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Inverse free electron laser and accelerating electrons with applied oscillatory voltages

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Abstract— In this article we try to expend the theory of high gradient laser excited electron accelerator by an inverse free-electron laser. The wiggler used in our scheme is produced by segmented cylindrical electrodes with applied oscillatory voltages. We can describe the inverse free electron accelerator by the equations that govern the electron motion in the allied fields of both laser pulse and Paul wiggler field. By focusing on electron energy and electron trajectories and using fourth order Runge-Kutta method, it is found that the electron energy reaches different peaks for different initial axial velocities. It is perceived that a suitable small initial axial velocity of e-beam procreates substantially high energy gain. According to transverse confinement of the electron beam in a Paul wiggler, there is no applied axial guide magnetic field in this devise.

Keywords—Electron acceleration, Inverse free-electron laser, Paul wiggler, Runge-Kutta method.

I. INTRODUCTION

Laser-driven accelerators are derived as a potential scheme to create experimental facilities that produce high energy particle beams [1, 2]. Different laser-based advanced acceleration techniques to lessen the size and expense of the particle accelerators, like a laser wake-field accelerator [3, 4] and inverse free-electron laser [5-8], have been given. In an inverse free-electron laser, relativistic electrons copropagate by a laser beam through a wiggler.

Wiggler field has the duty to supply a pairing between the e-beam and electromagnetic radiation fields those results in a pondermotive force along the axis of the beam. Moreover, the wiggler procreates a small oscillatory transverse velocity in a path parallel to the electric vector of the electromagnetic wave thus energy can be shifted from the wave to the electrons [9, 10].

Recent experiments have indicated that IFEL can reach both very high-energy gradient and relatively good output beam quality [11, 12]. Other substantial privileges over different advanced accelerator schemes consist the fact that IFEL does not need any medium such as plasma or dielectric in the interaction region [12, 16].

In this article we use up a theory of IFEL based on an electrostatic wiggler. This wiggler is caused by segmented cylindrical electrodes with applied oscillatory voltages V_osc (t) over 90-degrees segments. The In this paper we mention the relativistic equations of motion for an electron in the Paul wiggler inverse-FEL are derived in Section 2. In the long run, the conclusions of numerical studies of electron orbits and electron energy gain are supplied in Section 3.

II. THEORETICAL MODEL

Suppose a Paul wiggler with oscillatory voltages $V_{osc}(t)$ with $V_{osc}(t+T) = V_{osc}(t)$ and $\int_0^T V_{osc}(t)dt = 0$ over 90° segments. In lots of applications, the electrodes can be excited sinusoidally $V_{osc}(t) = V_{o\,max}\sin(2\pi ft)$, while $f = 1/T$ is the oscillation frequency. Representing the applied electric field the appropriate boundary conditions at $r = r_w$ is given by[22]

$$\emptyset(r,t) = \frac{4V_{o\,max}}{\pi}\sin(2\pi ft)\sum_{l=1}^{\infty}\frac{\sin(\frac{l\pi}{2})}{l}\left(\frac{r}{r_w}\right)^{2l}\cos(2l\theta) \quad (1)$$

For $0 \le r \le r_w$ and $0 \le \theta \le 2\pi$. Near the cylinder axis ($r \ll r_w$), the recent equation gives to the lowest order $q\emptyset(r,t) = \frac{m}{2}\Gamma\sin(2\pi ft)(x^2 - y^2)$,
(2)
while the oscillation quadruple focusing coefficient Γ is specified by $\Gamma = 8qV_{o\,max}/m\pi r_w^2$. The electric field of the periodic quadruple focusing transport system (i.e., Paul wiggler) is given by

$$E_\omega = \frac{8eV_{o\,max}}{m\pi r_\omega^2}\sin(2\pi ft)\,[x\,\hat{e}_x - y\,\hat{e}_y] \quad (3)$$

The inverse-FEL interaction can be demonstrated by the equations that govern the electron motion in the composed fields of a laser pulse and a PT-wiggler field. The laser pulse is suppose with the following vector potential,

$$A_l = -A_0\ \mathrm{Sin}(\omega t - kz)\ \exp[-(t-(z-z_l))/c)^2/\tau_l{}^2)]\,\hat{e}_x \quad (4)$$

Where τ_l is the pulse duration,$k = (\omega/c)$ is the laser wavenumber, and z_l is the initial position of the pulse peak. At the first step we introduce the equation corresponding to the vector potential of wiggler field as follows,

$$A_w = \frac{-8V_{0max}}{\omega_w\pi r_\omega^2}\mathrm{Cos}(\omega_w t)(x\hat{e}_x - y\hat{e}_y) \quad (5)$$

Then, the Potential vector components of the combined laser and wiggler fields, and the E and B fields generated by them are as follows,

$$A_x = -A_0\mathrm{Sin}(\omega t - kz)\exp\left[-\frac{\left(\frac{t-(z-z_l)}{v_g}\right)^2}{\tau_l^2}\right] - \frac{8V_{0max}}{\omega_w\pi r_\omega^2}\mathrm{Cos}(\omega_w t)x \quad (6)$$

$$A_y = \frac{8V_{0max}}{\omega_w\pi r_\omega^2}\mathrm{Cos}(\omega_w t)y \ \ ,\ \ A_z = 0 \quad (7)$$

$$B_x = 0\ \ ,B_y = \frac{\partial}{\partial z}(A_L + A_{wx}),\ B_z = 0 \quad (8)$$

$$E_x = -\frac{1}{c}\frac{\partial}{\partial t}(A_L + A_{wx})\ \ ,E_y = -\frac{1}{c}\frac{\partial}{\partial t}(A_{wy}),E_z = 0 \quad (9)$$

An analysis of relativistic motion of an electron will be based on Lorentz equation,

$$\frac{dP}{dt} = -e[E_{laser} + E_{wiggler} + \frac{V}{c}\times B_{laser}] \quad (10)$$

By considering the equations of electric and magnetic fields, Eqs.(11-14) the scalar equations of momentum and energy of an electron are as follows,

$$\frac{dP}{dt} = \frac{d(m_0\gamma V)}{dt} = m_0\gamma\frac{dV}{dt} + m_0 V\frac{d\gamma}{dt} \quad (11)$$

So that,

$$\frac{dV_x}{dt} = \frac{1}{m_0\gamma}\left(\frac{e}{c}\left[\frac{\partial}{\partial t}(A_L + A_{wx}) + V_z\frac{\partial}{\partial z}(A_L)\right] - m_0 V_x\frac{d\gamma}{dt}\right) \quad (12)$$

$$\frac{dV_y}{dt} = \frac{1}{m_0\gamma}\left(\frac{e}{c}\left[\frac{\partial}{\partial t}(A_{wy})\right] - m_0 V_y\frac{d\gamma}{dt}\right) \quad (13)$$

$$\frac{dV_z}{dt} = \frac{1}{m_0\gamma}\left(\frac{-e}{c}V_x\frac{\partial}{\partial z}(A_L) - m_0 V_z\frac{d\gamma}{dt}\right) \quad (14)$$

$$\frac{d\gamma}{dt} = \frac{e}{m_0 c^3}\left[V_x\frac{\partial}{\partial t}(A_L + A_{wx}) + V_y\frac{\partial}{\partial t}(A_{wy})\right] \quad (15)$$

In the following survey we will use the dimensionless variables $t \to \omega t$, $\tau \to \omega\tau$, $\tau_l \to \omega\tau_l$ $x \to kx$, $y \to ky$, $z \to kz$, $z_l \to kz_l$, $\frac{dx}{dt} \to \frac{k}{\omega}\frac{dx}{dt}$, $\frac{dy}{dt} \to \frac{k}{\omega}\frac{dy}{dt}$, $\frac{dz}{dt} \to \frac{k}{\omega}\frac{dz}{dt}$, $k \to \frac{kc}{\omega}$, $\frac{\lambda_l}{\lambda_w} \to \frac{k_w}{k}$.

By using these variables, we can write Eqs. (12-16) as follows:

$$\frac{dV_x}{dt} = \frac{k}{\gamma}\left(\frac{\partial}{\partial t}(a_L + a_{wx}) + V_z\frac{\partial}{\partial z}(a_L) - \frac{1}{\gamma}V_x\frac{d\gamma}{dt}\right. \quad (16)$$

$$\frac{dV_y}{dt} = \frac{k}{\gamma}\left(\frac{\partial}{\partial t}a_{wy}\right) - \frac{1}{\gamma}V_y\frac{d\gamma}{dt} \quad (17)$$

$$\frac{dV_z}{dt} = \frac{k}{\gamma}\left(V_x \frac{\partial}{\partial z} a_L\right) - \frac{1}{\gamma} V_z \frac{d\gamma}{dt} \tag{18}$$

$$\frac{d\gamma}{dt} = \frac{1}{k}\left(V_x \frac{\partial}{\partial t}(a_L + a_{wx}) + V_y \frac{\partial}{\partial t} a_{wy}\right) \tag{19}$$

where $a_L = -a_0 \ \mathrm{Sin}(\omega t - kz)\ \exp[-(t-(z-z_l))/c)^2/\tau_l{}^2)]\,\hat{e}_x$, $a_w = -a_{0w}\,\mathrm{Cos}(\omega_w t)(x\hat{e}_x - y\hat{e}_y)$, $a_0 = \frac{eA_0}{mc^2}$ and $a_{0w} = e8V_{0max}/mc^2\omega_w \pi r_\omega^2$.

Equations (16-19) together with the relations $v_x = \frac{dx}{dt}$, $v_y = \frac{dy}{dt}$, $v_z = \frac{dz}{dt}$ are seven coupled equations which are solved numerically using the fourth order Runge-Kutta method.

III. NUMERICAL RESULTS

A numerical study of electron energy and electron trajectories in an inverse free-electron laser and accelerating electrons with applied oscillatory voltages as an electrostatic wiggler has been made in this section.

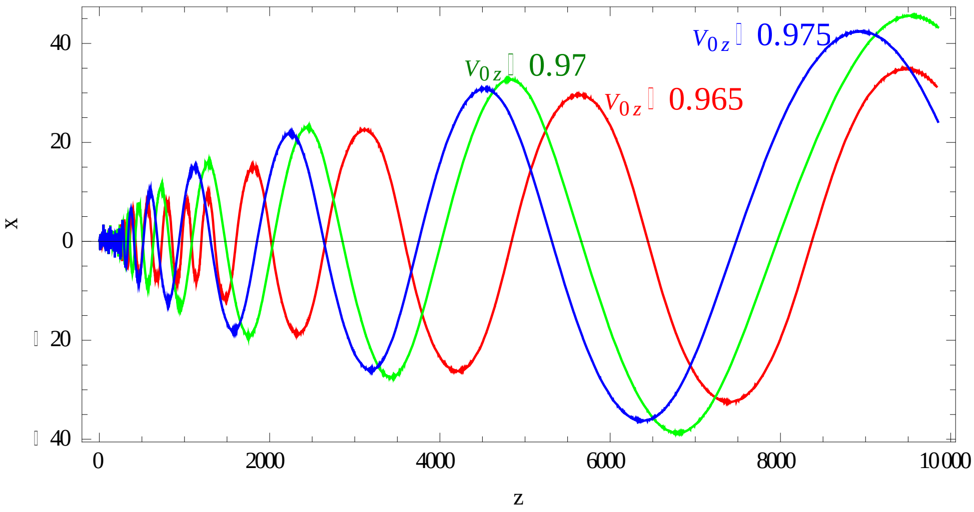

Fig. 1 Electron trajectories in the x – z plane for v_{0z} *=0.97,* v_{0z}*= 0.965, 0.97 and 0.975, respectively.*

Figs. 1 demonstrates the transverse component of electron trajectory in (x,z)-plane. It is shown that with proliferating the axial initial velocity v_{0z}, these oscillations become wider (as the wavelength becomes higher) and larger as the electron drives in longer z.

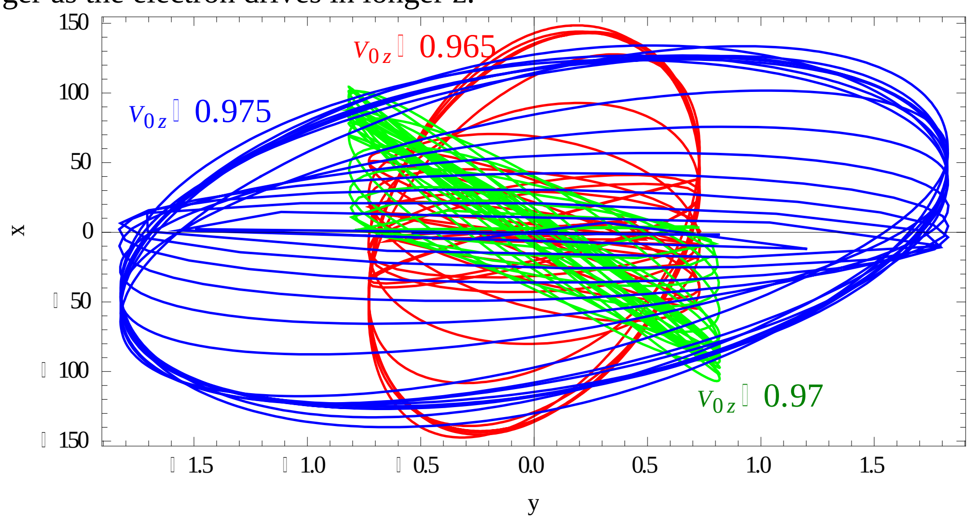

Fig. 2 Electron trajectories in the (x,y)-plane v_{0z} *=0.97,* v_{0z}*= 0.965, 0.97 and 0.975.*

Fig. 2 shows the normalized transverse displacements in (x,y)-plane for various initial electron velocities v_{0z}. As you can see in this figure, when the enlargement of the normalized v_{0z} increasing, the cross-section of transverse movements become narrower.

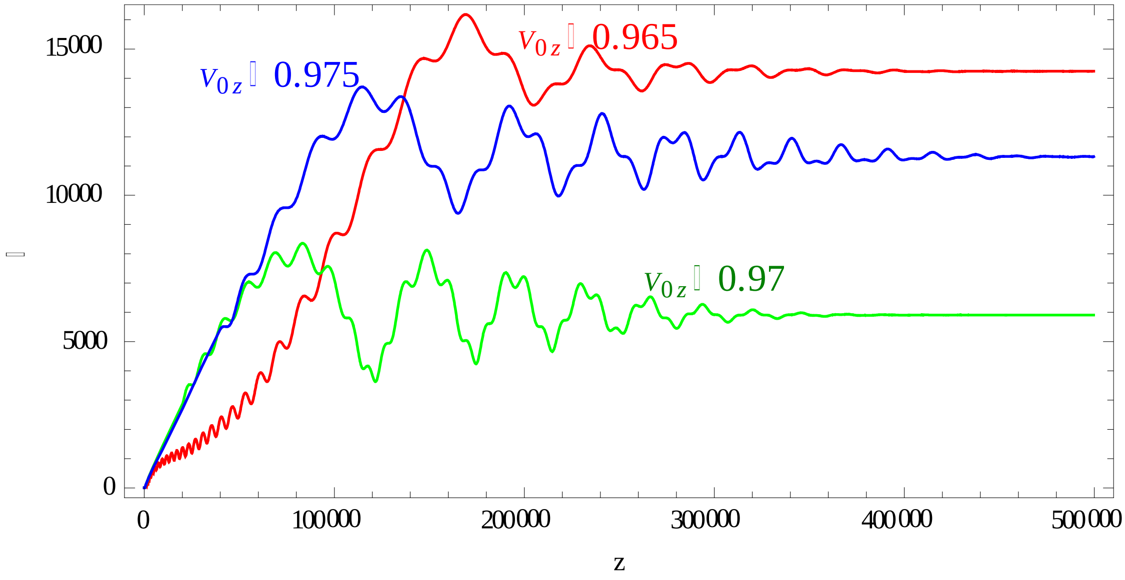

Fig. 3 Electron energy γ as a function of z for $a_0 = 2$, k =1, a_{0w} = 8, and v_{0z}= 0.965 and 0.97, 0.975, respectively.

To represent the effect of V_{0z} on electron acceleration, we have plotted the energy gain with z for different V_{0z} in Fig. 3. It can be easily found that the electron energy oscillates and increases inchmeal with z.

IV. CONCLUSION

In summary, in this paper we have shown the electron acceleration in an inverse free electron laser by an electrostatic wiggler. This electrostatic wiggler, witch is named Paul wiggler, utilizes oscillatory voltages applied to the external electrodes to provide transverse confinement of the e-beam. It was found that in the presence of the Paul wiggler field the electron experiences a ponderomotive force owing to laser pulse. Hence, it oscillates as it drives in the wiggler. In addition, we found that the electron energy gains different peaks for different initial axial velocities. It is seen that the electrons gain energy about 4 GeV (for $V_{0z} = 0.97$ c) and 8 GeV (for $V_{0z} = 0.965$ c), respectively. So that it can be concluded that a suitable small initial axial velocity of e-beam produces substantially high energy gain. Note that, there is no applied axial guide magnetic field, with regard to transverse confinement of the electron beam in a Paul wiggler.

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