Observation of Coherent Transition Radiation

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Coherent transition radiation, generated by the passage of mm-long bunches of electrons through a thin metal foil, has been observed in the far infrared. The intensity was compared to the smaller amount of Cherenkov radiation produced when SF_6 gas was introduced into the electron path. Wake-field radiation was ruled out by varying the geometry of the metal chamber near the electron beam. The intensity, the polarization, and the spectral and angular distribution of the transition radiation were measured and its coherent nature was identified.

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Recently, coherent synchrotron [1,2] and Cherenkov [3–5] radiation produced by relativistic electron bunches have been reported. In this Letter, we describe the observation of coherent transition radiation generated by electron bunches passing through a metal foil. We also distinguish transition radiation from Cherenkov radiation generated by the passage of the electrons through a dielectric medium by varying the dielectric constant, and from the wake-field radiation emitted by the electrons' passage near metal structures by changing the experimental geometry. For our experiments transition radiation dominates and MW peak power at psec pulse length results.

Transition radiation, first considered by Frank and Ginzburg [6], is produced by the passage of charged particles through the interface between media with different dielectric constants and has been studied extensively both theoretically [7] and experimentally [8]. It is caused by a collective response of the matter surrounding the particle trajectory to readjust to the electromagnetic field of the charged particle. For electrons passing through the interface between a perfect conductor and vacuum, the angular distribution of the spectral energy (per unit frequency interval) is [6]

$$E(\omega,\Theta)=\frac{\beta^2e^2}{\pi^2c}\frac{\sin^2\Theta}{(1-\beta^2\cos^2\Theta)^2}, \quad (1)$$

where Θ is the angle between the electron trajectory and the emitted radiation, ω the angular frequency of the radiation, c the speed of light, v the electron velocity, and $\beta=v/c$. For relativistic electrons ($\beta\sim1$) the emission is sharply peaked in the region of small Θ, and shows a maximum for $\Theta\sim1/\gamma$, where γ is the Lorentz factor. The plane of polarization is given by the electron trajectory and the direction of observation.

To obtain the small angular distribution of Eq. (1), the path of an electron must be unobstructed for a distance greater than the formation length [7]

$$\Lambda\approx2c/\omega(1-\beta^2+\Theta^2). \quad (2)$$

If the free path d is smaller than Λ, the angular distribution is broadened by diffraction effects and the radiation is strongly suppressed below an angle of

$$\Theta_m\approx(2c/\omega d)^{1/2}. \quad (3)$$

Integrating Eq. (1) over angle, the spectral energy can be expressed as [6]

$$E_T(\omega)=\frac{e^2}{\pi c}\left(\ln\frac{2}{1-\beta}-1\right). \quad (4)$$

To obtain the intensity emitted by a beam of charged particles, one usually adds the intensity of the single electrons giving a total intensity proportional to the number of particles. For bunched beams, however, the emitted radiation from different particles adds coherently when the wavelength λ is comparable to or longer than the bunch length. Therefore the intensity is proportional to the number of electrons squared. For a 1-mm-long Gaussian bunch the coherent enhancement is substantial for wavelengths longer than 3 mm. Detailed calculations show that the Fourier-transformed spectrum of the coherent radiation reflects the longitudinal shape of the electron bunch [2,9]. Thus, measuring the spectral distribution of the coherent radiation provides information about the bunch shape.

The electron beam was produced by the 300-MeV linear accelerator (linac) that is part of the injector of the Cornell Electron Storage Ring. The linac operates at 2.856 GHz, the bunch length is estimated to be 1–2 mm, and the number of electrons per bunch can be up to 10^{11}. In our experiment, single bunches with a repetition rate of 7–15 Hz were used. The diameter of the beam at the source of the radiation is about 6 mm.

A schematic view of the apparatus used to study the coherent transition radiation is shown in Fig. 1. Two setups were used to investigate different properties of the radiation. The first setup shown in Fig. 1(a) minimizes wake-field radiation with an open metallic structure and is used to measure the angular distribution of the transition radiation. The electron bunches from the linac pass through a 0.25-mm-thick Be window, coated with a 300-nm Au film. They enter an evacuable brass tube covered with a 75-μm-thick stainless-steel window mounted at a distance of 4.5 cm from the Au-coated mirror as shown in Fig. 1(a). The electrons then traverse a mirror (a 50-mm-diam, 1.5-mm-thick, Au-coated fused quartz disk), a fluorescent screen that is used to position the electron beam, and finally enter a copper beam dump.

Angular measurements of the radiation were performed by rotating the mirror around its vertical axis and reflecting the radiation into an assembly of aluminum-coated, 5-cm-wide parallel mirrors, 3 cm apart, which guide the radiation vertically onto a 5-mm-wide vertical slit. The vertical and horizontal resolution of the apparatus were 14° and 0.6°, respectively. To study the polarization of the radiation, a wire grid polarizer was mounted on the slit. A Golay cell, filtered to have a flat spectral response in the wavelength region between 6 mm and 100 μm, was used to detect the radiation.

Figure 1(b) shows the modification of the setup to study the quadratic dependence of the coherent radiation, its spectral distribution, and also to investigate Cherenkov radiation. The steel window has been removed and an aluminum chamber has been inserted to allow the evacuation of the electron path from the Be window to the beam dump. The chamber containing the Au mirror can be filled with gas to study the presence of coherent Cherenkov radiation emitted by the electrons on their 12-cm-long path from the Be window to the Au mirror.

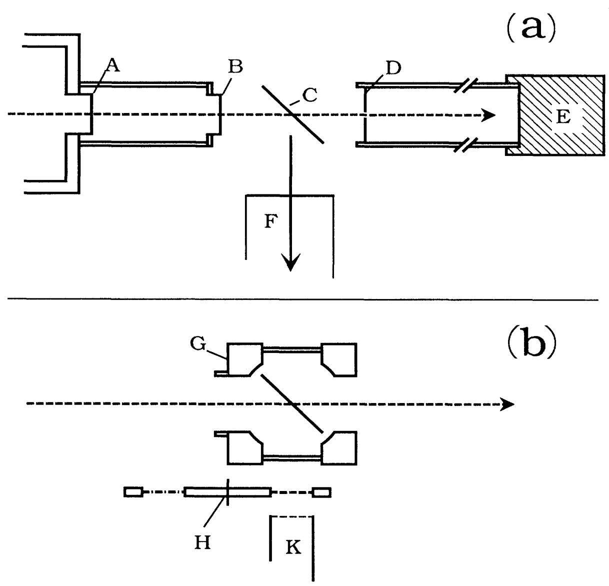

FIG. 1. (a) Experimental arrangement in air. The electron beam, represented by the dashed arrow, passes through (A) the Au-coated Be window, (B) the stainless-steel window, (C) the rotatable Au-coated quartz mirror, (D) the fluorescent screen, and then enters (E) a Cu beam dump. (F) The mm wave radiation is transmitted by a set of vertically stacked parallel mirrors to the Golay cell detector. (b) Experimental arrangement in vacuum. By removing window (B) and inserting chamber (G) into the open section, the electron path from (A) to (E) can be evacuated or filled with SF_6 gas. (H) identifies the filter wheel and (K) the Al light pipe.

The transition radiation emitted from the Be window and any Cherenkov radiation are reflected by the 45° Au mirror through a crystalline quartz window. Additional radiation from the Au surface is also directed towards the detector and passes through metal mesh filters to make spectral measurements. Finally, it is guided through 2.5-cm-inner-diameter aluminum tubing to the Golay cell detector.

Using the apparatus of Fig. 1(a) we measured the angular distribution of both polarized and unpolarized mm wave radiation. The results, shown in Fig. 2, were obtained by rotating the gold mirror around its vertical axis, thereby deflecting the transition radiation emitted from the stainless-steel window and from the reflecting surface of the gold mirror onto the detector. Transition radiation has the unique feature that the backward pattern of the radiation is centered on the direction of the specular reflection of a ray coincident with the electron trajectory, as shown in Fig. 3. Thus, by rotating the mirror by an angle $\Theta/2$ the radiation emitted both at the steel window and at the gold mirror are scanned by an angle Θ. The angular distribution of the radiation with no polarizer (solid line in Fig. 2) is similar to that measured for horizontally polarized radiation (dashed line) but completely different from that measured for vertical polarization (dotted line) as expected for a radially polarized source when it is scanned horizontally. Therefore Fig. 2 shows characteristics of transition and Cherenkov radiation; radially polarized emission in a conelike pattern. The asymmetry in the observed angular distributions in Fig. 2 may result from a combination of factors: At small angles, surface waves emerge from the metal-dielectric interface [8], and the emission from the Au mirror de-

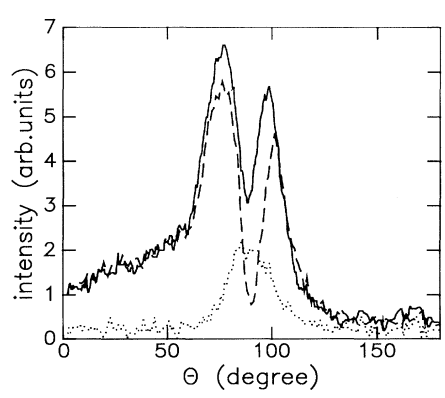

FIG. 2. Far-infrared intensity as a function of the radiation deflection angle Θ. The solid line shows the unpolarized angular distribution; the dashed and dotted lines show the horizontally and vertically polarized distributions, respectively.

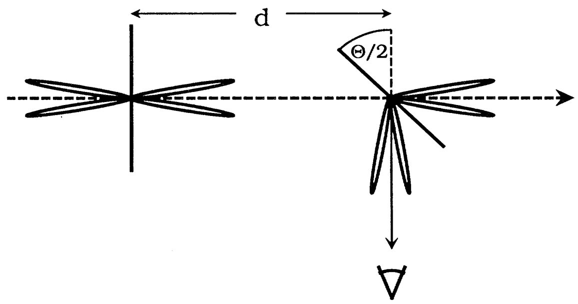

FIG. 3. Backward and forward pattern of transition radiation for normal and oblique incidence.

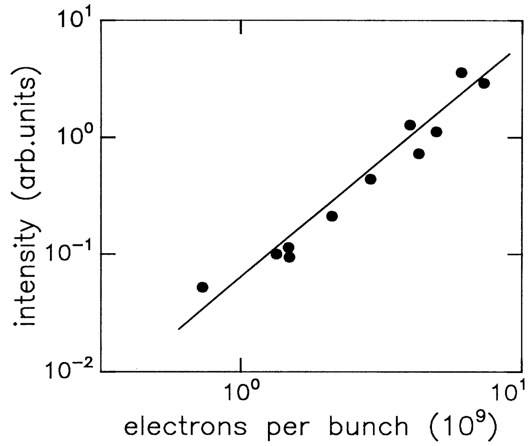

FIG. 4. Dependence of the far-infrared radiation intensity on the number of electrons in a bunch. The solid line represents a fit of the data by a square-law dependence.

creases with increasing deflection angle [7]. The radiation cone in Fig. 2 centered at $\Theta = 90°$ shows an opening of about 14°, which is much larger than the value of $\Theta_{max} \sim 1/\gamma$, obtained from Eq. (1). This angular distribution is consistent with the cutoff angle given by Eq. (3), caused by the reduction of the formation length due to the Au mirror in the electron path.

Cherenkov radiation has a similar angular distribution and polarization dependence; related diffraction effects have been worked out in detail by Neighbours and coworkers [3]. These two generation processes, however, can be distinguished by their relative strengths. The spectral energy of the Cherenkov radiation emitted by a single electron is given by [10]

$$E_C(\omega) = \frac{e^2 \omega l}{c^2} \left(1 - \frac{1}{\beta^2 \varepsilon} \right), \tag{5}$$

where l is the path length of the electron in the medium with the dielectric constant ε. The ratio of the spectral energies between Cherenkov and transition radiation is

$$\frac{E_C(\omega)}{E_T(\omega)} \approx \frac{\pi \omega l}{c} \frac{1 - 1/\varepsilon}{\ln[2/(1-\beta)] - 1}. \tag{6}$$

With $\varepsilon(\text{air}) = 1.00059$ and $l = d = 4.5$ cm, using a mean frequency $\nu = 1/\lambda = 3\ \text{cm}^{-1}$, and taking into account that transition radiation is emitted at both the steel window and the Au mirror, we find for the ratio of Cherenkov to transition radiation in our experiment $E_C/E_T = 0.006$.

To verify the ratio between the intensity of Cherenkov and transition radiation experimentally, we increased the path length of the electrons to $d = 12.7$ cm with the evacuable chamber of Fig. 1(b) and introduced SF_6 gas which has a high dielectric constant, $\varepsilon = 1.00207$. The 8% increase in the radiation intensity observed each time the chamber was filled to atmospheric pressure is attributed to Cherenkov radiation generated on the electron path between the Be window and the Au mirror. Equation (6) gives a ratio for this configuration of $E_C/E_T = 0.05$ in agreement with the experiment. Performing a low-resolution measurement of the angular dependence of the coherent radiation by rotating the Au mirror, no difference in the relative angular distribution of the radiation for the evacuated and SF_6-filled chambers could be observed. For the total transition radiation we find a value of 1.7 μJ for 5×10^9 electrons per bunch. This value should be compared with that calculated for a 1-mm Gaussian electron beam incident on a perfect conductor which gives 15 μJ radiated at frequencies greater than 1 cm^{-1}.

If wake fields were an important source of radiation, the aluminum box that surrounds the mirror would be a major source in the configuration shown in Fig. 1(b). Similar radiation intensity detected with and without the box present confirms the absence of wake-field radiation. The agreement between the experimental results and theoretical predictions for the ratio of Cherenkov and transition radiation also indicates that other coherent sources like wake-field radiation are unimportant.

The dependence of the far-infrared intensity on the number of electrons in a bunch is shown on a log-log plot in Fig. 4. The data points were obtained by varying the number of electrons in a bunch between 7×10^8 and 8×10^9. The setup shown in Fig. 1(b), without any mesh filter, was used to collect and detect the infrared radiation. The solid line in Fig. 4 represents a fit of the data by a quadratic dependence of the infrared intensity on the number of electrons in a bunch, characteristic of coherent radiation.

A spectrum of the transition radiation as a function of frequency is shown in Fig. 5. It was obtained by measuring the power transmitted through metal mesh high-pass filters with different cutoff frequencies. The difference in the amount of transition radiation transmitted through filters of adjacent mesh size was divided by the difference in their cutoff frequency to estimate the spectral intensity of the radiation. The spectrum decreases rapidly at high frequencies, as expected for coherent radiation generated

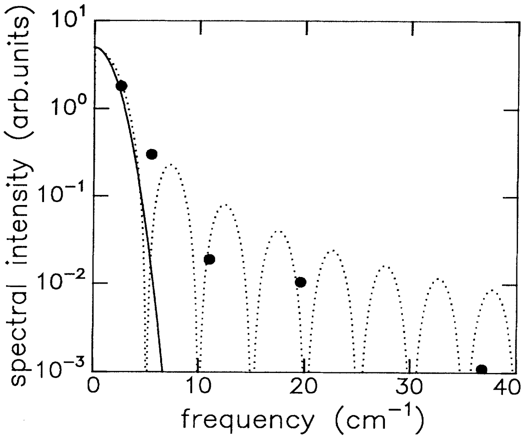

FIG. 5. Spectral intensity obtained with the metal mesh spectrometer. The solid points represent the experimental data, the solid line shows the spectral intensity expected for a Gaussian charge distribution, and the dotted line the one for a rectangular distribution; see Ref. [11].

by bunched electrons. A comparison of the data with a calculated spectrum [11] for a Gaussian electron distribution (solid line) with a half-width $\sigma_z = 1$ mm shows that the theoretical spectrum decreases more rapidly than the experimental one. This suggests that the electron bunches of the Cornell linac have either a submillimeter length or, more likely, a shape that is non-Guassian, which can lead to a substantial increase of high-frequency radiation, as shown for the spectrum of a rectangular charge distribution (dotted line) with, again, a width of $\sigma_z = 1$ mm.

In conclusion, we have found that transition radiation, generated by the passage of short electron bunches through metal foil, is emitted coherently in a wavelength region comparable to or longer than the bunch length. Since the radiation is emitted in psec, peak powers on the order of MWs are observed. For Cherenkov radiation, similar intensities at 3 cm^{-1} would require a 1.5-m path length in air.

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[11] A calculated spectrum is proportional to the square of the Fourier transform of the longitudinal electron distribution, see, e.g., Ref. [2], Eqs. (10)-(12).