SYNCHROTRON RADIATION LOSSES IN LASER-PLASMA ACCELERATORS

I.Yu. Kostyukov[1], E.N. Nerush[2], A. Pukhov[3]
[1]Institute of Applied Physics RAS, Nizhny Novgorod, 603950, Russia
[2]Nizhny Novgorod University, Nizhny Novgorod, 603950, Russia
[3]Heinrich-Heine-Universitat Dusseldorf, 40225, Dusseldorf, Germany
E-mail: kost@appl.sci-nnov.ru

Like in conventional accelerators, a synchrotron radiation can significantly suppress an acceleration in a bubble. The dynamics of accelerating electron in the bubble with consideration of the synchrotron radiation reaction force is studied. The total suppression of electron acceleration by the radiation losses is discussed.

PACS: 41.60.Ap, 52.40.Mj

1. INTRODUCTION

A mechanism, based on the acceleration of charged particles in strongly nonlinear plasma wave generated by an ultrahigh intensity short laser pulse, is one of the perspective candidates for the accelerators of the future. The low acceleration rate leads to the huge-scale acceleration facility, which poses a serious limit for conventional accelerators to increase the energy of the accelerated particle, while the laser-plasma acceleration scheme can provide much higher acceleration gradient. Recently, an impressive progress in the generation of short quasi-monoenergetic bunch of ultra relativistic electrons in laser plasma was achieved [1].

One of the models [2], describing the generation of a quasi-monoenergetic bunch of ultra relativistic electrons, assumes that the generation is caused by a transition to a strongly nonlinear regime of laser-plasma interaction. 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 as well as external electron bunch can be trapped in the bubble and can be accelerated up to very high energy. Acceleration is accompanied by the electron betatron oscillations because of the ultrahigh intense transversal field in the bubble. As a result of betatron wiggling the trapped electrons radiate electromagnetic waves. The radiation spectrum of the ultra relativistic electrons lies in the X-ray range because of the Doppler effect [3]. Like in conventional accelerators, the radiation losses can significantly suppress the acceleration in the bubble.

2. ELECTRON DYNAMICS UNDER ACTION OF RADIATION REACTION FORCE

The space-time distribution of the electromagnetic fields in the bubble can be approximated by a linear function of the coordinates and time [4]

$$E_x = (x-t)/2,\ E_y = -B_z = y/4,\ E_z = B_y = z/4, \quad (1)$$

where 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 $mc\omega_p/e$, and 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 electron plasma frequency, e and m are the electron charge and electron mass, respectively. It is assumed that laser pulse propagates along x-axis. Then, the Lorentz force acting on a relativistic electron with $v_x \approx 1$ inside the cavity is

$$F_x = -(x-t)/2,\ F_y = -y/2,\ F_z = -z/2. \quad (2)$$

We assume that the electron trajectory is confined in xy plane; the electron is slowly accelerated in x direction and $p_x >> p_y >> 1$, where p_x is the longitudinal momentum of the electron and p_y is the transversal momentum of the electron. In this case we can neglect the action of the longitudinal force ($E_x = 0$). Thus, the electron trajectory is given by the relation [5]

$$x(t) = \left(1 - \frac{\nu^2}{4}\right) t - \frac{r_0\nu}{8}\sin(2\omega_b t),\quad y(t) = r_0 \sin(\omega_b t), \quad (3)$$

where $\omega_b = 1/\sqrt{2\gamma}$ is the betatron frequency of the electron oscillations in the bubble, $\nu = p_y/p_x = r_0/\sqrt{2\gamma}$, γ is the relativistic electron gamma-factor, r_0 is the amplitude of the electron betatron oscillations. The electron trajectory in the ion channel is similar to the trajectory of an electron moving in the homogeneous magnetic field. In the latter case, the electron trajectory is spiral-like. As a result, the radiation spectrum of the relativistic electron undergoing betatron oscillations in the ion channel is close to the spectrum of synchrotron radiation [5].

The relativistic equations of the electron motion with radiation reaction force is given by the relation [6]

$$\frac{du^i}{ds} = F^{ik}u_k + \mu g^i, \quad (4)$$

$$g^i = \frac{\partial F^{ik}}{\partial x^l} u_k u^l - F^{il}F_{kl}u^k + \left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i, \quad (5)$$

where F_{ik} is the tensor of the electromagnetic field, u_k is the 4-velocity of the electron, $\mu = 2e^2\omega_p/(3mc^3)$. Substituting Eqs.(1) and (3) into Eq.(4), we can calculate the radiation reaction force on the relativistic electron undergoing betatron oscillations in the ion channel. As a result, the equation describing the evolution of the electron energy can be derived

$$\frac{d\gamma}{dt} \approx -\frac{1}{8}\mu r_0^2\gamma^2. \quad (6)$$

The energy loss of an electron per unit distance is

$$Q = 1.5\times 10^{-45}\left(n_e\left[cm^{-3}\right]\ r_0[\mu m]\ \gamma \right)^2 \frac{MeV}{cm}. \quad (7)$$

It is seen from Eq.(7) that the radiated power is proportional to the square of gamma-factor.

It is known [7] that the longitudinal velocity is invariant of motion for the electron dynamics in homogeneous magnetic field under action of the synchrotron radiation reaction force. It is not the case for the electron undergoing betatron oscillations. Making of use Eq.(4), the equation for longitudinal velocity of the electron can be derived

$$\frac{dv_x}{dt} \propto \mu r_0^2 \frac{1}{\gamma}. \quad (8)$$

It follows from Eq.(7) that the characteristic time, during which the longitudinal velocity is significantly changed, is much more than the time, during which the electron energy is converted into the radiation. So, we can consider the longitudinal velocity of the electron as invariant of motion, too. Moreover, the conservation of the longitudinal velocity becomes more accurate as the electron energy increases. Making of use the invariant $v_x \approx const$, the final momentum components of the electron can be predicted in the limit $t \to \infty$. Let at $t = 0$ the electron momentum be $p_x = p_0$ and $p_y = p_1$, then $\gamma = \left(1 + p_0^2 + p_1^2\right)^{1/2}$, $v_x = p_x/\gamma = p_0/\left(1 + p_0^2 + p_1^2\right)^{1./2}$. Thus, the final momentum components of the electron are $p_x = p_0/\left(1 + p_1^2\right)^{1/2}$ and $p_y = 0$ at $t \to \infty$, that is the transversal energy of the electron is converted into the radiation energy.

3. NUMERICAL SIMULATION RESULTS

Equations of motion (4) with fields (2) are numerically integrated for the electron with the initial conditions $p_x = 10^5$, $p_y = 0$, $x_0 = -8$, $r_0 = 2$ at $t = 0$ and plasma density $n_0 = 10^{19}$ cm^{-3}.

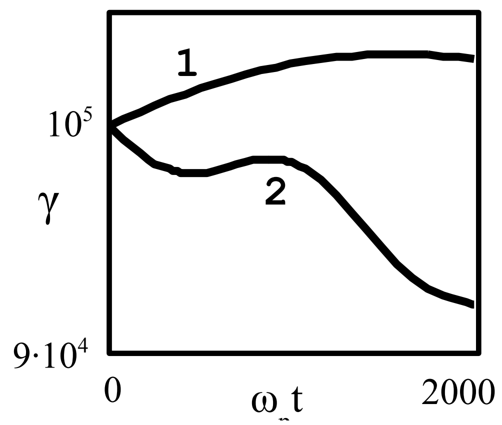

Fig.1. γ as a function of time without radiation reaction force (line 1) and with radiation reaction force (line 2)

The electron energy as a function of time with and without consideration of a photon recoil is shown in Fig.1. It is seen from Fig.1 that the electron is accelerated in the bubble fields if radiation reaction is not taken into account while it is significantly decelerated if the effect of radiation is taken into account. Therefore, the radiation reaction force can strongly suppress the acceleration of the ultra relativistic electrons in the bubble.

The effect of the radiation on electron acceleration is also studied by a two-dimensional relativistic particle-in-cell 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 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 in the code.

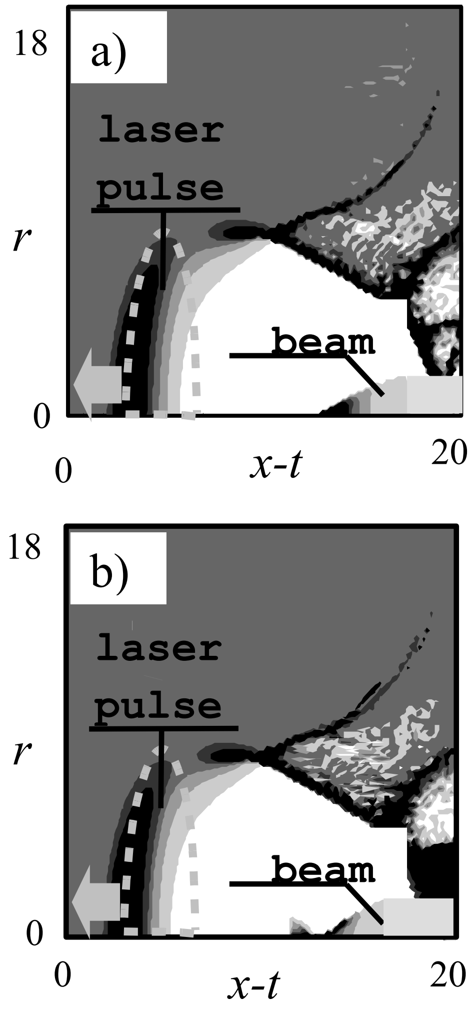

Fig.2. Density plot of electron beam acceleration in the bubble with radiation reaction force (a) and without of that (b). The darker is the gray color, the higher is the electron density

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}. This laser pulse generates the bubble. We simulate the X-ray emission from the external electron bunch with $\gamma = 10^4$, radius $r_b = 2$ and density $n_b = 10^{-17}$ cm^{-3}, propagating in the bubble. The density plot is shown in Fig.2 with consideration of the radiation reaction force (Fig.2,a) and without consideration of that (Fig.2,b). The bunch electron distribution function is shown in Fig.3. The bunch is monoenergetic at the beginning of interaction (line 1 in Fig.3). The radiation reaction force decelerates the part of the bunch electrons with large amplitude of the betatron oscillations, while the electrons with small amplitude are accelerated by the longitudinal electric field (see line 1 in Fig.3). The bunch electrons are accelerated if photon recoil is not taken into account (line 3 in Fig.3). The bubble forces focus the bunch (Fig.2,a.). The deceleration by the radiation losses leads to the bunch focusing at earlier moment of time (see Fig.2,b.) than that without radiation reaction.

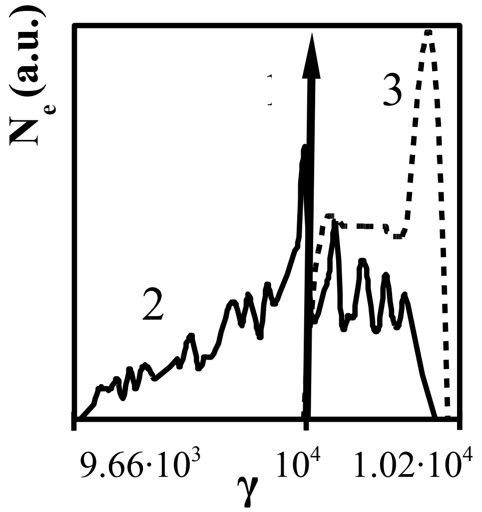

Fig.3. The electron distribution function of the bunch in the bubble: initial distribution function (1), final distribution function with radiation reaction force (2) and without radiation reaction force (3)

4. CONCLUSIONS

It follows from Eq.(6) that the radiation reaction force increases as square of the electron energy while the accelerating force determined by the longitudinal electric field does not depend on the electron energy. Therefore, the radiation reaction can totally suppress the electron acceleration in the bubble. The energy threshold can be estimated from the balance of the radiation reaction force and the accelerating force.

This work has been supported by Russian Foundation for Basic Research (Grant No. 04-02-16684).

REFERENCES

1. T. Catsoleas. Electrons hang ten on laser wake // *Nature.* 2004, v.431, №9, p.515-516.
2. A. Pukhov and J. Meyer-ter-Vehn. Laser wake field acceleration: the highly non-linear broken-wave regime // *Applied Physics.* 2002, v.B74, №3, p.355-361.
3. S. Kiselev, A. Pukhov, and I. Kostyukov. X-ray generation in strongly nonlinear plasma waves // *Phys. Rev. Lett.* 2004, №13, p.135004-1-135004-4.
4. I. Kostyukov, A. Pukhov, and S. Kiselev. X-ray generation in an ion channel // *Physics of Plasmas.* 2003, №10, p.4818-4828.
5. I. Kostyukov, A. Pukhov, and S. Kiselev. Phenomenological theory of laser-plasma interaction in bubble regime // *Physics of Plasmas.* 2004, №14, p.5256-5264.
6. L.D. Landau and E.M. Lifshitz. *The classical theory of field.* M.: "Nauka", 1988, p.268-277.
7. V.L. Ginzburg. *Theoretical physics and astrophysics*. M.: "Nauka", 1988, p.58-74.

ПОТЕРИ, СВЯЗАННЫЕ С СИНХРОТРОННЫМ ИЗЛУЧЕНИЕМ, В ПЛАЗМЕННЫХ УСКОРИТЕЛЯХ

И.Ю. Костюков, Е.Н. Неруш, А. Пухов

Как и в случае традиционных ускорителей, потери, связанные с синхротронным излучением, могут существенно снизить эффективность ускорения. В работе исследована динамика электрона в ионной полости с учетом действия силы реакции синхротронного излучения. Обсуждается полное подавление ускорения электронов радиационными потерями.

ВТРАТИ, ПОВ'ЯЗАНІ ІЗ СИНХРОТРОННИМ ВИПРОМІНЮВАННЯМ, У ПЛАЗМОВИХ ПРИСКОРЮВАЧАХ

І.Ю. Костюков, Є.Н. Неруш, А. Пухов

Як й у випадку традиційних прискорювачів, втрати, пов'язані із синхротронним випромінюванням, можуть істотно знизити ефективність прискорення. У роботі досліджена динаміка електрона в іонній порожнині з урахуванням дії сили реакції синхротронного випромінювання. Обговорюється повне придушення прискорення електронів радіаційними втратами.