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Observation of coherent synchrotron, Čerenkov, and wake-field radiation at millimeter wavelengths using an L-band linear accelerator

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Spectra of synchrotron radiation (SR) and Čerenkov radiation (CR) in air have been observed in the wavelength range of 1.15–8 mm using bunched electrons accelerated by an L-band linac, whose energy and radio frequency are 40 MeV and 1300 MHz. The observed intensities of SR and CR at $\lambda=4$ mm are enhanced by factors of 9×10^7 and 1×10^7 in comparison with calculated intensities of ordinary SR and CR, respectively. Radiation of the rf wake induced in a chamber has also been observed. Bunch form factors are derived from the observed spectra, and the electron distribution in a bunch is discussed.

Recently, powerful coherent synchrotron radiation emitted from bunched electrons accelerated by an S-band linac (rf frequency; 2856 MHz) has been observed at submillimeter and millimeter wavelengths [1–3]. It has been shown that the intensity of coherent synchrotron radiation was enhanced by a factor of about 10^6 at a wavelength of $\lambda\sim1.5$ mm in comparison with ordinary incoherent synchrotron radiation. The enhancement occurred at wavelengths comparable to or longer than a bunch length of electrons and the enhancement factor was the same order of magnitude as the number of electrons in one bunch. A bunch length of electrons accelerated by an L-band linac is expected to be longer than that by the S-band one. Moreover, the number of electrons in one bunch in the linac used in the present experiment is estimated to be 2.65×10^{10}. Hence, intense coherent radiation is expected in the millimeter wave region. In this Rapid Communication, we report observation of spectra of three kinds of coherent radiation using the L-band linac (rf 1300 MHz): synchrotron radiation (SR), Čerenkov radiation (CR) in air, and the rf wake due to impedance of metallic wall of a chamber. From the observed spectra of both SR and CR, bunch form factors are derived to discuss electron distribution in a bunch.

According to the theory of coherent SR from bunched electrons, the intensity is given by [3]

$$N_{\mathrm{SR}}(\lambda)=N_e[1+N_e f(\lambda)]G(N_b,\lambda)p_{\mathrm{SR}}(\lambda)\,, \tag{1}$$

$$f(\lambda)=\left|\int \exp[-i2\pi(\mathbf{n}_r\cdot\mathbf{r})/\lambda]S(\mathbf{r})d\mathbf{r}\right|^2, \tag{2}$$

$$G(N_b,\lambda)=\left[\frac{\sin(\pi L_b N_b/\lambda)}{\sin(\pi L_b/\lambda)}\right]^2, \tag{3}$$

where N_e, N_b, and L_b stand for the number of electrons in a bunch, the number of bunches per second, and the distance between successive bunches, respectively, and $p_{\mathrm{SR}}(\lambda)$ is the intensity of SR emitted from one electron [4]. A unit vector $\mathbf{n}_r$ is directed from an electron to the observation point and $\mathbf{r}$ is a position vector of the electron. The bunch form factor $f(\lambda)$ is defined by the Fourier transform of a density distribution function of an electron in a bunch, $S(\mathbf{r})$. Interference effect by successive bunches [5] is given by $G(N_b,\lambda)$. When resolution of a spectrometer used is low, as in the case of the present experiment described below, $G(N_b,\lambda)$ is reduced to its average [3], N_b.

In the microwave region the angular distribution of coherent CR in air has been studied by Buskirk and coworkers [6–8]. It has been shown that due to a diffraction effect coherent CR in air spread over more widely than the Čerenkov angle. However, no spectral intensity of coherent CR has been observed. The intensity of coherent CR in air by a train of bunched electrons [7] is expressed using the factors $f(\lambda)$ and $G(N_b,\lambda)$ as

$$N_{\mathrm{CR}}(\lambda)=N_e[1+N_e f(\lambda)]G(N_b,\lambda)p_{\mathrm{CR}}(\lambda)\,, \tag{4}$$

$$p_{\mathrm{CR}}(\lambda)=\alpha n\left[\frac{L}{\lambda}\right]^2\left[\frac{\Delta\lambda}{\lambda}\right]\int \sin^2\theta\left[\frac{\sin T(\lambda,\theta)}{T(\lambda,\theta)}\right]^2 d\Omega\,, \tag{5}$$

$$T(\lambda,\theta)=\frac{\pi}{\beta}\left[\frac{L}{\lambda}\right](1-n\beta\cos\theta)\,, \tag{6}$$

where n, L, α, and β stand for the refractive index of air, the path length of electrons in air, the fine-structure constant, and the ratio of speed of electrons to that of light in vacuum; $p_{\mathrm{CR}}(\lambda)$ stands for the intensity of CR emitted from one electron [6]. When $f(\lambda)=0$ and $G(N_b,\lambda)=N_b$, Eqs. (1) and (4) give the intensities of ordinary incoherent SR and CR, respectively.

Experimental setup is shown in Fig. 1. A train of bunched electrons was accelerated by the L-band linac of the Research Reactor Institute, Kyoto University. The energy of electrons was 40 MeV and the energy width (full width at the half maximum) was typically 16%. About 43 bunches formed a pulse which had a duration of 33 nsec and a repetition of the pulse was 55 Hz. During the present experiment, an average beam current was about 10 μA; then, N_e was 2.65×10^{10}. A magnetic field of 417 G was applied by the bending magnet M_B for emis-

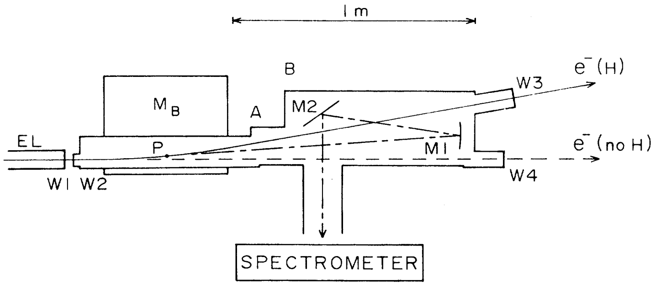

FIG. 1. Schematic layout of experiment. Trajectories of electrons with and without magnetic fields are shown by the solid and dashed lines, respectively. EL: electron linac; M_B: bending magnet; P: emission point of SR; M1: collecting mirror; M2: plane mirror; W1–W4: titanium foil windows.

sion of SR. The radius of the electron orbit was 3.2 m and the characteristic wavelength of SR was 27.9 μm. Radiation collected by a spherical mirror M1 was led to a far-infrared spectrometer [3]. Horizontal and vertical acceptance angles of M1 were 80 and 100 mrad. The spectrometer with four gratings and appropriate filters covered the wavelength range from 1 to 8 mm, and its resolution was 0.13 cm^{-1} (3.9 GHz) at $\lambda = 4$ mm. Radiation was detected by a liquid-helium-cooled silicon bolometer. A vacuum chamber including the collecting mirror was separated from the linac with a titanium foil window. The air path length between two foil windows W1 and W2 was 4 cm and the thickness of each foil was 20 μm. The measuring system was calibrated by a blackbody radiation source at a temperature of 1200 K. The observational error in the absolute intensity of the spectra was estimated to be within a factor of 1.5.

Without the magnetic field electrons do not emit SR. After turning off the bending magnet, however, radiation was detected at millimeter wavelengths, though the residual magnetic field was carefully eliminated. The radiation is considered to be rf wake (WR) due to impedance of the metallic chamber, i.e., an electromagnetic field induced in the chamber by periodic bunches [9,10]. The observed intensity was an order of magnitude weaker than the one under the magnetic field. When an aluminum foil was used to screen off any radiation emitted from upperstream at a flange *A* in Fig. 1, the intensity was decreased by about two orders of magnitude. This indicates that the radiation was emitted from electrons in a rectangular aluminum duct held between pole pieces of the bending magnet. The inner cross section of the duct was 114 (horizontal) $\times$ 54 (vertical) mm^2. The observed spectrum of WR is shown in Fig. 2 by the dashed line.

Under the magnetic field an observed spectrum was composed of SR and WR. Hence, the spectrum of SR was obtained by subtracting the observed intensity of WR from the observed spectrum under the magnetic field. We have ignored the difference between the intensity of WR under the magnetic field and that without magnetic field. The spectrum of SR thus obtained is shown in Fig. 2. The spectrum has a broad peak at the wavelength around 4 mm and decreases sharply towards shorter wavelengths. The intensity of SR was much higher than that of a high-pressure mercury lamp of 100 W (Ushio Co.) with an effective aperture of 10 mm; the former was 450 times as large as the latter at $\lambda = 1.5$ mm and was more than four orders of magnitude larger than the latter at the wavelengths $\lambda > 3$ mm.

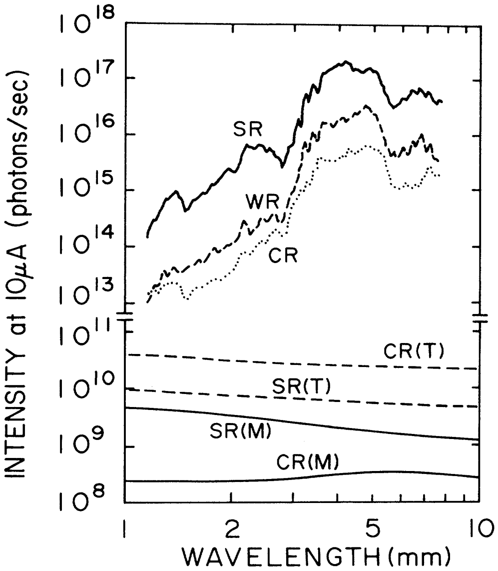

FIG. 2. Observed intensities of coherent SR, WR in vacuum, and CR in air. The ordinate shows intensity in units of photon numbers per second per bandwidth of 1%, i.e., per $\Delta\lambda/\lambda = 0.01$, at the beam current of 10 μA. The observed intensities were calibrated by blackbody radiation at temperature of 1200 K. Calculated intensities of incoherent SR and CR are also shown: SR(T) and CR(T) show total intensities emitted from electrons moving along each trajectory, and SR(M) and CR(M) the intensities led to the spectrometer by the collecting mirror.

To observe a spectrum of CR in air, all ducts upperstream of the flange *B* in Fig. 1 were removed to suppress the influence of WR. The observed spectrum is shown in Fig. 2 by the dotted line. The structure of the spectrum of CR is similar to that of SR and WR.

To analyze the experimental results, the total intensity of incoherent SR emitted from electrons moving along the whole length of the orbit in the magnetic field has been calculated by Eq. (1). The intensity of incoherent SR collected by the mirror M1 has also been calculated considering the geometry of the optical system. The results of the total and collected intensities are shown as SR(T) and SR(M) in Fig. 2. In the calculations, we have assumed the electron beam to be a narrow line and have ignored the divergence of the beam. The total and collected intensities of incoherent CR were also calculated by Eq. (4) using the following values; the refractive index of air $n = 1.00027$ and $L = 160$ cm which was the length between W1 and M1 in Fig. 1. The calculated results are shown in Fig. 2 by CR(T) and CR(M). In Fig. 2, the observed intensities of SR and CR at $\lambda = 4$ mm are enhanced by factors of 9×10^7 and 1×10^7, respectively. These enhancement factors confirm a coherent character of the radiation, though each enhancement factor is less than N_e.

The calculated spectral intensities of incoherent SR and CR in Fig. 2 are smooth and flat. On the other hand, all the observed spectra resemble one another; each spectrum has a broad peak at around $\lambda = 4$–5 mm and decreases sharply towards shorter wavelengths. This indicates that the observed spectra are characterized by a common bunch form factor which is determined by the electron distribution in a bunch. It implies that observed WR is also coherent.

Bunch form factors were derived from the observed spectra of coherent SR and CR. The results are shown in Fig. 3. They are parallel to each other, but the one derived from CR is less than the SR one by a factor of 8. The reason for this discrepancy is not clear at present. It is partially due to the fact that the electron beam diverges more in air than in vacuum and CR is emitted in diffused directions, but this reason alone does not quantitatively explain the difference.

It is difficult to obtain the distribution function of electrons by the inverse transform of the bunch form factor in Fig. 3 because of lack of information of the spectrum at longer wavelengths. The wavelength dependence of the observed form factor in the range $\lambda < 3$ mm is nearly λ^4 and disagrees with the case of Gaussian distribution of electrons in a bunch [2], which gives a much steeper decrease of the spectrum. The electron distribution of the S-band linac has a sharp local concentration of Gaussian type with a size of 0.3 mm [3]. The wavelength dependence of the form factor in Fig. 3 does not indicate such a narrow structure. In the figure, the dashed curve shows the form factor calculated on an assumption that $S(r)$ is given by a uniform ellipsoidal distribution [2] with a longitudinal bunch length of 14 mm. The envelope of the calculated form factor is in agreement with the experimental one of SR. The envelope may be compared with the observation, because fine structure will be smeared for the following reasons. The distribution of electrons in a bunch is probably not exactly the same in every bunch and the bunch length may fluctuate, and, furthermore, the spectrometer has the finite resolution. As was expected, the bunch length estimated here is longer than that of 2 mm for the S-band linac [3].

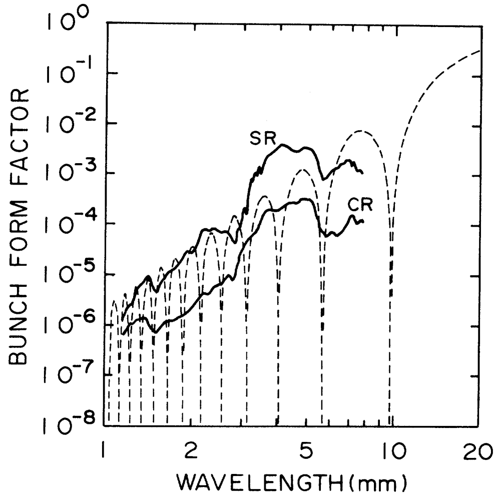

FIG. 3. The bunch form factors derived from the observed spectra of coherent SR and CR. A dashed line shows the form factor calculated on an assumption of ellipsoidal distribution of the electrons in a bunch with the length of 14 mm.

A careful survey of Fig. 2 shows that the observed spectrum of WR is not completely parallel to the spectrum of CR but it is more intense on the long-wavelength side. If the wavelength dependence of a ratio of the collected intensity of WR to the total one is similar to that of CR, this result suggests that the intensity of WR from a single electron increases towards longer wavelengths. Then, the impedance of the chamber increases with the wavelength, since the intensity of WR is proportional to the impedance. The result is in a qualitative agreement with the analysis by Hofmann *et al.* [10] that a wall impedance of a cylindrical chamber is proportional to $\lambda^{3/2}$ at high frequencies.

Note added in proof. According to a further experiment we performed, the radiation assigned to the rf wake in this paper is possibly coherent transition radiation from the upperstream titanium window.

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