Studies of super-short pulse generated by a free-electron lasers at perfect synchronism

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Three-dimensional (3D) simulations and theoretical analyses on super-short pulse generated using free-electron lasers (FELs) at perfect synchronism are carried out with the help of our 3D OSIFEL code. The evolution of longitudinal pulse width in the Japan Atomic Energy Research Institute (JAERI) experiment is simulated. The results show that the optical pulse is compressed on successive passes due to the slippage between the optical and electron beams, and an ultra-short 221-fs optical pulse is finally obtained, which agrees with the experiment. Furthermore, to shorten wavelength such as soft ultraviolet (SUV) spectrum range, an ultra-short pulse generated at perfect synchronism is analyzed and studied. Finally, the relationship between the optical pulse length compressed and the peak electron beam current is calculated. It shows that the higher the electron beam current, the shorter the output FEL width length, due to the higher gain.

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Free-electron lasers (FELs) have some unique features such as wavelength tunability and design-ability, and potentialities for high efficiency and good beam quality etc. Recent developments in accelerator technologies and new discoveries about the physics of FELs have allowed researchers to push performance into new frontiers of high power, short wavelength, and ultrashort pulse[1,2]. To generate ultrashort radiation pulses is a potentially important feature of FELs. It may be attained the ultrashort radiation pulse by the ultrashort electron beams[3], but to attain the high quality ultrashort electron beam is very difficult due to the effect of space charge. A new development in FEL theory has been the behavior of laser operating at perfect synchronism[4]. In general FEL oscillators, optical cavity shortening from perfect synchronism is required to compensate the "laser lethargy", which is a phenomenon that FEL optical group velocity becomes somewhat slower than the speed of light in vacuum because there is no gain at the beginning of FEL interaction[5]. The perfect synchronism is the case that, the cavity length, where the cavity round-trip times for vacuum speed of light equals the injection period of electron bunches. The Japan Atomic Energy Research Institute (JAERI) group has demonstrated laser pulse at 23 μm with a full-width at half-maximum (FWHM) of less than 260 fs at perfect synchronism[6,7]. Three-dimensional (3D) simulations and theoretical analyses on FEL perfect synchronism should been done in order to understand the evolvement of optical pulse length when optical field from the start-up to saturation.

In this letter, 3D simulations and theoretical analyses on super-short pulse generated using a FEL at perfect synchronism are carried out with the help of our 3D OSIFEL code[8,9]. An ultra-short 221-fs optical pulse is finally formed in a FEL oscillator at the perfect synchronism which agrees with the experiment. Furthermore, on shorter wavelength such as soft ultraviolet (SUV) spectrum range, an ultra-short pulse generated at perfect synchronism is analyzed and studied. Moreover, the relationship between the optical pulse length and the peak electron beam current is simulated. It shows that the higher of the electron beam current, the shorter the output FEL pulse length.

The simulation is based on our 3D FEL oscillator code[8,9]. Basic equations and code model are composed of the electronic motion equations and the optical field equation. The electron and optical coupling equations can be obtained following the single-particle theory of FEL[10]. We assume that the x-direction is perpendicular to magnetic field, and the y-direction is parallel to the magnetic field.

The electronic energy and phase equations are

$$\frac{\mathrm{d}\gamma}{\mathrm{d}z}=-\sum_{n}\frac{\omega F_u a_{\mathrm{w}}\,|a|}{2c\gamma\beta_z}\sin\left(\theta+\phi\right), \tag{1}$$

$$\begin{aligned}\frac{\mathrm{d}\theta}{\mathrm{d}z}={}&k_{\mathrm{w}}+k-\frac{\omega}{c}-\frac{\omega}{c\beta_z(1+\beta_z)\gamma^2}\\&\times\Big[1+\frac{1}{2}a_{\mathrm{w}}^2+\frac{1}{2}|a|^2-F_{\mathrm{u}}a_{\mathrm{w}}|a|\\&\times\cos(\theta+\phi)+\gamma^2\beta_{\perp\beta}^2\Big],\end{aligned} \tag{2}$$

where $a_{\mathrm{w}}=\frac{e}{mc^2}A_{\mathrm{w}}$; $a=|a|\,e^{\mathrm{i}\phi}$; $u=\frac{\omega a_{\mathrm{w}}^2}{8c\gamma^2k_{\mathrm{w}}}$; $F_u=J_0(u)-J_1(u)$; $k_{\mathrm{w}}=2\pi/\lambda_{\mathrm{w}}$; $\omega=2\pi c/\lambda_{\mathrm{s}}$; λ_{w} is the period of wiggler; λ_{s} is the optical wavelength; c is the velocity of light in vacuum; θ and ϕ are the phase of electron and optical field; e and m are the electron charge and mass; γ and $\beta_{\perp\beta}$ are the energy and betatron velocity of the electron.

The optical field equation with the source is expressed as

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+2\mathrm{i}k\frac{\partial}{\partial z}\right)a_s=-\frac{4\pi e}{mc^3}\frac{I}{\Delta S}\frac{1}{N_e}\Big(\mathrm{Fu}a_{\mathrm{wx}}\frac{e^{-\mathrm{i}\theta}}{\gamma\beta_z}\Big)_j, \tag{3}$$

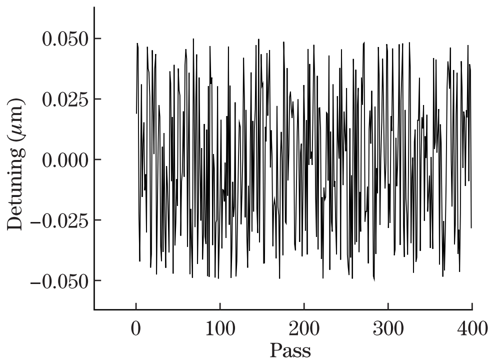

Fig. 1. Random detuning length versus optical pass.

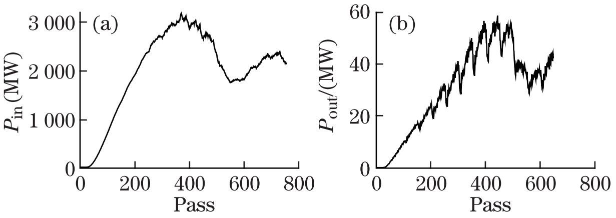

Fig. 2. Evolvement curves of FEL power in the (a) resonator and (b) output power as a function of optical pass.

where Ne represents the number of electron in the calculation area ΔS, I is the current of electron beam.

In the simulations, the distribution functions of transverse position and velocity and energy of the electrons are assumed to be Gaussian. The corresponding initial values of the sample electron are determined by a Monte Carlo method and the initial phases are loaded according to the 'quiet start' scheme to eliminate the numerical noise. The energy spread and emittance are specified as FWHM and root mean square (RMS), respectively. The emittance in y-direction is the same as that in x-direction and the initial size of the electron beam is chosen to obtain a circular cross-section at the center of the wiggler[8]. The cavity length is shift due to random jitter of the electron bunch interval, so we use the random detuning length in the simulation; the random detuning is shown in Fig. 1.

The FEL power in the resonator as a function of optical pass is calculated by our 3D-OSIFEL code using the JAERI perfect synchronism FEL experiment parameters seen in Table 1. The results are shown in Fig. 2 as following. One can see that evolution of the optical power and the optical field is saturated at about the 350th pass.

Furthermore, the evolvement curves of the longitudinal pulse width at deferent stages are simulated. The results are shown in Figs. 3(a)–(f). Figure 3(a) shows the horizontal distribution of the initial optical field as a function of time. With the development of the optical field, it can be seen from Fig. 3(b) that only the tail of optical pulse is magnified due to the slippage between the optical and electron beams, that is the "laser lethargy". The center of optical pulse is retarded on successive passes before 50th pass. Then, the center of laser pulse moves slowly to ahead as shown in Figs. 3(d) and (e). The gain along optical pulse is uneven. The part of the optical pulse which has a gain larger than the loss will develop while the other part of the optical pulse without enough gain will dissipate. So, this results in an optical pulse shorter than the electron pulse. Furthermore, in the following pass, the optical field with a pulse shape will cause the gain distribution in the pulse more uneven, so the optical pulse becomes shorter and shorter. Finally, it can be seen from Fig. 3(f) that the output FEL pulse length is about as short as 221 fs (FWHM)

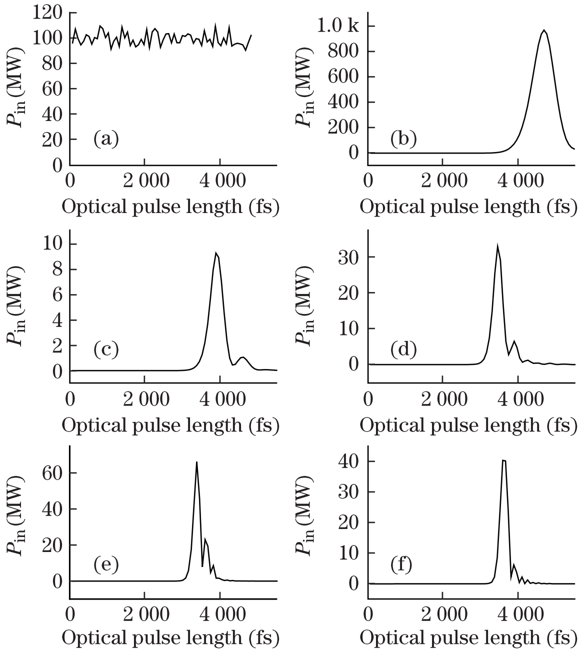

Fig. 3. Evolution curves of the FEL pulse width. Initial optical field, (a) optical pass=1; (b) 50; (c) 100; (d) 200; (e) 400; (f) 600.

Table 1 Input Simulations Parameters of JAERI Experiment

Electron Beam	Value	Wiggler	Value
Energy (MeV)	16.5	Period (cm)	3.3
Average Current (mA)	5.3	Peak Field Strength (kG)	3.17
Bunch Charge (ps)	0.51nC	Number of Periods	52
Peak Current (A)	127.5	Optical	Value
Micro Bunch (ps)	2.5	Wavelength (μm)	22.3
Emittance (mm mrad)	40(x)*22(y)	Cavity Length (m)	14.4
Energy Spread (%)	1 (FWHM)	Mirror Radii (cm)	6
Repetition Rate (MHz)	10.4125	Rayleigh Range (m)	1

when optical field is saturation, as the balance between the gain and loss is reached, a greatly shorten compared to the electron pulse of 2 500 fs. An ultra-short optical pulse with the length of 221 fs is finally attained in a FEL oscillator at the perfect synchronism, which is accorded with the experiment value of 260 fs, taking into account that the simulation condition is perfect.

To shorter wavelength such as soft UV spectrum range, an ultra-short pulse generated at perfect synchronism is analyzed and simulated. The electron-beam and wiggler parameters used in the simulation are listed in Table 2, which are the main parameters for the proposed SUV-FEL.

Figures 4(a)–(f) show the evolution of the FEL pulse in the case of the peak electron beam current is 400 A. Figure 4(a) shows the horizontal distribution of the initial optical field as a function of time. With the development of the optical field, it can be seen from Fig. 4(b) that only the tail of optical pulse is magnified due to the slippage between the optical and electron beams. It can be seen from Fig. 4(f) that the output FEL pulse duration is about as short as 2 fs (FWHM) when optical field is saturation as the balance between the gain and loss is reached, a greatly shorten compared to the electron pulse of 10 fs. An ultra-short optical pulse is finally attained in a FEL oscillator at the perfect synchronism. Compared with far-infrared JAERI experiments, shown in Fig. 3(a)–(f), the compress ratio of pulse width is decreased due to lower gain in UV spectrum range.

Table 2 Simulation Parameters

Electron Beam	Value
Energy (MeV)	280
Peak Current (A)	400
Micro Bunch (fs)	10
Emittance (mm mrad)	0.5π
Energy Spread (%)	0.2 (FWHM)
Wiggler	Value
Period (cm)	2.5
Peak Field Strength (kG)	4.4
Number of Periods	54
Optical	Value
Wavelength (nm)	64
Cavity Length (m)	2.767
Mirror Curvature (m)	1.49

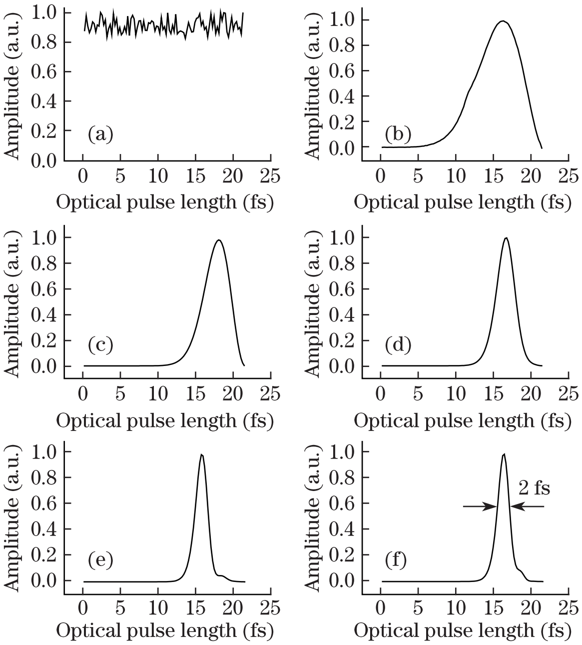

Fig. 4. Evolution of the FEL pulse in the case of the peak electron beam current is 400 A. Initial optical field, (a) optical pass=1; (b) 5; (c) 50; (d) 100; (e) 200; (f) 995.

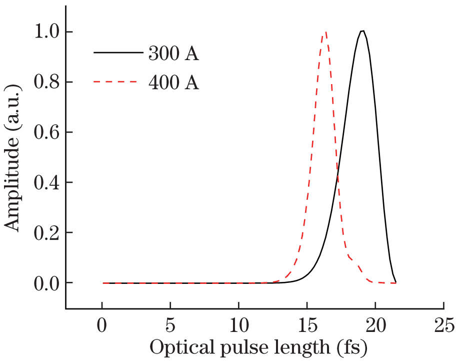

Fig. 5. Temporal distributions of optical pulse are plotted at different peak electron beam currents when optical field is saturation.

The temporal distributions of optical pulse at saturation are plotted at different peak electron beam current as shown in Fig. 5. It can be seen that the optical pulse width shortened at the perfect synchronism determined by the peak electron beam current. The higher of the electron beam current, the shorter the output FEL pulse length will be. This may be due to the higher gain as the higher electron beams current and the super radiant happened when the current is higher. The FEL pulse is compressed such that it can be significantly shorter than the input laser pulse[11].

In conclusion, 3D simulations and theoretical analyses on super-short pulse generated using a FEL at perfect synchronism are carried out with the help of our 3D OSIFEL code. The evolution of longitudinal pulse width in the JAERI experiment is simulated. The results shows that the optical pulse is compressed on successive passes due to the slippage between the optical and electron beams, and an ultra-short 221-fs optical pulse is finally obtained, which agrees with the experiment. Furthermore, to shorter wavelength such as SUV spectrum range, the pulse evolution at perfect synchronism is analyzed and studied. An ultra-short optical pulse with the length of 2 fs is finally attained. Compared with far-infrared JAERI experiments, the compress ratio of pulse width is decreased due to lower gain in UV spectrum range. Moreover, the relationship between the optical pulse length and the peak electron beam current is simulated. It shows that the higher of the electron beam current, the shorter the output FEL width length due to the higher gain.

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