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COHERENT SYNCHROTRON RADIATION

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Abstract Coherent effects in synchrotron radiation (SR) have been observed for the first time from 180 MeV short electron bunches of 1.7 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 at wavelengths of 0.33 to 2.0 mm. This enhancement factor roughly 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.

INTRODUCTION

The possibility of intense coherent synchrotron radiation (SR) in an electron storage ring was proposed by F.C.Michel[1] in 1982. A small bunch of the electrons might emit coherent SR at wavelengths which are comparable to or longer than the longitudinal bunch length. The SR intensity was expected to be intensified by the number of electrons in a bunch, which is about 10^{10} in case of an ordinary electron storage ring. Therefore we might be able to obtain an intense photon flux with a continuous spectrum in far-infrared or milli/submillimeter wavelengths. In this paper we will take "bunch length" to be the longitudinal bunch size.

A positive sign of the presence of coherent SR has been observed by J.Yarwood et al.[2] in SRS, Daresbury. However, its existence has not been conclusively established by their experiments nor by those of E.Schweizer et al.[3] in BESSY, Berlin. In a recent experiment G.P.Williams et al.[4] at NSLS, BNL could observe no enhancement. In these experiments the wavelength region observed was much shorter than the bunch length, which is several centimeters in the ordinary storage rings.

A short bunch of a few millimeters is obtained from an electron linac. We used the Tohoku 300 MeV Linac to observe the SR spectra at milli/submillimeter wavelengths, which are comparable to the bunch length of this linac. In this paper we will present experimental results showing evidence of coherent SR for the first time.

EXPERIMENTAL METHOD

At a light emitting point "P" in FIGURE 1. a magnetic field of 0.247 T was applied to the 180 MeV electron beam to produce SR. In the Tohoku Linac the accelerating rf frequency was 2856 MHz and the repetition of the burst was 300 pps, where each burst is a train of bunches with a duration of 0.1 to 2 micro sec. Therefore, in the case of 2 micro sec duration, there were 1.7×10^6 bunches per sec. The average beam current was monitored with a secondary emission monitor downstream of the bending magnets and could be varied to a maximum of 2 micro amps by a beam profile defining slit at the last stage of the linac.

In terms of the rf-phase the phase width of bunches leaving the linac was estimated to be 5 degrees[5], which corresponds to about 1.5 mm in bunch length. The bunch length at the point "P" was stretched due to the dispersion of the beam energy analyzing magnets. As the beam energy spread was selected to be 0.2 % with an energy analyzing slit, the bunch length at "P" was estimated to be about 1.7 mm. A long bunch of 15 mm could be obtained using an energy compressing system[5] (a debuncher).

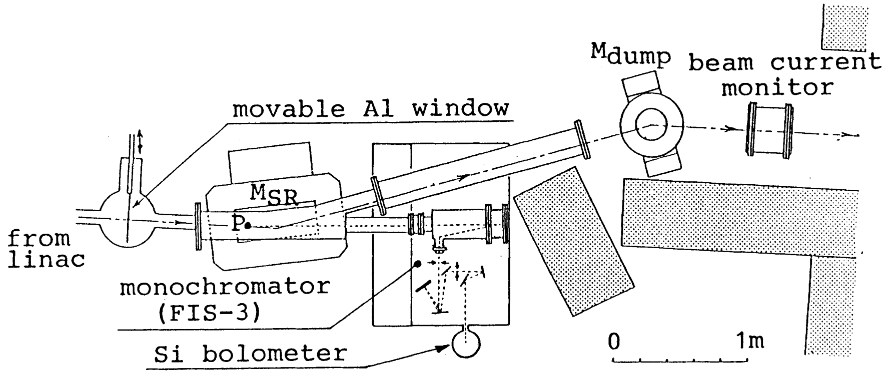

FIGURE 1. Experimental assembly. The chain line with arrows shows an electron beam trajectory. The point "P" in the bending magnet M_{SR} is an SR light emitting point. M_{dump} is used to dump the electrons into a beam catcher through a beam current monitor.

Emitted SR was collected by a concave mirror with an acceptance of 70 mrad. The SR spectrum was monochromatized by gratings and long-wave pass filters in the FIS-3 far-infrared spectrometer[6] (Hitachi Co. Ltd.), and detected with a liquid-He-cooled Si bolometer. To avoid absorption by water vapor all the light passage was evacuated. The only material in the light path was a quartz window separating the beam line vacuum and the monochromator vacuum. The resolution of the monochromator was about 1 cm^{-1}. The radioactive background noise has been measured to be negligible.

The absolute sensitivity of this measuring system was calibrated with a mercury discharge lamp, which was supposed to be a blackbody radiation source of 4000 K[7,8] at these wavelengths. The SR intensity at visible wavelengths was measured with the same optical system and same calibration procedure in order to confirm the correctness of the absolute data. A photomultiplier tube with color glasses and interference filters was used instead of the Si bolometer. A calibrated halogen lamp was used as a standard visible light.

EXPERIMENTAL RESULTS

As is shown in circle "A" of FIGURE 2.(a), the SR intensity is drastically enhanced at long wavelengths, comparable to the bunch length. The enhancement factor, defined as the ratio of intensities of observed SR and calculated incoherent SR, is 1.5 to 7.0X10^5 for "A". According to the theory[4] of coherent SR, this enhancement factor is a product of N, the number of electrons in a bunch, and the square of the bunch form factor, the Fourier transform of the spatial electron distribution in a bunch. As the SR intensity is normalized for N = 10^6, the bunch form factor at these wavelengths is considered to be 0.4 to 0.8 for a 1.7 mm bunch. In contrast with "A", the intensity for the 15 mm bunch shown in "B", and so also the square of the bunch form factor, reduced by a factor of about 10^{-4}. Data in "C" at visible wavelengths are consistent with the calculated incoherent SR, and this confirms the absolute magnitude of the data in this experiment. However, the data points in this figure are not corrected for the vertical acceptance because of lack of knowledge about the vertical angular distribution of coherent SR, i.e. 100 % vertical acceptance is assumed. An obvious intensity decrease is not perceptible in "A" at

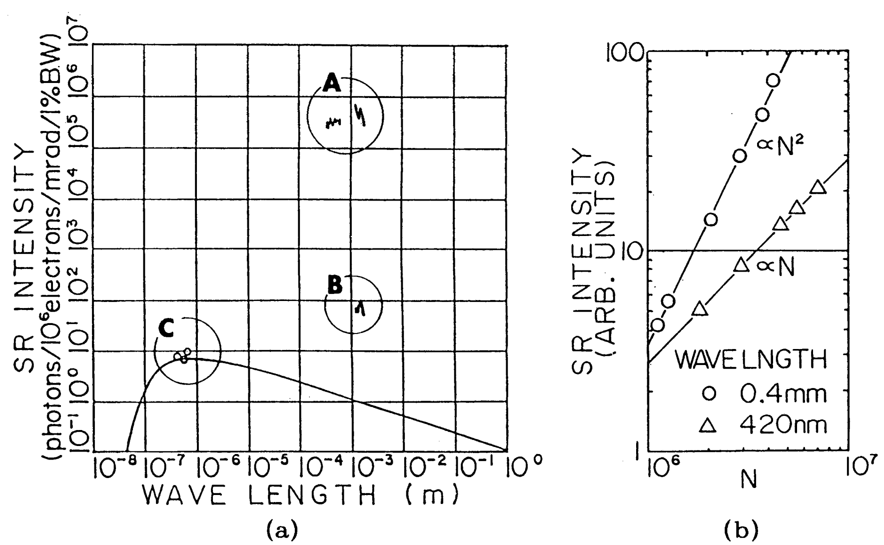

FIGURE 2. Observed SR spectra (a) and beam current dependence of the SR intensity (b). (a) Data in circle "A" and "C" are the spectra for the bunch length of 1.7 mm, and in "B" for 15 mm. All the data are measured with the same optical system. A solid curve shows the incoherent SR intensity calculated for this experimental condition. These intensities are normalized for a bunch of 10^6 electrons. (b) N is the number of electrons in a bunch, which is proportional to the beam current. The values of intensity should not be compared between two wavelengths.

wavelengths shorter than 1.7 mm, the bunch length. 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 around the wavelength comparable to the bunch length.

The SR intensity is proportional to N^2 at a wavelength of 0.4 mm, while to N at 420 nm (FIGURE 2.(b)). In the previous experiments in the same conditions[9] the SR intensity was almost proportional to N at a wavelength of 0.02 mm, though the absolute intensity was not measured. Therefore a big growth of the SR intensity is expected at wavelengths between 0.02 and 0.33 mm.

The degree of polarization P is defined as $P = (I_{//} - I_{\perp}) / (I_{//} + I_{\perp})$, where $I_{//}$ and $I_{\perp}$ are the SR intensities which have an electrical vector parallel and perpendicular to the orbital plane, respectively. The polarization of SR has been measured to be P = 0.73 and 0.92 at wavelengths of 0.4 and 1.5 mm, respectively. The radiation is mainly polarized in the orbital plane. For comparison the calculated P for incoherent SR for the same optical aperture is 0.64 and 0.77 at wavelengths of 0.4 and 1.5 mm, respectively. The diffraction correction must be done to compare these values with observed P.

The properties of induced rf in the vacuum chamber 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. The value of rf wake can be calculated by the knowledge of the impedance of the vacuum chamber. Extrapolating the impedance measured in the ISR[10], CERN, and assuming that the bunch is a point charge of 10^6e, we estimated the rf intensity induced in the vacuum chamber to be 3×10^6 photons/1%BW/m, at 1 mm wavelength, per unit vacuum chamber length. The radiation intensity detected in our optical solid angle was about $3\text{X}10^7$ photons/ 1%BW. Though this is an overestimate and negligibly small in comparison with radiation measured, we confirmed the induced RF effect experimentally. The rf power induced in a long vacuum chamber upstream will come down into the optical measuring system. To intercept this rf power, a thin movable aluminum window was set as shown in FIGURE 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. This result excludes the possibility of the influence of the induced rf. The degree of polarization of 0.73 to 0.92 is consistent with the production of coherent SR and not with the induced rf. It is hardly possible for the induced rf which diffuses in the vacuum chamber to have such a strong polarization.

CONCLUSION and DISCUSSION

The observed SR intensity is proportional to N^2 and enhanced by about N times that of incoherent SR. Induced rf effects were excluded experimentally. From these criteria, we conclude that we observed coherent SR produced by electron bunches at wavelengths of 0.33 to 2.0 mm.

It is demonstrated that the bunched electron beam accelerated by a linac has sufficient feasibility as a strong light source at milli/ submillimeter wavelengths. If we suppose a bending radius of 1 m, a 100 MeV electron linac with a high peak current is suitable for the applications. A single bunch of 5×10^{10} electrons with length of 1.5 mm has been already obtained[11]. Experiments for studying the transient phenomena will be enabled by the intense pulse radiation from the electron linac beam. Another promising application of coherent SR, especially for linear colliders, is a bunch form monitor, for its spectrum is regarded as the square of the bunch form factor.

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