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Observation of interference between coherent synchrotron radiation from periodic bunches

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An interferogram of synchrotron radiation emitted from a train of bunched electrons accelerated by an *S*-band linac has been observed in the far-infrared region using a polarizing interferometer whose maximum optical path difference covers a distance between adjacent bunches. The interferogram shows that radiation emitted from successive bunches is coherent, and that coherent synchrotron radiation emitted from periodic bunches has a spectrum of a line series, i.e., higher harmonics of the radio frequency of the linac.

At the early stage of synchrotron study, coherent synchrotron radiation (SR) from bunched electrons was treated theoretically [1,2]. Several years ago, intense coherent SR in the far-infrared region from electron storage rings was predicted by Michel [3], by analogy with the intense radio-frequency radiation from the pulsar. However, coherent SR from storage rings has not clearly been observed in the far-infrared region [4-6], since coherent SR is expected in the wavelength range comparable to or longer than the longitudinal length of the bunch, which is typically a few centimeters or more in the storage rings. The coherent SR in the submillimeter and millimeter wavelength range was first observed using a linear accelerator [7,8], in which the bunch length was estimated to be about 2 mm. The observed intensity was enhanced by a factor of about 1×10^6 in comparison with usual incoherent SR, and was proportional to the square of an electron-beam current. The enhancement factor was the same order of magnitude as the number of electrons in the bunch.

According to the classical electrodynamics, the electric field at an observation point is related to the current-density vector describing an electron beam [9,10]. If two electrons follow the same trajectory with a given time delay, a certain phase difference between the two radiation fields is determined and interference between the two fields will be observed.

To elucidate the coherence effects of SR from periodic bunches, an interference experiment has been carried out in the far-infrared region; an interferogram of the light pulse of SR from the periodic bunches was measured by a polarizing interferometer [11], whose maximum optical path difference (OPD) covered the bunch distance L_B, i.e., a distance between the adjacent bunches in a bunch train.

The experimental assembly is shown in Fig. 1. Electrons accelerated by the Tohoku 300-MeV linac were led into a magnetic field of 0.206 T to emit SR. The energy of electrons and the energy spread were 150 MeV and 0.2%. The radius of the electron orbit and the characteristic wavelength of SR were 2.44 m and 404 nm, respectively. The accelerating rf frequency of the linac was 2856 MHz and a repetition of a burst was 300 pulse/sec. The burst means a train of bunched electrons with a duration of 2 μsec (see Fig. 2). The bunch distance L_B was 104.97 mm. A longitudinal bunch length was estimated to be about 2 mm from the characteristics of the linac. The average beam current was observed by a secondary emission monitor downstream of the bending magnet, and it was about 0.5 μA during the experiment.

Emitted SR was collected by a round spherical mirror M1 in Fig. 1 with the acceptance angle of 70 mrad, and propagated into a polarizing interferometer. The maximum OPD between two arms was 110 mm. Two wire grid polarizers, G1 and G2, had the wire spacing of 25 μm. The angle between the direction of the wire of G1 and electron orbital plane was 45°, and that of G2 was 0°. The radiation was detected by two helium-cooled Si bolometers; one was used to observe the interferogram and the other to monitor the intensity fluctuation of SR

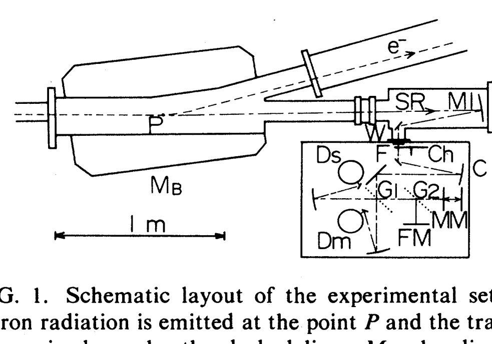

FIG. 1. Schematic layout of the experimental setup. Synchrotron radiation is emitted at the point *P* and the trajectory of electrons is shown by the dashed line. M_B: bending magnet; M1: collecting mirror of SR; W: wedged quartz window; Ch: chopper; F: filter; C: collimator; G1, G2: wire grids; FM: fixed mirror; MM: movable mirror; Ds, Dm: helium-cooled Si bolometers for interferometer and monitor.

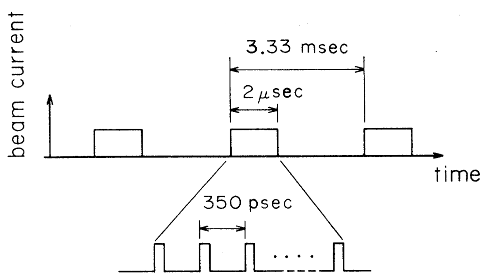

FIG. 2. Schematic diagram of temporal structure of an electron beam from the linac. A burst includes about 5.7×10^3 bunches and the distance between successive bunches is 104.97 mm.

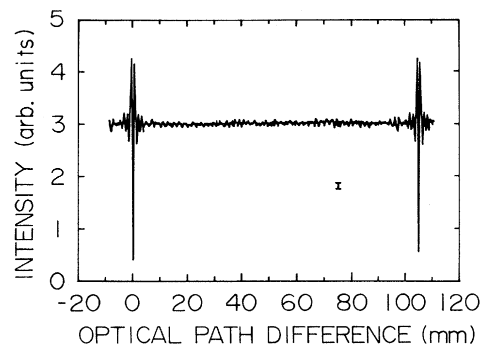

FIG. 3. An observed interferogram of coherent SR. Sampling interval was 0.1 mm in the optical path length. The vertical bar shows 3 times the standard deviation of the measurement.

due to beam instability. Though the upperstream of the quartz window was in vacuum, the interferometer was under the atmospheric condition.

Figure 3 shows an observed interferogram, which has been corrected for the beam fluctuation. The interferogram was observed using a low-wave-number-pass filter of 35 cm^{-1}, i.e., a long-wavelength-pass filter of 285 μm, and a sampling interval was 0.1 mm in the optical path length. It is clearly shown that the interference modulation at the OPD around zero is repeated at around L_B. Figure 4 shows the comparison of the two minima in an expanded scale. The interference pattern at the OPD around L_B is in agreement with the one at around zero within the accuracy of the experiment.

The interference modulation at the OPD around zero shows interference of radiation from a bunch with itself and the one around L_B shows interference between radiation from the adjacent bunches. The result indicates that SR from every bunch is coherent and electric fields at the observation point by the j and $j+1$ bunches satisfy the relation $F_j(X,t)=F_{j+1}(X-L_B,t)$, where X is an optical path length of the observation point from the emission one.

The result is interpreted as follows. We consider light pulses of SR emitted from a train of bunched electrons and treat the phase relation of electromagnetic waves [12]. Let x be a curvilinear coordinate along the circular orbit, and r_m and r_f the optical path lengths of the interferometer for the movable and the fixed arms, respectively. Then, the electric field at the observation point is given by

$$E_T(\lambda)=\sum_{j=1}^{N_B} E_0(\lambda)K(\lambda)\{\exp[-i2\pi(r_m-jL_B)/\lambda]+\exp[-i2\pi(r_f-jL_B)/\lambda]\}\left(\sum_{n=1}^{N_e}\exp(-i2\pi x_{jn}/\lambda)\right), \quad (1)$$

where N_e and N_B stand for the total number of electrons in a bunch and the total number of bunches, $|E_0(\lambda)|^2$ is the intensity of SR at wavelength λ from one electron [13], and $|K(\lambda)|^2$ is the efficiency of the beam divider. The notation x_{jn} indicates the position of the nth electron in the jth bunch relative to the bunch center and $S(x)$ is a density distribution function of an electron in one bunch. Then, the interferogram is given by [11]

$$\int E_T E_T^* d\lambda = 2\int B(\lambda)|K|^2 \times\{1-\cos[2\pi(r_m-r_f)/\lambda]\}d\lambda\,, \quad (2)$$

$$B(\lambda)=|E_0(\lambda)|^2 G(\lambda) N_e^2 f(\lambda)\,, \quad (3)$$

$$f(\lambda)=\left|\int \exp(-i2\pi x/\lambda)S(x)\,dx\right|^2, \quad (4)$$

$$G(\lambda)=\left|\sum_{j=1}^{N_B}\exp(i2\pi jL_B/\lambda)\right|^2 =[\sin(\pi L_B N_B/\lambda)/\sin(\pi L_B/\lambda)]^2\,, \quad (5)$$

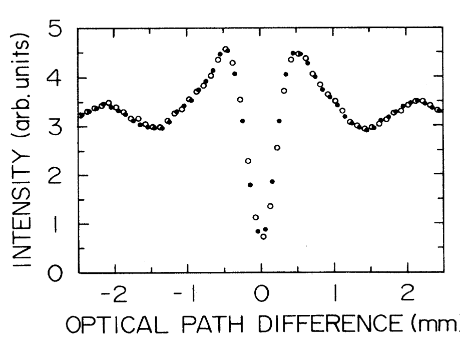

FIG. 4. Comparison of the two minima in the observed interferogram in Fig. 3. Sampling data at the optical path difference around zero are given by open circles, and those around 105 mm are given by solid circles after shifting abscissa by the bunch distance L_B.

where $B(\lambda)$ stands for the spectrum of coherent SR from the periodic bunches, and $f(\lambda)$ the bunch form factor. The function $G(\lambda)$ gives the interference effect due to the successive bunches.

When the OPD approaches the bunch distance, it can be replaced by

$$r_m-r_f=L_B+r_m'-r_f\,, \quad (6)$$

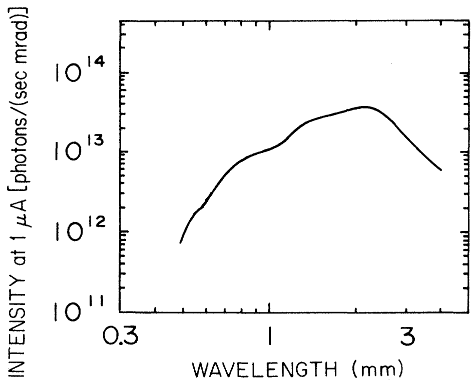

FIG. 5. A low-resolution spectrum of coherent SR transformed from the observed interferogram. Resolution of the spectrum ($\Delta\nu$) is about 2 cm^{-1} (60 GHz). The intensity of the ordinate is given in units of photon numbers per second per 1 mrad of the orbit per bandwidth of 1%, i.e., per $\Delta\nu/\nu=0.01$, at the beam current of 1 μA.

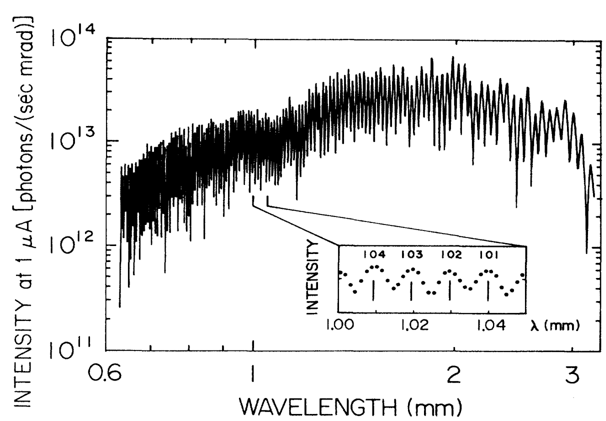

FIG. 6. A high-resolution spectrum of coherent SR transformed from the observed interferogram. The resolution is about 0.09 cm^{-1} (2.7 GHz). The intensity of the ordinate is given in units of photon numbers per second per 1 mrad of the orbit per bandwidth of 1%, i.e., per $\Delta\nu/\nu=0.01$, at the beam current of 1 μA. In the inset, the spectrum in the narrow wavelength range, 1.00 mm $<\lambda<$ 1.05 mm, is given by solid circles. The vertical bars and the figures in the inset show the peak position and order of the higher harmonics of ν_B, 2856 MHz.

where $r_m'-r_f$ shows a relative coordinate shifted by L_B. Then, the interferogram is expressed as

$$\int E_T E_T^* d\lambda = 2\int B(\lambda)|K|^2\{1-\cos[2\pi(r_m'-r_f)/\lambda] + O(1/N_B)\}d\lambda\,. \quad (7)$$

When $N_B \gg 1$, the interference pattern around the OPD zero is repeated every L_B, as has been observed.

The factor $G(\lambda)$ in Eq. (3) shows rapid oscillations with the wavelength. When $N_B \gg 1$, the spectrum of SR from the periodic bunches is composed of a series of lines. Frequencies of the lines are given by higher harmonics of the fundamental frequency defined by $\nu_B=c/L_B$, i.e., the radio frequency of the linac, 2856 MHz. The interference effect can be measured only with an apparatus whose resolution is higher than ν_B. When the resolution is lower than ν_B, $G(\lambda)$ reduces to its average, N_B [12]. Then, Eq. (3) gives the continuous spectrum proportional to the spectral intensity of coherent SR from the single bunch.

Figure 5 shows the low-resolution spectrum transformed from the double-sided interferograms. The maximum OPD was 5 mm; hence the resolution was about 2 cm^{-1} (60 GHz), and the spectrum was continuous. The spectral intensity was calibrated by a blackbody radiation source of 1500 K, which was located at the emission point of coherent SR. The accuracy of the absolute intensity of coherent SR is estimated to be within a factor of 1.5. Figure 6 shows a high-resolution spectrum transformed from the one-sided interferograms. The maximum OPD was 110 mm and the resolution of 0.091 cm^{-1} (2.7 GHz) was higher than ν_B. As shown in the inset of Fig. 6, the spectrum shows oscillations corresponding to the higher harmonics of the rf frequency of the linac, 2856 MHz. A similar line structure has been predicted for coherent Čerenkov radiation in the microwave region [14].

The observed spectrum in Fig. 5 has a broad peak around $\lambda\sim 2$ mm, and the peak intensity is enhanced by a factor of 7.9×10^6, in comparison with the calculated intensity of ordinary incoherent SR. The enhancement factor is the same order of magnitude as the average number of electrons in a bunch, 3.6×10^6. The spectrum is qualitatively in agreement with the previous result [12]. The peak wavelength is, however, about 1.5 times as long as the previous one. The reason for this discrepancy is not clear at present, but is considered to be due to changes of some conditions in the linac.

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