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Original Article

Electron Acceleration in the Inverse Free-Electron Laser with A Tapered Helical Magnetic Wiggler

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Abstract

Electron acceleration by a laser pulse having Gaussian and temporal profile of intensity is studied numerically in the presence of helical magnetic wiggler in vacuum. For a specific value of k/k_w, the inverse free-electron laser resonance condition is satisfied and energy gained by the electron increases. It can be maintained for longer duration for a suitably tapered wiggler period and the electron can gain much higher energy.

Key words: Electron, Acceleration, Laser

INTRODUCTION

Inverse free-electron laser was first described in the 1970s and as a particle accelerator with high gradients is proposed for future. In 1990, the experiments in this fieldwere started with making the first inverse free-electron laser at the University of California. These experiments were followed by using CO_2 laser pulse with a power of about GW and nanosecond pulse durability in national laboratory of Brookhaven. STELLA experiment was also performed in the same laboratory and two inverse free-electron laser were used in this experiment; the first IFEL transforms the electron band into a microband in order to accelerate in the second IFEL.In inverse free-electron laser, the electron beam and the laser beam within the magnetic field known as the Wiggler in vacuum are propagated. Wiggler causes the electron pathway to fluctuate in a transverse direction. However, if the electric field of laser pulse has a component in the direction of electron, the field can accelerate electron or be accelerated by electronaccording to the sign of the electric fieldof laser pulse(the relative phase to the electron). In order to obtain and exchange the energy during the Wiggler, the resonance condition in the free-electron laser $\gamma^2 = (1+K^2)\dfrac{\lambda_w}{2\lambda_l}$ should be satisfied. Where λ_l , λ_w , $K = eB_w k_w / 2\pi mc$ are the laser wavelength, Wiggler wavelength, and Wiggler parameter, respectively. In Wiggler parameter B_w, m, c are the magnetic wiggler amplitude, mass of the electron and the speed of light, respectively. One of the main constraints of this scheme is the non-fuzzy acceleration of the electron in comparison with the laser pulse. As the energy of electron increases, the resonance condition of the free-electron laser cannot be maintained for a long time; this problem can be solved in two different ways: the period and (or) the amplitude of the magnetic field are slowly changed, or that the laser pulse is used with the variable frequency. In this paper, the interaction of an inverse free-electron laser with a Wiggler whose period is variable is studied numerically. The resonance condition in a free-electron laser indicates that when an electron is placed on a laser optic period, it also propagates during a Wiggler period. Thus, for Wiggler variable period, the resonance bandwidth in inverse free-electron laser becomes considerably larger, indicating the fact that electron energy can be effectively changed before fuzzy disappears in the interaction.

In this study, the equations of relativistic motion of a single electron are numerically stimulated using fourth order Runge-Kutta method which is summarized below. In the second section, the relativistic equations for electron

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acceleration are formulated. In the third section, the numerical results are presented and in the fourth section, the conclusion is presented.

Electron dynamics

The laser pulse of Gaussian TEM (0,0)mode, with circular polarization is assumed. The transverse components of the electric field are expressed as:

$$E_x = E_0 \frac{w_0}{w(z)} \times exp\left(-\frac{x^2+y^2}{w^2(z)}\right) exp(i\psi) f(z-ct) \quad (1)$$

$$E_y = E_0 \frac{w_0}{w(z)} \times exp\left(-\frac{x^2+y^2}{w^2(z)}\right) exp\left[i\left(\psi - \frac{\pi}{2}\right)\right] f(z-ct) \quad (2)$$

Where E_0, w_0, k, ψ are the amplitude of electric field, the plane of beam, laser wave number, Gaussian beam phase, respectively. The Gaussian beam parameters are defined as:

$$w(z) = w_0\left[1+\left(\frac{2z}{kw_0^2}\right)^2\right]^{\frac{1}{2}} \quad (3)$$

$$R(z) = z\left[1+\left(\frac{kw_0^2}{2z}\right)^2\right] \quad (4)$$

$$\psi = \left[kz - \omega t - \varphi(z) + \frac{k(x^2+y^2)}{2R(z)} + \varphi_0\right] \quad (5)$$

$$\varphi(z) = \tan^{-1}\left(\frac{2z}{kw_0}\right) \quad (6)$$

Where φ_0 is the initial phase and $\varphi(z)$ is the value of phase shift which is added to the typical phase shift of plane wave and is known as the Guoy phase. The laser pulse Gaussian cover is assumed to be the following.

$$f(z-ct) = exp\left[-\frac{\left[\left(z - z_{0p}\right) - ct\right]^2}{\sigma_p^2}\right] \quad (7)$$

Where z_{0p} is the initial position of the laser pulse peak, and σ_p is the pulse length. The one-dimensional helical Wiggler field is as:

$$\vec{B}_w = B_w\left[\hat{x}\cos\left(\frac{k_w z}{1+\alpha z}\right) - \hat{y}\sin\left(\frac{k_w z}{1+\alpha z}\right)\right] \quad (8)$$

Where B_w, k_w, α are the amplitude, the wave number, and parameter of magnetic Wiggler period variations, respectively.

The longitudinal electric field component of laser pulse is obtained using Piraaxial approximation.

$$E_z = \frac{Re(E_x)}{k}\left[-\frac{2y}{w^2(z)} - \frac{kx}{R(z)}\right] - \frac{Re(E_y)}{k}\left[-\frac{2x}{w^2(z)} + \frac{ky}{R(z)}\right] \quad (9)$$

The components of the laser pulse magnetic field are obtained using the following equation:

$$\vec{B} = -\left(\frac{ic}{\omega}\right)\vec{\nabla}\times\vec{E} \quad (10)$$

To study the dynamic of electron motion in these fields, three-dimensional simulation is constructed for a particle by using therelativistic equation of Newton-Lorentz.

$$\frac{d}{dt}(\gamma m_0 \vec{v}) = -e\left(\vec{E} + \frac{\vec{v}\times\vec{B}}{c}\right) \quad (11)$$

m_0, e, v are the mass in the stasis, electron load, and electron velocity, respectively. $\vec{E}$ is the laser pulse electric field and $\vec{B} = \vec{B}_w + \vec{B}_l$ where $\vec{B}_w$ is the Wiggler magnetic field and $\vec{B}_l$ is the magnetic field produced by the laser pulse.

In this study, the quantities x, y, z, σ_p, w_0, $w(z)$, and $R(z)$ are became dimensionless with the laser wave number, the electric and magnetic fields with $e/m_0 c\omega_0$ and t with ω_0. The following dimensionless variables are used in the equations.

$$\frac{eE_0}{m_0 c\omega_0} \to a \quad , \quad \frac{eB}{m_0 c\omega_0} \to b$$

$$\frac{v_i}{c} \to \beta_i \quad , \quad \alpha \to \frac{\alpha}{k}$$

Using these variables, the dimensionless equations of electron motion are as follows.

$$\frac{d\beta_x}{d\tau} = \frac{1}{\gamma}\left[a_x\left(\beta_x^2-1\right)+\beta_y\left(\beta_x a_y-b_z\right)+\beta_z\left(\beta_x a_z+b_y\right)\right] \quad (12)$$

$$\frac{d\beta_y}{d\tau} = \frac{1}{\gamma}\left[a_y\left(\beta_y^2-1\right)+\beta_z\left(\beta_y a_z-b_x\right)+\beta_x\left(\beta_y a_x+b_z\right)\right] \quad (13)$$

$$\frac{d\beta_z}{d\tau} = \frac{1}{\gamma}\left[a_z\left(\beta_z^2-1\right)+\beta_x\left(\beta_z a_x-b_y\right)+\beta_y\left(\beta_z a_y+b_x\right)\right] \quad (14)$$

And the energy changes can be written as follows.

$$\frac{d\gamma}{d\tau} = -\left(a_x\beta_x + a_y\beta_y + a_z\beta_z\right) \quad (15)$$

The equations are solved by fourth order Runge-Kutta method.

Numerical results

In this section, we will consider the numerical results of a single electron in the presence of a magnetic Wiggler which its period changes as a function of the location. The results are presented based on the dimensionless variables. The dimensionless parameters oflaser pulseare $\tau_p = 1000$, $z_{0p} = -\tau_p$, $a = 0.6$ and $w_0 = 100$ which equal to the pulse duration about 5ps, intensity $4.5\times\frac{10^{15}W}{cm^2}$, and peak power about $400\,MW$ for CO_2 laser pulse with the wavelength $\lambda = 10.6\,\mu m$ and the plane of beam $160 \propto m$. And in accordance with the resonance conditions in free-electron laser $\lambda_w / \lambda = 450$. In all Figures, the initial location of electron is $z_0 = 5.1$ and the initial velocity is $v_{0z} = 0.999$.

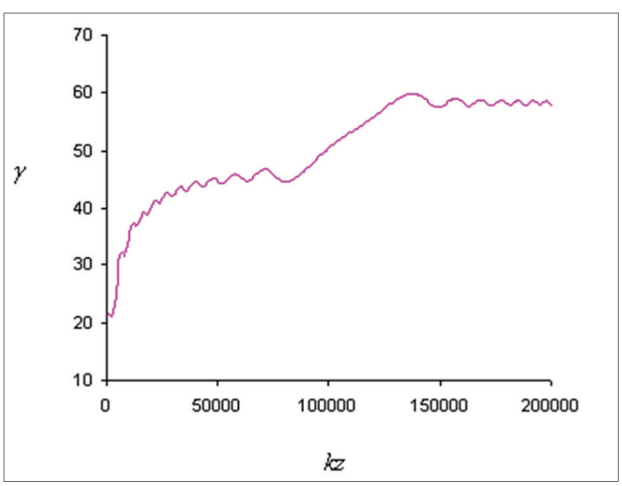

Figure 1. Electron energy in term of dimensionless z

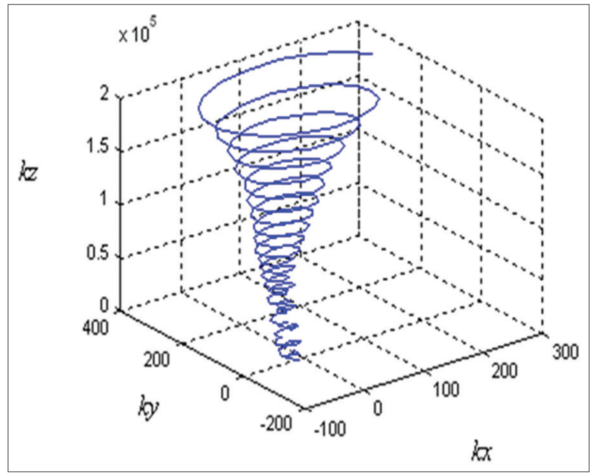

Figure 2. Trajectory of the electron

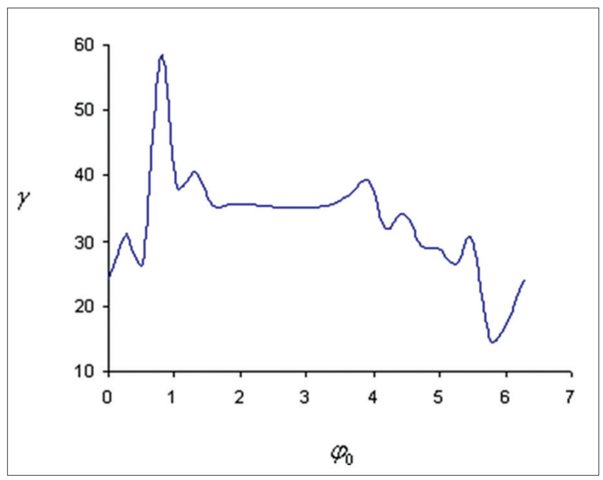

Figure 3. Electron energy in terms of the initial phase

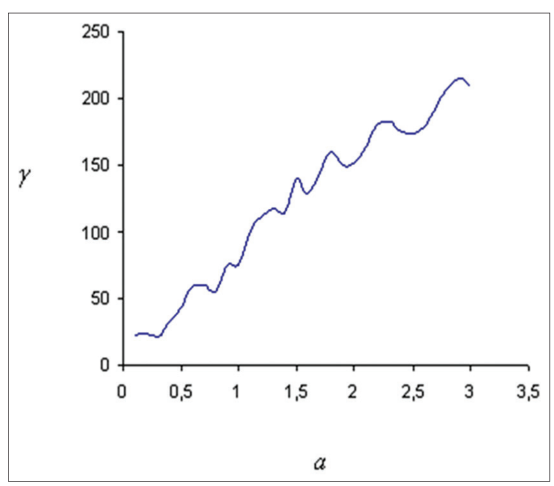

Figure 4. Electron energy in terms of laser pulse intensity

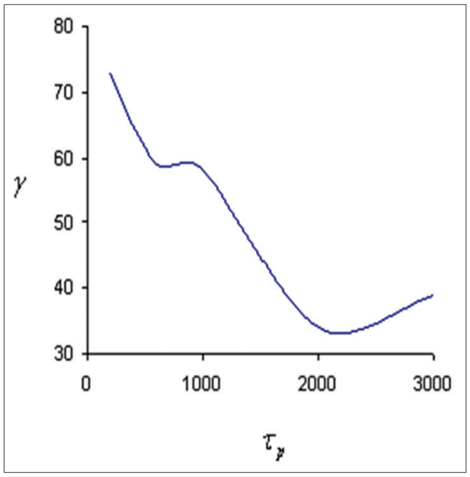

Figure 5. Electron energy in terms of pulse durability.

Figures 1 and 2 show the energy and path of the electron according to the location which the period of Wiggler magnetic field is variant and the parameter of this change is $\alpha = 8 \times 10^{-6}$. As shown in Fig.3, the electron energy is very sensitive to the relative phase of the laser pulse. Other parameters are as shown in Fig.1.

In the above figure, the effect of laser pulse intensity on electron energy is observed; the higher the laser pulse intensity, the electron energy will also increase.

In Figure 5, the electron energy is shown in terms of the durability of the laser pulse which the parameter of variation of magnetic field period is optimized for each of them. By increasing the pulse durability, the electron energy decreases.

CONCLUSION

In a steady-state period of the magnetic Wiggler, after the electrons obtain a certain amount of energy, the fuzzy conditions disappear; if the Wiggler period changes appropriately, the resonance conditions are maintained for a longer period and the electrons gain considerable energy.

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