A NEW STRONG RADIATION SOURCE BY AN ELECTRON LINEAR ACCELERATOR 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. An electron linear accelerator will be applied to a strong light source from infrared to millimeter wavelengths instead of the storage rings. The bunch length of shorter than 1 mm can be observed by the spectrum measurement of coherent SR.

Introduction

It was January, 1989 that the coherent synchrotron radiation (SR) was observed[1] for the first time from the short electron bunch obtained by the Tohoku 300 MeV linac. In this paper we will present further conformation and new experimental results.

Coherent effects of radiation in an accelerator were considered theoretically by L. I. Schiff[2] in 1946 as the power loss limiting the energy achieved by the accelerator. In 1982 the possibility of intense coherent SR in an electron storage ring was proposed by F. C. Michel[3] from viewpoint of the astrophysics of the pulsars. 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 an ordinary electron storage ring. Therefore we might be able to obtain an intense photon flux with a continuous spectrum in far-infrared to milli/submillimeter wavelengths.

A positive sign of the presence of coherent SR has been observed by J. Yarwood et al.[4] in SRS, Daresbury. However, its existence has not been conclusively established by their experiments nor by those of E. Schweizer et al.[5] in BESSY, Berlin. In a recent experiment G. P. Williams et al.[6] 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. In this paper we will take "bunch length" to be the longitudinal bunch size.

Experimental method

As the experimental equipment is described in detail in Ref.1, the parameters of the experimental condition is concluded in Table 1.

Table 1
Parameters of the experimental condition.

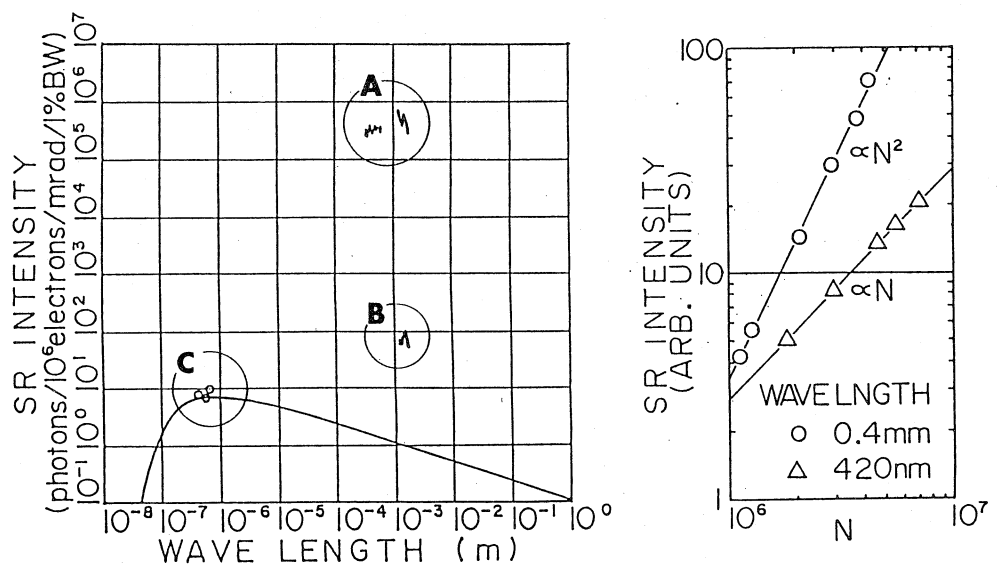
Accelerator	
Accelerating frequency	2856 MHz
Beam energy	180 MeV
Beam energy spread	0.2 %
Beam current	2 μA max
Pulse width of the burst	0.1 - 2 μsec
Repetition of the burst	300 Hz
Longitudinal bunch length	
without debuncher	1.7 mm
with debuncher	15 mm
SR measurement	
Bending magnetic field	0.247 T
Acceptance of SR	70 mrad
Analyzing range	0.1 - 2 mm
Resolution	1 cm^{-1}

Followings are those of improvement on the experiment of Ref.1.

A long bunch of 15 mm could be obtained by using an energy compressing system[7] or a debuncher.

The SR spectrum was monochromatized by gratings and longwave pass filters in the FIS-3 far-infrared spectrometer[8] (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 absolute sensitivity of this measuring system was calibrated with a mercury discharge lamp, which was



(a) (b)

Fig.1. 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.

supposed to be a blackbody radiation source of 4000 K[9,10] 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 Fig.1.(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 7.0×10^5 for "A". According to the theory[6] 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 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 (Fig.1.(b)). In the previous experiments in the same conditions[11] 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.

Fig.2. shows the degree of polarization of the observed SR. 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. The diffraction correction must be done to compare these values with observed P.

Conclusion

The observed SR intensity is proportional to N^2 and enhanced by about N times that of incoherent SR. The intensity of SR depends on the bunch length strongly. As induced rf effects were excluded experimentally[1], we conclude that we observed coherent SR produced by electron bunches at wavelengths of 0.33 to 2.0 mm.

Discussion

It is demonstrated that the bunched electron beam accelerated by a linac has sufficient feasibility as a strong light source at milli- and 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.

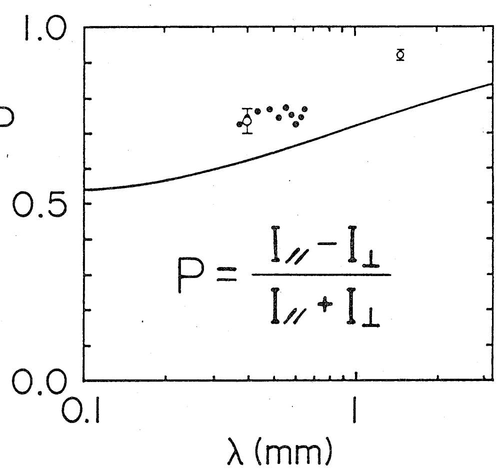


Fig.2. Observed degree of polarization P. P is defined by the expression in the figure, where $I_{//}$ and $I_{\perp}$ are the SR intensities which have an electrical vector parallel and perpendicular to the orbital plane, respectively. The solid curve shows the calculated value for ordinary SR with the same optical aperture.

$$P = \frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}}$$

A single bunch of 5×10^{10} electrons with a length of 1.5 mm has been already achieved[12]. The bunch compressing methods have been considered and a bunch length of the order of 70 μm is obtained by a calculation[13]. A higher accelerating frequency will make a shorter bunch. Those efforts for the research and development of the linear colliders will give an important technical basement to application of coherent SR. A complemented application of coherent SR is a bunch form monitor of the linear colliders, for its spectrum is regarded as the square of the bunch form factor.

Experiments for studying the transient phenomena will be enabled by the intense and extremely short, in the order of femtosecond, pulse radiation from the electron linac beam. The details of the application in the fields of solid state physics, chemistry and biology etc. are discussed in Ref.5.

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References

1. T. Nakazato et al., Phys. Rev. Lett. 63, 1245, 1989.
2. L. I. Schiff, Rev. Sci. Instrum. 17, 6, 1946.
3. F. C. Michel, Phys. Rev. Lett. 48, 580, 1982.
4. J. Yarwood et al., Nature 312, 742, 1984.
5. E. Schweizer et al., Nucl. Instr. and Meth. A239 630, 1985.
6. G. P. Williams et al., Phys. Rev. Lett. 62, 261, 1989.
7. M. Sugawara et al., Nucl. Instr. and Meth. 153, 343, 1978.
8. I. Iwahashi et al., Appl. Optics 8 583, 1969.
9. J. Bohdansky, Z. Phys. 149, 383 (1957)
10. A. J. Lichtenberg and S.Senic, J. Opt. Soc. Am. 56 75, 1966.
11. T. Nakazato et al., Research Report of Laboratory of Nuclear Science, Tohoku University, 21-1, 94, 1988 (Unpublished.)
12. J. Rees, in the Proc. of 1986 Linear Accelerator Conf., SLAC, Stanford, California, 1986, p209.
13. S. A. Kheifets et al., SLAC-PUB-5034, 1989