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Coherent transition radiation from short electron bunches

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Abstract

Coherent transition radiation can be produced when short electron bunches traverse a vacuum-metal interface. The radiation is of great interest as a potential high intensity THz or far-infrared radiation source and for femtosecond electron bunch length measurements. This paper presents experimental and theoretical investigation on the generation and characterization of high intensity coherent transition radiation from short electron bunches.

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Keywords: THz; Far-infrared; Femtosecond; Coherent; Transition radiation; Electron bunches

1. Introduction

An electron bunch can emit coherent radiation at wavelengths longer than or comparable to the bunch length with intensity proportional to the square of the number of electrons per bunch [1–3]. Since a typical population in a bunch is 10^8–10^{11} electrons, the coherent enhancement is expected to be that same large factor over incoherent radiation. Observation of coherent radiation from electron bunches has been reported since 1989 [4–11]. The coherent radiation generated from short electron bunches of some 100 μm (or 300 fs) lies in THz frequency range (0.3–3 THz or 1000–100 μm [12]), the region where development of a source is currently a challenge. The coherent radiation intensity is expected to be much more intense than conventional sources like synchrotron or black body radiation. Although, there are some FELs that are capable of covering most of the THz spectral band within their tuning range, e.g. UCSB-FEL (120 GHz to 4.8 THz:2.5 mm–60 μm) [13], Stanford FEL (15–80 μm) [14], FELIX (3–250 μm) [15], and other long wave length FELs listed in Ref. [12,16] and [17]. The FEL spectrum is, however, narrow band and not suited for some spectroscopy applications.

In principle, any method to produce radiation from electric charges can be used to generate coherent radiation. Transition radiation is a convenient process to convert short electron bunches to equally short radiation pulses. Thus, coherent transition radiation can be considered as a potential high intensity THz or far-infrared radiation source. Furthermore, it is a convenient source of radiation for femtosecond electron bunch length measurements [18–22].

2. Coherent radiation from electron bunches

Electromagnetic radiation from an electron bunch can be derived by superimposing the radiation field emitted by each electron in the bunch and the radiation power is just the electric field squared. The total radiated power from a mono-energetic bunch of N electrons can be written as $P(\omega) = P_0(\omega)N[1+(N-1)f(\omega)]$, where $P_0(\omega)$ is the radiated power from a single electron [1–3]. The function $f(\omega)$ is called *form factor* and defined as $f(\omega) = |\int e^{ik\hat{n}.\vec{r}} S(\vec{r})\, d^3r|^2$ where $S(\vec{r})$ is the 3-D particle distribution, k is the wave number and $\hat{n}$ is the unit vector in the direction of observation. The form factor reduces to zero for wavelengths

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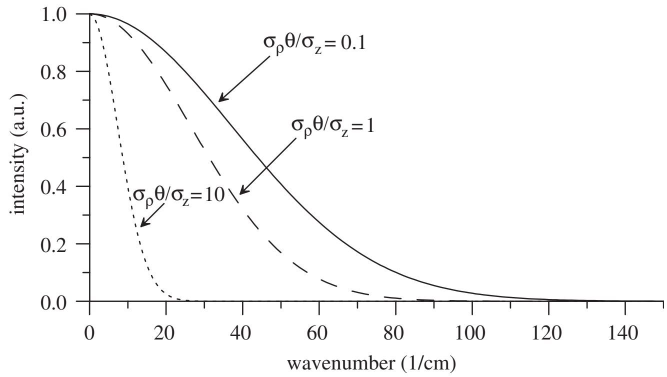

Fig. 1. Spectral distribution of coherent radiation when $\sigma_\rho\theta/\sigma_z = 0.1$ (solid), 1(dashed-line) and 10 (dotted-line).

shorter than the bunch length and approaches unity for longer wavelengths. The second term in the square bracket describes coherent radiation which is enhanced by a factor of $Nf(\omega)$.

For a bunch distribution $S(\vec{r})$ that can be expressed as $S(\vec{r}) = S_l(z)S_\perp(\vec{r}_\perp)$, where $S_l(z)$ is the longitudinal particle distribution and $S_\perp(\vec{r}_\perp)$ is the transverse distribution, we get $f(\omega,\theta) = \left|\int S_\perp e^{ikr_\perp \sin\theta} dr_\perp \int S_l e^{ikz\cos\theta} dz\right|^2$ with θ being the observation angle. When the transverse distribution can be neglected, we have $f(\omega) = \left|\int e^{ikz} S_l(z) dz\right|^2 = \left|S_l(\omega)\right|^2$, where $S_l(\omega)$ is the Fourier transform of the longitudinal distribution $S_l(z)$. The coherent spectrum is then determined solely by the longitudinal particle distribution. As the source radius and/or the observation angle increases, high frequency coherent radiation becomes suppressed. Effects of beam size can be demonstrated assuming a Gaussian bunch whose form factor $f(\omega) = e^{-(k\sigma_\rho \sin\theta)^2} e^{-(k\sigma_z \cos\theta)^2}$, where σ_ρ is the standard radial size of a round Gaussian beam and σ_z is the longitudinal parameter. One can see that the transverse effects can be neglected as long as $\sigma_\rho \sin\theta << \sigma_z \cos\theta$ or $\sigma_\rho \tan\theta << \sigma_z$ which can be approximated as $\sigma_\rho\ \theta << \sigma_z$ for the radiation from relativistic electrons. Fig. 1 displays spectral distribution of coherent radiation when $\sigma_\rho\theta/\sigma_z = 0.1$, 1 and 10 in which high frequency suppression is clearly visible. To obtain the full coherent spectrum which is bunch length limited, the electron beam size should therefore be as small as possible.

3. Transition radiation

Transition radiation, first predicted by Ginzberg and Frank [23], is emitted when a charged particle passes through an interface between two media with different dielectric constants [23,24]. Spectral angular distribution of the emitted radiation energy when an electron moves from vacuum to metal in a direction normal to the interface is given by

$$\frac{d^2 W}{d\omega\, d\Omega} = \frac{e^2\beta^2 \sin^2\theta}{\pi^2 c(1-\beta^2\cos^2\theta)^2}, \tag{1}$$

where θ is the emission angle with respect to the electron beam axis. The radiation intensity increases from zero in the forward direction to a broad peak at an angle $\theta \sim 1/\gamma$. The angular distributions of transition radiation generated by various electron energies are shown in Fig. 2 indicating more collimation for higher electron energies.

For transition radiation from 45°-incidence, the backward radiation emitted at 90° with respect to the beam axis with its spectral-angular distribution given by the contribution of parallel and perpendicular polarization radiation.

$$\frac{d^2 W^\parallel}{d\omega\, d\Omega} = \frac{e^2\beta^2}{2\pi^2 c}\left[\frac{2\sin\theta - \sqrt{2}\beta\cos\phi}{(\sqrt{2}-\beta\sin\theta\cos\phi)^2 - \beta^2\cos^2\theta}\right]^2 \tag{2}$$

and

$$\frac{d^2 W^\perp}{d\omega\, d\Omega} = \frac{e^2\beta^2}{2\pi^2 c}\left[\frac{\sqrt{2}\beta\cos\theta\sin\phi}{(\sqrt{2}-\beta\sin\theta\cos\phi)^2 - \beta^2\cos^2\theta}\right]^2, \tag{3}$$

where θ is the emission angle between the direction of emitted radiation and the $-z$ axis, while ϕ is the azimuthal angle defined in the xy-plane with respect to the $-x$ axis. The angular distribution of forward and backward transition radiation generated by a 25 MeV beam from 45°-oblique-incidence is shown in Fig. 3. Unlike the angular distribution for normal incidence which has an azimuthal symmetry, the distribution for 45°-oblique-incidence is both θ and ϕ dependent. The asymmetry appears only along horizontal angles but not along the vertical ones because the electrons intercept the interface with oblique incidence on the xz-plane. The distribution cross sections along horizontal and vertical angles are shown in Fig. 4 for the normal incidence (dashed-line) and for the forward radiation from 45°-incidence (solid). It can be clearly seen that only the distribution across horizontal angles is asymmetric. The asymmetry in angular distribution, however, vanishes for highly relativistic electrons. The angular distribution becomes closer to that of normal

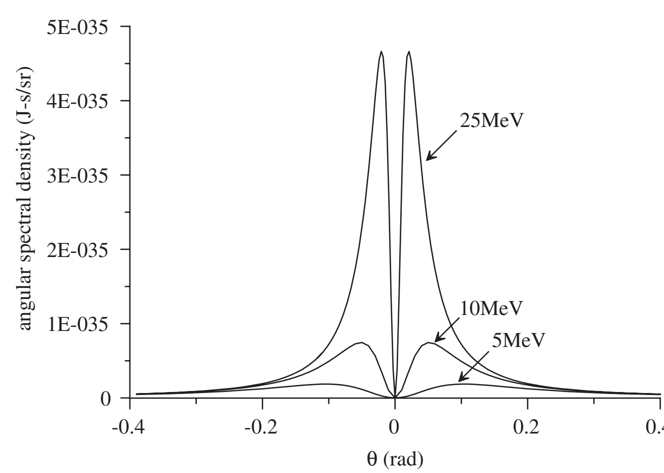

Fig. 2. Angular distributions of transition radiation for normal incidence generated by 5, 10 and 25 MeV electrons.