SIMULATION OF LASER-PLASMA SYNCHROTRON RADIATION SOURCE BY A RELATIVISTIC HYBRID CODE

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A 2D axially symmetrical hybrid PIC code is developed to study transformation of the laser energy into x-rays in plasma. A quasistatic approximation (the plasma wake is assumed to be slowly changed in a laser pulse frame) is used to accelerate computation. A comparison with simulation results obtained with a fully 3D electromagnetic PIC code is performed.

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The generation and application of high-brightness X-rays is a fast developing area of science and technology [1]. Diverse demands of multidisciplinary research (fast process probing, biology object imaging, investigation of chemical reactions, etc.), as well as industrial and medical applications, drive the quest for intense and compact x-ray sources. Contemporary synchrotrons equipped with wiggler magnets are the most intense X-ray sources available now. High cost and large-scale significantly suppress the wide use of those sources.

It has been recently predicted that part of the cold plasma electrons can be trapped by plasma wake and accelerated up to very high energy [2, 3]. Later this mechanism, called Bubble acceleration, has been observed experimentally [4]. In Bubble regime, the plasma wake is the solitary plasma cavity (Bubble), which is free from cold plasma electrons, behind the laser pulse. The trapped plasma electrons or external electron beam is accelerated and simultaneously undergoes betatron oscillations in the Bubble. They efficiently radiate X-rays due to the betatron wiggling.

Therefore, the laser-plasma X-ray source combines the acceleration and wiggling processes. Moreover, it dramatically downsizes the radiation source. The laser-plasma acceleration system is very compact (several meters) compared with that of conventional synchrotrons or free electron lasers (hundreds meters) while the effective plasma wiggler is also small (several centimeters) compared to the magnet wiggler (tens meters).

Since the ultrahigh intensity laser-plasma interaction is strongly nonlinear phenomenon, which is rich in complex processes, the theoretical analysis of this phenomenon is very difficult. The numerical simulation is still very important and powerful tool for the interaction investigation as well as the interpretation of the laser-plasma experiments. The most efficient numerical method for simulation of laser-plasma interaction among various numerical schemes is particle in cell (PIC) method [5]. However, this method requires a lot of computer resources for simulation of full-scale experiments. Several quick PIC codes with so-called quasistatic approximation [6] have been developed [7, 8] to accelerate computer simulations. In this paper we present a quick PIC code with quasistatic approximation for simulation of laser-plasma synchrotron radiation.

Let a laser pulse propagates along x-axis, and two-dimensional axially symmetrical geometry is adopted. The ions are considered to be immobile. It is assumed in the framework of quasistatic approximation that the plasma quickly responds on laser field, and plasma fields are the functions of r and $\xi = x - ct$, where c is the speed of light. The characteristic times of the laser pulse and the bunch of the trapped electrons are much longer than the plasma response time. Fist, plasma response is calculated, then the evolution of the laser pulse and bunch is found in the plasma field distribution, and then again plasma response is calculated for the new shape of the bunch and the pulse.

Like in PIC codes plasma is modelled by macroparticles. Each plasma macroparticle is determined by a longitudinal coordinate, ξ, a transverse coordinate, r, momentum components, p_r and p_x, a mass m, and a charge q. All particle parameters are functions of ξ, thus, ξ plays a role of time. Unlike PIC technique, the plasma macroparticles are the Langragian particles, which move along trajectory line determined by the initial value of transversal coordinate, r_0. Information propagates from the head of laser pulse ($\zeta = 0$) to negative values of ζ within the light speed frame. Accordingly, we integrate equation of motion slice by slice from $\zeta = 0$ to $\zeta = -L$, where L is the length of the simulation region. The plasma is assumed to be cold that is $p_r = 0$ and $p_x = 0$ at $\zeta = 0$.

Introducing a plasma wake potential $\Phi = \varphi - A_x$, the equations for the wake potentials and magnetic filed in quasistatic approximations in axially symmetrical geometry (no dependence on azimuthal angle θ) are

$$\Delta_\perp \Phi = j_x - \rho , \tag{1}$$

$$\frac{1}{r}\frac{\partial}{\partial r} r B_\theta = \frac{\partial^2}{\partial \xi^2}\Phi + j_x , , \tag{2}$$

where the gauge $\varphi = -A_x$ is used, φ is the scalar potential, $\mathbf{A}$ is the vector potential, B_θ is the azimuthal magnetic filed, $\mathbf{j}$ is the density of electron current, ρ is the electron density. We use dimensionless units, normalizing the time by $1/\omega_p$, the velocity by the speed of light c, the lengths by c/ω_p, the electromagnetic fields by $-mc\omega_p/q$, the electron density n by the background

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density n_0, $\omega_p = \left(4\pi q^2 n_0 / m\right)^{1/2}$ is the plasma frequency. The obtained equations are similar to that in Ref. [7].

In quasistatic approximations

$$H = \gamma - p_x + \Phi = 1, \qquad (3)$$

is the integral of motion [3], where $\gamma = \left(1 + p_x^2 + p_r^2 + \left\langle a^2 \right\rangle\right)^{1/2}$ is the relativistic gamma-factor of the electron, $\left\langle a^2 \right\rangle$ is the ponderomotive potential of the laser pulse [7]. p_x and γ can be found as functions of ξ, r, p_r and a_l^2 from Eq. (3). The equations of plasma macroparticle motion are [7]

$$\frac{dp_r}{d\xi} = \frac{1}{1+\Phi}\left(\gamma \frac{\partial \Phi}{\partial r} - \frac{1}{2}\frac{\partial \left\langle a^2 \right\rangle}{\partial r}\right) - B_\theta , \qquad (4)$$

$$\frac{dr}{d\xi} = \frac{p_r}{1+\Phi} . \qquad (5)$$

Making the use of Eqs. (4) and (5), the current density and the electron density can be found by the way adopted in PIC methods [5]. Eqs. (1)-(5) are solved using a finite difference scheme, in which a grid is set up in both the axial coordinate ξ and the radial coordinate r.

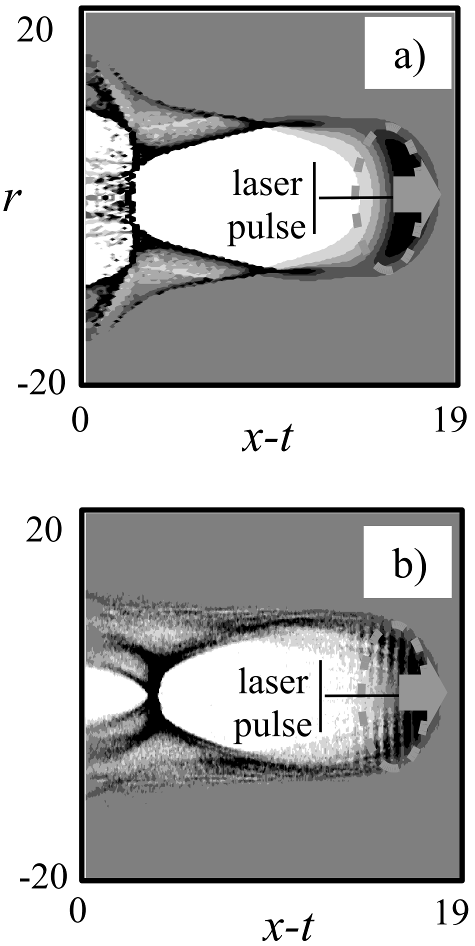
The evolution of the laser fired is described by a parabolic equation (see in more detail Ref. [7]). A particle is considered to be trapped if longitudinal velocity of the particle is more than the bubble velocity $v_x > v_b$. The bubble velocity is calculated from the solution of equation for dynamics of the laser pulse. The dynamics of the particle trapped is described by equations

$$\frac{d\mathbf{p}}{dt} = \frac{q}{v-1}\left(\mathbf{E} + [\mathbf{v} \times \mathbf{B}]\right) + \mathbf{F}_{rad} , \qquad (6)$$

$$\frac{dr}{dt} = \frac{p_r}{\gamma}, \quad \frac{d\xi}{dt} = \frac{p_x}{\gamma} - v_b , \qquad (7)$$

where $\mathbf{F}_{rad}$ is the radiation reaction force [9]. The emission of electromagnetic fields by the trapped electrons is included into the code. The emitted radiation exerts recoil on the electron. The recoil force is also included. The radiation generation and recoil force are taken into account only for the trapped particle because they are only the highly relativistic particles given the main contribution into the radiated power. The reversal effect of trapped electrons on the plasma wake is taken into account as well.

We verified that the code developed gave the results, which were similar to that obtained by a fully 3D relativistic PIC code [5] in a strongly nonlinear regime. For simplicity, we consider the laser-plasma interaction neglecting the trapped particle and the evolution of laser pulse. This regime corresponds to the beginning of the interaction when a laser pulse changes insignificantly and number of the particles trapped is small. 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 parameters of the laser pulse are $r_l = 5$, $L_l = 2$, $a_0 = 10$. The pulse propagates in plasma with the density $n_0 = 10^{-19}$ cm^{-3}. The result of simulation is shown in Fig.1. It presents the density plot of the short, ultrahigh intensity laser pulse propagating in plasma, calculated by (a) the axially symmetrical 2D PIC hybrid code; (b) the fully 3D PIC code [5]. The darker is gray color, the higher is the electron density. It is seen from Fig.1 that the results obtained are in a good



agreement with the simulation results obtained by the fully 3D PIC code.

Fig.1. The density plot of short, ultrahigh intensity laser pulse propagating in plasma, calculated by (a) axially symmetrical 2D PIC hybrid (b) by fully 3D PIC code [5]. The darker is gray color, the higher is electron density

To simulate the X-ray generation we assume that the electron radiation spectrum is synchrotron like at any given moment of time. The spectrum integrated over a solid angle is defined by a universal function $S(\omega/\omega_c)$, where $S(x) = x\int_x^\infty K_{5/3}(y)dy$, ω_c is the critical frequency [9]. The critical frequency is given by the relation $\omega_c = (3/2)\gamma^2 |F_\perp|$; $F_\perp$ is the transversal to the electron momentum force. In our code, we follow trajectories of each electron and calculate the emission during the interaction.

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We simulate the X-ray emission from an external electron bunch with $\gamma = 10^3$, length $L_b = 40$, radius $r_b = 3$ with total charge $Q_b = 4$ nC, propagating in the bubble. The photon flux, F_X, (photon number per second in 0.1% bandwidth) from the bunch as a function of the photon energy is shown in Fig.2. The photon flux obtained is in a good agreement with estimations for the flux [1].

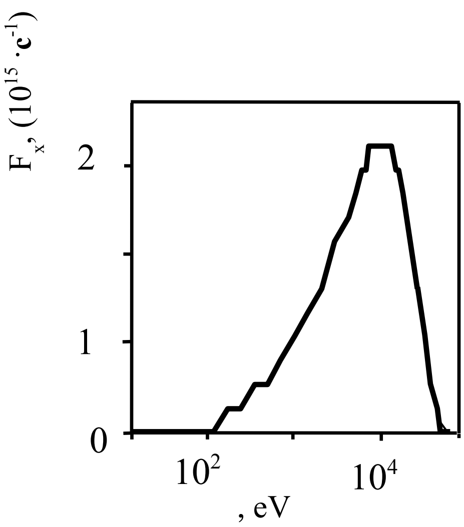

Fig.2. The photon flux as function of the photon energy

CONCLUSION

The X-ray generation from a relativistic electron bunch propagating in the laser plasma is modeled by the 2D axially symmetrical hybrid PIC code. The quasistatic approximation is used to accelerate the computation. The code includes the emission of electromagnetic field by the relativistic electrons. The emitted radiation exerts recoil on the electron and the recoil force is included into the code. The results obtained are in a good agreement with that obtained by the fully 3D electromagnetic PIC [5].

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МОДЕЛИРОВАНИЕ ИСТОЧНИКА СИНХРОТРОННОГО ИЗЛУЧЕНИЯ, ОСНОВАННОГО НА ПРЕОБРАЗОВАНИИ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ В ПЛАЗМЕ, ДВУХМЕРНЫМ РЕЛЯТИВИСТСКИМ ГИБРИДНЫМ КОДОМ

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Для моделирования трансформации лазерного излучения разработан двухмерный аксиально-симметричный гибридный численный код, использующий метод частиц в ячейках. В качестве упрощающего предположения использовалось "квазистатическое" приближение (плазменная волна медленно меняется в системе отсчета, связанной с лазерным импульсом). Проведено сравнение с результатами моделирования с помощью полностью трехмерного, электромагнитного кода, использующего метод частиц в ячейках.

МОДЕЛЮВАННЯ ДЖЕРЕЛА СИНХРОТРОННОГО ВИПРОМІНЮВАННЯ, ЗАСНОВАНОГО НА ПЕРЕТВОРЕННІ ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ В ПЛАЗМІ, ДВОМІРНИМ РЕЛЯТИВІСТСЬКИМ ГІБРИДНИМ КОДОМ

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Для моделювання трансформації лазерного випромінювання розроблено двомірний аксіально-симетричний гібридний чисельний код, що використовує метод часток в осередках. Як припущення, що спрощує, використано "квазістатичне" наближення (плазмова хвиля повільно міняється в системі відліку, пов'язаної з лазерним імпульсом). Проведено порівняння з результатами моделювання за допомогою повністю тривимірного, електромагнітного коду, що використає метод часток в осередках.

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