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Pre-wave zone effect in transition and diffraction radiation: Problems and solutions

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Abstract

Transition radiation (TR) and diffraction radiation (DR) appearing as a result of dynamic polarization of medium has widely been used for electron beam diagnostics during the last few years. A lot of techniques for electron beam diagnostics imply description of these phenomena assuming that the radiated area of the target is negligibly small in comparison with the radiation spot in the detector plane (far-field approximation). However, for high-energy electrons this area may reach a macroscopic dimension. In this Letter the general theory in the pre-wave zone is presented. Two new approaches for rejecting the pre-wave zone effect are described and analyzed. By installing a thin lens in the optical path of the measurement system or by developing a concave target, the pre-wave zone effect can be reduced or even rejected.

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1. Introduction

When a charged particle crosses an interface between two media with different dielectric constants (in ideal case when an electron crosses a vacuum—ideal conductor boundary) it induces currents changing in time [1] at the boundary. Those currents give rise in radiation called *transition radiation* (TR). TR has a tendency to propagate in two main directions: along the particle trajectory—forward transition radiation (FTR) and along the direction of specular reflection from the boundary—backward transition radiation (BTR). BTR has been widely used for different purposes because it allows registering the radiation at fine background conditions. The BTR application

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range is very broad: from transversal beam parameter measurements in optical wavelength range [2,3] upto the bunch length measurement and generation of intense radiation in mm and sub-mm wavelength range [4,5].

During the last few years the electron beam energies in the modern accelerators was incredibly increased. As a result new problems appeared, which were considered as negligibly small for moderate relativistic electron energies. One of them is the pre-wave zone effect in transition radiation. In simple words the pre-wave zone is the distance from the target, where the contribution of the radiation source size into the BTR spot size in the detector plane is significant and cannot be neglected. Afterwards, this effect has been considered in details by many theoreticians using different approaches [6–10]. However, all of them agreed that in order use the far-field zone approximation (the target radiating area is negligibly small), the distance from the target to detector must be larger than the parameter $\gamma^2\lambda$, where γ is the charged particle Lorentz-factor and λ is the radiation wavelength. Later the pre-wave zone effect was observed experimentally [11]. For example, at SLAC FFTB [2] the parameter $\gamma^2\lambda = 1.8$ km, which is really difficult to achieve. Moreover, when measuring the long wavelength transition radiation (where the BTR is coherent, i.e. the radiation wavelength is comparable to or smaller than the electron bunch length) [4,5] the pre-wave zone effect could be significant at lower energies.

Recently diffraction radiation (DR) appearing when the charged particle moves in the vicinity of a medium with impact parameter smaller than $\gamma\lambda/2\pi$ (effective electron field radius) has been suggested as a possible tool for non-invasive beam diagnostics [12–16]. DR is a relative effect to TR, because it is also produced as a result of dynamic polarization of medium. The backward diffraction radiation (BDR) in optical wavelength range has been measured and applied for transversal beam size diagnostics [17–20]. The BDR in mm and sub-mm wavelength range has been applied for non-invasive bunch length measurements [21,22]. However, it has similar problems with the pre-wave zone effect as TR.

So far nobody really knows how to deal with this effect. Some of them prefer to take into account the pre-wave zone effect [22] when comparison of the experiment with the theory is performed. However, the theory is very complicated for practical use. Moreover, in some cases the sensitivity of the far-field BTR and BDR to the electron beam parameters is higher.

This Letter describes the classical backward transition and diffraction radiation theory in far-field zone and in the pre-wave zone. The choice of backward radiation was made because in this case it is not necessary to take into account the self-field of the electron. It has been shown that the far-field theory is just a particular case of the pre-wave zone theory. Two possible ways for pre-wave zone suppression are considered. By installing a lens in the optical path or by choosing a concave target it might be possible to describe the BTR and BDR characteristics using the formulas obtained from the far-field theory.

2. Far-field approach

In this Letter I shall use the classical theory of backward transition radiation (BTR) and backward diffraction radiation (BDR) based on Huygen's principle of plane wave diffraction [1]. In this theory the particle field in introduced as superposition of its pseudo-photons. When the particle interacts with the target surface, the pseudo-photons are scattered from it converting into real ones and propagate in the direction of specular reflection. The difference from the plane wave is that the electron field strength depends on the distance from the particle.

Let an electron move along the z-axis which is perpendicular to an ideally conducting target plane. At the zero time moment ($z/\beta = 0$, where $\beta = v/c$ is the electron velocity in units of the light velocity) the electron crosses the boundary. Each point of the target surface can be represented as an elementary source. In this case two polarization components of TR field can be represented as a superposition of the waves from all elementary sources at certain distance:

$$E^l_{x,y} = \frac{1}{4\pi^2}\iint E^i_{x,y}(x_s, y_s)\frac{e^{i\varphi}}{r}dy_s\,dx_s. \tag{1}$$