PROPOSAL OF NEW Q-SWITCHING TECHNIQUE FOR STORAGE RING FREE ELECTON LASERS

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Abstract

In order to obtain strong power of a storage ring free electron laser (SRFEL), Q-switching technique has been used in the FEL operation. The typical Q-switching technique is based on a periodic longitudinal or transverse shift of an electron-bunch position from a synchronous optical pulse. However, the pulse width and line width of the FEL micropulse are much longer than those in the cw mode. The FEL peak power and peak brilliance are lost for the wide pulse width and line width. Then we propose new Q-switching technique "pre-narrowing" for the SRFEL. A simple simulation based on a one-dimensional theory of the electron-bunch heating shows that the pulse width and line width become halves by using the new Q-switching technique in the case of the NIJI-IV FEL.

INTRODUCTION

Studies of storage ring free electron lasers (SRFELs) have been progressed. In 1999, the first FEL oscillation in VUV region was achieved at a wavelength of 194 nm in the Duke FEL [1]. The shortest record of the SRFEL wavelength was moved to 190 nm by the ELETTRA in 2001 [2]. The NIJI-IV also achieved the FEL oscillation at a wavelength of 198 nm in 2003 [3]. There are a few plans to lengthen the wavelength. In the NIJI-IV and the NewSUBARU [4.5], SRFEL oscillations in the near and middle infrared regions are planned by using an optical klystron with long undulator period. The SRFELs are promising in the wide wavelength region as tuneable light source. They will meet needs in fields of medical treatments and material science.

The problem of the SRFEL would be low output power. Considering qualities of the SRFEL, the SRFEL in the cw mode would be the most useful. The SRFEL oscillation of which the output power exceeded 1 W was reported recently [6]. However, an SRFEL such strong output power can be realized only in the visible and UV regions where low-loss mirrors can be obtained as the cavity mirrors. A Q-switching operation will be used in experiments which high peak power will be demanded, such as experiments on multiphoton dissociation and isotope separation. The conventional Q-switching technique is based on a periodic longitudinal or transverse shift of an electron-bunch position from a synchronous FEL micropulse [7,8]. Tens of micro second is necessary to change the FEL gain in the Q-switching operations. Then it is difficult for the Q-switching technique to adjust the effective FEL gain within 10 μs. The pulse width and line width of the FEL micropulse in the Q-switching operations are much wider than those in the ideal cw mode. The FEL peak power and peak brilliance are lost for the wide pulse width and line width.

However, the theory of bunch heating predicts that the pulse width and line width can be sufficiently narrowed by a Q-switching operation with adjusting the effective FEL gain. The intensity of the FEL micropulse in this Q-switching technique is almost equal to that in the conventional one. In this article, we explain the pre-narrowing technique that the effective FEL gain is kept to be a small positive constant before the Q-switching, and we evaluate evolution of the pulse width and line width in the Q-switching with the pre-narrowing.

EVOLUTION OF THE SRFEL MICROPULSE

The evolution of the SRFEL micropulse is evaluated by the theory of bunch heating which describes a relationship between energy spread of an electron bunch σ_γ and SRFEL intensity I_F [9]. Especially a simulation based on this theory can describe the temporal characteristics of the SRFEL in the macropulse mode. According to this theory, the following finite difference equation for σ_γ holds:

$$\frac{d\sigma_{\gamma,n}^2}{dn} = -2\frac{T_0}{\tau_s}\left(\sigma_{\gamma,n}^2 - \sigma_{\gamma,i}^2\right) + \alpha_\sigma I_{F,n} , \qquad (1)$$

where T_0 and τ_s are round-trip time for the micropulse and synchrotron dumping time, respectively. The suffix i means the initial state where the electron beam and light pulse do not interact, and the suffix n means the round-trip number. Although the symbol α_σ is a function of the energy spread and the wavelength, we adopt the simplest model and consider it to be a constant. We express the longitudinal and spectral distribution of I_F as $I_F(\tau,\lambda)$, and the following equation holds:

$$I_F = \int_{\lambda_R(1-\Delta_\lambda)}^{\lambda_R(1+\Delta_\lambda)} d\lambda \int_{-T_0/2}^{T_0/2} I_F(\tau,\lambda) d\tau , \qquad (2)$$

where λ_R is a fundamental resonant wavelength of an undulator on the axis of the electron-beam trajectory and τ is local time of which period is equal to T_0. We assume that Δ_λ is equal to reciprocal of the number of periods in the undulator. The evolution of $I_F(\tau,\lambda)$ is given with gain distribution $G(\tau,\lambda)$ by

$$\frac{dI_{F,n}(\tau,\lambda)}{dn} = \left[G_n(\tau,\lambda) - l_c(\lambda)\right] I_{F,n}(\tau,\lambda) + I_{S,n}(\tau,\lambda) , \qquad (3)$$

where $I_s(\tau,\lambda)$ is the intensity distribution of the spontaneous emission on the axis of the electron-beam

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trajectory and $l_c(\lambda)$ is cavity loss which strongly depends on the wavelength.

In the case of the NIJI-IV FEL system, the electron bunch vibrates longitudinally [9]. However, the period of the vibration is 10 ms which is much longer than the rise time of the FEL macropulse in a Q-switching operation, and the influence of the vibration can be disregarded for the evolution of the FEL micropulse. Calculating the finite difference equations in order of the round trip, the evolution of the FEL micropulse can be described.

Q-SWITCHING TECHNIQUE WITH THE PRE-NARROWING

The FEL gain has not been adjusted with two or more steps in a Q-switching operation of the SRFEL. The reason is that it was difficult to adjust the FEL gain in the rise time of an FEL macropulse without changing the state of an electron bunch. However, if a high-rotation mechanical chopper which was used in a CO_2 laser is set in an optical cavity [10], this problem can be solved. Technology of turbo molecular pumps was applied to such a chopper device. The typical radius of the chopper wheel was about 100 mm, and the rotation rate was tens of thousands rpm. Here we consider a chopper device which is composed of two wheels as shown in Fig. 1. The wheels interrupt the optical beam axis excluding the missing parts on the circumference. They overlap by several times the optical beam size of the TEM_{00} mode. The FEL micropulse can pass when the missing parts synchronize on the optical beam axis. One can control the cavity loss, that is, the effective FEL gain by changing widths of the missing parts. Because the optical beam size becomes small about 1 mm in the UV and VUV region, such a chopper device is effective. It can change the effective FEL gain within 10 μs. The radius of the wheel is not large, so that period of the change of the effective FEL gain would be shorter than the synchrotron dumping time. Then, it is necessary to use a conventional Q-switching technique or a slow-rotation chopper to control period of the Q-switching operation.

The theory of bunch heating suggests that the pulse width and line width of the SRFEL micropulse do not narrow sufficiently compared with the Fourier limit even if the effective FEL gain is quickly changed. It is the cause that the effective FEL gain is positive in a wide temporal and spectral region. Energy spread of the electron bunch hardly changes until intensity of the FEL micropulse increases up to the equilibrium value in the cw mode [9]. Then, one keeps the effective FEL gain to be a small and positive value until the intensity reaches the equilibrium value. Because only an extremely narrow part around the center of the optical pulse where the effective FEL gain is positive can amplify, the optical pulse keeps growing up slowly, and the pulse width and line width keep narrowing for a long time. We call this procedure "pre-narrowing". When the intensity reaches the equilibrium value, the missing parts of the choppers are wider and the effective FEL gain is maximized quickly as well as a conventional Q-switching operation. The energy spread hardly increases in the pre-narrowing, so that the intensity in the Q-switching operation with the pre-narrowing is as high as the intensity in the Q-switching operation without the pre-narrowing. Therefore the brilliance of the FEL micropulse in the Q-switching operation with the pre-narrowing would be much higher than that without the pre-narrowing due to the narrow pulse width and line width. As the maximum FEL gain is higher, the rise time of the macropulse is shorter in a conventional Q-switching operation. The effect of a narrowing for the pulse width and line width is not sufficient. Then we can expect that procedure of the pre-narrowing is especially effective in the case of the higher maximum FEL gain.

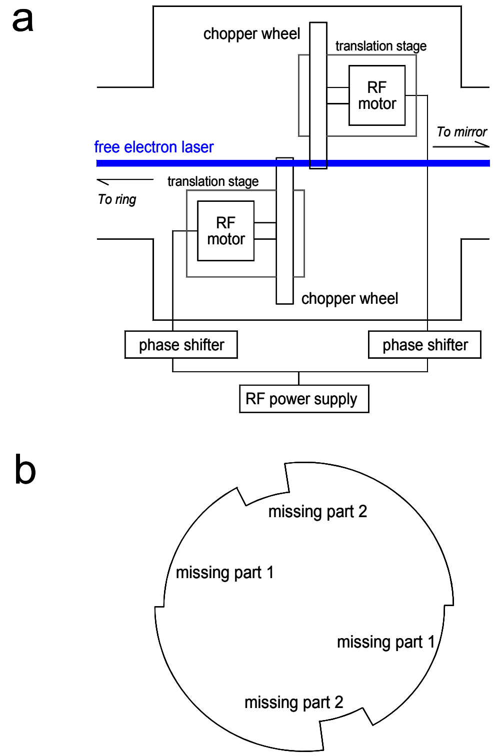

Figure 1: Schematic layout of the chopper device (a) and the chopper wheel (b).

SIMULATION OF EVOLUTION OF THE NIJI-IV FEL MICROPULSE

Now we simulate an example of evolution of the NIJI-IV FEL at the wavelength of 200 nm in a Q-switching operation with the pre-narrowing. The NIJI-IV is a compact storage ring with a 29.6 m circumference. The electron beam energy is usually 310 MeV in the FEL experiments, and the synchrotron dumping time is about 40 ms. The typical beam current is about 15 mA in a single-bunch operation, and the bunch length and energy spread are 63 ps and 3.6×10^{-4}, respectively. Although the maximum FEL gain expected from the electron-beam

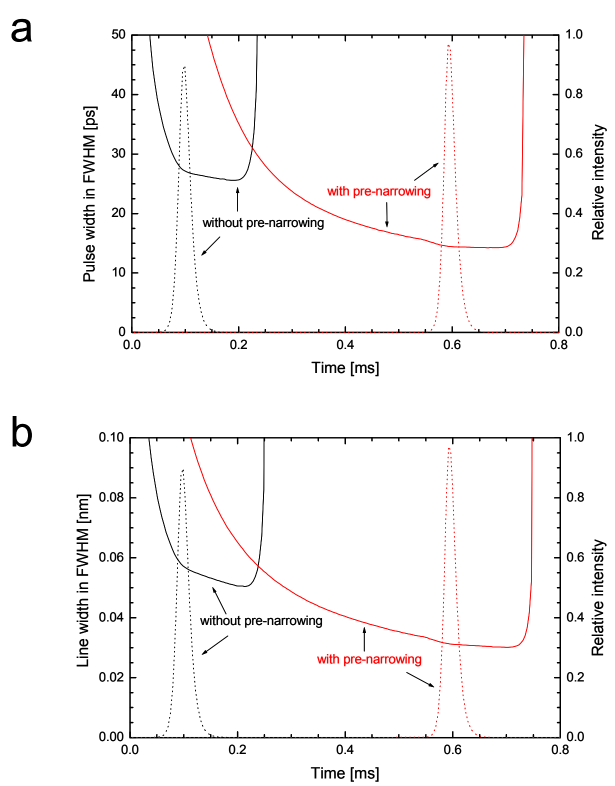

Figure 2: Evolution of the pulse width (a) and line width (b).

qualities is about 8%, the maximum FEL gain obtained in the experiments was 4% at most. The optical cavity has two cavity mirrors with the radius of the curvature of 10 m, and its length is 14.8 m. The cavity loss was estimated to be about 2% at 200 nm in the experiments.

Here we assume the expected performance of a chopper device. The radius of the wheel and the rotation rate are assumed to be 102.5 mm and 320 per second, respectively. Distance between the centers of the two wheels is 199 mm. The chopper device is set from the center of the optical cavity in 6.4 m, where the optical beam size at the wavelength of 200 nm is about 0.94 mm. For the simplification of this simulation, we neglect diffraction loss that the optical beam reflected from a near mirror is caused in the wheels. To obtain the effective FEL gain of 0.17% in the pre-narrowing, widths of the missing parts are set to be 3.48 mm from the circumference of the wheel. Because FEL micropulse needs 0.55 ms to reach the equilibrium intensity in the cw mode according to the simulation, lengths of the missing parts are set to be 110 mm. Widths of 6 mm from the circumference are enough for the missing parts in the Q-switching operation. The FEL macropulse almost decreases to the noise level 0.15 ms after the beginning of the Q-switching operation. Therefore lengths of the missing parts are set to be 30 mm. The calculated results of the evolution of the FEL micropulse with this chopper device are shown in Fig. 2. This figure also shows the evolution without the pre-narrowing. It is noted that the pulse width and line width

Table 1: Effect of the pre-narrowing technique for the various FEL gains.

Maximum FEL gain [%]	4.0	6.0	8.0
Pulse width in FWHM with / without the pre-narrowing [ps]	14.5 / 27.2	14.6 / 30.7	14.7 / 31.8
Line width in FWHM with / without the pre-narrowing [nm]	0.031 / 0.057	0.032 / 0.065	0.032 / 0.067

without the pre-narrowing quickly decrease but their minimum values are large. However, the minimum values of the pulse width and line width with the pre-narrowing become about halves of those without the pre-narrowing due to the long narrowing time. Table 1 shows that the effect of the pre-narrowing becomes clear as the maximum FEL gain increases. If the effective gain in the pre-narrowing is adjusted to be a smaller positive constant and the period of the pre-narrowing is set to be longer, product of the pulse width and line width can draw near the Fourier limit further.

CONCLUSIONS

We have proposed Q-switching technique with a pre-narrowing for SRFELs. The evolution of the FEL micropulse in the Q-switching operation with the pre-narrowing was calculated with the one-dimensional theory of bunch heating. As the result, it was shown that a more high-brilliance SRFEL could be obtained by this technique. However, control of the effective FEL gain with a chopper device has not been manufactured yet. To control the effective FEL gain correctly, it is necessary to adjust the width of the missing parts and the position of the wheel by the accuracy within 10 μm. It is a problem to solve the technical difficulties and to realize the high-brilliance FEL with pre-narrowing in the future.

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