MEASUREMENT OF ELECTRON-BUNCH LENGTH USING COHERENT RADIATION IN INFRARED FREE-ELECTRON LASER FACILITIES

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Abstract

We have studied techniques evaluating bunch length of micropulses in an electron beam. The bunch length of the electron beam is an important parameter for free-electron laser (FEL) facilities with linear accelerators. In order to obtain high FEL gain at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University and at Kyoto University Free Electron Laser (KU-FEL), the electron-bunch length is compressed to less than 1 ps in their undulator sections. Using the compressed electron beams, intense terahertz lights were generated by coherent radiation. We can extract the information of the bunch length of the electron-beam micropulse from the intense coherent radiation by using narrow-band diode detectors.

INTRODUCTION

Recently, a lot of compact light sources in the terahertz (THz) wave region have been developed [1, 2], and new applications with using THz waves have been proposed remarkably [3]. Because many materials have unique absorptive and dispersive properties in the THz wave region, unique THz light sources are useful on the frontiers of material, pharmaceutical and medical sciences [4-6]. The charm of the THz light source based on electron accelerators is high peak power. Although such a light source has been realized before 1990 [7, 8], in last years, various THz light sources based on electron accelerators have been developed with the innovation of the technique to shorten an electron bunch increasingly [9–11]. Especially, an energy-recovery linac (ERL), which can accelerate short-pulse electron bunches continually, is a THz light source superior in not only the peak output power but also the average power [12].

On the other hand, ERLs are expected to supply high-brilliance light sources by a resonant-type free-electron laser (FEL) in the vacuum ultra-violet and the x-ray regions [13]. High peak-power light sources in the x-ray region have been developed by a concept of a self-amplified spontaneous emission (SASE) FEL at LCLS and SACLA [14, 15]. However, the resonant-type free-electron laser in the x-ray region, which is called x-ray FEL oscillator (X-FELO), is expected to have a much higher brilliance than the SASE FEL [16, 17]. In addition, an X-FELO will have excellent stability of the oscillation wavelength. In order to operate the X-FELO stably, it will be necessary to monitor the qualities of the electron bunch in the ERL. Because the electron density in the bunch is extremely high to obtain the FEL gain, the length of the electron bunch depends on the charge in the electron bunch. The advanced light source desires a technique to measure a slight change of the bunch length caused by the change of the charge.

Then, we invented the technique to evaluate the bunch length easily by measuring intensity of coherent synchrotron radiation (CSR) from a bending magnet. We used the THz-wave CSR at the Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University [18] and at Kyoto University Free Electron Laser (KU-FEL) as a light source [19]. In this article, we explain the technique and demonstrate that it is effective to evaluate the bunch length for high-repetition micropulses.

MEASUREMENT OF BUNCH LENGTH USING A NARROW-BAND DETECTOR

When the number of electrons in a bunch, N, is sufficiently large and the wavelength of CSR λ is longer than the electron-bunch length, the intensity of CSR I is almost equal with the intensity of the synchrotron radiation, and the following equation holds:

$$I(\lambda) \cong N^2 F(\lambda) I_e(\lambda). \quad (1)$$

Here I_e is the intensity of the synchrotron radiation emitted from one electron, and $F(\lambda)$ is a bunch form factor defined by the Fourier transform of an electron-density distribution function in one bunch. When sensitivity efficiency of a narrow-band detector system is expressed by $B(\lambda)$, the measured CSR power P_m is given by

$$P_m \cong \int_{\lambda_L}^{\lambda_H} d\lambda\, N^2 B(\lambda) F(\lambda) I_e(\lambda), \quad (2)$$

where λ_H and λ_L are upper and lower limits of sensitivity of the detector system, respectively. When $F(\lambda)I_e(\lambda)$ is slowly varying function of a wavelength, the measured CSR power is approximately given by

$$P_m \cong N^2 \bar{B}(\lambda_c) \bar{F}(\lambda_c) \bar{I_e}(\lambda_c) \Delta\lambda, \quad (3)$$

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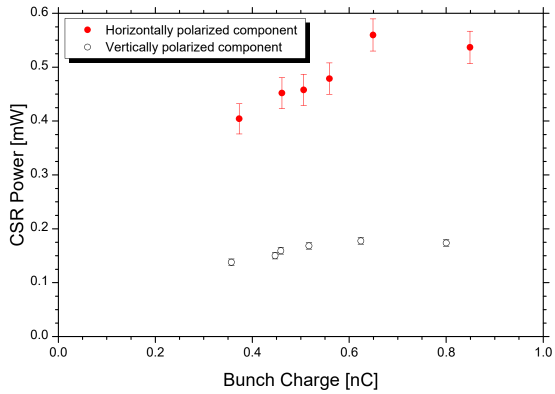

Figure 1: Measured dependence of the D-band CSR power on the electron-bunch charge in the burst mode.

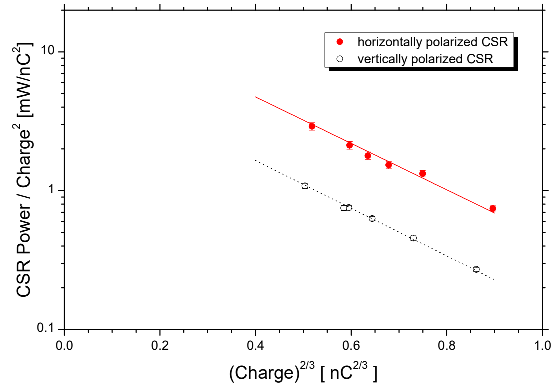

Figure 2: Relationship between the electron-bunch charge and the D-band CSR power.

where λ_c is a wavelength in which the CSR power measured by the detector system has a maximum, and $\Delta\lambda$ is a full width at half maximum of the measured CSR power. Symbol bar attached to each parameter means an averaged value from λ_H to λ_L. Because $\bar{B}(\lambda_c)$ and $\bar{I}_e(\lambda_c)$ are constant, a value of P_m/N^2, namely a value that divides the measured CSR power by square of the electron-beam charge, expresses dependency of $\bar{F}(\lambda_c)$ on the electron-beam charge.

In a low peak current region, the bunch length does not depend on the charge of the electron bunch. Then, when a charge q, which is proportional to N, exceeds a threshold q_{th}, we assume that the root-mean-square (RMS) bunch length σ is given as the following equation:

$$\sigma^2 = \sigma_{th}^2 + \sigma_{th}^2 \left(\frac{q-q_{th}}{q_{th}}\right)^n, q > q_{th}, \quad (4)$$

where n is unknown an exponent, and σ_{th} is the RMS bunch length at the electron-bunch charge of q_{th}. Generally, when electrons in a bunch have a Gaussian distribution, a form factor for a certain wavelength λ is given with a bunch length as

$$F(\lambda, \sigma) = \exp\left(-\frac{4\pi^2}{\lambda^2}\sigma^2\right). \quad (5)$$

In the case of $q \gg q_{th}$, eq. (5) can be rewritten with eq. (4) as the following approximate relation:

$$\bar{F}(\lambda_c, \sigma) \cong \bar{F}(\lambda_c, \sigma_{th}) \exp\left(-\frac{4\pi^2}{\lambda^2}\sigma^2{}_{th}\left(\frac{q}{q_{th}}\right)^n\right). \quad (6)$$

Because a parameter p_m/q^2 which is proportional to the form factor can be evaluated, a relationship between the form factor and the electron-bunch charge can be clarified experimentally.

A few THz coherent radiation sources have been developed at LEBRA [20,21]. We used a CSR beamline which was located at the upstream bending magnet in the FEL undulator line. The electron-beam energy was 100 MeV and the macropulse duration was 20 µs. These experiments were operated in the burst mode, where two high-charge micropulses (0.2-0.4 nC/micropulse) could be accelerated at intervals of 22.3 ns. The RMS bunch length was evaluated to be 2.9 ps at the charge of 0.49 nC per 2 bunches by measuring the CSR spectrum. Then, to observe the change of the bunch length, we used a D-band diode detector whose sensitivity had a maximum at 0.1 THz. The full width at half maximum of the detector system was approximately 23 GHz. Figure 1 shows a relationship between the CSR intensity and the charge, which was measured by this detector system. As shown in Fig. 1, CSR intensity saturated at approximately the charge of 0.7 nC. That is because the bunch length increases due to a space-charge effect as the electron-bunch charge becomes higher.

We investigated a dependence of p_m/q^2 on q^n based on the data plotted in Fig. 1. Fitting the experimental data to a curve given by eq. (6), the exponent n was 0.64±0.04 for the horizontally polarized component and 0.68±0.02 for the vertical polarized component, respectively. As shown in Fig. 2, it is noted that p_m/q^2 in the burst mode decreased exponentially in the case of $n = 2/3$. Then, a relationship $\sigma \propto q^{1/3}$ could be experimentally obtained between the bunch length and the charge in the burst mode.

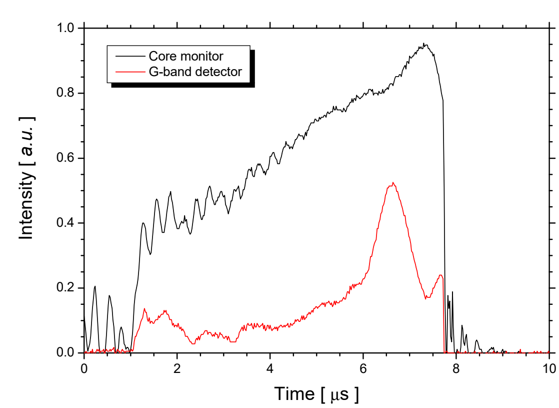

Figure 3: Evolution of the electron-bunch charge (black) and the -band CSR power (red) in a macro-pulse.

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We can quantitatively evaluate a variation of the bunch length for the data plotted in Fig. 2. The bunch length at $q = 0.49$ nC per 2 bunches was evaluated to be 2.9 ps, so that the form factor at $q = 0.49$ nC is estimated to be 0.0362 by Eq. (5). It is noted that the bunch length increases gently as the electron-bunch charge becomes higher above the threshold current. On the other hand, the form factor decreases remarkably, so that it is easy to detect the change of the bunch length when the bunch shape does not change. Therefore, by measuring the CSR power with a narrow-band detector when the electron-bunch charge changes, the change of the bunch length can be measured precisely through the evaluation of the form factor [22].

EVAULATION OF BUNCH LENGTH OF MICROPULSES

Although a CSR beam extracted from a vacuum port includes the component reflected on the inner vacuum chambers, we can remove the influence of the reflection component on the CSR power measurement by using a narrow aperture. Because the diode detector has a time resolution of a few nanoseconds, the change of the bunch length in units of the several microbunches can be observed for the S-band linac. Then, we observed the change of the bunch length in a macropulse using the CSR at KU-FEL. Although the macropulse duration is up to 8 μs, modification of the electron beam quality occurs due to back-bombardment effects on the RF gun for the second half of the macropulse. Figure 3 shows a typical temporal structure of a macropulse measured by a core monitor located in front of the upstream bending magnet. The electron-beam energy was 35 MeV in the experiment, and the micropulse charge averaged in a macropulse was 30 pC. The macropulse duration was 6.8 μs. It was presumed that the bunch length of the micropulse changed in the macropulse.

The power of the CSR was measured at the angle of 30° in the upstream bending magnet of the undulator section. The CSR spectrum was measured using a Michelson interferometer, it had a maximum at the frequency of 0.1 THz. By applying the least squares method to the data in the frequency region of 0.1-0.4 THz and assuming a Gaussian distribution, the RMS bunch length was evaluated to be 1.6 ps. Figure 3 shows the measured temporal structure of output of the G-band diode detector in the macropulse. As shown in this figure, the CSR intensity at the G band was not proportional to the second power of the charge. Then, the form factor at the G band was calculated by using the relationship between the micropulse charge and the output of the G-band diode detector, and the evolution of the RMS bunch length was evaluated from the form factor with RMS bunch length averaged in the macropulse, as shown in Fig. 4(a). It is noted that the bunch length at the upstream bending magnet had a minimum at the time of 6.5 μs. Figure 4(b) shows the evolution of the FEL power measured by a HgCdTe (MCT) detector at the undulator gap of 16.5 mm.

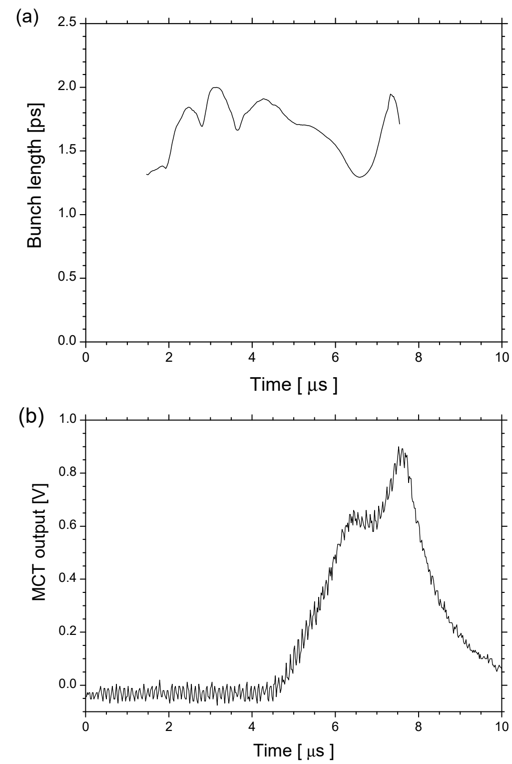

Figure 4: Evolution of the RMS bunch length (a) and the FEL power (b) in a macropulse. The data from 1.5 to 7.5 μs are expressed in (b).

It is noted that the FEL gain had a minimum at the time of 6.5μs. The FEL power and the RMS bunch length have a correlation. It is qualitatively supposed that the change of the bunch length due to the back-bombardment effects caused the stationary FEL gain. We demonstrated that the change of the bunch length could be observed on scale of nanosecond by measuring the CSR power with a narrow-band detector.

CONCLUSION

We measured the CSR power using a narrow-band diode detector with a fast time resolution in the FEL facilities and evaluated the evolution of the bunch length in a macropulse. By limiting the measurement band for the CSR power, it was clarified that the change of the RMS bunch length could be accurately evaluated for the known electron-bunch shape. Moreover, it was demonstrated that the change of the bunch length was correlated with the evolution of the FEL power in a macropulse. To evaluate the bunch length more accurately, the number of the measurement bands should be increased. We will develop a method of the evaluation of the bunch length with two narrow-band diode detectors.

APPENDIX

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