a given driving pulse, the bunch of accelerated electrons is formed.

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