Spectrum of Coherent Synchrotron Radiation

T. Nakazato, M. Oyamada, N. Niimura, S. Urasawa, Y. Shibasaki, R. Kato and S. Niwano,
Laboratory of Nuclear Science, Tohoku University
Mikamine, Taihaku-ku Sendai, 982, JAPAN
M. Ikezawa, T. Ohsaka, Y. Shibata, K. Ishi, T. Tsutaya, T. Takahashi, H. Mishiro and F. Arai,
Research Institute for Scientific Measurements, Tohoku University
Katahira Aoba-ku Sendai 980, JAPAN
and Y. Kondo
Department of Applied Physics, Faculty of Technology, Tohoku University,
Aramaki Aoba-ku, Sendai 980, JAPAN

Abstract

A spectrum of coherent synchrotron radiation were measured at wavelengths from 0.16 to 3.5 mm. A bunch shape was estimated by the Fourier analysis for this spectrum. This result agrees with that of simulation for the bunching process in the injector of the accelerator. The interferential effects between radiation which were emitted by the successive bunches were observed by an interferometer. It was shown that every radiation had the same phase when it was emitted by a bunch.

I. Introduction

In 1989 the coherence effects in SR were observed for the first time from short bunches accelerated by an electron linac[1]. It had a continuous spectrum and its intensity was more than 10^6 times as strong as that of ordinary SR at $\lambda = 0.33 \sim 2.0$ mm. This enhancement factor was almost as same order as N, the number of electrons in a bunch. The radiation intensity was proportional to square of the beam current or N^2. Radiation was mainly polarized in the orbital plane. The spectrum of coherent SR was dominated by the bunch length of the electron beam as expected by the theory[2, 3].

We will present the measured spectrum and discuss about the relation between the bunch shape and the spectrum. The interferential effects among radiation from different bunches were observed by an interferometer to show a direct evidence of coherent SR.

II. Experimental Method

The experiment was carried out using the Tohoku 300 MeV Linac whose accelerating frequency was 2856 MHz. In this experiment the electrons were accelerated up to an energy of 150 MeV. A duration of the bunch train, or burst width, was 2 μsec and its repetition rate was 300 pulses/sec. The bunch length was designed to be 1.2 mm (4° in RF phase) at the end of the first accelerating structure, where the beam energy was 10 MeV. Accelerated electrons were led to an experimental room through a beam transport, where the bunch length would be stretched to about 1.7 mm (6°). The number of electrons in a bunch was about 3.6×10^6 at an average beam current of 1 μA. The transverse beam size was about 2×2 mm^2 and the beam energy spread was 0.2 %.

The field strength of a bending magnet which was used to generate SR was 0.206 T and a bending radius was 2.44 m at the light emitting point of the electron orbit. The layout of the experimental setup is given in Ref.[1, 2, 3].

Emitted SR was collected by a spherical mirror with the acceptance angle of 70 mrad and was led to a far-infrared spectrometer of Czerny-Turner type through a crystal quartz window. Five echelette gratings were prepared to obtain a precise spectrum of coherent SR in the wavelength region from 0.1 mm to 4.0 mm. The resolution $(d\lambda/\lambda)$ of the spectrometer was about 0.01 at $\lambda \sim 1$ mm. The intensity of SR was detected by a LHe-cooled silicon bolometer. The absolute sensitivity of the measuring system was calibrated by a blackbody radiator, which was a graphite cavity of 1500 K. Details of the spectrometer and the calibration method are given in Ref.[4].

An interference experiment was carried out to clarify the emission mechanism of coherent SR. An interferogram of pulsed SR from the successive bunches was measured by a polarizing interferometer[5]. The schematic layout of the interferometer is shown in Figure 1. Radiation which was emitted by a bunch was delayed by ΔL, the optical path difference between two arms, and interfered with another radiation which was emitted by the next bunch. The distance between the successive bunches L_B was 104.97 mm, which corresponded to the wavelength of the accelerating RF. As the variable range of ΔL was from -9 to 110 mm, it covered the bunch distance L_B. (For details of the interferometer see Ref.[6])

III. Experimental Results

As is shown in Figure 2, the complete SR spectrum was obtained in the wavelength region of $0.16 \sim 3.5$ mm. Radiation intensity is normalized for a bunch of $N = 1\times10^6$, which corresponds to an average beam current of 0.28 μA. The spectrum is continuous in these wavelengths and shows a broad peak at $\lambda \sim 1.5$ mm. The intensity decreases rapidly for $\lambda \leq 0.5$ mm. The enhancement factor at $\lambda = 1$ mm is obtained to be 0.92×10^6, which is almost as same value as N.

According to the classical electromagnetic theory, the intensity of coherent SR $I_{coh}(\omega)$ is given by

$$I_{coh}(\omega) = I_{incoh}(\omega)\{1 + (N-1)F(\omega)\} \qquad (1)$$

$$F(\omega) = \left|\int e^{j\omega\mathbf{n}\cdot\mathbf{r}/c} S(\mathbf{r})d\mathbf{r}\right|^2 \qquad (2)$$

where $S(\mathbf{r})$ is the density distribution of electrons in a bunch, $\mathbf{n}$ a unit vector toward the observing point and $F(\omega)$ a bunch form factor defined by the Fourier transform of $S(\mathbf{r})$. Assuming that the bunch shape $S(\mathbf{r})$ is an even function of $\mathbf{r}$, we can estimate the bunch shape by using the Fourier transform from the observed SR spectrum. Estimated bunch shape is shown in Figure 3(a). The bunch shape resembles a Gaussian function with a sharp peak. The longitudinal bunch length is about 0.25 mm at full width of a half maximum, which is much shorter than the bunch length of 1.7 mm estimated from the characteristics of the linac.

In order to examine a possibility of the sharp structure of the electron distribution in the bunch, the bunching process was simulated by tracking the longitudinal motion of the electrons. The calculation was carried out according to the formulae in Ref. [7, 8]

The bunch shape depends strongly on the relative phase of the RF supplied to the prebuncher, buncher and the first accelerating structure. One of the result of this simulation is shown in Figure 3(b). The main body of the bunch is 1.3 mm in longitudinal length and it has three spikes, which are about 0.1 mm. This result is not an exact but similar shape as our experimental condition, and is consistent with the result of Figure 3(a). The effects of the beam loading and the space charge are not taken into account in the above simulation. To consider these effects, a rough calculation was done by the one-dimensional disk model[9]. The beam intensity was so small that the results was almost same as Figure 3(b).

The observed interferogram by the interferometer is shown in Figure 4. It is clear that the interference modulation at around ΔL=0 mm is repeated at around $\Delta L = L_B$=105 mm. The first modulation at around ΔL=0 mm shows the interference of SR from a bunch with itself, and the second one at around ΔL = 105 mm corresponds to the mutual interference with radiation from the next neighbor bunch. These two interference modulation patterns are congruous with each other within the accuracy of the experiment, i.e. the first radiation emitted by a bunch has the same amplitude and phase as the second one by the next bunch. This is a direct evidence that observed radiation is coherent.

IV. Conclusion

Two additional important results were obtained by the recent experiments.

1) The bunch length which is calculated by Fourier analysis of the radiation spectrum is consistent with the simulated result of the bunching process in the injector of the linac.

2)The coherent property of radiation was directly observed by the interferometer.

V. Acknowledgments

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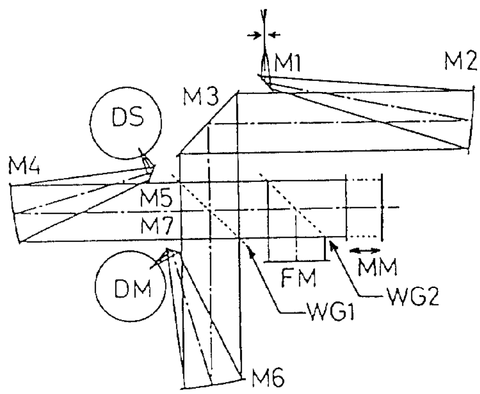

Figure 1. Interferometer to measure the interference effect between the bunches. M1, M3, M5 and M7: plane mirrors, M2, M4 and M6: collimators, WG1 and WG2: wire grids, FM and MM: fixed and moving mirrors, DS and DM: LHe-cooled silicon bolometer for detecting the signal and monitoring.

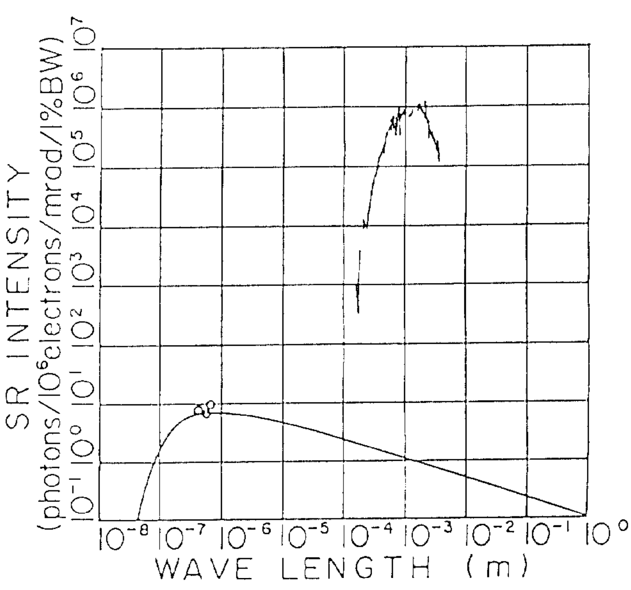

Figure 2. An observed spectrum of coherent SR. The intensity is normalized for a bunch of 1×10^6 electrons. A curve at the bottom is the calculate intensity for incoherent SR. Three circles are the measured intensity of visible SR to confirm the absolute value of this experiment.

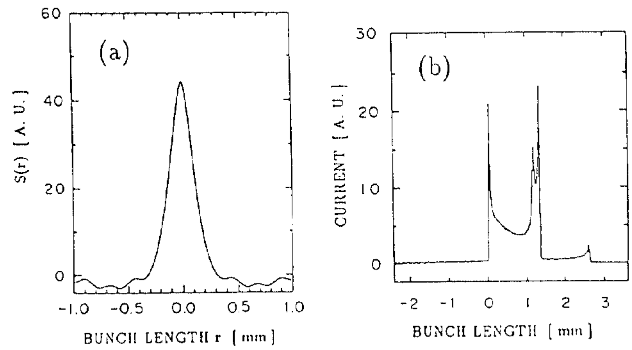

Figure 3. Longitudinal bunch shape obtained (a) from SR spectrum and (b) by the simulation of the bunching process.

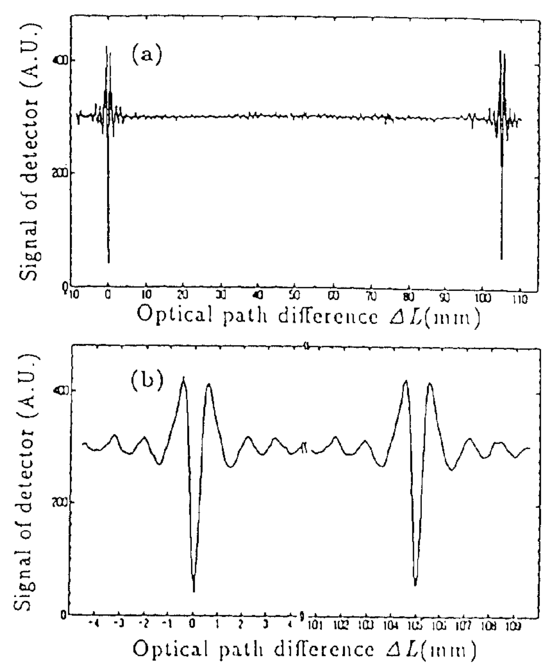

Figure 4. Interferogram of coherent SR.
(a) Full picture.
(b) Enlarged detail at around $\Delta L = 0$ and 105 mm.