Observation of Coherent Synchrotron Radiation

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Coherent effects in synchrotron radiation (SR) have been observed for the first time from 180-MeV short electron bunches of 2.5 mm using the Tohoku 300-MeV Linac. The intensity of the coherent SR was about 10^5 times as strong as that of incoherent SR in the wavelengths of 0.4–2.2 mm. This enhancement factor corresponds to the number of electrons in a bunch. The SR intensity showed a quadratic dependence on the electron beam current. The radiation was mainly polarized in the orbital plane. The possibility of induced rf in a vacuum chamber was excluded experimentally.

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An intense coherent synchrotron radiation (SR) might be produced in the far-infrared region in a storage ring where small bunches of electrons circulate. This possibility was proposed by Michel[1] in 1982. The enhancement due to the coherent effect is expected to be N, where N is the number of electrons in a bunch. Thus from storage rings which have about 10^{10} electrons in a bunch we might be able to obtain intense photon flux with a continuous spectrum at far-infrared wavelengths. A positive sign of the presence of coherent SR has been observed by Yarwood *et al.*[2] at the Synchrotron Radiation Source (SRS), Daresbury. However, its existence has not been conclusively established by their experiments as well as by Schweizer *et al.*[3] at the BESSY, Berlin. In a recent experiment, Williams *et al.*[4] could observe no enhancement in the wavelength region of 30–400 μm due to the long bunch length (about 30 cm) of the BNL National Synchrotron Light Source ring. According to Michel, the enhancement due to the coherent effect can be expected in a wavelength region comparable to the longitudinal bunch length. Since the longitudinal bunch length of an electron linac is generally much shorter than that of an ordinary electron storage ring, we used the Tohoku 300-MeV Linac[5] to observe the SR in the long-wavelength region. In this paper we will present experimental results showing the evidence of coherent SR.

The assembly of this experiment is shown in Fig. 1. A

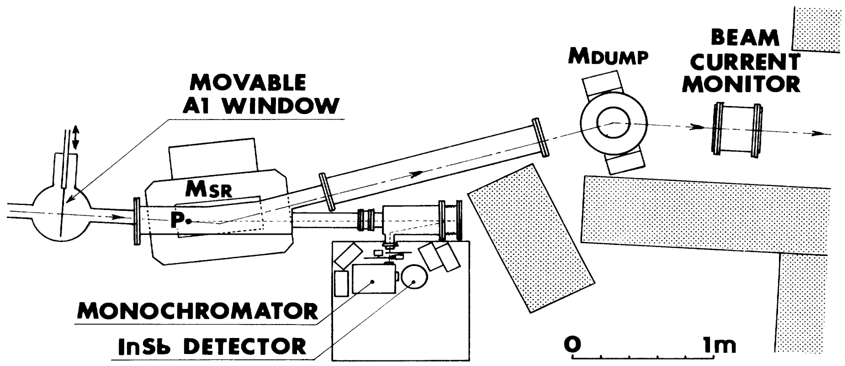
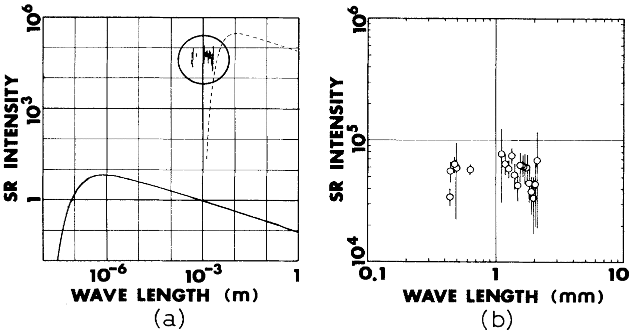


FIG. 1. Experimental assembly. The chain line with arrows shows an electron-beam trajectory. The point P in the bending magnet M_{SR} is the light emitting point of the SR. M_{dump} is used to dump the electron into the beam catcher through the beam-current monitor.

magnetic field was applied to the 180-MeV electron beam to produce SR. The strength of the bending magnetic field was 0.247 T at the light emitting point on the electron orbit. As a consequence, we obtain a bending radius of 2.44 m and a characteristic wavelength λ_c of ordinary SR of 230 nm. A duration of the burst, or the electron bunch train, is 0.1–2 μsec and its repetition is 300 pulses/sec. The average beam current can be varied continuously from 0 to 300 nA by a beam profile defining slit at the last stage of the linac, which scrapes the electron bunches. The average beam current was measured by a secondary-emission monitor downstream of the bending magnets. The accelerating rf frequency in Tohoku 300-MeV Linac is 2856 MHz. As the phase distribution of a bunch was estimated[6] to be about 5°, the longitudinal bunch length was about 1.5 mm. In passing through the beam transport system from the linac to the experimental room, the bunch length was stretched to about 2.5 mm at the light emitting point, where the transverse bunch size was about 2×2 mm^2 and the beam energy spread was 0.2%.

Emitted SR was collected by a concave mirror with an acceptance of 70 mrad, dispersed with a 30-cm Littrow-type grating monochromator and detected by a liquid-He-cooled InSb bolometer. Three gratings of 0.5, 1, and 2 grooves/mm were prepared to cover over the wavelengths from 0.4 to 2.2 mm. The monochromator was complemented by long-wave pass filters with cutoff wavelengths of 0.33 and 1.0 mm, a quartz plate, and black polyethylene. Its resolution $(d\lambda/\lambda)$ was about 0.1. The absolute sensitivity of this measuring system was calibrated with a 140-W mercury discharge lamp, which was assumed as a blackbody-radiation source of 4000 K [7,8] in these wavelengths. The optical geometries, such as the solid angle or the f number, were considered in the above calibration. The radioactive background noise has been measured to be negligible.



(a) (b)

FIG. 2. Observed spectrum of coherent SR. The data points in the circle in (a) are enlarged in (b). A unit of SR intensity is (photons/bunch)/(mrad/1% bandwidth), i.e., the number of photons which are emitted by a bunch of electrons for 1 mrad of the electron orbit arc and for a 1% bandwidth. Data in these figures are measured at the average beam current of 250 nA, which corresponds to about 1×10^6 electrons in a bunch on the average. The intensity of ordinary incoherent SR calculated for the same experimental condition is shown by a rigid curve for comparison. The dashed curve shows the coherent SR intensity for a Gaussian bunch shape with $2\sigma = 2.5$ mm expected by theory (Refs. 4 and 9). The observed spectrum suggests that the beam of the linac has a complicated bunch structure, which has higher Fourier components in its bunch form factor, more than that of a Gaussian form. The bars on the data points show the fluctuation of SR intensity caused by the beam instability during the measurement.

Figure 2 shows the spectrum of SR observed together with a curve calculated for ordinary incoherent SR. The intensity of SR is drastically enhanced compared to that of incoherent SR calculated. Now consider an enhancement factor g defined as $g=$ (measured intensity of SR)/(calculated intensity of incoherent SR). Hence, the enhancement factor g is about 10^5 for Fig. 2. Taking account of the bunch form factor, we consider that this value corresponds roughly to the average number of the electrons in a bunch, N, which is estimated at be 10^6 for the beam current of these experiments. At the wavelength of 2 mm, a relation $g \simeq 0.15N$ has been obtained for $N < 5\times10^6$. Therefore the value of the bunch form factor was considered to be 0.15 for this wavelength.

The dependence of the SR intensity on the electron beam current was also measured. The results are shown in Fig. 3 for the wavelength of 2 mm. The observed SR intensity is clearly proportional to the square of the electron beam current. According to theory[1,4,9] of the coherent SR, its intensity is proportional to N^2, and moreover, is enhanced by N times to that of incoherent SR. From these two criteria, we conclude that we observed coherent SR in the wavelength region from 0.4 to 2.2 mm.

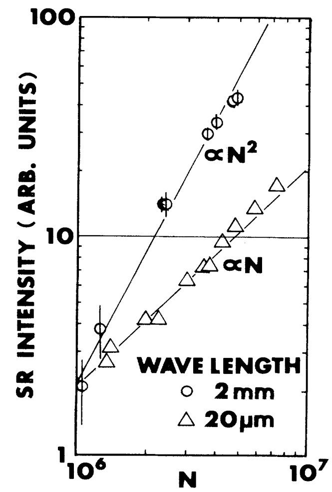


FIG. 3. Beam-current dependence of the SR intensity. N is the number of electrons in a bunch, which is proportional to the electron beam current. The SR intensity is proportional to N^2 at a wavelength of 2 mm, while to N at 20 μm. The values of intensity should not be compared between the two wavelengths.

Previously, we measured the SR intensity in the shorter wavelengths between 3 and 30 μm by using wide-band-pass filters.[10] At a wavelength of 20 μm the SR intensity was proportional to the electron beam current as shown in Fig. 3, although absolute calibration of the intensity was not made. In this wavelength region coherent SR was not ascertained. Therefore a big growth of the SR intensity is expected in the wavelengths between 30 and 300 μm. Measurements around this region will be carried out in the near future.

The spectrum of coherent SR corresponds to the square of the bunch form factor.[4,9] In Fig. 2(b) the obvious intensity decrease in not evident in the region of the shorter wavelength than the longitudinal bunch length of 2.5 mm. This spectrum suggests that the electron bunch from the linac has a complicated form. For, if it had a simple shape like a Gaussian, the intensity of coherent SR would change drastically, like the theoretical curve in Fig. 2(a), around the wavelength comparable to the bunch length. A study of bunch shape will give us important information to understand the mechanism of the coherent SR production.

The degree of polarization P is defined as $P=(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp})$, where $I_{\parallel}$ and $I_{\perp}$ are the SR intensities which have an electric vector parallel and perpendicular to the orbital plane, respectively. The polarization of coherent SR has been measured to be $P=0.6$–0.7 for the wavelength region from 0.3 to about 2 mm; i.e., the radiation is mainly polarized in the orbital plane. On the other hand, the calculated P for incoherent SR in the same optical aperture is 0.62 and 0.80 for wavelengths of 0.3 and 2 mm, respectively. These results suggest that the angular distribution of coherent SR is similar to that of incoherent SR. In addition, by calculating the vertical angular distribution for incoherent SR, the optical acceptance is obtained to be 74%, 51%, and 40% of total intensity integrated over all the vertical angles for wavelengths of 0.3, 1.0, and 2.0 mm, respectively. In Fig. 2 the data points were not corrected by the optical acceptance because of the lack of knowledge about the vertical angular distribution of coherent SR; i.e., 100% vertical acceptance is assumed.

When a bunch of charged particles passes through a vacuum chamber, an rf electromagnetic field will be excited in it. The properties of induced rf are similar to those of coherent SR. The rf intensity is proportional to the square of the beam current, or N^2, and its spectrum depends on the bunch form factor. One must distinguish coherent SR from induced rf. The value of the rf wake can be calculated by the knowledge of the impedance of the vacuum chamber.[11] Using the impedance function measured at the Intersecting Storage Ring,[12] CERN, and assuming that the bunch is a δ-function-like point charge of 10^6e, we estimated the order of the rf intensity induced in the vacuum chamber near the light emitting point. The spectral energy deposit by the rf wake at 1-mm wavelength with 1% bandwidth per unit vacuum chamber length per one bunch is estimated to be about 5×10^{-16} J/(1% bandwidth/m), while the radiation intensity measured in our optical solid angle was about 3×10^{-15} J/(1% bandwidth) in the same conditions. The calculated value of the rf wake is an overestimation because we assumed a point charge. Although this estimation is negligibly small in comparison with radiation measured, we confirmed the influence of induced rf experimentally.

The rf power, which is induced in a long vacuum chamber in the upper stream of the light emitting point, will come down through the chamber to the optical measuring system. In order to intercept the rf power from the upper stream, a thin movable aluminum window was set as shown in Fig. 1. No difference in the radiation intensity was observed when the window was inserted. If the induced rf intensity was considerable, the radiation intensity must be changed by the interception. Therefore, a possibility of the influence of the induced rf has been excluded by this result. The degree of polarization of 0.6–0.7 is another reason to stand for coherent SR instead of rf wake. It is hardly possible for the rf wake, which is diffused in the vacuum chamber, to have such a strong polarization.

It is demonstrated that the bunched electron beam accelerated by a linac has sufficient feasibility as a strong light source in the milli-submillimeter wave region. Suppose the bending radius of 1 m, a 100-MeV electron linac with a high peak current, is suitable for applications. A single bunch of 5×10^{10} electrons with length of 1.5 mm has been already obtained.[13] The experiments for the transient phenomena will be enabled by the intense pulse radiation from the electron linac beam.

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