A BUNCH LENGTH MONITOR USING COHERENT RADIATION FOR JLC

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Abstract

Bunch length monitoring methods using coherent synchrotron radiation, coherent transition radiation and coherent Čerenkov radiation are discussed and the experimental results using a prototype bunch length monitor or a polychromator is presented. The spectrum of these types of radiation at submillimeter wavelength corresponds to the bunch form factor, which is the Fourier transform of the longitudinal bunch shape of an electron beam. A real time bunch length measurement for a 50 Hz bunch repetition has been achieved by the polychromator and fast data conversion method from frequency to time domain.

Introduction

Since coherent synchrotron radiation[1] was observed in 1989, studies on coherent radiation have been carried out at Tohoku University[2, 3, 4, 5] and the other institutes[6]. In 1991 coherent effects from bunched electron beam were observed in Čerenkov radiation[7] and transition radiation[8, 9, 10, 11]. In this paper coherent synchrotron, Čerenkov and transition radiation are denoted generically as coherent radiation. The elementary radiation process is different among these types of radiation, however, properties of coherent effects were confirmed to be same, i.e. the radiation intensity is proportional to a square of the number of electrons in a bunch and the bunch shape is reflected in the radiation spectrum.

Observed spectrum of coherent synchrotron radiation (A) and spectrum of elementary process (B) are shown in Fig. 1 as an example. In this experiment the beam energy was 150 MeV, bending radius 2.44 m, number of electrons in a bunch 3.6×10^{6} and bunch length about 1.7 mm. As is shown in next section, one can obtain the bunch shape from this spectrum.

The bunch length σ_z is 80 μm for JLC, which corresponds $\sigma_t = 250$ fsec. A streak camera has been commonly used to measure the bunch shape and its fastest time resolution is realized to be 200 fsec[12]. However, its time jittering of the trigger makes it impossible to accumulate the image of bunches and an intense photon flux is needed for a single shot measurement. The time resolution become worse because of the dispersion of optics, if wide wavelength region is detected to gain an enough photon intensity.

On the other hand, the method using coherent radiation is a frequency domain measurement, in which the response speed of the trigger, detectors, signal processing circuits can be slow enough. The frequency response of the measuring system can be correct easily when data in the frequency domain is converted into the time domain. It is the feature of this method that it is easier to measure the bunch length if it becomes shorter. The radiation from shorter bunch is easier to detect because it consists of higher energy photons.

Theory for measurement

The power spectrum of coherent radiation $P(\omega)$ is given by

$$P(\omega) = N\{1 + (N-1)F(\omega)\}p(\omega) \sim N^2F(\omega)p(\omega) \qquad (1)$$

where ω is the angular frequency of radiation, N the number of electrons in a bunch, $p(\omega)$ the power spectrum of elementary radiation process by an electron. $F(\omega)$ is the bunch form factor defined by

$$F(\omega) = \left| \frac{1}{Ne} \int_{-\infty}^{\infty} i_{beam}(t)e^{i\omega t}dt \right|^2 \qquad (2)$$

where $i_{beam}(t)$ is the beam current or the bunch shape in the time domain, and e is the charge of an electron. There exist many articles on the elementary process of radiation, however, notice should be taken of the formation length and the suppression effect of radiation due to the conducting boundary condition by a vacuum chamber.

The formation length Z_f for transition radiation in vacuum is given by $Z_f = \beta\lambda/2\pi(1-\beta cos\theta)$ where λ is the wavelength of radiation, θ the direction of the observation point, and $\beta = v/c$. For the peak radiation angle of $\theta = 1/\gamma^2 = 1-\beta^2$ it is approximated to be $Z_f \sim \gamma^2\lambda/2\pi$. In the case of the parameters of linear collider, $\lambda \sim \sigma_z$ and $\gamma \gg 1$, Z_f becomes much longer than the ordinary emission length of the bunch length monitor and one need to correct $p(\omega)$ [9, 10].

The suppression effect of synchrotron radiation appears for $\lambda > 6\sqrt{a^3/r}$ [13, 14], where a is the aperture radius of the vacuum chamber, and r is the bending radius. This effect is negligible for 1.54 GeV, the energy of the bunch compressor, however, it must be considered for higher energy beam because of an increase in bending radius.

Supposing a symmetric bunch shape, the bunch shape i_{beam} is obtained from (1) and (2) by

$$i_{beam}(t) \propto \int_0^\infty \sqrt{P(\omega)} cos\omega t d\omega. \qquad (3)$$

For the discrete data points of $P(\omega_j)$, (3) is replaced by a summation as

$$i_{beam}(t_i) = \sum_{j=1}^{n} A_{ij}\sqrt{P(\omega_j)} \qquad (4)$$

$$A_{ij} = \sqrt{\eta_j/p(\omega_j)}\ \xi_{ij}\delta\omega_j cos\omega_j t_i \qquad (5)$$

where η_j are response functions or correction factors at frequency ω_j, ξ_{ij} the apodization coefficients, and $\delta\omega_j$ the band width between the next neighbor data points. As all the parameters of the right side of (5) are known, the coefficients A_{ij} can be stored in the memory and bunch shape $i_{beam}(t_i)$ can be calculated by (4) in a short time.

Experimental method

The data of Fig. 1 was measured by a monochromator using a set of gratings and a couple of silicon bolometers[3], however, it takes two or three hours to measure the spectrum of this graph. To observe the spectrum of coherent radiation from each bunch, a prototype bunch length monitor or a polychromator, see Fig. 2, for millimeter wavelengths was developed. An array of ten detectors enables us to measure radiation at ten wavelengths at a same time. The signals from ten detectors is processed by amplifiers, sample-hold circuits and an ADC with a multiplexer in a personal computer with a program coded by PASCAL. The bunch shape was displayed on the CRT of the personal computer in real time.

Backward coherent transition radiation from a radiator of 50 μm aluminum foil was measured to obtain the bunch shape because the radiator can be used like a screen monitor on the beam line. The radiator was set at an angle of 45 degrees to the electron beam axis so that backward transition radiation was emitted at the right angle to the beam axis. The beam tests were carried out at Tohoku University and at ATF, KEK. The beam energy was 200 MeV at Tohoku University and 80 MeV at ATF.

Experimental results

The bunch shape at Tohoku University was measured in real time at 50 Hz repetition. However, the bunch length at ATF, which was measured to be about 5 mm by streak camera, was too long for the measuring wavelengths of grating of polychromator used in this experiment. The beam did not consist of a single bunch but about fifteen bunches for a shot, however, the intensity of signal was strong enough even for a single bunch of 1×10^7 electrons. The repetition of shots was 50Hz. The rise time and pulse width of amplified signal were 2 μsec and 5 μsec, respectively.

We could figure out the short bunch from longer one by the displayed bunch shape, however, the displayed bunch shape did not seem to be the real one. This disagreement caused by the following problems. 1)The real bunch is generally asymmetric, 2)the number of data points was only ten and the wavelength range covered by data points was insufficient, and 3)the apodization coefficients of Fourier transform used in these experiments were improper.

In spite of the above problems, this bunch length monitor allowed us to optimize the parameters such as the phase and power of the bunching section at Tohoku University. Moreover, the bunch length was found to be very unstable even if the beam energy and current is stable.

Conclusion

The prototype bunch length monitor enabled the real time monitoring of bunch length and tuning of parameters at Tohoku University. More data points are needed and the measuring wavelength region should be extended to obtain a realistic bunch shape. The bunch shape obtained by this method should be checked by the other data such as those by a streak camera. As the bunch from a damping ring of JLC is expected to have a symmetric Gaussian-like shape, the bunch length monitoring by this method is considered to be promising.

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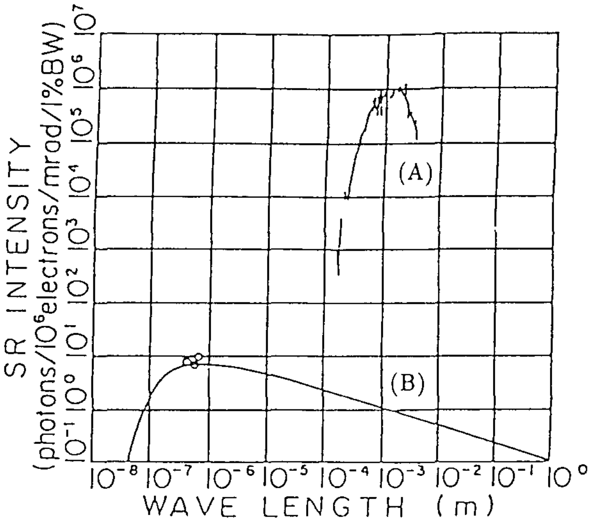

Fig. 1 Spectrum of coherent synchrotron radiation (A). Elementary radiation process shown by (B) is proportional to $\lambda^{-1/3}$ in long wavelengths.

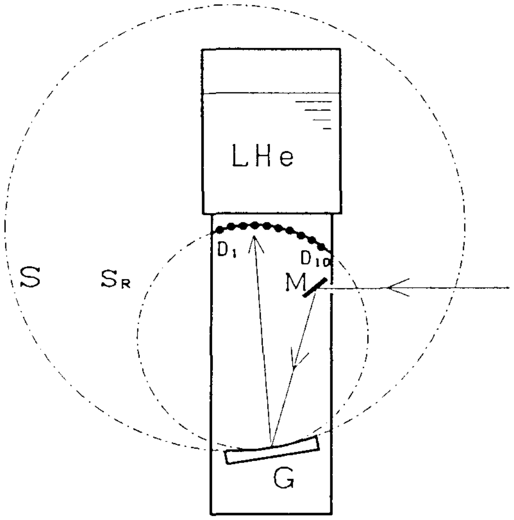

Fig. 2 Polychromator. Radiation, whose path is shown by arrows, is reflected by a plane mirror M, dispersed by a spherical grating G, and focused on the array of InSb detectors from D_1 to D_{10}, shown by dot points. Detectors are placed on the Rowland circle S_R and cooled at liquid helium temperature. The radius of the surface S of the grating is twice as big as that of S_R for the focusing condition. Each signal from ten detectors is processed by amplifier, sample-hold circuit and ADC in a personal computer.