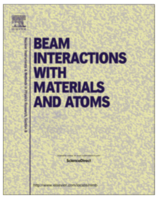
Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb



Ratio of the contributions real and virtual photons diffraction in thin perfect crystals. Comparison of calculation and experiment

Yu.A. Goponov, S.A. Laktionova, M.A. Sidnin, I.E. Vnukov *

Belgorod National Research University, Belgorod, Russia

ARTICLE INFO

Article history:
Received 9 December 2016
Received in revised form 7 February 2017
Accepted 24 February 2017
Available online xxxx

Keywords:
Thin crystal
Fast electron
Parametric X-ray radiation
Diffracted transition radiation
Diffracted bremsstrahlung

ABSTRACT

To evaluate and improve the previously proposed method of calculating diffracted photon yields in thin perfect crystals, a comparison between calculated and experimental results in wide range of photons and electrons energy was carried out. It is shown that the proposed method describes all investigated experimental results for bremsstrahlung diffraction and transition radiation one with an error less than ten-fifteen percent. Consequently, the method may be used for calculation of the electron beam divergence influence on the diffracted transition radiation angular distribution.

1. Introduction

Beam size and angular divergence are one of the most important parameters in the field of accelerators, and many beam diagnostic methods have been developed. For electron accelerators, one conventional method is to use optical radiation such as fluorescent light, optical transition radiation (OTR) [1], optical diffraction radiation (ODR) [2], and Smith-Purcell radiation [3]. However, it was recently found that radiation in optical region cannot be used for profile measurements of an electron beam at modern accelerators and the projected electron–positron linear colliders such as International Linear Collider (ILC) [4] and Compact Linear Collider (CLIC) [5] because it becomes coherent when the bunch size of the beam is sufficiently small [6] in comparison with the measured photons wavelength.

In order to avoid the coherence, photons with shorter wavelength are required. Some years ago, the use of radiation in the X-ray region, the so-called parametric X-ray radiation (PXR) were proposed [7,8]. To a first approximation, PXR can be considered as coherent scattering of the charged particle's electromagnetic field on the electron shells of periodically arranged atoms in a target, see e.g. [9] and reference therein. It is emitted in the Bragg direction when a relativistic charged particle moves across a crystalline target. Recently, proof-of-principle experiments on beam profile measurements using PXR have been demonstrated at SAGA Light Source (SAGA-LS) [8,10] and Mainzer Microtron (MAMI) [11].

For fast electrons PXR is always accompanied by radiation diffracted in the crystal which is born directly inside the target or on its surface [12,13]. In the first case we can talk about diffracted bremsstrahlung (DB) and in the second one about diffracted transition radiation (DTR). The first is dominated by under the condition $\omega \gg \gamma\omega_p$, where ω is photon's energy, γ-Lorentz factor, and ω_p-plasma frequency of the medium, [14,15] and the second under opposite conditions [13]. If condition $\omega \sim \gamma\omega_p$ is true, the contributions of both mechanisms of radiation are observed [12]. Method for calculation of real photons diffraction contribution into measured photon yield was suggested in Ref. [16].

In Ref. [17] using the method [16] we have shown that for high electron energy the DTR angular density becomes essentially larger than PXR one, therefore the DTR angular distribution measurements are more preferable for estimation of high energy electron beam parameters in comparison with PXR one.

Advantage of a beam diagnostic method using diffracted transition radiation for future electron–positron colliders [4,5] is connected with the fact that the beam divergences in both planes are not so small (of the order of tens μrad) and is by far greater than the transition radiation characteristic angle γ^{-1}. Therefore measurements of DTR angular distributions in both planes provides estimation of electron beam divergences in these planes and the electron beam spatial sizes if we know the beam emittance which may be calculated or measured on the previous stage of acceleration [18].

---

* Corresponding author.
E-mail address: vnukov@bsu.edu.ru (I.E. Vnukov).

http://dx.doi.org/10.1016/j.nimb.2017.02.068
0168-583X/© 2017 Elsevier B.V. All rights reserved.

Please cite this article in press as: Y.A. Goponov et al., Ratio of the contributions real and virtual photons diffraction in thin perfect crystals. Comparison of calculation and experiment, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.02.068

The transition radiation arises when a fast charged particle crosses an interface of media with different dielectric constants. If one medium is a single crystal and another is vacuum, transition radiation is produced at the entrance surface of the crystal and then a part of its satisfying Bragg's law is diffracted by the crystal target and emitted in the Bragg direction. PXR is generated in the crystal volume, therefore the DTR contribution in comparison with PXR one is comparatively large for thin crystals only. As it was shown in Ref. [19] the DB contribution may be also clearly observed for thin crystals only.

Contribution of real photons diffraction was observed not only in the above mentioned experimental works, however quantitative comparison between calculations and experiments up to date was not made jet. Consequently, it is clear that a comparison of the results of total emission angular distribution measurements in thin crystals with calculations taking account all emission mechanisms and the experiments features is important and relevant.

2. Calculation technique

As it was remarked above the main goal of the paper is to compare known results of the experiments devoted to investigation of X-ray emission from the thin crystal irradiated by fast electrons with calculation in accordance with the method proposed in Ref. [16]. It takes into account such types of the electron emission in crystals as PXR, DB and DTR. The special features of the method are following:

(a) The kinematic PXR theory [20] is used;
(b) The bremsstrahlung suppression due to the density effect [21] is taken into account;
(c) The so-called Garibian formula for the transition radiation (TR) spectral-angular distribution [9] is used. It is supposed that the TR is generated directly at the inlet into crystal and then it is diffracted therein. TR photons polarization isn't taken into account;
(d) The electron beam divergence and multiple scattering in the crystal, the emission collimation angle and other experimental conditions are taking into account in accordance with the methodology of Ref. [22].

The main peculiarity of the method [16] is the definition of the X-ray reflectivity in a perfect crystal. As it is well known the angular distribution of diffracted radiation relative to the center of reflex along axis x(see, for example, [12]) can be represented as:

$$Y_{DR}(\omega,\theta_x) = \int d\omega \int \frac{d^2I^*}{d\omega d\Omega} R(\omega,\vec{n},\vec{g},\Theta_D) S(\omega,\vec{n}) d\Omega, \qquad (1)$$

where $\frac{d^2I^*}{d\omega d\Omega}$ is a spectral-angular distribution of the radiation, taking into account the divergence of the primary electron beam, multiple electron scattering an so on. $R(\omega,\vec{n},\vec{g},\Theta_D)$ is reflectivity for these directions of the vectors $\vec{n}$ and $\vec{g}$, defined the crystal orientation angle Θ and the location of the detector Θ_D. Here, $\vec{n}$ is the individual vectors corresponding to the initial photon (with the energy ω), $\vec{g}$ is the reciprocal lattice vector. $S(\omega,\vec{n})$ is a function taking into account the photon absorption in the crystal and the geometry of the experiment.

To determine the output of the diffracted radiation we need information about $R(\omega,\vec{n},\vec{g},\Theta_D)$. In accordance with [23] for a fixed photon direction $\vec{n}$ from the beam with the spectral-angular distribution of $d^2I^*/d\omega d\Omega$ satisfying Bragg's condition for photons with energies of ω only photons in the energy range $\Delta\omega = \omega\cos(\Theta_B)/\sin(\Theta_B)\Delta\Theta$ will be reflected. For unpolarized radiation and lack of absorption $\Delta\Theta = 2\cdot\eta\Delta\theta_0$, where $\Delta\theta_0 = 2\cdot\delta/\sin 2\Theta_B$ is an amendment to the Bragg angle Θ_B because of the refraction of waves in a crystal, $\delta = (\omega_p/\omega)^2/2$ is a difference between the refractive index from 1, and $\eta = f(\vec{g})(1+\cos(2\Theta_B))/2f(0)$. $f(\vec{g})$ is the Fourier component of the spatial distribution of electrons in a crystal atom.

The characteristic parameter of the model is the primary extinction length, which is dependent on the photon energy, reflection order and the parameters described above, and may be written as [23]:

$$l_{ex} = d/(2\bar{\xi}\sin\Theta_B), \qquad (2)$$

where $d$is an inter planar distance, and $\exp(-2\bar{\xi})$ is an impairment of the intensity of the primary wave as it passes through a plane with the reciprocal lattice vector $\vec{g}$.

For the part of the crystal with a thickness much smaller than l_{ex}, the probability of reflection of photons with an energy of ω and direction $\vec{n}$, for which the Bragg condition is satisfied, is proportional to the number of planes crossed by them [23]. Therefore, the dependence of the number of photons, which have not undergone the reflection, on the way length in the crystal t can be written as $N_\gamma(t) = N_\gamma(0)\exp(-t/l_{ex})$ [23], where $N_\gamma(0)$ is the number of photons at a starting point.

Taking into account the Bragg reflection, photon absorption and scattering on atoms the dependence of the number of photons on passable way can be rewritten as:

$$N_\gamma(\omega,\vec{n},t) = N_\gamma(0)\exp(-\mu_{tot}(\omega,\vec{g},\vec{n})t), \qquad (3)$$

where $\mu_{tot}(\omega,\vec{g},\vec{n}) = \mu(\omega) + \mu_{dif}(\omega,\vec{g},\vec{n})$ is a total coefficient of linear absorption of radiation with energy ω, for the direction of the crystal reflecting plane $\vec{g}$ and the photon velocity direction $\vec{n}$. Here $\mu(\omega)$ is a linear absorption coefficient of photons due to the all processes on separate atoms and $\mu_{dif}(\omega,\vec{g},\vec{n}) = 1/l_{ex}(\omega,\vec{g},\vec{n})$ is due to diffraction. The possibility of such notation allows us to use a well-known in experimental physics method of statistical simulation of photon transmission through a matter for perfect crystals also, see [16] for details.

We may ignore the influence of the radiation polarisation on the diffraction process for small Bragg angles only when $\cos(2\Theta_B)$ is about one. In this case photons with σ and π polarization are diffracted with close efficiency and have the same extinction length value. In the contrary case the extinction length for photons with different polarization differs. As the transition radiation is polarized in outlet plane [9] the simulation process was made for both polarization components separately.

3. Comparison of calculation and experiment results

The main aim of this study is to compare results of the experiments where contribution of real photon diffraction was clearly observed with the calculation in accordance with techniques reported in Ref. [16] and briefly described in the previous section. These are experiments with thin crystals, strong emission collimation and known values of photon yield [12,14,15] and measurements for large observation angles, where PXR contribution and diffracted real photons one are separated by the emission angle relatively Bragg direction [13].

The experiment [14] was performed at Kharkov linear accelerator. Electron beam energy of 900 MeV with divergence $\vartheta_e \sim 0.2$ mrad hits on a silicon crystal thickness of 30 μm. Reflection (2 2 0) in Laue geometry was being investigated. The system of detecting with the round aperture diameter of 5 mm was located at a distance of 8.2 m from the crystal at an angle

Please cite this article in press as: Y.A. Goponov et al., Ratio of the contributions real and virtual photons diffraction in thin perfect crystals. Comparison of calculation and experiment, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.02.068