

Coherent Synchrotron Radiation

M. Oyamada, S. Urasawa, T. Nakazato, R. Kato, S. Niwano and M. Yoshioka
*Laboratory of Nuclear Science, Tohoku University
 Mikamine Taihaku-ku Sendai 982, Japan*

M. Ikezawa T. Ohsaka K. Ishi, Y. Shibata, T. Tsutaya,
 S. Kimura, T. Takahashi, H. Arai and T. Kanai
*Research Institute for Scientific Measurements,
 Tohoku University, Katahira Aoba-ku Sendai 980, Japan*

Y. Kondo
*Department of Applied Physics, Faculty of Engineering,
 Tohoku University, Aramaki Aoba-ku Sendai 980, Japan*

Abstract

Coherent synchrotron radiation, produced by the passage of mm long electron bunches through a bending magnetic field, has been observed at wavelengths from 0.16 to 3.5 mm. Complete spectrum was obtained using a grating-type far-infrared spectrometer and two helium-cooled silicon detectors. A bunch shape was estimated by Fourier analysis from this spectrum.

The interferogram between coherent synchrotron radiation, which were emitted by the successive bunches, has been measured using a Martin-Puplett type polarizing interferometer. Both interference patterns, which corresponded to the optical path differences around zero and bunch spacing, resembled closely each other. It is clear that every radiation has the same phase to the bunch.

Introduction

Several authors^{1,2} studied the increase of energy loss due to the effects of coherent synchrotron radiation (SR) theoretically. Schiff¹ gave the expression of the emission rate of SR in case where the electrons are distributed in a Gaussian shape. Nodvick and Saxon² gave the expression of the spectral intensity of coherent SR in the presence of finite parallel plate metallic shields. Recently, a possibility of millimeter coherent radiation in electron storage rings was proposed by Michel³ in 1982 and Wingham⁴ in 1987.

According to the theories,¹⁻⁴ the intensity of SR is expected to be greatly enhanced due to the coherent effects, when the wavelengths are comparable to the the longitudinal bunch length. The enhancement factor should be equal to the number of electrons in a bunch, in comparison with that of usual incoherent SR.

A positive sign of the coherent effects of SR was reported by Yarwood et al.⁵ in 1984 who used the Synchrotron Radiation Source (SRS) at Daresbury. However, the coherent SR from a storage ring has not been conclusively confirmed. Schweizer et al.⁶ could not observe any enhancement in the wavelength range from 1 μm to 667 μm at the storage ring BESSY with the bunch length of about 3 cm. Williams et al.⁷ could observe no enhancement in the wavelength region from 30 μm to 400 μm , using the National Synchrotron Light Source ring, BNL, with the bunch length of 30 cm. Nanba et al.⁸ also obtained a negative result in the millimeter region with the bunch length of 6 cm at the UVSOR facilities of the Institute for Molecular Science. They, all, have intended to observe radiations which wavelengths were much shorter than the bunch lengths in their experiments.

Experimental Method

We observed the coherent effects of SR for the first time in the far-infrared region using the Tohoku 300 MeV Linac in 1989⁹⁻¹² and have extended our work thereafter.^{13,14} Fig. 1 shows the layout of our recent experimental setup. The energy of electrons delivered from the linac was 150 MeV and a bending radius of the electron orbit was 2.44 m, then the characteristic wavelength of the SR was 404 nm. A duration of the bunch train was 2 μs and its repetition rate was 300 pulses/sec. The average beam current was measured by a secondary emission monitor SEM at the downstream of the bending magnet. The longitudinal bunch length was estimated to be about 1.7 mm at the light emitting point P, where the transverse bunch size was about $2 \times 2 \text{ mm}^2$ and the beam energy spread was 0.2 %. The number of electrons in the bunch was about 3.6×10^6 at average beam current of 1 μA .

Emitted SR was collected using a spherical mirror with the acceptance angle of 70 mrad and was led to a homemade far-infrared spectrometer of Czerny-Turner type through a crystal quartz window. Five echelette gratings of 5, 2.5, 1.25, 0.625 and 0.3125 grooves/mm were prepared to obtain a precise spectrum of coherent SR in the wavelength region from 0.1 mm to 4.0 mm. The grating was used together with a set of short- and long-wavelength-cut filters; the former was used to eliminate the higher order light of the grating, and the latter to cut off the stray light caused by the property of coherent SR which was stronger

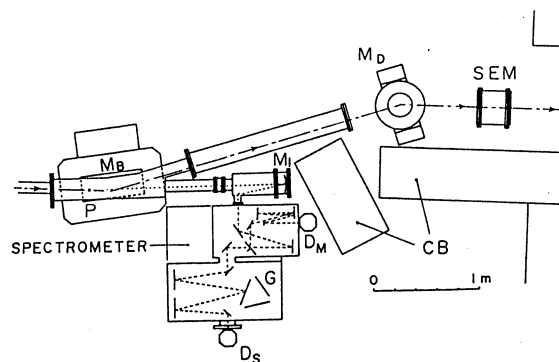


Fig. 1. The experimental setup. P: light emitting point of SR, M_B : bending magnet, M_D : dumping magnet, SEM: secondary emission monitor, M_1 : collecting mirror, G: gratings, D_S and D_M : LHe-cooled detectors for signal and SR monitor, and CB: concrete blocks for radiation shield. Trajectory of bunched electron beam is shown by a chain line.

at the longer wavelengths. The resolution of the spectrometer was about 0.1 cm^{-1} at $\lambda \sim 1 \text{ mm}$.

The SR was detected by a LHe-cooled silicon bolometer D_S and its signal was transmitted to an amplifier phase-locked to the 10 Hz chopper mirror. The radiation reflected by the chopper was converged onto monitor bolometer D_M , which was used to correct the SR intensity fluctuation caused by the drift of electron beam intensity. All optical components were set in a vacuum tank to eliminate the absorption loss by water vapor.

Experimental Results

The spectrum of coherent SR was observed in the wavelength range from 0.16 to 3.5 mm.¹³ The observed spectrum is shown in Fig. 2.

The spectrum shows a broad peak at $\lambda \sim 1.5 \text{ mm}$, and the peak intensity is enhanced by a factor of 5×10^6 in comparison with the usual incoherent SR. The enhancement factor is comparable with the number of electrons in a bunch, 3.6×10^6 .

The intensity of SR at wave number σ from one bunch which includes N_e electrons, is given by²

$$P_{coh}(\sigma) = p(\sigma)N_e[1 + (N_e - 1)f(\sigma)] \approx p(\sigma)N_e^2 f(\sigma), \quad (1)$$

$$f(\sigma) = \left| \int_{-\infty}^{\infty} \exp(2\pi i \sigma x) S(x) dx \right|^2, \quad (2)$$

where $p(\sigma)$ is the intensity of SR emitted by single electron at wavenumber $\sigma (= 1/\lambda)$, x is a curvilinear coordinate along the circular orbit and $f(\sigma)$ is a bunch form factor defined by the Fourier transform of $S(x)$, the density distribution function of an electron in a bunch. The value of the bunch form factor varies from zero at wavelengths $\lambda \ll x$ (incoherent limit) to unity at $\lambda \gg x$ (coherent limit).

By the definition, the bunch form factor Eq. (2) is symmetry, $f(-\sigma) = f(\sigma)$. Therefore, the inverse Fourier transformation of $f(\sigma)$ gives only the even component of the distribution function.

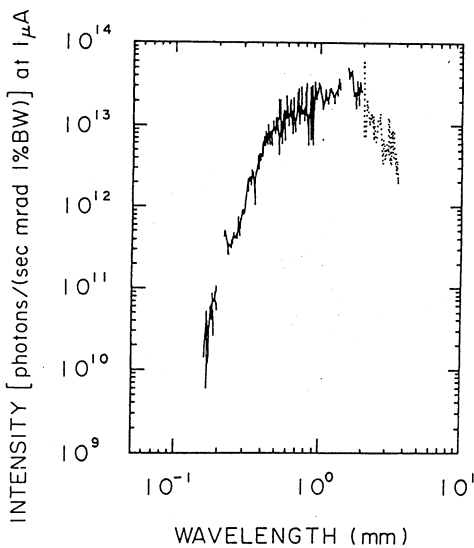


Fig. 2. The observed spectrum of coherent SR. The intensity was calibrated by a blackbody radiation of 1500 K.

$$S(x) = \int f(\sigma)^{1/2} \cos(2\pi\sigma x) d\sigma. \quad (3)$$

The electron distribution function derived from the observed spectrum by Eq. (3) is shown in Fig. 3. The bunch shape resembles a Gaussian function with a sharp peak. The longitudinal bunch length (full width at half intensity of the peak) is about 0.25 mm, which is much shorter than the estimated bunch length of 1.7 mm.

Fig. 3 shows that the electrons are confined in the narrow length along the circular orbit, $|x| < 0.4 \text{ mm}$. Hence, according to the asymptotic property of Eq. (2), the bunch form factor in the range $\lambda > 1.6 \text{ mm}$ should increase monotonically to unity, as the wavelength increases. On the contrary, the observed bunch form factor decreases towards longer wavelength. Coherent SR might be suppressed by a metallic boundary condition².

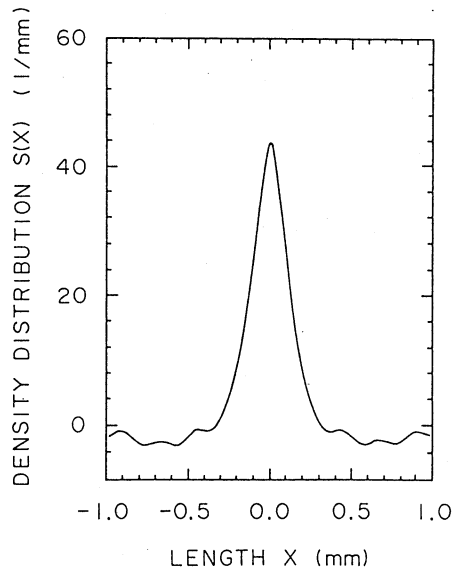


Fig. 3. The electron distribution function in the bunch obtained from the observed spectrum.

Interference Experiment of SR

To clarify the emission mechanism of coherent SR, an interference experiment has been performed,¹⁴ an interferogram of the light pulse of SR from the successive bunches was measured by a polarizing interferometer.¹⁶

The schematic layout of the interferometer is shown in Fig. 4. The distance L_B between the successive bunches was 104.97 mm.

The maximum optical pass difference between two arms was about 110 mm and covered L_B . Two wire grid polarizers, WG1 and WG2, had the wire spacing of $25 \mu\text{m}$. The angle between the direction of WG1 and the electron orbital plane was 45 degree, and the angle of WG2 was 0 degree. The radiation was detected by two LHe-cooled Silicon bolometers; one was used to observe the interferogram and the other was used to monitor the intensity of SR.

Fig. 5 shows the observed interferogram. It is clearly shown that the interference modulation at the optical pass difference around zero is repeated at the optical pass difference around L_B . When the optical pass difference is L_B , the interferogram shows a sharp minimum just like the one observed at the optical pass difference of zero.

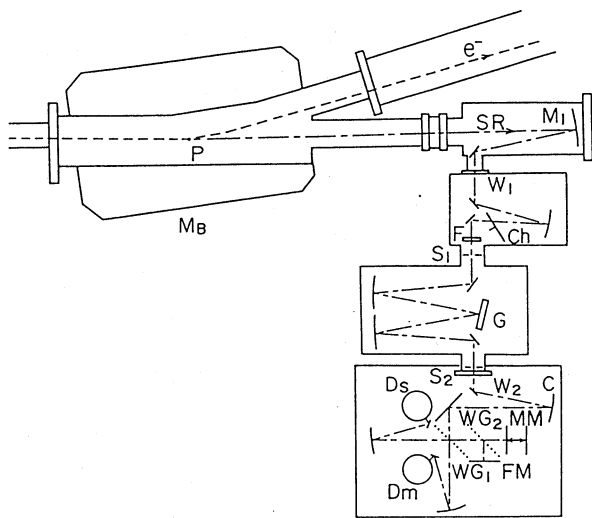


Fig. 4. Schematic layout of setup for the interference experiment. M_B : bending magnet, M_I : collecting mirror of SR, W_1, W_2 : wedged quartz windows, Ch: chopper, F: filter set, G: grating, S_1, S_2 : slits, C: collimator of the interferometer, WG_1, WG_2 : wire grids, FM: fixed mirror, MM: moving mirror, D_S, D_M : LHe-cooled Silicon bolometers for interferometer and monitor. The grating in the spectrometer was replaced by a plane mirror during the interference measurement.

The interferogram around the zero optical pass difference shows interference of SR from a bunch with itself and the one around L_B shows interference of SR between the next neighbor bunches. The result clearly indicates that SR from every bunch is coherent, and SR from the individual bunches are indistinguishable.

Conclusion

A complete spectrum of coherent SR in the wavelengths from 0.16 to 3.5 mm was obtained by the far-infrared spectrometer and the bunch length was calculated to be about 0.25 mm by the Fourier transform.

We observed the direct evidence of the coherence by interference experiment in addition to the supporting evidences, i.e. the SR intensity was enhanced by about N_e and is proportional to N_e^2 .⁹⁻¹² These results might be significant information to understand the emitting process of coherent SR.

Recently, our results have been supported by Blum et al.¹⁶ using a linear accelerator at Cornell University.

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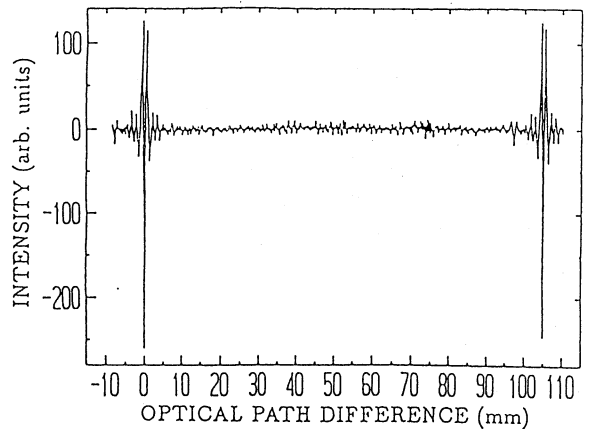


Fig. 5. Observed interferogram of coherent SR. Sampling interval was 0.1 mm in the optical pass length.

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