Coherent Radiation at Submillimeter and Millimeter Wavelengths

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Abstract

The paper describes the experimental results on coherent synchrotron radiation(SR), coherent Cherenkov radiation(CR) and coherent transition radiation(TR) at submillimeter and millimeter wavelengths. Coherent radiation intensities vs. He-gas pressure are shown at λ = 500 nm and 4 m. Angular distributions of coherent CR and/or coherent TR were obtaind in vacuum and at the atmospheric pressure. Coherent TR spectra at different emission lengths were obtained at λ = 0.2 ~ 5 mm.

I. INTRODUCTION

Complete spectrum of coherent synchrotron radiation, produced by the passage of mm long electron bunches through a bending magnetic field, has been obtained. [1],[2], [3] Our results on coherent SR have been supported by Blum et al. using a linear accelerator at Cornell University. [4] Ohkuma et al. observed the high-intensity coherent Cherenkov radiation emitted in air from a high current single bunch at Osaka University. [5] Happek et al. observed coherent transition radiation at Cornell. [6] We have measured the coherent CR spectrum and angular distributions at the wavelengths of 0.6 to 4.0 mm and the coherent TR ones at 0.2 to 6.0 mm using a grating-type spectrometer and a polarizing interferometer. Broad peaks of the angular distributions of coherent CR and coherent TR were observed at the angles larger than the usual Cherenkov angle, $\cos^{-1}(1/n\beta)$, and the transition radiation angle, $1/\gamma$, respectively. Bunch shapes were estimated by Fourier analysis from these spectra, and they agreed with one from coherent SR spectrum.

II. COHERENT SYNCHROTRON RADIATION

Michel pointed out that intense coherent SR could be observed from bunched electron beam. [7] The intensity of coherent SR is given as follows;

$$\begin{aligned} P_{coh}(\lambda) &= p_0(\lambda)N_e[1+(N_e-1)f(\lambda)], \\ &\cong p_0(\lambda)N_e[1+N_e f(\lambda)], \end{aligned} \tag{1}$$

$$f(\lambda) = \left| \int \exp(i2\pi x/\lambda)S(x)dx \right|^2, \tag{2}$$

where $p_0(\lambda)$ is the intensity from an electron, $f(\lambda)$ bunch form factor, $S(x)$ the density distribution of electrons and Ne the number of electrons in a bunch.

In 1989 the coherent effects in SR were observed for the first time by using Tohoku 300 MeV electron linac. [1] Careful efforts have been done to get the complete spectrum from a few tenth mm to several mm wavelengths region. [2] Figure 1 shows the observed spectrum of coherent SR. Intensity was calibrated absolutely by black body radiation of 1500 K. The accuracy of the absolute intensity of coherent SR after correction was estimated to be within a factor of 1.5. The spectrum shows a broad peak at the wave length $\lambda \cong 1.5$ mm and the peak intensity is enhanced by a factor of 5×10^6 in comparison with ordinary incoherent SR. The enhancement factor is comparable with the number of electrons in a bunch. The bunch form factor was derived from the observed spectrum normarized by the incoherent spectrum and the square of the number of electrons in a bunch. The electron distribution function in the bunch was obtained by the Fourier transform of the bunch form factor and the half width of the distribution curve is = 0.25 mm.

The spectrum in the region $\lambda > 2$ mm declines below the theoretical tendency of the incoherent SR spectrum which does as $\lambda^{-1/3}$. This suggests the suppression effect of coherent SR by a metallic boundary condition as predicted by Nodvick and Saxon. [8] This effect will be discussed in another paper at this conference. [9]

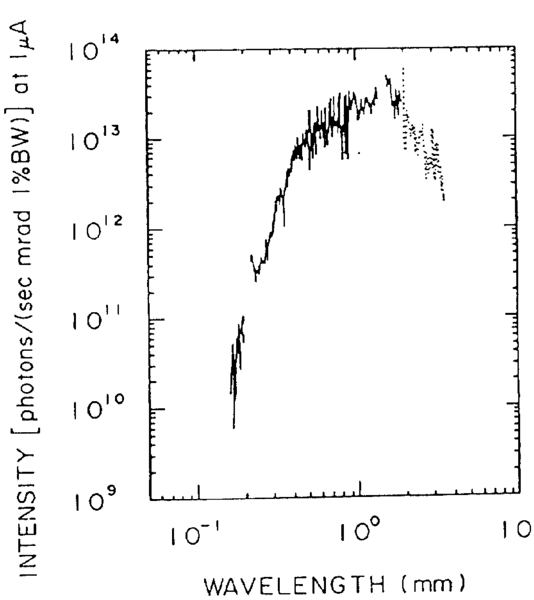

Figure 1. The Observed spectrum of CSR. The intensity is calibrated by blackbody radiation of 1500 K.

III. COHERENT CHERENKOV RADIATION

Coherent CR using travelling-wave linac has been investigated in the microwave region. [10],[11] They found that the peak in the microwave CR occus at an angle much larger than that expected from application of the ordinary Cherenkov formula, $\theta = \cos^{-1}(1/n\beta)$.

Figure 2 shows the schematic layout of our recent experiments on coherent CR and coherent TR. Titanium beam windows (W1,W2) of 20 µm separates the vacuum between the linac and an experimental chamber, which is evacuated or filled with He-gas at various pressures. Movable aluminum foil (15 µm thick) bounds the emission length from 75 mm up to 880 mm and emitted radiation is guided to the spectrometer using plane mirrors (M1, M2, M3) and a spherical mirror (M3). The grating-type far-infrared spectrometer was used with liquid-He cooled Si-bolometer in the far-infrared region and photomultiplier tube in the visible region, respectively. The experiments were performed at 150 MeV and energy spread of electrons was 0.2% using momentum analyzer.

Figure 3 shows the relations of the coherent CR and/or coherent TR intensities vs. He-gas pressure at the emission length L = 165 mm. The open and solid circles show the observed intensity at λ = 500 nm and 4 mm, respectively. The dashed and broken curves show the theoretical values for each wavelengths. The intensities are normalized to those in vacuum. The pressure of the Cherenkov threshold p_{th} and the formation length Z at the atmospheric pressure are 126 mmHg and 17.1 mm at λ = 500 nm, and 127 mmHg and 138 m at λ = 4 mm, respectively. The intensity at λ = 500 nm increases rapidly above the Cherenkov threshold pressure. On the other hand, in the case of λ = 4 mm, the intensity is almost constant and independent on the pressure. This suggests that the observed radiation at λ = 4 mm should be transition radiation from an aluminum foil. The horizontal angular distributions obtained in vacuum and in atmospheric He-gas, at λ = 500 nm, 1 mm and 4 mm, are shown in figure 4. The broken lines, dotted lines and solid lines show horizontal and vertical components, and total intensities, respectively.

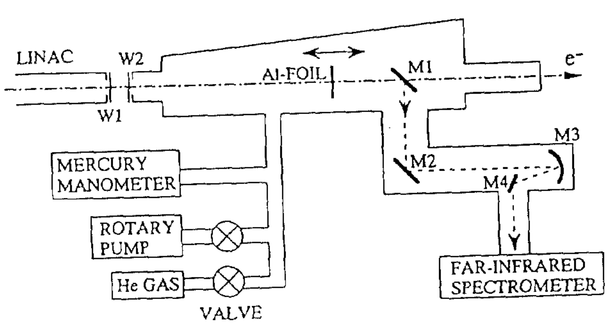

Figure 2. The schematic layout of the CCR and CTR experiments.

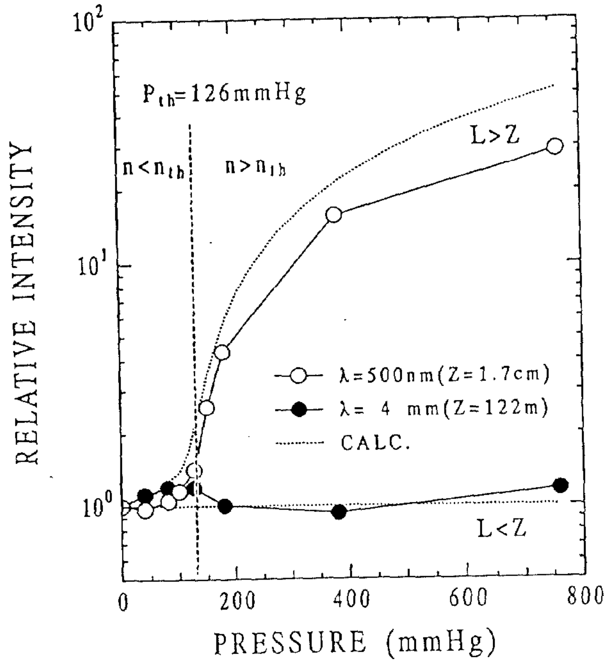

Figure 3. The relation of the intensities of CCR and/or CTR vs. He-gas pressure.

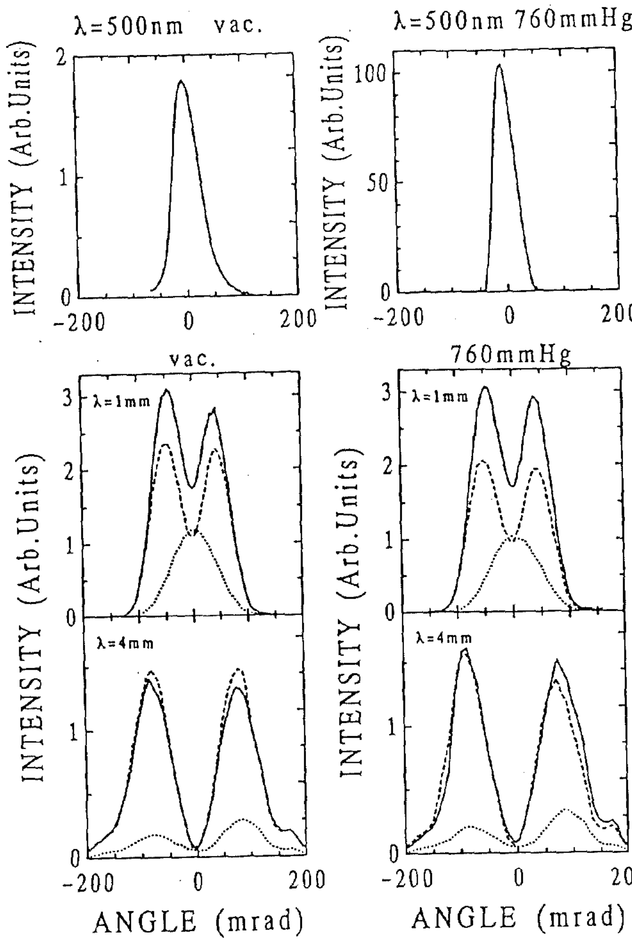

Figure 4. Angular distributions of CCR and/or CTR in vacuum and atmospheric He-gas.

IV. COHERENT TRANSITION RADIATION

The intensity of metal-vacuum TR is given as follows, [12]

$$P = 2p_f\{1-\cos(L/Z)\} \approx p_f\left(\frac{L}{Z}\right)^2, \quad (3)$$

$$p_f \approx \frac{\alpha\beta^2\sin^2\theta}{4\pi^2\lambda(1-\beta\cos\theta)^2}, \quad (4)$$

$$Z = \frac{\beta\lambda}{2\pi(1-\beta\cos\theta)}, \quad (5)$$

where α, β, θ, and L are the fine structure constant, the ratio of a velocity of electrons to that of light, the angle between the direction of the observing point and the trajectory of electrons, and the emission length of TR. Z defines a formation length.

A spectrum of coherent TR emitted from 150 MeV electron bunches passing through aluminum foil has been observed in the wavelength region from 0.2 mm to 5 mm. The intensity at wavelength of 1 mm is enhanced by a factor of 0.9 × 10^6 in comparison with that of incoherent TR. This factor is about a quarter of the number of electrons in a bunch. The intensity shows nearly quadratic dependence on the electron beam current. The electron distribution in a bunch has been derived from the observed spectrum. It has the full width at half maximum of 0.28 mm and agrees with the value derived from the coherent SR experiment. Figure 5 shows the observed spectra from the emission lengths of 156 mm (A) and of 872 mm. The intensities are given in the unit of photons per second per 1 % band width at a beam current of 1 μA. Vertical bars show estimated observational errors. The dashed lines show the theoretical intensities of incoherent TR for the emission lengths of 156 mm (A) and 872 mm (B). The observed intensities have been confirmed to be proportional to the square of emission length at these wavelengths.

V. CONCLUSION

Complete spectra of coherent SR and coherent TR have been obtained. The bunch lengths derived from these spectra coincide each other. Bunch length monitor using coherent SR and coherent TR is useful for a short bunch accelerator operation.

Coherent CR is not so intense in the case of short emission length even though the pressure is above the Cherenkov threshold. Electron passing through a beam window emit intense coherent TR.

The intensity of the coherent TR is proportional to the square of emission length which is much shorter than formation length. Broad peaks of the angular distribution shift to the angle larger than the theoretical transition angle, 1/γ.

Intense coherent SR and coherent TR are useful source for spectroscopy.

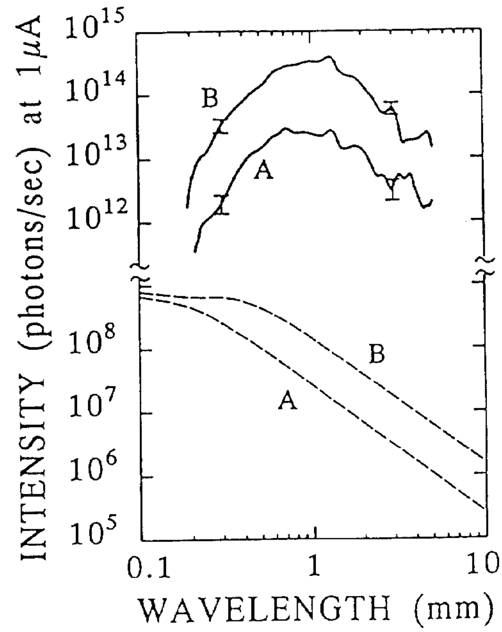

Figure 5. Coherent TR spectra at different emission lengths.

VI. REFERENCES

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