CHIN.PHYS.LETT. Vol.12,No.12(1995)720

Compression Effect of Ultrashort Pulse in Far Infrared Waveguide Free Electron Laser

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(Received 6 April 1995)

Compression mechanism of ultrashort pulse in far infrared waveguide free electron laser driven by radio frequency linear accelerator was investigated. With a pertinent waveguide gap b, when the original phase velocity of the electron bunch ensures the positive gain and the refractivity of the optical pulse monotone increasing along the relative slip distance, the longitudinal length of optical pulse will be continuously shortened so that the pulse power increases quickly until saturation occurs. To offset the "lethargy" effect, an optimal cavity detuning ΔL_c has been accurately determined.

PACS: 41. 60. Cr, 42. 65. Re

As we know, far infrared free electron laser (FIR-FEL) is the unique high power and tunable coherent radiation source in the far infrared spectral region.[1] Most FIR-FEL facilities employ a radio frequency linear accelerator (RF-Linac). This type of accelerator has the property that electrons emerge as a train of picosecond-long bunches. These bunched electron bunches propagating the wiggler can generate picosecond optical pulse.[2] However, more and more experiments need more short subpicosecond even femtosecond ultrashort pulse to research many ultrafast phenomena, such as the biological dynamics, ultrafast chemical reaction kinetics and ultrafast relaxation in solid-state materials and so on.[3] Therefore, the problem, whether we can compress the picosecond optical pulse radiated by the radio frequency modulated electron bunches, occurs to us.

Because of the long wavelength and the short electron bunch, the short pulse effect of FIR-FEL is very serious.[4] The slip between the electron bunch and the optical pulse impedes the development of an ultrashort pulse FIR-FEL.[5] Waveguide is usually applied to reduce the slippage.[6,7] At the linear wiggler exit of a waveguide FEL, the slip distance is defined as

$$\Delta = (\beta_g - \beta_z) N \lambda_w / \beta_g \ , \tag{1}$$

where $\beta_g = ck/\omega$, $\beta_z \approx [1-(1+K^2)/\gamma^2]^{1/2}$ are respectively the relativistic group velocity of the optical pulse and the electron bunch longitudinal velocity, γ is the well-known Lorentz factor of electrons. The dimensionless magnetic field rms parameter equals to $K = eB_0\lambda_w/2\sqrt{2}\pi mc^2$; B_0, N and λ_w are respectively the peak magnetic field, the number of periods and period of the wiggler.

Here, we assume that the electron bunch is monoenergetic, and only the high resonant frequency branch is considered and TE_{01} mode is prior to be excited in the rectangular metal waveguide. The dispersion relation of the electron beam and the radiation $k_{01}^2 = \omega^2/c^2 - \pi^2/b^2$ is shown in Fig. 1, where b is the rectangular waveguide gap. When the electron beam is resonant with the radiation field, the slip distance may be simplified as

$$\Delta = \delta N \lambda_s \ , \tag{2}$$

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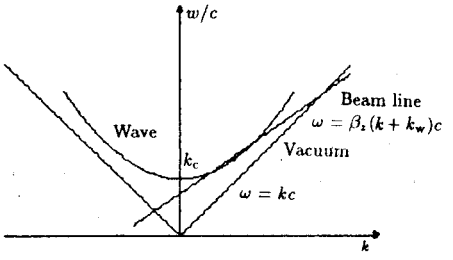

Fig. 1. Dispersion relation of waveguide FEL on the plane $[w/c, k]$, k_c is the cut off wavenumber of the waveguide.

where λ_s is the radiation wavelength. The waveguide effect parameter δ is written as[8]

$$\delta = \sqrt{1 - \frac{\pi^2}{\beta_z^2 \gamma_z^2 k_w^2 b^2}} \tag{3}$$

for TE_{01} mode, where γ_z is the part of γ along z axis, $k_w = 2\pi/\lambda_w$ is the wiggler wavenumber. From Eqs. (2) and (3), we can see that narrowing the waveguide gap b may reduce the slip distance Δ. As the following condition equation (4) is satisfied, the slip distance is just equal to the electron bunch length l_b:

$$b = \frac{\pi N \lambda_s}{\beta_z \gamma_z k_w} \frac{1}{\sqrt{N^2 \lambda_s^2 - l_b^2}} . \tag{4}$$

In other words, if the optical pulse overlaps with the tail of the electron bunch at the entrance of the wiggler, the optical pulse will undergo all electrons of the bunch during interaction. The condition equation (4) is necessary to compress the picosecond pulse and to operate FIR-FEL at high efficiency.

Now, let us investigate the mechanism of optical pulse compression. In order to have an insight into the interaction, we substitute the relative slip coordinate $z', z' = z - \beta_z ct$, for the absolute location coordinate z of the optical pulse center. Thus, the electron density can be expressed as

$$\begin{cases} n_e(z') = n_0[1 - \frac{(z'-l_b)^2}{l_b^2}] , & 0 < z' < l_b , \\ n_e(z') = 0 , & \text{else} , \end{cases} \tag{5}$$

where n_0 is the maximum density of the electron bunch. This transformation causes the coordinate partial differential operation to change, namely $\partial/\partial z \to (1/\beta_z c)(\partial/\partial z' - \partial/\partial t)$.

At the beginning, we assume that the optical pulse overlaps the tail of the electron bunch at the wiggler entrance. A pertinent waveguide gap b ensures the relative coordinate z' varying from 0 to l_b during interaction. Simultaneously, the normalized time variance $\tau = \beta_z ct/L = z'/l_b$, which describes the electron bunch propagating through the wiggler, changes from 0 to 1.

In case of low current and small signal regime, waveguide does not change the interaction mechanism of wave and electron beam. The phase evolution of the optical field still keeps the approximate expression:[9]

$$\phi(\beta_0, z') = j(z') \left[\left(2 \sin \frac{\beta_0 z'}{l_b} - \frac{\beta_0 z'}{l_b} (1 + \cos \frac{\beta_0 z'}{l_b}) \right) / \beta_0^3 \right] + \cdots \tag{6}$$

for TE_{01} mode, where $\beta_0 = [(k_{01} + k_w)\beta_z - \omega/c]$, L is the dimensionless original phase velocity of electrons. The dimensionless current density is $j(z') = 8N(e\pi K L(J_0(\xi) - J_1(\xi))]^2 n_e(z')/\gamma^3 mc^2$, where the wiggler length is equal to $L = N\lambda_w$, J_0, J_1 are the first kind Bessel functions with parameter $\xi = K^2/2(1 + K^2)$. The wave extracts energy from, or transfers its own energy to, electrons over the interaction length. Consequently, the wave is gained or deamplified by electrons. The interaction procedure during the optical pulse passing through the electron

bunch may be demonstrated by an equivalent refractivity. According to Ref. 10, the refractivity can be derived as following:

$$n(\beta_0, z') = 1 + \frac{c}{\omega}\frac{\partial\phi(\beta_0, z')}{\partial z} = 1 + \frac{c}{\omega}\left(\frac{1}{\beta_z c} - \frac{l_b}{L}\right)\frac{\partial\phi(\beta_0, z')}{\partial z'} , \tag{7}$$

in waveguide FEL, $c/\omega \neq 1/k_{01}$. substituting Eq. (6) into above expression, we obtain the equivalent refractivity which is a function of the relative location z' and the original phase velocity β_0, that is

$$n(\beta_0, z') = 1 + \frac{2A}{\beta_z} f(\beta_0, z')(l_b - z') - \frac{cA}{L} g(\beta_0, z')(2l_b z' - z^2) , \tag{8}$$

where the parameters

$$A = \frac{8N(e\pi KL(J_0(\xi) - J_1(\xi))]^2 n_0}{\gamma^3 m\omega c^2 \beta_0^3 l_b^2} ,$$

$$f(\beta_0, z') = 2\sin\frac{\beta_0 z'}{l_b} - \frac{\beta_0 z'}{l_b}\left(1 + \cos\frac{\beta_0 z'}{l_b}\right) ,$$

$$g(\beta_0, z') = \beta_0 \cos\frac{\beta_0 z'}{l_b} - \beta_0 + \frac{\beta_0^2 z'}{l_b}\sin\frac{\beta_0 z'}{l_b} .$$

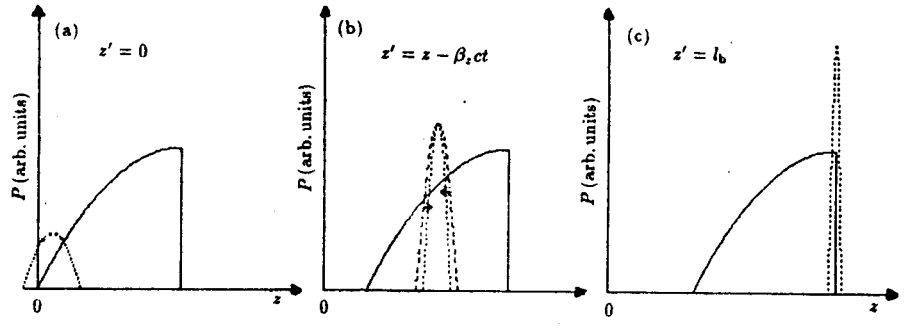

Fig. 2. The procedure of the optical pulse compression in a waveguide FEL. Dashed line represents optical pulse, solid line is electron density configuration. (a) the beginning case, (b) at the wiggler center case, the dashed profile covering optical pulse is the case without compression, (c) at the wiggler exit case, the longitudinal length of the optical pulse is shortened.

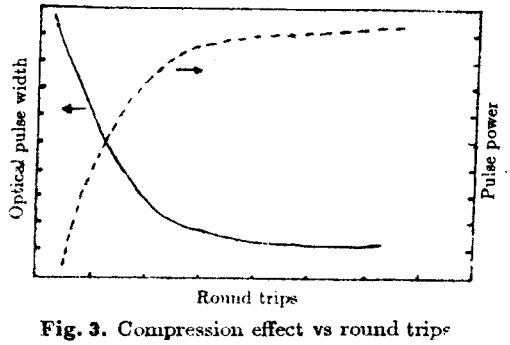

Fig. 3. Compression effect vs round trips

In order to compress the optical pulse, $n(\beta_0, z')$ must be monotone increasing along z' axis. It means that only when the dimensionless original phase velocity β_0 satisfies the requirement $\partial n(\beta_0, z')/\partial z' > 0$ during the relative slip coordinate z' changing from 0 to l_b, the compression of the optical pulse is effective. Therefore, with an available original electron phase velocity β_0, the monotone

increasing $n(\beta_0, z')$ suggests that the refractivity of the leading edge of the optical pulse, $n(\beta_0, z' + \Delta z')$, is larger than that of the trailing edge, $n(\beta_0, z' - \Delta z')$. In other words, as seen from the center of the optical pulse, the leading edge interacts with the high density and "fresh" electrons, thus the high gain impedes it to move forward. On the contrary, the trailing edge encounters the low density and perturbed electrons, the small gain induces the trailing edge to move fast toward the center. Consequently, the longitudinal length of the optical pulse is shortened. Figure 2 indicates the compression process. As an example, assuming the electron bunch length $l_b = 1\,\text{mm}$, $\lambda_w = 4\,\text{cm}$, $L = 0.8\,\text{m}$, $b = 2.86\,\text{mm}$, $K = 1.0$ and $\gamma = 10.0$, we numerically calculate the radiation wavelength $\lambda_s = 758\,\mu\text{m}$ and the dimensionless original phase velocity β_0 condition required by the positive gain and the monotone increasing refractivity along z' axis, the result is $0 < \beta_0 < 1.2$. The compression effect versus round trips is shown in Fig. 3.

From Eq. (8), we can see that the refractivity $n(\beta_0, z') > 1$ means the optical pulse propagating the electron bunch with a velocity slightly smaller than the light velocity c in vacuum. The delay effect is so called "lethargy". In an FEL oscillator, the pulse reflected by the cavity mirrors rounds back to the wiggler entrance, then interacts with the next electron bunch again. Therefore, in order to offset the "lethargy" effect, an exact cavity length detuning ΔL_c is very essential, which can be quantitively calculated as following:

$$\Delta L_c = \frac{\beta_g}{1 - \beta_z} \int_0^{l_b} \left(\frac{1}{n(\beta_0, z')} - 1 \right) dz' \,. \tag{9}$$

So far, we have investigated the compression mechanism of the ultrashort optical pulse in RF-FIR-FEL. If the rectangular waveguide with a pertinent gap b confines the relative slip and if the dimensionless original phase velocity β_0 of the electron bunch satisfies a certain condition, the longitudinal width of the optical pulse will be compressed and the pulse power will increase quickly before saturation. However, when the saturation occurs, the leading and trailing edge of the optical pulse maintain the same gain level so that they move forward with the same velocity. Thus, the compression process stops.

In addition, we may also consider Gaussian, Lorentzian or cosine electron beam density configuration. Only we ensure the relative slip not to exceed the range in which the electron density is monotone increasing, is the compression still possible.

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