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Pre-wave zone studies of Coherent Transition and Diffraction Radiation

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ABSTRACT

Advanced accelerator technology, based on plasma structures, requires high brightness electron beams, which can be used also to drive advanced radiation sources. Indeed, electron beams to be injected into the plasma and accelerated in the plasma channel are characterized by small transverse size and ultra-short time duration, allowing the production of coherent radiation in the THz range. In the present work we report both theoretical and experimental studies on the spatial/angular distribution of Coherent Transition and Diffraction Radiation in the pre-wave zone.

1. Introduction

Transition and Diffraction radiation (TR and DR, respectively), though deeply investigated, still excite great interest from their widely use in electron beam diagnostics, due to a strong dependence of intensity and angular distribution on beam size, angular divergence and energy. In addition, TR and DR, generated by ultra-short (sub ps) electron beams, is increasingly used as source of coherent THz radiation for a wide variety of applications spanning from science to biology, from medicine to industry [1]. Therefore a great interest is growing in the optimization of compact sources of intense THz radiation as those driven by plasma-based accelerators. In the present work we investigate numerically and experimentally the spatial/angular distribution of both coherent transition (CTR) and diffraction (CDR) radiation in pre-wave zone as produced at the SPARC_LAB test facility [2] by high brightness electron beams as needed for particle driven plasma acceleration. First measurement of CDR spatial distribution at THz frequencies are also reported.

After a brief history about TR and DR observation, in Section 2 we introduce the theoretical background, needed for introducing and discussing the model we developed in order to validate the measurement. In Section 3 we describe the experimental geometry and apparatus used to acquire the CTR/CDR spatial distribution, and we report the electron beam longitudinal phase space optimized for the production of THz radiation. Section 4 is dedicated to the comparison of measurement data with numerical model at different THz frequencies. Finally, the results are discussed in Section 5.

2. Theory and simulations

Transition radiation is emitted when a charge particle crosses the boundary between two media with different dielectric constants. The theory of TR was discussed in several works [3,4]. The first analytical expression for TR angular distribution was obtained in [3] and today it is widely known as Ginzburg–Frank formula. Diffraction radiation was first observed on periodical structure and today this special case of the DR is called Smith–Purcell radiation [5]. Later the DR was studied in [6,7], where the "pseudo photon" method[1] was used in order to obtain the analytical expression for DR angular distribution. In both cases the radiation was considered under several conditions, such as infinite perfectly

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[1] Weizsacker–Williams method of virtual quanta [8], where the electron field is replaced with equivalent electromagnetic wave.

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conducting target and wave zone approximation, which impose some restriction on the field of application. Later further studies were conducted in order to generalize the obtained results beyond the ideal conditions, therefore finite screen size and observation in pre-wave zone [4,9–11]. Here and further we use terms wave and pre-wave zones as they were used by Verzilov in [9].

The wave zone approximation for TR and DR can be applied if several conditions are satisfied. The detector should be placed beyond the pre-wave zone of radiation with respect to the source. For TR and DR the size of the pre-wave zone can be estimated as minimum out of $\lambda\gamma^2$ or target size, here λ is the wavelength of radiation and γ is the Lorentz factor of the bunch. In approximation of the infinite screen, for THz radiation wavelength and for electron beam with energy of the order of 100 MeV the wave zone condition is satisfied at several meters from the source. Thus, in most of the cases, we can work either in a pre-wave zone or we should use a suitable optical system. In order to use the infinite screen approximation the conditions should be imposed on the target size. The TR and DR can be considered as an interaction between electron field and the target material. At high energy, due to the relativistic effects, the electron field becomes a flat disc in a plane perpendicular to the electron velocity vector, whose "effective" size can be estimated as $\sim \lambda\gamma$ [4,11,12]. For the wave zone approximation [3,6] the size of the target was considered as infinite with respect to the electron field, and in order to satisfy this condition the size of the target should be larger than the effective size of the electron field. For optical wavelengths this condition is normally achieved even at GeV energies, while for THz wavelengths the effective size of the field can be either comparable with the size of the target or exceed it, even at low electron beam energies, i.e. few hundreds MeV. Thus for THz radiation the size of the pre-wave zone at some point may be given by the size of the target. In this work pre-wave zone effects as well as effects caused by finite screen size with respect to the effective size of the field have been studied theoretically and experimentally, and the measured CTR/CDR spatial distribution compared with the numerical model.

In our work the pseudo photons approach is used. The field of the particle is considered as consisting of pseudo photons, which become real during the interaction with the target material [12]. For ultrarelativistic electrons ($\gamma \gg 1$) the transverse components of the electric field of the single particle can be written as:

$$E^e_{x,y} = \frac{e\omega}{\pi\gamma v^2}\frac{x,y}{\rho}K_1\left(\frac{\omega\rho}{v\gamma}\right), \qquad (1)$$

where e is the electron charge, ω is the radiation angular frequency, v is the particle velocity, $\rho = \sqrt{x^2+y^2}$, with x and y the coordinates in the plane perpendicular to the beam trajectory, $E^e_{x,y}$ is the component of the electric field along X and Y (Fig. 1), k is the wave vector, and K_1 the modified Bessel function of the second kind. In the following simulations the longitudinal component of the electron field was neglected, being γ times smaller. As particular case we will consider DR emission. According to the pseudo photons method we replace the electron field with electromagnetic wave. Thus the outgoing radiation can be considered as scattering on the target and calculated by the Huygens–Fresnel principle:

$$E^i_{x,y}(x',y',\omega) = -\frac{ik}{2\pi}\int_{-b/2}^{b/2}\int_{-a/2}^{-d/2}E^e_{x,y}(x,y)\frac{e^{ikR}}{R}dxdy + \frac{ik}{2\pi}\int_{-b/2}^{b/2} \times \int_{d/2}^{a/2}E^e_{x,y}(x,y)\frac{e^{ikR}}{R}dxdy, \qquad (2)$$

where x', y' are the coordinates of the observation point, $R = \sqrt{Z^2+(x'-x)^2+(y'-y)^2}$, and Z is the distance from the target to the observation plane. Here a and b are the sizes of the rectangular target and d is the size of the slit in it. The two integrals in Eq. (2) represent the DR field from the two semi-planes. In case of effective field size smaller than the target size, the finite limits in the integrals would tend to infinite.

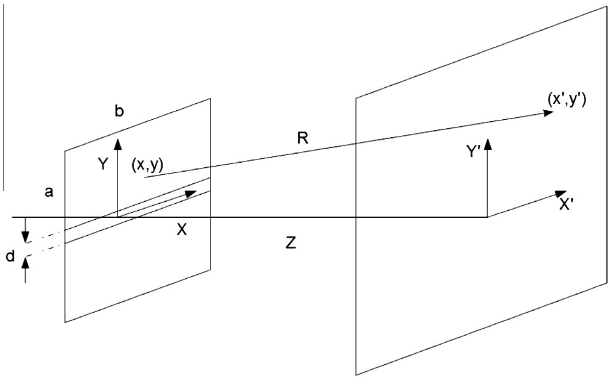

Fig. 1. Diffraction radiation geometry.

So far a single electron has been considered. In practice, we have to deal with a beam of N electrons (typically $N \approx 10^9$). The full intensity of radiation, basically any kind of radiation, emitted by a beam of N electrons can be presented in the following form:

$$I(\omega) = I_e(\omega)[N + N(N-1)F(\omega)], \qquad (3)$$

where $I_e(\omega)$ is the radiation emitted by a single electron, and $F(\omega)$ is the beam form factor. The beam form factor, in general, is the Fourier transformation of the normalized 3D distributions, and characterizes the level of coherence with respect to the radiation: the completely incoherent beam has form factor equal to 0, while 1 corresponds to completely coherent beam. In the cases reported in the paper the full form factor is replaced with its longitudinal component F_l, because the contribution of the transverse one is negligible [13]:

$$F_l(\omega) = \left|\int S_l(z)e^{-\frac{i\omega z}{c}}dz\right|^2, \qquad (4)$$

where $S_l(z)$ is the normalized beam longitudinal distribution, and c is the speed of light. Therefore coherent radiation is observed at wavelengths larger than the beam longitudinal size. In the THz region coherent radiation can be produced by beams, whose bunch duration is of the order of 100 fs and less. Here we assume a beam with Gaussian longitudinal distribution. For simulations the DR target made of 2 half planes (3×3 cm each) separated by a 3 mm gap was used, while the effective size of the field for used parameters (i.e. $\gamma = 200$ and $\lambda = 600$ µm, corresponding to 0.5 THz radiation frequency) is $\lambda\gamma \approx 12$ cm. In our work frequencies up to 5 THz and lower were considered. At low frequencies, such as 0.5 THz, the beam form factor is close to 1, which allows to consider a completely coherent beam for simulations. For the higher frequencies the beam form factor is less than 1. The spectral-angular distribution in the pre-wave zone has been calculated by means of the following expression:

$$\frac{d^2U}{d\omega d\Omega} = cR^2\left[\left(\sum_{i=1}^{N}E^i_x\right)^2 + \left(\sum_{i=1}^{N}E^i_y\right)^2\right], \qquad (5)$$

where N is the total number of electrons in the bunch, $E^i_{x,y}$ is the electric field component of radiation emitted by the single particle (Eq. (2)) and Ω is the solid angle. The simulation results for the vertical component are presented in Fig. 2a and b and show the dependence of CDR angular distribution on the distance Z between the source and the detector. The CDR angular distribution in pre-wave